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Handedness development during infancy could be represented as a progressive expansion of a hand-use preference across a wider range of increasingly complex skills. The goal of the present study was to explore the development of role-differentiated bimanual manipulation (RDBM) during infancy as an expansion of the development of handedness for acquiring objects and unimanual manipulation. Infants were categorized according to their handedness status for acquiring objects (right-hand, left-hand, or no distinct hand-use preference). This status was determined from nine monthly assessments performed during 6-14 month period and resulted in a sample of 90 normally developing infants (30 right-handers, 30 left-handers, and 30 no preference infants). These infants were tested monthly from 9 to 14 months for unimanual manipulation and RDBM handedness. The results of the multilevel analyses showed that lateralization of handedness for toy acquisition increased during 6-12 month interval and decreased thereafter. Lateralization of handedness for unimanual manipulation and RDBM increased during 9-14 month period. Furthermore, handedness for toy acquisition was found to be positively related to handedness for unimanual manipulation, which, in its turn, was positively related to handedness for difficult, but not simple, RDBM. Also, handedness for toy acquisition was positively related to handedness for difficult RDBM. Thus, it was concluded that handedness for toy acquisition concatenates into unimanual handedness which further influences the development of RDBM handedness.

DEVELOPMENT OF HANDEDNESS FOR ROLE-DIFFERENTIATED BIMANUAL MANIPULATION OF OBJECTS IN RELATION TO THE DEVELOPMENT OF HAND-USE PREFERENCES FOR ACQUISITION DURING INFANCY

by

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APPROVAL PAGE

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CHAPTER I

INTRODUCTION

Handedness as a Way to Study Hemispheric Lateralization

Handedness is usually defined as a preference to use one hand more than the other, or that one hand performs faster or more skillfully on certain manual tasks that are not likely to have been practiced. For humans, there is a remarkable asymmetry in the distribution of handedness with no more than 12% of the population ever showing a left hand preference (e.g., Annett, 1985). Since the precise control of movements of the hands and fingers derives from the activity of neurons in the contralateral hemisphere, the predominance of right handedness in the population likely means that the left hemisphere activity is responsible for the expression of right handedness. Moreover, neurological evidence from anatomical, physiological, and behavioral studies reveals that the left hemisphere is responsible for controlling other fine motor movements for the majority of people, including the fine motor abilities involved in speech production. Therefore, handedness and hemispheric control of speech, language, and other fine motor movements often are related in research investigations.

Hemispheric lateralization refers to the ability of the two cerebral hemispheres to operate and process information differently. Thus, the left hemisphere has been shown to be responsible for speech production, whereas the right hemisphere is considered to be responsible for processing the emotional aspects of language, usually called emotional prosody (Gazzaniga, Ivry, & Mangun, 2009). Moreover, the right hemisphere has been reported to be superior in processing environmental noises, melodies, and rhythms, whereas the left hemisphere is superior for making phonological distinctions of language-related sounds (Kimura, 1973). The right hemisphere is considered to be superior in visuospatial processing such as the perception of faces and differentiation between faces and non-faces, whereas the left hemisphere is capable of facial recognition and generation of voluntary facial movements (Gazzaniga et al, 2009).

Previous research suggested that the left hemisphere excels at processing analytic/local details whereas the right hemisphere is superior for processing more holistic/global aspects of events (the big picture) (Bogen, 1969; Levy, 1969, 1972; Navon, 1977; but see Fairweather, Brizzolara, Tabossi, & Umilta, 1982, and Trope, Rozin, Nelson, & Gur, 1992). Also, Sergent (1982a, 1982b) proposed that the left hemisphere is better able to process the detailed high frequency information in events, whereas the right hemisphere is better able to process the less detailed low frequency information in events (but see Fendrich & Gazzaniga, 1989).

The right hemisphere was reported to be more effective in drawing causal inferences, whereas the left hemisphere excelled more in causal perception (Roser, Fugelsang, Dunbar, Corballis, & Gazzaniga, 2005). In addition, the left hemisphere appears to be more likely to seek patterns of events and to build hypotheses whereas the right hemisphere tends to approach problem solving in a simpler manner (Wolford, Miller, & Gazzaniga, 2000). Davidson (1992) observed greater activation in the frontal region of the left hemisphere in response to positive emotions, and arousal in the frontal region of the right hemisphere in response to negative emotions in infants and adults. He proposed that the hemispheres differed in their emotional tone and expression with the left hemisphere controlling positive "approach" activities and the right hemisphere controlling negative "withdrawal" activities.

Thus, many different psychological functions are unequally distributed (i.e., lateralized) between the two hemispheres and handedness is one of these lateralized functions. Since handedness represents an easily observable sensorimotor skill that reflects a distinct lateralized asymmetry in hemispheric functioning (Serrien, Ivry, & Swinnen, 2006), the early development of handedness might serve as a model for the exploration of the development of other forms of hemispheric lateralization (Michel, 1983, 1988).

It should be emphasized that handedness in adults is not only an indicator of hemispheric asymmetry of motor coordination, but also an aspect of hemispheric specialization of function (Beaumont, 1974) that is related to other aspects of hemispheric specialization such as speech (Annett, 1975). Therefore, handedness status may affect the prognosis of recovery of function after unilateral brain damage (Hecaen, De Agostini, & Monzon-Montes, 1981). In addition, atypical structural asymmetries of the brain and atypical patterns of handedness (e.g., left-handedness or variable handedness) as well as right hemisphere specialization for fine motor movements and language have been associated with certain aspects of individual cognitive style (Mebert & Michel, 1980; Newland, 1984; Peterson, 1979), particular neurobehavioral dysfunctions such as learning disabilities (Geschwind & Behan, 1982; Grouios, Sakadami, Poderi, & Alevriadou, 1999; Narbona-García, 1989; Nichols & Chen, 1981), autism (Barry & James, 1978; Bryson, 1990; Colby & Parkinson, 1977; Kleinhans, Müller, Cohen, & Courchesne, 2008), dyslexia (Hugdahl et. al, 1998), stuttering (Costa & Kroll, 2000), bipolar disorder (Stahlberg, Soderstrom, Rastam, & Gillberg, 2004), and schizophrenia (Ribolsi et al., 2009; Sommer, Ramsey, Kahn, Aleman, & Bouma, 2001). Perhaps, the exploration of early trajectories of lateralized hand-use might provide insights into our understanding of the development of other neurobehavioral dysfunctions.

The investigation of handedness development must adopt a life-span approach, beginning with the earliest manifestations of handedness in simple manual actions during prenatal development and in neonates. Thereafter, the examination of handedness development must proceed through childhood and adulthood. It is important to emphasize that the adult handedness, which appears to be a manifestation of the underlying hemispheric specialization of function, must have its origins in infancy (when the individual's handedness patterns are likely established) because even children as young as three years, exhibit adult-like patterns of handedness lateralization (Annett, 1972; Connolly & Elliott, 1972).

In order to investigate the development of hemispheric specialization appropriately, one needs a well-defined example of lateralization of function that can be identified early in infancy. For most lateralized brain functions (e.g., language, cognitive, and emotional processing), a researcher must employ extensive inferential judgment to relate the observed behavioral differences of infants to differences in their cognitive or emotional processing. Such inferences rely on operational definitions that may generate more controversy than understanding about differences in the cognitive and emotional processing.

In contrast, distinct differences in manual behavior require little inference about their relation to handedness. Even very young infants (although they cannot follow instructions and be tested on manual tasks that assess hand speed, skill, and accuracy) often choose to use one hand vs. the other. Although researchers call this behavior a preference, it is not a choice similar to ice-cream versus cake, but rather it is likely that infant's preferred hand-use reveals a difference in the neuromotor mechanisms controlling each hand's performance. Thus, what appears to be a choice to use one hand versus the other is rather the consequence of the differences in the sophistication of the mechanisms controlling the hands. These differences result in faster, more accurate, and more complex actions from one hand compared to the other. Infant hand-use preference reflects a differential control of hands that involves skill, speed, and accuracy of movement, and each of these characteristics of manual action can be studied experimentally at older ages.

Charting the development of the manifestation of handedness makes the development of human cerebral asymmetry uniquely transparent. Studying handedness may bring important insights about the emergence and trajectories of other forms of hemispheric specialization of function. Thus, investigation of handedness might help us create a developmental model of hemispheric lateralization that may apply to other aspects of psychological functioning that are more difficult to study during infancy.

Theories of Lateralization Development

Before studying developmental patterns of hemispheric lateralization, we need to establish that hemispheric lateralization is developing. For more than four decades, two competing theories of the developmental origins of hemispheric lateralization have been explored in research. Lenneberg (1967) proposed the progressive lateralization theory (PLT) and argued that an individual brain develops progressively from a point of little or no lateralization toward stages of greater and more complete lateralization of functions. The continuous character of this development was used to explain a relation among patterns of lateralization at different ages. Lenneberg's (1967) idea of "equipotentiality" (initial zero hemispheric lateralization) was later rejected by many researchers reporting some forms of anatomical lateralization observed prenatally. Moreover, some asymmetry exists even before the conception of an individual since ovum is asymmetrical before it gets fertilized (Morgan, 1977).

In contrast, the invariable lateralization theory (ILT) (Kinsbourne, 1975, 1981; Witelson, 1980) proposed that infants' brains are virtually completely lateralized at birth and cerebral asymmetry does not develop postnatally. Rather, cerebral asymmetry only appears to develop because as many cognitive, emotional, and social abilities develop increasing complexity, they begin to rely on the inherent asymmetrical processing functions of the brain. This increasing reliance creates the appearance of developing asymmetry whereas the asymmetry of cerebral functional organization was always present. If infant handedness is simply a reflection of a consistent underlying asymmetry of cerebral functioning, then any variability in measurement of handedness status would be constrained by the infant's cerebral asymmetry. Consequently, frequent measures of handedness throughout infancy can serve as relatively independent assessments of that underlying cerebral asymmetry (despite any disruptions of hand-use that might be produced by factors such as the infant's state or postural control).

The invariant lateralization theory assumed that cerebral hemispheres are pre-programmed for a particular degree and direction of lateralization, and all emerging skills would exhibit the original innate lateralization and would not be influenced by earlier emerging skills. Although ILT accounted for early manifestation of hemispheric specialization of function, it failed to advance our understanding of the development of hemispheric lateralization because the theory failed to specify the mechanism by which lateralization could be programmed. If this mechanism is genetic, then it is not clear how the spatial asymmetry of oocyte could affect gene expression and change the resulting lateralization patterns (Morgan, 1977).

However, some previous research *seems* to support the invariant lateralization approach. Thus, Hepper, Wells, and Lynch (2005) found that fetus's movement patterns are predictive of later lateralization patterns. Hepper et al. (2005) found a strong relation between the hand preferred for prenatal thumb sucking and handedness manifested at 10-12 years of age (100% of right-handed fetuses remained right-handed, and 67% of left-handed fetuses remained left-handed, whereas 33% of left-handed fetuses became right-handed) and concluded that "prenatal lateralized behavior is predictive of postnatal lateralized motor behavior" (p. 314). If valid, then such results would mean that 15 week old fetuses are manifesting lateralization patterns for handedness similar to those exhibited in later childhood. This would support the theory that hemispheric specialization is invariant.

Unfortunately, Hepper et al. (2005) used an ultrasound procedure to define the fetus's thumb position in relation to the face. At the time those ultrasounds were recorded, it was very difficult to ensure accurate 3D information about the position of the mouth and thumb (indeed, all relative positions), but accurate information about the orientation of the fetus and the signal projecting/recording device is essential. Examining video of ultrasounds without knowing the position of the wand (as was done in Hepper et al., 2005) might create illusory hand-in-mouth images. Instead, prolonged (as much as an hour) recording with shifting positions of the wand was needed to build confidence about the position of limbs and mouth. This procedure was implemented by de Vries, Wimmers, Ververs, Hopkins, Savelsbergh, and van Geijn (2001), who failed to replicate Hepper's earlier results (Hepper et al., 2005). Thus, de Vries et al. (2001) did not find any lateralized preference of unimanual hand-head contacts in fetuses of 12 to 38 weeks of gestational age observed longitudinally in serial ultrasound recordings.

Therefore, there is no reliable evidence that hemispheric specialization for handedness is either initially equipotential or invariant in its development. It has been proposed that in order to understand the development of hemispheric specialization, a modification of the progressive lateralization theory (MPLT) is needed (Michel, 1983, 1988, 1998). This modification proposes that any manifested lateralization of function does not begin from a point of zero laterality; however, the lateralization of the function will change during development. Thus, hemispheric lateralization is necessarily influenced by the developmental history of an individual with earlier lateral biases contributing to later-developing biases. Consequently, handedness development may be represented as a progressive expansion from a primitive form of lateralized function across a wider range of increasingly complex skills. Handedness development may begin with the influence of the asymmetry of the neonate's supine head orientation preference (HOP) affecting the infant's hand/arm movements and visual-manual experience; which, in turn, expands into hand preferences for reaching, and subsequently into hand preferences for acquiring objects, manipulating them, subsequently with role-differentiated bimanual manipulation (RDBM), and expanding into hand-use preferences for construction and tool using skills (Michel, 2002).

Developmental Cascade of Handedness

Using the modified progressive lateralization theory, let us propose a scenario for handedness development (cf., Michel, 2002). Development of hemispheric specialization for handedness might begin with the constraints of the asymmetrical oocyte (Morgan, 1977) within the asymmetry of the uterine environment under the influence of hormones and the right-to-left developmental gradient (Best, 1988). Asymmetries of the fetal position in utero (Fong, Savelsbergh, van Geijn, & de Vries, 2005; Michel & Goodwin, 1979) expand to influence neonate's supine head orientation preference (Kurjak et al., 2004; Michel, 1981; Michel & Goodwin, 1979; Schaafsma, Riedstra, Pfannkuche, Bouma, & Groothuis, 2009), which in turn, leads to lateralized asymmetries in the hand

and arm activation, as well as visual, tactile and proprioceptive feedback that the infant receives from the hand and arm movements (Michel & Harkins, 1986). The underdeveloped corpus callosum (Cernacek & Podivinsky, 1971; Salamy, 1978) prevents effective interhemispheric communication during infancy, thus, restricting early sensorimotor experiences primarily to one hemisphere (the hemisphere contralateral to the active hand). These sensorimotor asymmetries facilitate the formation of the "action systems" that underlie the lateralized use of the forelimbs (Michel, 1988; Michel & Harkins, 1986). As a result, the head orientation preference influences early development of hand-use preferences for reaching toward objects (Michel, 1981; Michel & Harkins, 1986).

Furthermore, hand-use preferences for reaching further cascade into preferences for acquiring objects (Michel, 1983). These object acquisition preferences then expand into hand-use preferences for unimanual manipulation as each hand independently manipulates a single toy (Hinojosa, Sheu, & Michel, 2003). Hand-use preferences in object acquisition and unimanual manipulation would influence hand-use preferences for the later-developing role-differentiated bimanual manipulation (RDBM) – when two hands perform different but complementary movements on one or several objects (Michel, 1998; Michel, Ovrut, & Harkins, 1985). The development of RDBM requires sophisticated bimanual coordination and considerable interhemispheric transfer of information. Eventually, manual preferences for RDBM form the foundation of handedness in tool use and construction skills (Vauclaire, 1984) which involve higher-level cognitive skills such as imitation of complex actions, planning, decision making, and the ability to account for spatial and temporal characteristics of objects and situations.

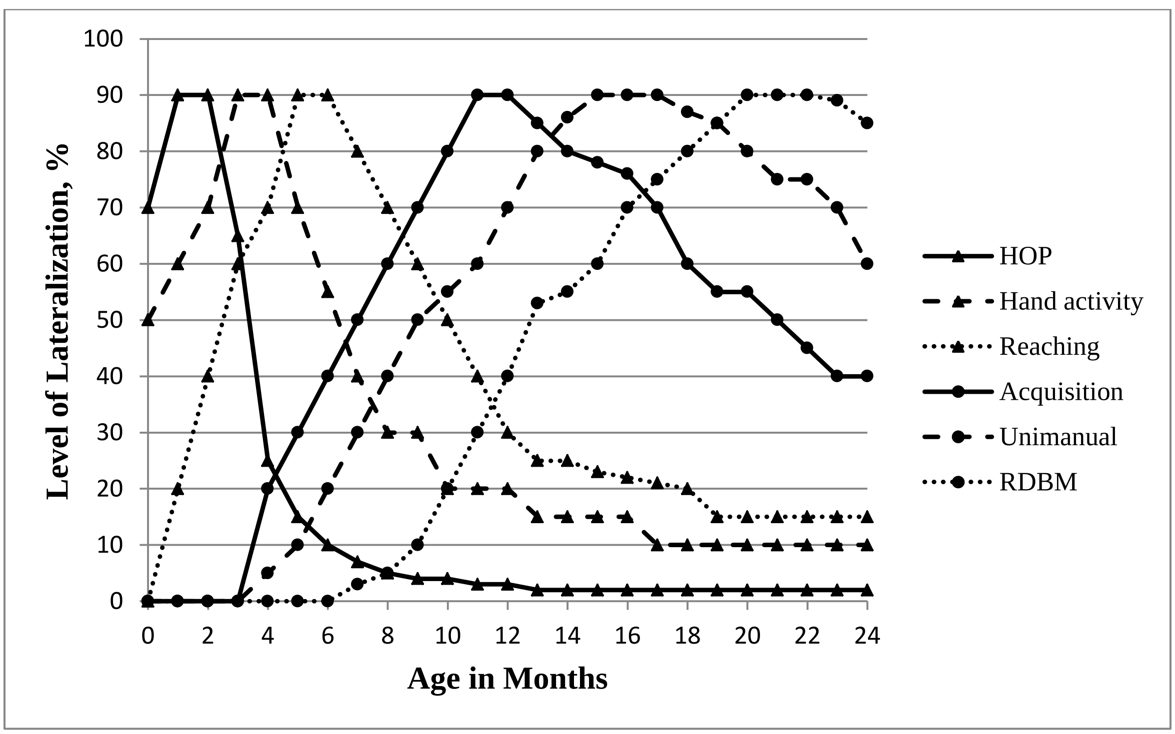
Note that handedness is not emerging independently in any succession of more complex manual skills, but rather handedness for simple reaching and acquisition of objects is getting expanded onto later-emerging more complex skills. It could be hypothesized that at the time when a particular motor skill is emerging, clear hand-use preferences would likely not be observed in this skill. Thus, 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 deliberate planning (Kimmerle, 2010). These early role-differentiated bimanual manipulations may be performed in the absence of interhemispheric communication and would involve minimum level of hemispheric specialization. They would be of short duration and heavily constrained to the properties of the objects. Thus, one may expect to observe less hand-use preference during earlier role-differentiated bimanual manipulations. However, as the RDBM actions become more sophisticated and less constrained by object properties, a hand-use preference will be expressed.

Furthermore, the hand-use preference for any newly emerging skill might become clearer and resemble more the hand-use preference for earlier-developed motor skills as the newly emerging skill gets mastered. Eventually, the lateralization of a skill may decrease when it becomes automatic. Thus, Fagard and Lockman (2005) noted non-linear trend in the development of manual lateralization: whereas 18-36 month-old infants manifest clear handedness for complementary bimanual manipulation, 48-month-olds seem to lose consistent hand-use preference for this task. Fagard and Lockman (2005) explained this non-linear trend by “the effect of experience which makes the task too easy at 48 month for handedness to be clearly expressed” (p. 312). In the same way, the automatic skill not being reflective of the underlying hemispheric specialization can be illustrated by the right-handed adult turning on light with the left hand if the switch is on the left-hand side. In this situation, an automatic skill of reaching can be easily accomplished with the non-preferred hand in order to minimally adjust the current posture while taking into account the position of the target. As a result, the trajectory of the level of lateralization observed in a particular skill is predicted to have an inverted U-shape form with lateralization being low at the time of the emergence of the skill, increasing as the skill gets mastered, and then decreasing as the skill becomes automatic and does not require considerable effort (Figure 1). Note that Figure 1 presents hypothetical data.

Such cascading transformations in handedness lateralization during infancy may change the manifestation of handedness for reaching, unimanual manipulation, role-differentiated bimanual manipulation, construction and tool use resulting in the observation of fluctuations in the development handedness (Michel, 2002). Some researchers argued that the observed variability in infant handedness (Corbetta & Thelen, 1999; Corbetta & Thelen, 2002; Fagard, 1998; Fagard & Lockman, 2005; McCormick & Maurer, 1988; Piek, 2002; Thelen, 1995; Thelen, Corbetta, & Spencer, 1996) is likely to represent “competition from the development of several motor skills” (Fagard &

Lockman, 2005, p. 313). However, they did not specify what was in competition. Alternatively, handedness may cascade from one skill to the other rather than compete with one another. In this alternative case, the observed variability in handedness is considered to derive from variability of succession of different kinds of handedness that are related to each other developmentally. Therefore, it is likely that by measuring handedness in reaching, RDBM, and other manual activities we do not assess the same construct.

Figure 1. Cascading character of hypothetical handedness development; HOP = head orientation preference; RDBM = role-differentiated bimanual manipulation (adapted from Figure 9.3 of Michel, Nelson, Babik, Campbell, and Marcinowski (2013))



Thus, the timing of measurement becomes critical. For example, Hinojosa et al. (2003) found that infants exhibiting right- or left-handedness for reaching and grasping objects are more likely to use the same hand during unimanual manipulation at the age of 11 months, but not at 7 months, when unimanual manipulation is initially being expressed. Thus, a researcher may not obtain a valid measure of handedness while using unimanual procedure to assess handedness in 7-10-month-olds.

Furthermore, Fagard and Marks (2000) explored the development of handedness for unimanual reaching, as well as unimanual and bimanual manipulation for 18-36 month old infants. They found a higher percentage of right-handers for the bimanual manipulation compared to unimanual reaching. Therefore, Fagard and Marks (2000) concluded that “grasping is not the best task to employ to look for robust evidence of handedness, and that bimanual tasks offer a better way to estimate handedness in children” (p. 137). This conclusion was made because the researchers chose to study an age period in which handedness for simple reaching is less lateralized than handedness for bimanual manipulation. Instead, their conclusion should have been that bimanual tasks offer a better way of estimating handedness compared to reaching tasks *in 18-36 month old infants*. Fagard and Marks (2000) seemed to assume that lateralization in manual tasks can only increase in time, but it cannot decrease. This notion led them to a conclusion that “bimanual handedness seems to be strongly expressed earlier than unimanual handedness… [for] reaching and grasping” (p. 145) that was at variance with previous research that showed that handedness for unimanual manipulation preceded handedness for bimanual coordination (Hinojosa et al., 2003).

Using conclusions made by Fagard and Marks (2000), some researchers might hypothesize that role-differentiated bimanual manipulation is a more valid measure of handedness than reaching in one-year-old infants. In contrast, it was demonstrated that although RDBM may be observed as early as at the age of 7 months (Kimmerle, Mick, & Michel, 1995), infants prior to 13 months do not show evidence of “planning” in the manifestation of their RDBM actions, and a hand-use preference in RDBM does not appear until about 13 months of age as infants begin to master the skill of such actions (Kimmerle, Ferre, Kotwica, & Michel, 2010). In this case, assessing handedness for RDBM in 11-12-month-olds might not produce a valid measure of handedness lateralization.

Thus, understanding the developmental cascade of change in handedness lateralization may help a researcher choose a correct time and task for handedness evaluation in order to relate handedness to other developing neuropsychological functions. Moreover, deeper understanding of the cascading nature of handedness development can help us to establish a model for studying the development of other forms of hemispheric specialization of function. If we establish that handedness observed in different skills (reaching, unimanual manipulation, RDBM, tool use, etc.) during development represents a cascade of different types of hemispheric specialization concatenating in one another and scaffolding each other, we may also suspect that hemispheric specialization for language may also develop as a cascade of different skills representing different kinds of hemispheric specialization with different mechanisms, and start exploring how those different mechanisms relate to each other developmentally.

Early Postural and Manual Asymmetries

So far, we have explored generally the idea of the developmental cascade of handedness and emphasized the necessity of studying longitudinally handedness development in separate manual skills. Now let us look closely at each of the developing manual skills – from early head orientation biases, to biases in reaching, grasping, unimanual and bimanual manipulation, as well as role-differentiated bimanual manipulation. Let us begin with early postural and motor asymmetries.

By the age of 9 to 10 weeks prenatally, fetuses exhibit independent limb movements. Ultrasound recording showed that the majority of fetuses (75%) moved their right arm more frequently than their left arm at the age of 10 weeks prenatally, whereas the proportion of fetuses preferring their left hand reached only 13% (Hepper, McCartney, & Shannon, 1998). By the age of 15 weeks prenatally, the most fetuses exhibited a preference to suck the right-thumb, rather than the left-thumb, and this was interpreted to reflect early hemispheric specialization (Hepper, Shahidullah, & White, 1990; but see de Vries et al., 2001), particularly since it seems to be predictive of later handedness at 10-12 years of age (Hepper et al., 2005).

Such early asymmetry of arm movements likely reflects spinal reflexes rather than brain-stem or cortical circuits (Hopkins & Rönnqvist, 1998). It is likely that, if such lateralized processes controlling limb actions existed at the level of the spinal cord, they would contribute to the developmental formation of the neural processes associated with further cerebral lateralization (brain stem, basal ganglia, limbic system, and cortex). Therefore, if fetal asymmetrical hand actions predict late childhood handedness, then they must do so by contributing to the biasing of the development of the midbrain and forebrain mechanisms controlling handedness in adults (Michel, Babik, Nelson, Campbell, & Marcinowski, 2013).

In the last trimester of pregnancy, when the uterine space becomes very limited and restricts fetus' movements, the asymmetry of the uterine space and the specific gravity of the fetus combine to make the left occiput anterior presentation position (fetus's head "down" and the left side "pressed" against the mother's backbone and pelvis) the most probable one with about 85% of fetuses exhibiting it (Michel, 1983). This position restricts left arm movement and head turns directed toward the left. The maintenance of this fetal position throughout last months of pregnancy likely produces differential elasticity of the arm and neck muscles as well as sets some general "set-points" in the muscle spindle cells of the arm and neck. After delivery, gravity induces muscle stretch that violates set-points of the spindle cells. As a result, only when the neonate's head is turned in the same direction as in utero, does the vestibular system provide equalized activation (Caesar, 1979; Previc, 1991). This results in the supine head orientation preference of the neonate (Coryell & Michel, 1978; Michel & Goodwin, 1979; Rönnqvist, Hopkins, van Emmerik, & de Groot, 1998).

Thus, asymmetries of the fetal position and actions in utero have been proposed to concatenate into the neonate's supine head orientation preference (Michel & Goodwin, 1979). Intrauterine position is considered to be a major contributor to the organization of postnatal posture and "reflexes" (Caesar, 1979; Schulte, 1974) since the neonate's postural preference approximates its prenatal posture (Dunn, 1975). Since the early asymmetry reflects brain stem reflexes rather than cortical circuits (Rönnqvist et al., 1998), the asymmetry of mechanisms controlling the neonatal HOP is likely a consequence of asymmetrically lateralized activation of neuromotor mechanisms at the level of brain stem nuclei, cerebellum, thalamus and basal ganglia that have been established as a result of the asymmetry of the fetus's intrauterine position rather than being simply a reflection of hemispheric specialization (Michel, 1983).

As a consequence of the head orientation preference, a neonate might be more responsive to auditory and tactile stimulation of one ear and cheek, respectively, than the other. Turkewitz and colleges proposed that the neonatal lateralized asymmetry of sensory and motor characteristics is an early precursor and sensitive indicator of later forms of lateralized neurobehavioral organization of an individual, including handedness (Turkewitz, 1977; Turkewitz and Birch, 1971). The majority of tested infants (approximately 85%) had a strong preference of turning their heads to the right, whereas the rest of the infants did not have a distinct postural preference (Turkewitz & Birch, 1971). Similarly, Michel (1981) reported that the majority of infants (65%) prefer to lie with their heads turned to their right and about 15% prefer to turn their heads to the left for the first two months postpartum.

It was proposed that the relation between asymmetric position of the head and lateral differences in the infant's sensitivity has a reciprocal character – the asymmetric head position might increase sensitivity on the preferred side and those lateral differences in responsiveness may further strengthen the existing postural asymmetries (Turkewitz & Creighton, 1974). Thus, increased sensitivity on the infant's right side would facilitate more turning to the right side. Indeed, Turkewitz, Birch, Moreau, Levy, and Cornwell (1966) demonstrated that infants are more responsive to auditory stimuli presented to the right than to the left ear. It was suggested that since in the most common infant position with the head turned to the right side, the right ear becomes at least partially occluded, the level of auditory stimulation penetrating this ear is lower than that for the left ear (Turkewitz et al., 1966). This difference in stimulation by the ambient sounds might result in significant asymmetrical differences in adaptation to sound between the ears and hence in differences in responsiveness to auditory stimuli of the same level of intensity applied to the right and the left ears. Such differences in infant responsiveness to auditory stimuli was reported by Turkewitz, Moreau, and Birch (1966), whereas similar differences in response to somesthetic stimulation presented laterally to the perioral region was shown by Turkewitz, Moreau, Birch, and Crystal (1967).

There are a few possible explanations to the observed lateral differences in infant responsiveness to auditory and somatosensory stimuli. For example, the lateralized head turning may be due to the differential pre-stimulation or to the asymmetry in muscle tone (Turkewitz, Moreau, Davis, & Birch, 1969). It was shown that both the asymmetry in muscle tone and differential somesthetic stimulation contribute to differences in asymmetric responsiveness to external stimulation (Turkewitz et al., 1969). Moreover, Turkewitz and Birch (1971) suggested that "such lateral differences may contribute to the subsequent development of lateral dominance, lateral preference, and hemispheric differentiation" (p. 35).

Head orientation preference results in differential proprioceptive experience of the hands that is important for the development of their visually guided control (Hein, 1980). The direction of HOP also affects limb differences with the face-side hand/arm exhibiting more movement and grasping actions and availability for visual regard (Michel & Goodwin, 1979; Michel & Harkins, 1986). Within days after birth, a visual stimulus elicits eye-head orienting. Neonates are reported to move their right arms more frequently and to "swipe" at objects in their field of view. Thus, von Hofsten (1982) showed that 3-day-old infants, supported in a reclined infant seat, exhibited more forward-extending arm movements (swiping) which were closer to a moving target during fixation as compared to when they were not fixated on the target.

However, Ruff and Halton (1978) provided evidence indicating that this early "reaching" may be more apparent than real. Using a camera angle that created the impression for the coder that an object was in front of the infant whereas is was actually behind the infant and out of sight, they identified more swiping at the object when the infant's eyes/head were directed toward the object's apparent position than when the eyes/head were not. Thus, arm movements are elicited by the infant's head orientation and this can create the impression of visually directed swiping at a target. Michel and colleagues (Coryell & Michel, 1978; Michel & Harkins, 1986) did not observe such differential "swiping" during "fixation" for the ages 2-10 weeks. However, by 10-12 weeks, more arm movements were observed when the infant's head (and, presumably, eyes) are directed toward the object than when they are not (Coryell & Michel, 1978; Michel & Harkins, 1986).

By 12 weeks, the hand that had been on the face side of the infant's supine HOP during the first 8 weeks was the more active hand for "swiping at objects" (Michel, 1981). It is likely that the head orientation preference results in an asymmetry of visual-proprioceptive map of space because the face side hand is moved more, creating more proprioceptive and corollary neural activity associated with that hand's position in visual space and its "felt" position relative to the body. As a result of such a map, the face side hand ought to have an advantage in reaching for objects located in space relative to the infant's body. That advantage concatenates into a greater probability of contacting the object, acquiring it and building more extensive cortical-basal ganglia re-entrant circuits for the "motivational" control of that arm (McFarland, 2009).

The asymmetrical "experiences" manifested during head orientation preference predict the hand that will be later used for reaching. Thus, Michel & Harkins (1986) found that the hand that was on the face side during the earlier observed HOP is the same hand that was used initially for swiping at visually presented objects in the infant's midline at 12-16 weeks. Both the neonatal and the post-neonatal HOP were predictive of infant hand-use preferences for prehension, although the post-neonatal HOP was the more reliable predictor (Michel & Harkins, 1986). It seems that the two months of hand regard and differential activity prompted by the infant's supine head orientation preference is sufficient to establish a hand-use preference for visually-elicited swiping at objects. Thus, the development of handedness during infancy begins with a head orientation preference which creates asymmetrical motor actions and hand regard.

Furthermore, during their first two months postpartum, neonates exhibit a hand difference in duration of “reflexive” grasping of objects (Caplan & Kinsbourne, 1976). Caplan and Kinsbourne (1976) reported that most newborn infants hold a rattle longer in their right than the left hand. The hand difference is primarily a consequence of the influence of the infant’s head orientation preference on manual actions (Schwartz & Michel, 1992). The direction of the head turn results in greater probability of “dropping” by the hand away from the direction of head turn and hence a shorter duration of left-hand grasping by the majority of infants with a rightward head orientation preference (and vice versa for the minority of infants with a leftward HOP). In this way, the head orientation preference can contribute to lateralized differences in grasping.

By 16 weeks of age, infants are frequently contacting objects with their swipes (Michel & Harkins, 1986; von Hofsten & Rönnqvist, 1988). Also, Young and Wolff (1976) reported that infants predominantly use their right hand for directed swiping at toys, and the consistency of this pattern was observed from task to task (as cited in Young, 1977). However, there is little evidence in the literature for the acquisition of those objects that were contacted at the age of 3-3.5 months. In contrast, by 5 months, infants can reliably contact objects, show a hand-use preference for such contact (as predicted by the direction of their HOP), and often acquire them (Michel & Harkins, 1986). Thus, it was argued that the head orientation preference influences early lateralized asymmetries of hand and arm actions and subsequently predicts development of hand-use preferences for reaching for, and acquiring, objects (Michel, 1981; Michel & Harkins, 1986).

Reaching and Toy Acquisition

Although reaching, at least in a very rudimentary form, can be observed as early as at birth (Bower, 1982; von Hofsten, 1982), first clear reaching attempts were reported at the ages 12 to 22 weeks (2.8-5.1 months) when infants "adjust the force and compliance of the arm, often using muscle coactivation" (Thelen et al., 1993, p. 1058). Lee, Liu, and Newell (2006) observed no infant reaching at the age of 9 weeks (2.1 months), which they explained by "the lack of visual acuity to locate and perceive the properties of the object… and/or the limitations that arises from the immaturity of the motor system" (p. 489). Goal-directed reaching that often resulted in object contact was recorded at the age of 15 weeks (3.5 months) (von Hofsten & Lindhagen, 1979) or, according to another source, at 17 weeks (4 months) (Lee et al., 2006). Thelen et al. (1993) suggested that reaching emerged from "the ability to visually locate the toy in space, intention to reach and grab the toy and transport it to the mouth, growing control of the head and trunk, and the increasing ability to modulate the force and compliance of the arms" (p. 1093).

Some researchers studied the type of information (e.g., haptic vs. visual) used by infants while reaching for objects. Note that visually guided reaching is not usually observed until the age of 4 to 5 months (Coryell & Michel, 1978; Field, 1977; Lasky, 1977) when infants contact objects on a regular basis (Lee et al., 2006) and start manifesting confident prehension (reaching and grasping) of objects. Newell, Scully, McDonald, and Baillargeon (1989) explored the development of grip configuration in infancy in order to determine whether the infant's hand was shaped appropriately before or after the contact with an object. Newell et al. (1989) concluded that 4-month-olds have to rely on both visual and haptic information while reaching (but see Field, 1977). Similarly, Lee et al. (2006) demonstrated that infants at the age of 19-27 weeks (4.4-6.3 months) use haptic perceptual information for reaching. In contrast to younger infants, 8-month-old infants are able to rely only on visual information while reaching for an object and shaping the hand for a grip (Newell et al., 1989). Using only the visual system to obtain relevant information about the required grip configuration allows older infants to execute "more anticipatory mode of action" (Newell et al., 1989, p. 829).

Thus, relying on visual information allows the infant to anticipate some properties of the object and adjust the configuration of the grip before the contact with the object. Previous research showed that by the age of 29-37 weeks (6.8-8.6 months), infant hand configuration patterns show the anticipation of a particular grasp required for the given size, shape, and texture of an object (Lee et al., 2006). Possible anticipatory mode of reaching in infancy was also explored by von Hofsten and Rönnqvist (1988). They used an optoelectronic technique to measure the distance between the thumb and the index finger while monitoring hand movements during reaching and grasping of an object. Infant patterns of opening and closing of the hand during the reach towards objects of different sizes were compared to those manifested by adults. von Hofsten and Rönnqvist (1988) showed that adults started closing the hand in anticipation of the grasp well in advance before the contact with an object. Also, in adults, the size of the object influenced both the timing of the hand closure and the eventual distance between the thumb and the index finger at the moment of contact.

Infants of all studied age groups (5-6, 9, and 13 months) exhibited an anticipatory closing of the hand (von Hofsten & Rönnqvist, 1988). However, only 13-month-olds showed a pattern of closing similar to adults, whereas both younger groups of infants started closing the hand closer to the moment of contact with an object. Note that Twitchell (1965) suggested that shoulder movement associated with the extension of the arm is likely to initiate the reflex mechanism that would result in the closure of the hand. Thus, seemingly "voluntary" hand closure might, instead, represent the automatic grasping response.

Furthermore, similar to adults, all infants adjusted the *distance* between the thumb and the index finger at the grasp to the size of the object (von Hofsten & Rönnqvist, 1988). However, in contrast to adults, infants did not adjust the *timing* of the hand closure according to the size of an object. Thus, although young infants (5-6 months) show anticipation while reaching for objects, the complex pattern of hand adjustment during reaching continues to develop past the first year of the infant's life. von Hofsten and Rönnqvist (1988) highlighted the continuous character of the transition between reaching and grasping with the hand closing into a grasp "without any interruption in the approach" (p. 610).

Although infants considerably improve their reaching skills throughout the first year of life, there are frequent fluctuations between unimanual and bimanual reaching. Interestingly, whereas adults' choice between unimanual and bimanual reaching patterns depends on the perceptual information about the size of an object, in infants, size of an object does not usually relate to the type of reaching (Corbetta & Thelen, 1996; Fagard &

Jacquet, 1996; Newell et al., 1989). White, Castle, and Held (1964) argued that at the onset of reaching the majority of infants perform mostly symmetrical bimanual movements disregarding an object's properties. They attributed this bimanual tendency to an increase in symmetry due to the disappearance of the asymmetric tonic neck reflex that usually takes place after the age of 3 months. Similarly, Fagard and Pezé (1997) reported that infants exhibit high frequency of bimanual reaches before the age of 7 months. However, they suggested that relatively high frequency of bimanual reaches at this age might reflect a high level of coupling between the two hands.

Bimanual reaching was reported to decrease in infants at the age of 5–6 months (Bresson, Maury, Pieraut-Le Bonniec, & Schonen, 1977; Gesell & Ames, 1947; Ramsay & Willis, 1984; Rochat, 1992). Fagard and Pezé (1997) suggested that a decrease in bimanual reaching during 7-10 month-age period is associated with a decrease in infants' mouthing of objects and an increase in unimanual manipulations. Interestingly, the frequency of bimanual reaches increases again by the end of the infant's first year (Corbetta & Thelen, 1996; Fagard & Pezé, 1997). This pattern of manual activity might reflect the development of role-differentiated bimanual manipulation (Babik, Campbell, & Michel, 2014; Fagard & Pezé, 1997; Goldfield & Michel, 1986).

The choice between unimanual and bimanual reaching was also shown to depend on task constraints such as the object's size and shape. Thus, large objects are more likely to elicit bimanual grasping than small objects (Fagard & Jacquet, 1996; Fagard & Pezé, 1997; Newell et al., 1989). Bimanual grasping was more frequently observed when the target object consisted of two parts (Fagard & Lockman, 2005). Moreover, it was suggested that task constraints might affect not only the infant's choice between unimanual and bimanual reaching, but also manifestation of infant handedness. Thus, Fagard and Lockman (2005) observed stronger hand-use preferences (or stronger manual lateralization) in tasks requiring a higher level of precision.

In general, there is no consensus in previous research about the onset of hand-use preferences for pre-reaching movements, as well as for reaching and prehension. This inconsistency of results could be due to the difficulty of assessing manual preferences at an early age, differences in infants' manual proficiency levels, or differences in sample sizes, implemented methodologies and statistical analyses used in different studies. Although some researchers reported asymmetries in arm coordination starting at the age of 12 weeks (2.8 months) (Piek, Gasson, Barrett, & Case, 2002), others found no significant hand-use asymmetries in infant hand-use during the pre-reaching period from 8 weeks (1.9 months) to the onset of reaching (Lynch, Lee, Bhat, & Galloway, 2008). Thus, Lynch et al. (2008) suggested that manual preference develops after the reach onset.

In accord with Lynch et al., Flament (1973) recorded first signs of manual asymmetry at the age of about 5 months (as cited in Young, 1977). Other researchers reported that 4 to 6 month infants manifest hand-use preference for swiping at and reaching for objects (Michel & Harkins, 1986), whereas 6 to 7 month infants exhibit preference for reaching and prehension (Michel, 1981, 1982; Michel et al., 1985). Michel and Harkins (1986) also reported that the majority of infants manifest quite stable hand-use preference for the next year. Cohen (1966) found that the majority (about 74%) of 8-month-old normally developing infants preferred their right hand for reaching.

In contrast, Rönnqvist and Domellöf (2006) did not observe clear manual asymmetry in 6 to 9 month old infants. They concluded, similar to Corbetta and Thelen (1999), that the onset of manual preference takes place at the age of about 12 months, whereas a consistent hand-use preference may be recorded only at 36 months. Also, considerable fluctuations in manual preferences were observed not only at the age of 6 months (McCormick & Maurer, 1988) which is often considered as the onset of stable prehension movements (von Hofsten, 1991), but also during the entire 6 to 12 month interval (Carlson & Harris, 1985).

The inconsistency in conclusions about the onset and stability of infant handedness for reaching and toy acquisition is likely to result from differences in the definition of handedness and assessment methods used by different researchers. Thus, McCormick and Maurer (1988) used a handedness assessment procedure similar to that used by Michel et al. (1985). However, for classification of infants into categorical status of right-, left-, or no hand-use preference, they used the cut-off z = 1.0. It is obvious that, compared to the cut-off z = 1.65 used by other researchers (e.g., Hinojosa et al., 2003; Michel et al., 1985), z = 1.0 is more likely to underestimate the number of no preference infants and over-estimate the number of lateralized infants (both right- and left-handers). Thus, it is not surprising that McCormick and Maurer (1988) did not find consistency of handedness in their arbitrary handedness status groups.

Furthermore, Carlson and Harris (1985) examined handedness for reaching while defining reach “as an extension of the hand in the direction of the object without a requirement that the object be touched” (p. 163). It is conceivable that examining reaching movements that do not lead to the contact with the target object is likely to result in collecting information on non-goal-directed incidental and associated movements. Again, it would not be surprising that such a procedure would not identify stable hand-use preferences during infancy. Finally, von Hofsten (1991) made his conclusions about inconsistency of infant handedness based on his longitudinal data collected from a sample of five infants. The question is whether we can reasonably generalize the conclusions made by von Hofsten (1991) on five infants to the general population of infants.

The consistency/inconsistency of handedness manifested by infants in different manual skills was studied by Michel et al. (1985) in a cross-sectional study in 6-13 month infants. They reported 31.5% of infants being right-handed for pick-ups of blocks during the block play, 15.5% being left-handed and 53% of infants having no distinct handedness. Interestingly, the distribution of handedness was quite different when Michel et al. (1985) evaluated infant handedness for reaching on a set of 21 different toys (28 presentations). They found that 53% of infants exhibit right hand-use preference, 24 % – left handedness, whereas 23% show no hand-use preference. Although handedness for reaching for toys was found to be significantly related to handedness manifested for block pick-ups, the discordance rate between the handedness statuses defined by the two procedures reached alarming 48%. Michel et al. (1985) concluded that the majority of infants exhibit hand-use preference during 6 to 13 month period, and that right bias in handedness is observed as early as at the age of 6 months and does not change significantly during 6-13 month period. Note that a cross-sectional nature of the study conducted by Michel et al. (1985) did not allow confident conclusions about the development of handedness.

Unimanual Manipulation

During 6 to 18 month period, reaching becomes gradually incorporated into more sophisticated sensorimotor skills (Uzgiris & Hunt, 1975). Thus, hemispheric lateralization for reaching cascades into lateralization for unimanual manipulation (Michel, 2002). Unimanual manipulation is the simplest form of manual manipulation that does not require bimanual coordination and interhemispheric transfer of information. Unimanual manipulation likely forms the foundation for more sophisticated forms of manipulation such as bimanual non-differentiated manipulation and role-differentiated bimanual manipulation.

The earliest instance of unimanual manipulation of objects is usually observed at the age of about 5 months, and only at the age of 7 months, and not at 5 months, infants start manifesting hand-use preferences for unimanual manipulation (Ramsay, 1980b). While exploring unimanual manipulation, Ramsay (1980b) observed infants' unimanual contacts with four toys, and defined the unimanual contact as an attempt to manipulate any movable part of the toy while the other hand was not in the supporting role. Ramsay (1980b) concluded that his research should be replicated using a larger number of objects and a larger sample size that would likely capture the development of handedness in infants with different handedness status. Interestingly, the first appearance of handedness for unimanual manipulation is related to the onset of repetitive bubbling (Ramsay, 1984), which could be perceived as an important link expanding our understanding of the relation between hand-use preference and hemispheric specialization of function (Michel et al., 1985).

Previous research explored the relation between handedness for unimanual manipulation and handedness for reaching. Thus, Michel et al. (1985) evaluated unimanual manipulation using block play procedure as well as manipulation of a set of 21 different toys (28 presentations). Unimanual actions of interest were pick-up, transfer, shake, hold, bang, throw, scrape, push, pull, and reorient. z-scores $[(R – L)/(R + L)^{1/2}]$ were calculated for each visit for each infant, and $z > +1.65$ was assumed to indicate right-handedness at a particular age, $z < –1.65$ indicated left-handedness, and the rest of the observations were considered to show no distinct hand-use preference. For unimanual manipulation of *blocks*, Michel et al. (1985) reported that 33.4% of infants were right-handed, 13.6% were left-handed, whereas 53% exhibited no distinct hand-use preference. For unimanual manipulation of *toys*, 51% of infants were identified as right-handed, 20% as left-handed, and 29% as having no hand-use preference (Michel et al., 1985). Note that handedness distributions obtained from the two procedures are quite different from each other. The differences in handedness distribution might have resulted from transformation of continuous raw z-scores into handedness status categories which reduces the precision of the data.

Handedness for manual manipulation of blocks was found to be significantly related to handedness exhibited by infants for block pick-ups with only 2% infants being discordant in their handedness statuses. Moreover, Michel et al. (1985) found a significant relation between handedness for toy manipulation and handedness for block manipulation, but the rate of discordance between the two handedness categorizations reached 48% (the same discordance rate was observed for the reaching skill in blocks and toys).

Furthermore, Kimmerle et al. (1995) suggested that between ages 6 and 11 months unimanual manipulation becomes a significant part of infants' manual repertoire. They also found no significant change in frequency and types of manual manipulations from 7 to 11 months. Thus, Kimmerle et al. (1995) proposed that the skill of unimanual manipulation remains quite stable during 7 to 11 months period. The question is whether the degree and direction of lateralization for unimanual manipulation changes during this period.

This question was addressed by Hinojosa et al. (2003). They defined handedness preferences for reaching in a sample of 25 infants tested with 24-29 toys at the ages of 7, 9, and 11 months. Calculated z-scores were converted into categorical handedness status using $z = 1.65$ as a cut-off point. Note that infants in this sample manifested consistent handedness classification for reaching across all three visits. Hinojosa et al. (2003) also tested infants' hand-use preference for unimanual manipulation during 7 and 11 months visits during play with the same set of the toys.

Hinojosa et al. (2003) reported no significant differences among right-handers, left-handers and no preference infants in the total number of performed unimanual manipulations corrected for the number of presented toys. Moreover, infants performed about the same number of unimanual manipulations at the age of 7 and 11 months. Then, Hinojosa et al. (2003) explored lateralization of unimanual manipulation in different handedness groups at the two ages. All performed unimanual manipulations were used in calculation of the cumulative z-scores for each age and each infant. Each z-score would lead to a hand-use classification into right-handed, left-handed, or no preference group at particular month for a particular infant. Hinojosa et al. (2003) found that from 7 to 11 months, more infants being right-handed for reaching became right-handed for unimanual manipulation (3 at 7 months vs. 8 at 11 months), whereas left-handers for reaching increased their left-handedness for unimanual manipulation (1 infant at 7 months vs. 5 infants at 11 months). At the same time, infants exhibiting no distinct hand-use preference for reaching became more right-handed for unimanual manipulation (1 infant at 7 months vs. 3 infants at 11 months).

Although Hinojosa et al. (2003) originally coded the hand-use for twenty-five types of unimanual manipulation (e.g., finger, in mouth, throw, drop, clack, scrape, etc.), the small number of infants in each handedness group did not allow them to analyze longitudinal data using a parametric test. Thus, Hinojosa et al. (2003) decided to combine all actions into five categories (finger, hand, wrist, arm and finger, limb), and to convert z-scores into binary data indicating either increase or decrease in right-handedness during unimanual manipulation from 7 to 11 months. Hinojosa et al. (2003) estimated the percentage of infants in each handedness group who increased (or decreased) their right-handedness between the two observations. They reported a significant difference in change with age between right-handers and left-handers, as well as between left-handers and no preference infants, but not between right-handers and no preference infants. However, more important would be to know whether the change in manual lateralization from 7 to 11 months was statistically significant within each group, as well as to define how this change has occurred. Answering these questions would require at least monthly testing of a larger number of subjects, and multilevel analysis of raw longitudinal data without reduction to the binary representation of data.

An important aspect of the study conducted by Hinojosa et al. (2003) is that they tried to evaluate the Invariant Lateralization Theory (Kinsbourne, 1975; Witelson, 1980) against more recently suggested a modified version of the Progressive Lateralization Theory (Michel, 1983, 1988, 1998, 2002). Since the ILT predicts that the development of lateralization for each skill would occur while this skill is developing, Hinojosa et al. (2003) suggested that showing no change in unimanual skill co-occurring with a significant change in the lateralization for this skill would result in rejection of hypotheses stated in ILT. First, Hinojosa et al. (2003) showed no significant change in the skill of unimanual manipulation from the ages of 7 to 11 months. Second, Hinojosa et al. (2003) claimed that they found significant change in the degree of lateralization from 7 to 11 months. As a result, they concluded that their results contradicted ILT and supported MPLT. However, as I noted before, it is not clear from the study by Hinojosa et al. (2003) that the change in lateralization was significant within handedness groups. Therefore, this issue demands further investigation.

Role-Differentiated Bimanual Manipulation

Many researchers suggested that the major shift in the infant's manual skills happens during the transition from unimanual reaching and manipulation of objects to the role-differentiated bimanual manipulation (e.g., Bruner, 1970; Connolly & Dalgleish, 1989). Role-differentiated bimanual manipulation, when two hands perform different but complementary movements on one or many objects, may be considered to represent a new level of manual skill since it requires sensorimotor coordination of the two hands that was not required for reaching and unimanual manipulation of objects (Bruner, 1971). Role-differentiated bimanual manipulation also requires sequencing of actions performed by both hands, and, thus, it reflects hemispheric lateralization as well as collaboration between the two hemispheres (Michel et al., 1985; Ramsay, Campos, & Fenson, 1979). Thus, the development of RDBM may reflect a major shift in motor organization (Haaland, Elsinger, Mayer, Durgerian, & Rao, 2004), cognitive functioning (Bruner, 1970; Connolly & Dalgleish, 1989; Ramsay & Weber, 1986) and neural functional organization (Michel, 1987, 2002; Serrien et al., 2006).

During the first two years of the child's life, bimanual manipulation is developing from non-differentiated bimanual movements through partially differentiated movements to high levels of hand-use differentiation (e.g., de Schonen, 1977; Fagard, 1998; Fagard & Jacquet, 1989; Fagard & Marks, 2000; Fagard & Pezé, 1997). Before 11 months, infants often produce "in-phase" or mirror movements while manipulating objects. At this time, “anti-phase”, or parallel, movements are minor occurrences in the infant’s repertoire because they demand higher levels of intermanual coordination (Kelso, Putnam, & Goodman, 1983) and, thus, depend on interhemispheric communication. By 11 months, however, infants consistently engage in more parallel (non-mirror) actions that necessitate complementary actions performed by both hands (Goldfield & Michel, 1986). The appearance of symmetrical bimanual manipulations before the asymmetrical ones was also shown by Fagard and Jacquet (1989) who concluded that whereas more symmetrical bimanual actions in the infant’s repertoire can be observed as early as at 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.

Thus, the appearance of incomplete differentiation precedes the onset of role differentiation in the manual repertoire of infants. For example, Fagard and Lockman (2005) demonstrated 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. Ramsay and Weber (1986) also suggested the “progressive differentiation” of bimanual coordination and reported 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. Also, Fagard and Pezé (1997) pointed out that first successful bimanual manipulations observed at the age of 8-10 months lacked temporal coordination. Interestingly, Ramsay and Weber (1986) related infants’ incomplete bimanual differentiation to the Piagetian (e.g., Piaget, 1952) fifth stage of groping solution or trial and error, whereas the complete bimanual differentiation was suggested to appear at the sixth stage that enables the infant's representational ability to plan and coordinate complex sequences of complementary bimanual actions.

Previous research suggested that asymmetrical cooperation between the two hands in bimanual manipulation becomes possible with a decrease in intermanual coupling (Fagard & Pezé, 1997). In agreement with their hypothesis, Fagard and Pezé (1997) observed a significant decrease in infants' bimanual reaches just before the onset of first successful role-differentiated bimanual manipulations. They concluded that the increased independence between hands (demonstrated in reaching) facilitates the appearance of complementary movements of the two hands necessary for successful RDBM. The same conclusion had been previously reached by Goldfield and Michel (1986) as well as Diamond (1991).

Furthermore, the ability of the infant to exhibit complementary actions during RDBM might also reflect independent hemispheric control of the two hands and more effective interhemispheric communication. Thus, Fagard and Corroyer (2003) demonstrated significant association between interhemispheric transfer and *bimanual* coordination, but not between interhemispheric transfer and the *unimanual* laterality index. Moreover, Fagard, Hardy, Kervella, and Marks (2001) suggested that more effective interhemispheric communication through the corpus callosum enables coordination between hands performing complementary non-mirror movements during bimanual manipulation. Complementary movements of the two hands become possible with the bilateral development of supplementary motor area (SMA) and the development of projections through the corpus callosum that allow inhibition of the coupling of movements performed by the two hands (Diamond, 1991). Thus, some researchers suggested that the emergence and development of RDBM in infancy might be an important neurological marker of callosal functioning (e.g., Wolff, Michel, & Ovrut, 1990).

First occurrence of rudimentary complementary bimanual manipulations was observed in 4-5 month-old infants by Rochat (1989). In contrast, clear RDBM was reported to appear at the age 7 months (Kimmerle et al., 1995; Kimmerle et al., 2010) or at the age of approximately 9 to 10 months (Bruner, 1971; Fagard & Pezé, 1997; Ramsay et al., 1979). However, the hand-use preference in RDBM does not appear until the age of about 12-13 months in the majority of infants (Bruner, 1970; Fagard, 1994; Fagard & Jacquet, 1989; Fagard & Lockman, 2005; Ramsay et al., 1979; Ramsay & Weber, 1986).

Ramsay et al. (1979) studied the onset of bimanual manipulation in 24 normally developing infants during a play with 3 toys (2-4 trials per each toy which is 6-12 possible opportunities). All infants were tested monthly from the age of 10 months until 5 months after the recorded “clear hand preference” in bimanual manipulation. Infants were assigned handedness for each trial when bimanual manipulation was attempted and not necessarily performed successfully. Consistent handedness was defined when infants used the same hand on the first two trials, or on three out of the four trials. Note that according to the binomial probability distribution (Mendenhall, Beaver, & Beaver, 2013), 3 out of 4 bimanual manipulations do not reflect a significant hand-use preference with *p*

= .250. Defining handedness by the first two trials is even more problematic (p = .375 on the bimanual test).

Ramsay et al. (1979) recorded "the first indication of handedness" when the infant used the same hand consistently on at least two out of three toys, and "the clear hand preference" was defined when the infant manifested a consistent handedness while bimanually manipulating all three toys (p. 71). Ramsay et al. (1979) found the onset of "the clear hand preference" to be on average at the age of 12.8 month in 18 right-handed infants (75% of the sample) and at 14.9 months in 5 left-handers (21% of the sample). One infant did not show any consistent hand preference for bimanual manipulation during this observation period. Moreover, infants that showed hand-use preferences were consistent in their handedness during the next 5 months. The observed results show that by the age of 15 months, 96% of infants were credited with a hand-use preference for bimanual manipulation. Also, one might suggest that left-handers are delayed (about 2 months) in their development of handedness for bimanual manipulation compared to right-handers. However, more research in this area is necessary in order to make any confident conclusions.

Ramsay et al. (1979) also tested the onset of hand-use preference for bimanual manipulation in another sample of 100 infants (a cross-sectional study). Consistent handedness was identified when the infant manipulated more than 5 out of the 9 toys with the same hand. Ramsay et al. (1979) reported that 85 infants (71 right-hander and 14 left-handers) manifested handedness for bimanual manipulation during 14-16 months interval, whereas another 9 infants (6 right-handers and 3 left-handers) – during 18-21 months interval. Thus, by the age of 18 months, 94% of infants were reported having hand-use preference for bimanual manipulation. Among the limitations of their study, Ramsay et al. (1979) noted the small number of toys (3 to 9) and the fact that some toys were not effective at eliciting consistent role-differentiated bimanual manipulation.

Interestingly, Ramsay (1980a) found the onset of role-differentiated bimanual manipulation at 11.5 months to be related to the appearance of dissimilar syllables (different consonant and vowel sounds across syllables) in infant speech. A possible explanation for the co-occurrence of the two phenomena might be that both require finely tuned sequences of actions (Bruner, 1973b). For example, production of dissimilar syllables (as well as speech in general) is the result of appropriately sequenced transitions between movements of the tongue, vocal cord, lips, and jaws. Similarly, successful role-differentiated bimanual manipulation requires each hand to follow a highly coordinated spatiotemporal sequence including movement onset, transitions among actions, and action trajectories of the two hands. It has been demonstrated that the left hemisphere plays a dominant role in planning and performing such sequences (e.g., Grafton, Hazeltine, & Ivry, 2002; Kimura & Archibald, 1974).

Thus, both the development of dissimilar syllables and the development of hand-use preference for role-differentiated bimanual manipulation might be a reflection of the development of hemispheric specialization with the left hemisphere becoming dominant (in both right- and left-handers) for the coordination of the fine motor movements and finely timed sequences of actions. In this case, the onset of both dissimilar syllables and RDBM might reflect a developmental change in the underlying hemispheric specialization (Ramsay, 1980a). Combined with the evidence of the association between the onset of unimanual manipulation and repetitive bubbling (Ramsay, 1984), that the onset of handedness in role-differentiated bimanual manipulation is significantly related to the appearance of complex syllables might suggest an important link between handedness development and the development of hemispheric specialization of function (Michel et al., 1985).

The relation between handedness for role-differentiated bimanual manipulation and handedness for earlier manifested unimanual reaching was studied by Ramsay (1980b). He reported that from 28 infants tested at the age of 13 months for bimanual manipulation handedness, 22 infants (79%, 11 males and 11 females) were classified as right-handers, whereas the remaining 6 infants (21%, 5 males and 1 female) were classified as left-handers. Ramsay (1980b) also found that bimanual handedness identified at the age of 13 months corresponded with the unimanual contact handedness observed at the ages 7 and 9 months in 23 out of 28 infants (82% of right-handers and 83% of left-handers). Although Ramsay (1980b) did not explore the development of handedness during 9 to 13 month period, he claimed that he demonstrated the transition of hand-use preferences from the unimanual contact to the role-differentiated bimanual manipulation.

Furthermore, a significant association between handedness for RDBM and handedness for unimanual manipulation was also reported by Michel et al. (1985). They assessed handedness for bimanual coordinated actions (same as RDBM) during infant play with a set of 21 different toys (28 presentations). Michel et al. (1985) observed

RDBM skill in 1% of infants at the age of 8 months, in about 42% at 9 months, in 50% at 11 and 12 months, and in all 100% of infants only at the age of 13 months. They identified 59% of infants as being right-handed for RDBM, 22% being left-handed, and 19% having no distinct hand-use preference at 13 months.

Interestingly, at 13 months, handedness for RDBM during toy play was significantly related to handedness for unimanual manipulation (although with 30% misclassification rate), but not related to handedness for reaching (Michel et al., 1985). Note that authors' decision to reduce raw scores into categorical handedness statuses decreased the precision of handedness classification. Moreover, Michel et al. (1985) explored cross-sectional rather than longitudinal data, and although they analyzed change in handedness with age, these results do not inform us about the developmental trajectories of handedness for each skill and relations among those trajectories. Also, a larger sample size would allow more confident conclusions about handedness development with age.

Importantly, Michel et al. (1985) reported that infants in their sample on average reduced their right-handedness for reaching at the age of 13 months. During 9 to 12 month period, handedness for reaching and RDBM were almost always concordant, whereas at 13 months hand-use preferences for those two skills were often discordant. Therefore, Michel et al. (1985) proposed that infants at 13 months might have different handedness statuses for different manual skills. More research is necessary to explore changes that take place in handedness for reaching and RDBM during infancy studied longitudinally on a bigger sample and possibly beyond the age of 13 months. Replication of the above-mentioned results in the new longitudinal study might provide an opportunity to test the cascade theory. Thus, according to the cascade theory, we would expect the decrease in the lateralization of reaching handedness around the age of 12-13 months and an increase in lateralization of RDBM handedness starting at the age of about 13 months.

The development of role-differentiated bimanual manipulation was thoroughly explored by Kimmerle et al. (1995) in a sample of 24 infants tested bimonthly from 7 to 13 months during a play with 10 infant toys. Kimmerle et al. (1995) demonstrated that RDBM occurs as early as at 7 months of age but represents only a very small proportion of the infant's manual repertoire for engaging with objects and is greatly restricted to the characteristics of objects (toys) that strongly afford accidental RDBM. Thus, early RDBMs are likely to represent affordances of particular toys rather than complex understanding of object properties and planning of sequential actions on the part of the infant (Kimmerle et al., 1995).

At the age of 7 months, RDBM was observed in repertoire of only 79% of infants, whereas by the age of 11 months, all infants in the sample demonstrated RDBM. By 11 months of age, RDBM of objects begins to increase in the manual repertoire of the infant (Kimmerle et al., 1995; Kimmerle et al., 2010) but are still dependent on the characteristics of the toys. Although Kimmerle et al. (1995) observed a dramatic increase in the number of RDBMs between 12 and 13 months, statistical analysis (Tukey HSD post hoc test) suggested a significant difference in the number of performed RDBMs only between 7 and 13 months (exactly the beginning and the end of the observation period in this study).

The researchers noted that all infants were identified as either having a stable hand-use preference across the four visits or manifesting no stable handedness. Apparently, right-handers and left-handers (if the latter were present in this sample) were combined into one stable handedness group. Unfortunately, no details were provided to describe this handedness status identification procedure. Moreover, Kimmerle et al. (1995) found no significant differences between stable vs. unstable handedness groups in the timing of their highest frequency of RDBM actions (early peak at 7-9 months vs. late peak at about 13 months) possibly suggesting no benefits in the timing of RDBM acquisition for infants with stable handedness.

It would be interesting to explore the development of RDBM handedness in this sample across age, but the researchers were unable to statistically analyze this trend because of the insufficient number of recorded RDBMs. It is conceivable that this type of statistical analysis would have been possible if a larger sample of infants was observed monthly while using a greater number of toy presentations. Monthly observations would describe the development of RDBM handedness more adequately than bimonthly ones (Ferre, Babik, & Michel, 2010).

Furthermore, Kimmerle et al. (1995) suggested that the number of the recorded RDBMs depended on toy characteristics, but only for later, and not earlier observed RDBMs. Thus, it was suggested that earlier RDBMs are manifested without specific contextual support in occasions when speed and great precision are not required.

Observation of RDBMs at the age of 7 months also questions the notion of RDBM being a marker of callosal development (Diamond, 1991) since SMA is not considered to be developed by this age unless the RDBMs are accidental. Alternatively, it might be suggested that later, but not earlier, RDBM might necessitate callosal involvement and reflect callosal development. This notion would lead to an argument that later, but not earlier, RDBMs should better highlight the infant's manual lateralization.

When can RDBM be considered an emerging skill rather than a result of toy affordances? Previous research suggested that an emerging skill would become more frequent in the repertoire of the infants and would be observed across different tasks (Kimmerle et al., 2010). Kimmerle et al. (2010) explored frequency of RDBMs across age and reported that RDBMs occurred at least once in 80% of 7 month old infants and in 100% of 11 month olds.

RDBM actions rather than being a homogenous skill, can be conceptualized as a set of skills that exhibit developmental pattern in their order of emergence. Fingering seems to emerge first followed by stroking (75% of infants demonstrate these skills by 7 months). Although fingering is often considered to be a more advanced skill than stroking since it requires more precise manipulation by one or two isolated fingers rather than whole hand manipulation, it was suggested that stroking may require more advanced coordinated action, whereas fingering may occur just by chance when the fingers on one hand slip into openings and slots of a toy (Kimmerle et al., 2010). Object removal, first observed at 7 months and becoming frequent (67% of infants) by 11 months, preceded object insertion, observed first at 9 months and manifested by 75% of the infants by 13 months. Kimmerle et al. (2010) suggested that by the age of 13 months, RDBM actions represent only 20% of the infant's manual repertoire during a play with toys that readily afford RDBM. Also, previous research showed that RDBM represents 25% of manual repertoire of the infant at the age of 19 months, and 50% – at the age of 3 years (Kimmerle, 1991).

Another criterion used by Kimmerle et al. (2010) in order to define the emerging RDBM as a skill was the degree of lateralization manifested by infants during manipulation. A significant shift toward increased lateralization was suggested to define a skill. Whereas hand-use preference for unimanual manipulation was observed as early as at 7-9 months, infants' actions did not become lateralized for RDBM until the age of 13 months (Kimmerle et al., 2010). But how was the degree of lateralization defined? Kimmerle et al. (2010) calculated the z-score $[(R - L)/(R + L)^{1/2}]$.

Although Kimmerle et al. (2010) did not specify their cut-off point for z-scores, they reported that half of the tested infants were lateralized at 13 months (11 right and 1 left), whereas two infants had no significant preference, and the rest of the infants did not perform enough RDBM actions to make any reliable conclusions about their handedness. Altogether, it is not clear, what were the criteria that allowed Kimmerle et al. (2010) to state that RDBM becomes a lateralized skill by 13 months. More research is necessary to explore developmental trajectories of infants' hand-use preferences for RDBM and define the timing of the significant increase in manual lateralization for this skill.

Does the early manifestation of RDBM depend on the affordances of toys? One might argue that certain types of toys more likely to elicit RDBMs than others. Thus, it was suggested that not all toys are equally successful at eliciting role-differentiated bimanual manipulation actions (Fagard & Marks, 2000). It was shown that motor requirements of a task (symmetry vs. asymmetry, simultaneous vs. successive movements) affect the successful manipulation of a toy (Fagard & Jacquet, 1989). In order to explore whether early RDBM appear as a result of toy affordances, Kimmerle et al. (2010) investigated differences in infants' manipulation of single-part and double-part toys. The latter had two parts, thus, allowing complex actions like insertion and removal. Fagard and Marks (2000) reported that "double" toys were more likely to elicit lateralized hand-use since they demanded clear differentiation of supportive and active roles between the two hands.

Kimmerle et al. (2010) hypothesized that RDBM actions would appear later for two-part toys compared to single-part toys since those more complex RDBMs are less likely to be exhibited due to affordances of a toy and more likely to require more sophisticated manipulation skills. Kimmerle et al. (2010) explored the age of appearance and frequency of RDBMs produced during a play with single and double toys. They reported that both types of toys elicited RDBM actions at 7 months. A statistically significant increase in manual activity (unimanual, bimanual non-differentiated and RDBM actions combined together) was observed for double toys, but not for single toys.

For single toys, relative frequency of RDBMs increased with age, whereas the frequency of unimanual and bimanual actions decreased. For double toys, there was a significant increase in frequency of RDBMs, whereas frequency of unimanual and bimanual actions was not found to change significantly with age. Therefore, Kimmerly et al. (2010) concluded that “toy type did not seem to delimit the infant’s manifestation of RDBM actions” (p. 174). However, separate analysis of RDBM frequency for single and double toys did not provide a base for direct comparison between the two types of toys. Instead, frequencies of RDBM actions had to be analyzed in a multilevel model of change with age while controlling for the type of a toy. Such direct comparison would allow a researcher to make a conclusion about statistically significant (or non-significant) differences in frequency of RDBM produced by different types of toys during the entire age range.

How can intentionality of infants’ RDBM be inferred? Kimmerle at al. (2010) suggested that the infant’s actions may be considered planned and intentional if the stable sequence of actions precedes the occurrence of RDBM. Although infants start developing the hand-use preference for reaching towards the second half of the first year (Michel et al., 1985), they may switch to the non-preferred hand while reaching in order to immediately engage in RDBM with the preferred hand. This sophisticated pattern of reaching would appear only if the infant is planning the RDBM action before reaching for the toy.

Kimmerle et al. (2010) explored sequences of actions preceding RDBM and reported that, regardless of the age of the infant and the type of a toy, initial contacts are usually made by unimanual manipulation of the toy. For single toys, Kimmerle at al. (2010) observed a shift in use of the left hand (60% left) for initial contact at the age of 11 months (with nearly all participants being right-handed), thus, suggesting that “at the age of 11 months we have the first potential evidence of an intention to engage in

RDBM" (p. 175). However, the authors did not report how hand-use preference for contacts changes with age from 7 to 13 months, and whether this observed shift at 11 months is statistically significant. Moreover, no information on the potential shift in the hand-use preference for contact of double toys was presented by Kimmerle et al. (2010).

The sequential analysis showed that for single toys statistically significant sequences were defined only for two-event sequences at 11 months, from which Kimmerle et al. (2010) concluded the intentionality of such actions. Note that there was no evidence that the same sequences were significant at 13 months. Therefore, it would be counter-intuitive to assume that intentionality is present at 11 months, but then disappears at 13 months. In contrast, for double toys, the distribution of contingent sequences (two and three events) leading to RDBM becomes significantly different from chance only at 13 months (Kimmerle et al., 2010). Note that three event sequences represent a much more elaborate coordination of actions resulting in RDBM. Thus, one may suspect intentionality and planning in execution of RDBM actions on double toys starting at the age of 13 months.

Since RDBM is first observed (at 7 months) long before it may be considered to be a "skill" or an "intentional" activity, it could be suggested that RDBM is emerging from accidental irregular manual manipulation of objects and slowly emerges as a skill and only then becomes intentional and deliberately produced (Kimmerle et al., 2010). Only this deliberate production at the age of about 12-13 months seems to be associated with the emergence of hand-use preference in the role-differentiated bimanual manipulation.

Importance of Studying RDBM Development

What is special about the role-differentiated bimanual manipulation and why is it important to study its development? As it was noted earlier, role-differentiated bimanual manipulation requires complementary movements of both hands which become possible only with interhemispheric communication through the corpus callosum (Jeeves, Silver, & Milne, 1988; Trevarthen, 1978). The corpus callosum (CC) permits the extension of available cortical space at no additional cost through the reduction of redundancy in information processing between the hemispheres. Thus, the two hemispheres can become functionally specialized as long as the CC enables the access to any specialized processing for the entire cognitive system.

There have been long debates about the role of the corpus callosum in the development of hemispheric asymmetry. It was suggested that the under-developed CC in infancy and early childhood may play an important role in the development of hemispheric asymmetries and handedness by restricting the completely shared processing of asymmetrical sensorimotor inputs to one hemisphere and thereby making it more apt in processing of particular types of stimuli (Gazzaniga, 2000; Hellige, 1993). In addition, it was argued that CC permits the transfer of excitatory and inhibitory information between the two hemispheres.

Thus, CC allows inhibition of one hemisphere by the activity that is currently taking place in the other hemisphere (Meyer, Röricht, Gräfin von Einsiedel, Kruggel, & Weindl, 1995; Schnitzler, Kessler, & Benecke, 1996). This inhibition makes possible complex role-differentiated bimanual manipulation. Sacco, Moutard, and Fagard (2006) demonstrated that 1-year-old infants with agenesis of the corpus callosum (ACC) are not significantly different in their handedness from the normally-developing control group when tested on a simple grasping task, but the performance of ACC infants on the bimanual task was significantly impaired compared to their typically developing peers. Sacco et al. (2006) suggested that agenesis of the corpus callosum may interfere with the establishment of more sophisticated bimanual coordination in infancy.

One might argue that deficiencies in early performance on tasks requiring role-differentiated bimanual manipulation may highlight some delays in underlying interhemispheric communication and the development of corpus callosum. Thus, it can be suggested that patterns of development of role-differentiated bimanual skills may serve as a marker of callosal functioning (Fagard et al., 2001; Kimmerle et al., 1995; Wolf et al., 1990) which enables hemispheric specialization that seems to be required for neurobehavioral functioning.

Furthermore, although cognitive and motor development are often treated as separate, non-related domains of ability, they may be functionally related, especially during infancy. Bojczyk and Corbetta (2004) suggested that the acquisition of the role-differentiated bimanual manipulation enables infants to solve complex tasks that require complementary hand movements and involve planning. Successful solving of such tasks might result in an increase in the infant's understanding of spatial and temporal relations between objects, which, in its turn, would facilitate the development of more sophisticated skills such as tool use. Thus, role-differentiated bimanual manipulation becomes possible with the development of cognitive and sensorimotor components

(Greenfield, 1991). At the same time, the development of role-differentiated bimanual manipulation might influence sensorimotor and cognitive development.

Handedness Status and Neurobehavioral Functioning

Should infant's handedness status be taken into account while exploring his/her patterns of neurobehavioral functioning? The answer would be positive if we establish that the developing handedness status affects the development of other abilities like object manipulation, bimanual coordination, object construction skills, tool-using skills, visual-spatial abilities, and executive functioning. The reciprocal interaction between the person's experiences and neural organization creates differences in early sensorimotor experiences and differential patterns of hemispheric organization, which, in turn, produce differences in further planning and execution of manual actions.

As a result, infants with early stable hand-use preferences for reaching for and acquiring objects are likely to create sensorimotor experiences and develop patterns of hemispheric lateralization that would be quite distinct from those exhibited by infants without a stable hand-use preference. However, we have little evidence that handedness status affects the development of other abilities such as tool use, construction, symbol manipulation, etc. (cf., Kotwica, Ferre, & Michel, 2008). In addition, these differences in hemispheric organization are likely to result in further differences in manual hand-use patterns manifested in later-developing more complex manual skills such as unimanual and role-differentiated bimanual manipulation.

Hildreth (1949) described the hand as "the instrument of the mind, a tool that surpasses in its flexibility, power, and strength any other tool in existence" (p. 197).

According to her, the division of labor between the two hands results in the efficiency of performance and contributes to the formation of a skill. Although some individuals consider themselves being ambidextrous (performing well with both hands), the majority of them are in reality ambisinistrals (manifesting inferior performance with both hands). Hildreth (1949) further suggested that "achieving handedness is essentially a learning process involving habit formation, spontaneous reaction, postural adjustment, expression of choice, and responding in social situations" (p. 210). Therefore, early formation of hand-use preference might lead to benefits in cognitive, motor, and emotional development.

In order to test this notion, Cohen (1966) explored the relation between the infant's laterality (hand preference vs. no hand preference) and developmental status in 8 month old infants. He considered the hand-use preference as an efficient mode of behavior, early establishment of which might result in better developmental outcomes. Cohen (1966) studied handedness patterns (grasping hand for three toys presented four times each) as well as mental and motor development (using Bayley Mental-Development and Motor-Development scales) in 100 normally developing infants. Note that handedness is a motor skill, and the motor development assessed by Bayley scales includes a measure of handedness; therefore, the Bayley motor development scale is not independent from handedness. Also, nine grasps out of possible twelve performed by the same hand was used by Cohen (1966) to classify the infant as having a hand-use preference (unfortunately, according to the binomial probability distribution (Mendenhall et al., 2013), 9 out of 12 grasps do not reflect a significant hand-use preference with p =

.054). The infant's performance on the Bayley scales led to the classification of the infant as "advanced", "normal" or "suspect" for mental and motor development.

Cohen (1966) found significant relation between the infant's lateralization status and developmental status only in the group of "advanced" infants (for both mental and motor Bayley scales). Thus, the statistically significant majority of "advanced" infants (24 out of 26) had a hand use preference, whereas the distribution of infants in the groups of "normal" and "suspect" development showed no significant differences between the number of handed and non-handed infants. Cohen (1966) concluded that early development of hand-use preference is related to a more advanced developmental status of the infant in both mental and motor development. In addition, Cohen (1966) suggested that a specific hand preference (right vs. left) does not relate to the developmental status of infants at 8 months. Delineating future direction of research, Cohen (1966) noted that "a longitudinal study of the relationship between the developmental status of a child and the time of establishment of the various aspects of lateral preference might prove to be a fruitful approach to understanding growth and development" (p. 345).

Previous research also showed that infants with stable hand-use preferences are more effective in object management skills such as acquisition and storage than those without stable hand-use preferences (Kotwica et al., 2008). Early development of hand-use preference might facilitate the interhemispheric communication through the corpus callosum (e.g., Fagard & Corroyer, 2003; Fagard et al., 2001) which makes easier intermanual coordination necessary for effective performance of complex sequential actions during manipulation of multiple objects. Kotwica et al. (2008) suggested that the observed differences may have further implications for the development of other perceptual/cognitive skills such as exploring properties of objects, understanding the relations between objects, and “planning” of actions. In agreement, Bruner (1973a) considered such object management skills to be important for the development of symbolic abilities since the ability to store objects requires the infant to “represent” the location of the object in order for it to be retrieved later. Unfortunately, the overwhelming majority of infants with a stable handedness for acquiring objects in Kotwica et al. (2008) were right-handed. Thus, this issue needs further investigation in the bigger sample representing infants with different handedness status.

It was also reported that infants with a stable hand-use preference for acquiring objects exhibit better coordination of their bimanual reaching when the preferred hand is perturbed by a barrier or when the preferred hand is perturbed by slightly weighting it (Goldfield & Michel, 1986; Michel, 2002). Thus, a hand-use preference was associated with the development of more effective bimanual control of the movement of the hands in space. Unfortunately, in these studies, the overwhelming majority of infants with a stable handedness for acquiring objects were right handed infants. If handedness *per se* is the explanation for the reported differences in performance, then the differences should be present in both right- and left-handed infants, but this notion requires further investigation.

Previous research demonstrated strong association between the preschool design-copying skills and the future success in the middle school mathematics, science, and reading achievement tests (Cameron et al., 2012; Grissmer, Grimm, Aiyer, Murrah, &

Steele, 2010). Although design copying skills are conventionally interpreted as visual-spatial abilities, they might more appropriately represent visual-motor manual skills. As such, individuals with early hand-use preferences ought to exhibit better skills when copying designs compared to individuals without early hand-use preference. If early handedness development is related to better design copying skills of children, then patterns of infant handedness development may reflect patterns of neurobehavioral development highly relevant for the development of scientific, reading (language), and math skills. For example, the relation between early handedness and later language abilities was studied by Nelson, Campbell, and Michel (2013b). They found evidence that the toddlers who developed handedness as infants during 6 to 14 month interval were more advanced on their standardized language skills (assessed with the Bayley Scales of Infant and Toddler Development) as two-year-olds when compared to those toddlers who had not exhibited handedness as infants.

So far, we have discussed difference in bimanual coordination between lateralized and non-lateralized infants. Would we expect to observe differences in bimanual coordination within the "lateralized" group – between left- and right-handers? Previous research suggested that larger corpus callosum is associated with weaker lateralization and non-right-handedness (Luders et al., 2010; Witelson, 1985). Thus, left-handers may have larger corpus callosum, but does it mean that left-handers would be better at bimanual coordination tasks? Fagard and Corroyer (2003) reported better bimanual coordination manifested in crank-rotation task in less right-handed subjects (children between 3 and 8 years old), but this issue needs further investigation.

Furthermore, complex role-differentiated bimanual manipulation requires a high level of coordination between the two hands for the execution of the spatiotemporal sequences of the RDBM actions. Since the left hemisphere is considered to be dominant for processing sequences of fine motor actions (e.g., Grafton et al., 2002; Kimura & Archibald, 1974), the well-established right hand-use preference may result in left hemisphere (contralateral to the right hand) being more efficient at execution of coordinated sequences. In this case, right-handers may be more efficient at tasks that demand sequencing (such as complex manual manipulation like RDBM and speech) than other individuals. That would be true if there was a direct correspondence between the dominant hand and the contralateral hemisphere for speech processing.

However, whereas the majority of right-handers (90-95%) were reported to be left-hemisphere dominant for language, about 70-80% of left-handers also have their language processing in the left hemisphere (Kimura, 1983; McKeever, Seitz, Krutsch, & Van Eys, 1995; Rasmussen & Milner, 1977; Szaflarski et al., 2002; Tzourio-Mazoyer, Josse, Crivello, & Mazoyer, 2004) which might suggest the left-hemisphere dominance for fine motor control in the majority of right- and left-handers. Thus, the role of handedness development for hemispheric processing is poorly supported by this research. Moreover, if left-handers, similar to right-handers, would have advantage in sequencing tasks such as RDBM compared to individuals without stable hand-use preference, they must be accessing their left hemisphere via the corpus callosum. Obviously, more research is needed before making any confident conclusions.

Current Study and Hypotheses

The goal of this dissertation was to examine a potential cascade in handedness development (i.e., the development of handedness for role-differentiated bimanual manipulation of objects as a cascade from the earlier development of hand-use preferences for acquisition and unimanual manipulation) while ensuring sufficient numbers of infants with right-, left- and no stable hand-use preference for toy acquisition. The hypotheses were:

1. Infants are predicted to increase in their lateralization of toy acquisition handedness during 6 to 12 month interval (before manifesting a hand-use preference for RDBM) and decrease thereafter when toy acquisition hand-use preference becomes subordinate to the hand- use preference for RDBM. Thus, right-handed infants on average are expected to decrease in their right-handedness, whereas left-handers are expected to decrease in their left-handedness for toy acquisition at the age of approximately 12 months when RDBM becomes a larger component of the infants' manual repertoire with objects. Moreover, a significant decrease in the proportion of infants lateralized for toy acquisition (right- and left-handers) is expected at the age of approximately 12 months. This trend is predicted because infants might start reaching and acquiring objects with the non-preferred hand in order to stabilize them and "set-up" the "intentional" and "planned" role-differentiated bimanual manipulation by the preferred hand.

2. Handedness for unimanual manipulation becomes more pronounced with age. Moreover, there are significant differences in hand-use preference for unimanual

manipulation among different handedness status groups. Thus, right-handers are predicted to be more right-handed for unimanual manipulation initially and develop towards more right-handedness, whereas left-handers are predicted to be less right-handed for unimanual manipulation initially and develop toward left-handedness. Moreover, a significant increase in the proportion of infants lateralized for unimanual manipulation (right- and left-handers) is expected by the age of approximately 11 months when unimanual manipulation peaks in the infant's manual repertoire with objects.

3. The hand-use preference for role-differentiated bimanual manipulation is predicted to become more pronounced with age. Also, differences in the trajectories of handedness for role-differentiated bimanual manipulation among all three acquisition handedness status groups are predicted. Thus, right-handers are predicted to be less handed initially and develop towards more right-handedness for RDBM, whereas left-handers are predicted to be less handed initially and develop toward left-handedness for RDBM.

4. Differences in the trajectories of handedness for role-differentiated bimanual manipulation among different handedness status groups for toy acquisition will be observed in difficult, but not in simple, RDBMs. It has been reported that simple RDBMs can be frequently observed early in the development (by the beginning of the study at 9 months), whereas difficult RDBMs are almost non-existent at 9 months and appear only later.

5. Infants with an established hand-use preference for toy acquisition (both right- and left-handers) are expected to perform more RDBM actions (especially difficult

RDBMs) at the early age of 9 months, as well as throughout the 9-14 month age interval as compared to infants without a distinct hand-use preference for toy acquisition. Thus, right- and left-handed infants are not expected to differ from each other in the number of performed RDBM actions across age, whereas infants without a distinct hand-use preference for toy acquisition are expected to perform fewer RDBMs initially and increase in the number of performed RDBMs with age but not as dramatically as lateralized infants.

6. Handedness for simple RDBMs would appear sooner than handedness for difficult RDBMs. A significant increase in the proportion of infants lateralized for RDBM (right- and left-handed) is expected to occur around the age of 13 months.

7. A significant decrease in the proportion of infants' bimanual acquisitions will be observed just before the significant increase in lateralization of handedness for role-differentiated bimanual manipulation.

8. Handedness for toy acquisition is predicted to be significantly positively related to the handedness for unimanual manipulation, which, in its turn, would be significantly positively related to the handedness preference manifested during role-differentiated bimanual manipulation. Moreover, handedness for toy acquisition is hypothesized to be significantly positively related to the handedness for role-differentiated bimanual lateralization.

CHAPTER II

METHOD

Subjects

Hand-use preference for toy acquisition was assessed in a large sample of 380 infants. Thirty infants with left-hand-use preferences (19 males, 11 females) from this sample were matched on sex and level of postural skills development (onsets of sitting, crawling and walking) with 30 infants with right-hand-use preferences and 30 infants without stable hand-use preference. All infants came from full-term pregnancies (a minimum of 37 weeks gestation) and uncomplicated single births. The current sample of 90 infants (57 males, 33 females) used for this study is 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 North Carolina population. All subjects were tested monthly, within +/-7 days from infants' monthly birthdays, from 6 to 14 months (total 9 visits) on toy acquisition and from 9 to 14 months (total 6 visits) for unimanual manipulation and role-differentiated bimanual manipulation. Infants' mean age at the beginning of the study was 6.13 months (roughly 6 months, 4 days, *SD* = 0.15 or 4.5 days) and at the end of the study the mean age was 14.25 months (roughly 14 months, 7 days, *SD* = 0.16 or 4.8 days).

Procedure

For each observation visit, infants' handedness for acquiring toys, unimanual manipulation, and role-differentiated bimanual manipulation was assessed in the Infant Development Center at the University of North Carolina at Greensboro. The procedure for recruitment, obtaining informed consent, data collection and presentation was in accordance with the regulations set by the UNCG Institutional Review Board for the protection of human subjects. Parents received a $10 gift certificate as compensation for each of their visits to the laboratory.

Assessment of a hand-use preference for toy acquisition. At each monthly visit, a reliable and validated handedness assessment (Michel et al., 1985) was administered while infants were sitting on their parents' laps, in an upright posture and at navel height to a table. This posture permitted free movements of the infant's arms. Parents were requested to hold the infant with both hands at the waist level, so that the infant could maintain a steady posture, and not to interfere with the infant's movements. Rare instances of accidental parental interference were excluded from coding and analysis.

Assessment of hand-use patterns consisted of separate, random-order, presentations of thirty-four infant toys: ten double presentations involving two identical toys presented in line with the infant's shoulders (7 pairs of toys presented on the table and 3 pairs suspended by string at the level of the infant's eyes), and twenty-four single toys presented midline to the infant (19 toys presented on the table, and 5 toys presented in the air). Alternating double and single presentations as well as air and table presentations ensured that infants were unlikely to establish any repetitive response bias.

The toys selected for the study were brightly colored, of medium size so that they could be easily grasped. Each toy presentation lasted approximately 15 seconds before the toy was taken away and the next one was presented.

Infants' hand-use when acquiring the toys was digitally recorded using two synchronized cameras that provided a split-screen with an overhead and a side view. The coding for hand-use was done in the Observer® XT (Noldus Information Technology, Wageningen, Netherlands) which permitted frame-by-frame coding of infants' manual actions. Coders viewed all recordings in real time, followed by a slow motion view in order to identify precisely the hand used for a toy acquisition (lifting the toy from the surface of the table). If the infant was observed to contact or pick up the toy using both hands within an interval of less than 0.25 sec between the hands, this manual action was coded as bimanual; beyond the 0.25 sec interval, the action was coded as unimanual (only the hand that acted on the toy first was coded). The quarter-second time window is well within the ability of the nervous system to coordinate the movements of the two arms.

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 another has a role of supporting the other hand's acts. Hand-use preference for RDBM was assessed longitudinally during play with an additional set of 20 multiple-part toys. Each toy was presented at midline on the table. All multiple-part toys were presented in the inserted position. The order of presentations was random. 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; “push” – when more than two fingers or the whole hand is repeatedly touching the surface of a toy; “stroke” – when more than two fingers or the whole hand is moving along the outside/inside surface of a toy; “spin” – when one hand spins a movable part of a toy; “pull” – when one hand pulls a part of a toy; “insert” – when one hand inserts a part of a toy into a larger toy. RDBM actions were coded in the Observer® XT in real time. The hand used for active manipulation (poke, push, stroke, spin, pull, insert) was identified. Also, RDBM was coded when bimanual manipulation was clearly attempted and not necessarily performed successfully.

Assessment of a hand-use preference for unimanual manipulation. Hand-use preference for unimanual manipulation was assessed longitudinally during play with a set of 20 multiple-part toys used for RDBM procedure. A unimanual action is an action such as poke, stroke, push, pull, insert, or spin produced by a single hand without the other hand being engaged in supporting the toy (such bimanual actions would be coded as RDBM). Unimanual manipulations were coded in the Observer® XT in real time. The hand used for unimanual manipulation was identified.

The data representing unimanual manipulation cannot be considered as completely independent from the data for role-differentiated bimanual manipulation since these data were collected from the same sample of toys during the same procedure. Such argument would be that if the infant has a limited time for manipulation of each toy, some actions will appear at the expense of other actions. Thus, in the current dissertation, any discussion of the relations between the frequencies of performed unimanual and role-differentiated bimanual actions will be avoided.

Although some infants (most likely younger infants) do not perform RDBM actions, they do perform unimanual actions. Therefore, for the purposes of this study, the relation of the infant's hand-use preference for unimanual manipulation to handedness for toy acquisition and RDBM is examined. In the current study, results can be obtained separately on the development of toy acquisition handedness, unimanual manipulation handedness and handedness for role-differentiated bimanual manipulation. Also, the relation between toy acquisition handedness and unimanual manipulation handedness may be explored, as well as toy acquisition handedness and role-differentiated bimanual manipulation handedness, since toy acquisition handedness was assessed separately from unimanual manipulation and RDBM handedness. Please note, however, that the relation between unimanual manipulation handedness and RDBM handedness can be potentially confounded because handedness for these two skills was assessed in the same procedure. Nevertheless, we would like to explore the potential relation between unimanual manipulation handedness and RDBM handedness.

Twenty percent of all coded videos were re-coded by a second coder for inter-rater reliability, which reached a mean Cohen's Kappa of 0.91 (*Mdn* = 0.91, range = 0.82 to 0.99) for toy acquisition and a mean Cohen's Kappa of 0.85 (*Mdn* = 0.85, range = 0.80 to 0.93) for RDBM and unimanual manipulation. Also, another 20% of the videos were re-coded by the same coder in order to check for intra-rater reliability which resulted in a mean Cohen's Kappa of 0.94 (*Mdn* = 0.94, range = 0.88 to 0.99) for toy acquisition and a mean Cohen's Kappa of 0.89 (*Mdn* = 0.88, range = 0.88 to 0.93) for unimanual manipulation and RDBM. All coding was done blind to the predicted hand-preference of infants.

Measures

To depict and statistically analyze developmental trajectories of handedness for acquisitions, as well as unimanual and RDBM actions in infancy, z-scores were used. Thus, the infant's monthly hand-use preferences for toy acquisition, unimanual manipulation, and RDBM were defined using a z-score conversion of their right and left-hand use [$z = (R–L)/(R+L)^{1/2}$], where R and L represent the total number of performed right-handed and left-handed actions for each infant during each monthly visit.

Handedness status of each participant was determined with group-based trajectory modeling (GBTM, Nagin, 2005) that was conducted on 380 infants' monthly (from 6 to 14 months) hand-use preference z-scores (Michel, Babik, Sheu, & Campbell, 2013), 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. Although this classification tends to ignore the continuous character of handedness development, group-based trajectory modeling enabled us to take into account infants' handedness trajectories while estimating their handedness status. It also enables us to identify groups of infants according to their handedness status. We can then compare the developmental trajectories of hand-use for unimanual manipulation and RDBM among these groups.

The GBTM revealed only three different types of developmental trajectories: those with a right-hand-use preference, those with a left-hand-use preference and those without a stable preference. From the 380 infants tested, 30 infants with left hand-use preferences for acquiring toys were identified and matched with 30 infants in each of the other two groups (those with a right hand-use preference and those without a stable hand-use preference) according to their sex and motor development.

Of interest in the current study was not only the lateralization of infants' manual actions (in z-scores), but also the proportion of bimanual acquisitions. The latter was estimated as a ratio of the number of bimanual acquisitions (B in formula) over the total number of acquisitions across all toy presentations calculated for each infant at each monthly visit [pr_BIM = B/(R + L + B)].

Multilevel modeling in HLM. Multilevel modeling was used to account for non-independence of multiple observations of the same subject. There are two levels in the current multilevel analyses – "within individual" Level 1, and "between individual" Level 2. Level 1 variables vary within each individual, whereas Level 2 variables remain the same within each individual and specify a particular status or membership of the individual. For example, age is a Level 1 variable since we have multiple visits per each individual, and age for each visit is different. In contrast, handedness status is a Level 2 variable since in the current study it specifies the person's membership in a particular handedness status group during the entire study, and thus, remains the same across multiple visits.

Multilevel models of change allow the simultaneous analyses of different research questions. Thus, Level 1 describes within-person variability in the sample and focuses on the individual change over time in hand-use preferences; whereas Level 2 describes the between-person portion of variability and addresses questions of how individual changes in hand-use vary across infants, and how grouping variables such as handedness status can add to the explanation of this change (Singer & Willett, 2003).

The advantage of the multilevel modeling is that it allows estimation of both fixed and random effects of all explanatory variables of interest. The fixed effect of a variable is the average effect of a particular variable in the entire population of individuals (Snijders, 2005). It is defined by the regression coefficient of the variable. In contrast, a random effect for a variable is specified when the random variation of the effects of a particular variable is expected between the Level 1 units (in our case, individuals). For example, one might predict an increase in manual lateralization with age in infancy. In this case, the fixed effect for the age variable would specify the average increase in manual lateralization with age in the population of infants. The random effect of the age variable would specify possible variation in the change of manual lateralization with age among infants. In the current study, all multilevel analyses were conducted using the HLM program (Raudenbush, Bryk, Cheong, Congdon, & du Toit, 2004).

CHAPTER III

RESULTS

Development of Handedness for Toy Acquisition

Previous research suggested that infants are quite capable of toy acquisition at the age of 6 months (at the beginning of our study). However, it is important to explore the change in the number of toy acquisitions with age, as well as possible differences in the number of acquisitions among the three handedness groups. For the multilevel analysis of change in the number of toy acquisitions, in the “within individual” level (Level 1) of the model, we entered age variables representing linear (AGE), quadratic $(AGE)^2$ and cubic $(AGE)^3$ trends of change. In the “between individual” level of the multilevel model (Level 2), we included the dummy-coded handedness status variable HS (HS1 would compare right-handers to left-handers; HS2 would compare right-handers to infants without a stable hand-use preference; infants with a right-hand preference were chosen as a reference group).

In the process of model building, we went through a sequence of models including the unconditional means model, the unconditional growth model, the full level 1 model, and, finally, the full level 1 and level 2 model (Singer & Willett, 2003). A model comparison framework was then used to reduce statistically non-significant fixed effects in the model, beginning with higher order interactions and working down to lower order interactions and main effects (Appelbaum & Cramer, 1974; Cramer & Appelbaum, 1980).

The multilevel analysis showed a significant cubic trend of change in the development of the number of toy acquisitions. Interestingly, this change is not significantly different among the three handedness groups. Thus, the dummy-coded handedness status variables were not statistically significant (HS1: $t(87) = 0.132$, $p = .895$; HS2: $t(87) = -1.037$, $p = .303$) and were dropped from the final multilevel model represented below.

Level 1 model: $n\_ACQ_{ij} = \pi_{0i} + \pi_{1i}*(AGE)_{ij} + \pi_{2i}*(AGE)^2_{ij} + \pi_{3i}*(AGE)^3_{ij} + \varepsilon_{ij}$

Level 2 models: $\pi_{0i} = \beta_{00} + \delta_{0i}$

$\pi_{1i} = \beta_{10} + \delta_{1i}$

$\pi_{2i} = \beta_{20}$

$\pi_{3i} = \beta_{30}$

In this model, n_ACQ_{ij} represents the number of toy acquisitions for child *i* at time *j*. The residual ε_{ij} corresponds to the portion of infant *i*'s acquisitions that is unpredicted at time *j*. The random effects for the intercept and the age variable, δ_{0i} and δ_{1i} respectively, allow accounting for heterogeneity of infants in their intercepts and linear components of change. Non-significant random effects for the quadratic and cubic trends of change were dropped from the model. Estimated parameters of this model are displayed in Table 1 (Model 1).

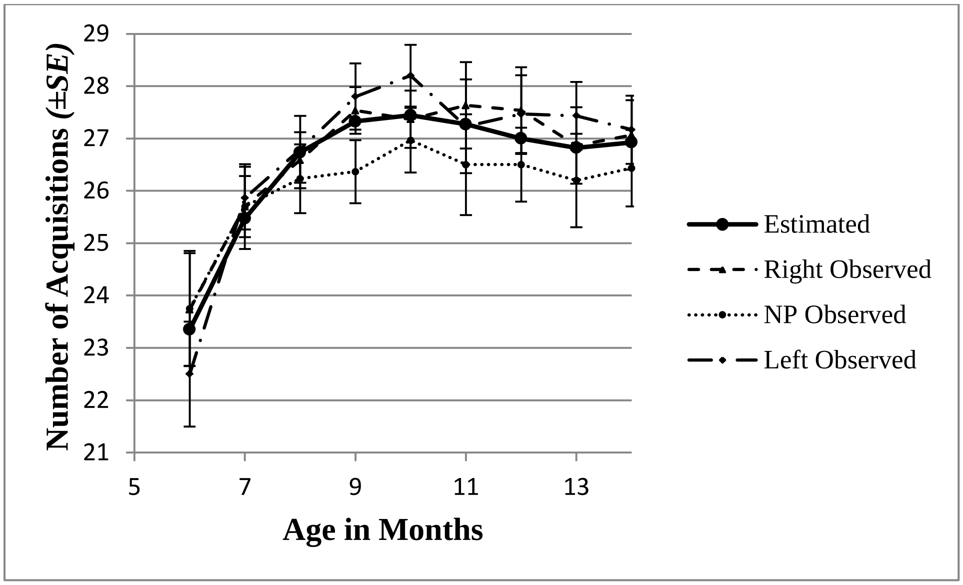
Table 1. Estimated fixed and random effects for the number of toy acquisitions

Level 1 Effects	Level 2 Effects	Parameters	Model 1	Model 2
		Fixed Effects		
Initial status, π_{0i}	Intercept	β_{00}	-17.259	26.483***
AGE, π_{1i}	Intercept	β_{10}	12.101***	0.314***
$(AGE)^2$, π_{2i}	Intercept	β_{20}	-1.074***	-0.048***
$(AGE)^3$, π_{3i}	Intercept	β_{30}	0.031**	0.038**
		Random Effects		
Level 1:	Within-person, ε_{ij}	σ_ε^2	8.906	6.715
Level 2:	Intercept, δ_{0i}	σ_0^2	46.463***	5.131***
	AGE, δ_{1i}	σ_1^2	0.400***	0.442***
	AGE^2, δ_{2i}	σ_2^2		0.003***
	AGE^3, δ_{3i}	σ_3^2		0.007***

Note. ** $p < .01$. *** $p < .001$

Since the presence of quadratic and cubic trends of change in the model might produce multicollinearity effects that could potentially bias the obtained results, the model was re-run with age coded using orthogonal polynomials (Kleinbaum, Kupper, Nizam, & Muller, 2008). Note that the updated model using orthogonal polynomials (Table1, Model 2) produced similar results illustrated in Figure 2. According to Figure 2, there is a steep increase in the number of toy acquisitions with age until approximately 10 months, and a slight, but significant, decrease thereafter. This trend of change is the same for all three handedness groups.

Figure 2. Observed (Mean and SE) and estimated trajectories of change in the number of toy acquisitions; NP = no preference



Furthermore, one of the hypotheses in the current study was that infants would increase in their lateralization of toy acquisition handedness during 6 to 12 month interval and decrease thereafter. In order to test this hypothesis, the change in the hand-use preference for toy acquisition with age was analyzed using the multilevel analysis. The final multilevel model is presented below, and its estimated parameters are displayed in Table 2. The observed and estimated trajectories of change in the handedness for toy acquisition are illustrated in Figure 3.

Level 1 model: $z\_ACQ_{ij} = \pi_{0i} + \pi_{1i}*(AGE)_{ij} + \pi_{2i}*(AGE)^{2}_{ij} + \varepsilon_{ij}$

Level 2 models: $\pi_{0i} = \beta_{00} + \beta_{01}* HS1_{i} + \beta_{02}* HS2_{i} + \delta_{0i}$

$$\pi_{1i} = \beta_{10} + \beta_{11} * HS1_i + \beta_{12} * HS2_i + \delta_{1i}$$

$$\pi_{2i} = \beta_{20} + \beta_{21} * HS1_i + \beta_{22} * HS2_i$$

In this model, z_ACQ_{ij} represents the hand-use preference for toy acquisition estimated in z-scores for child *i* at time *j*. The residual ε_{ij} corresponds to the portion of infant *i*'s hand-use that is unpredicted at time *j*. The random effects for the intercept and the age variable, δ_{0i} and δ_{1i} respectively, allow accounting for heterogeneity of infants in their intercepts and linear components of change.

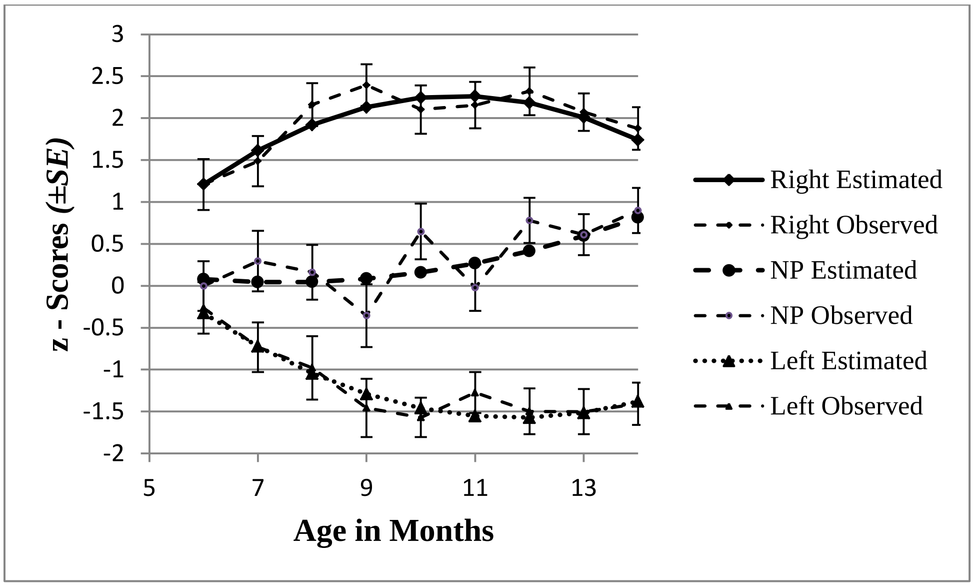
Table 2. Estimated fixed and random effects for acquisition handedness

Level 1 Effects	Level 2 Effects	Parameters	Model Estimates
	Fixed Effects		
Initial status, π_{0i}	Intercept	β_{00}	-3.216
	HS1	β_{01}	6.876***
	HS2	β_{02}	4.254
AGE, π_{1i}	Intercept	β_{10}	1.026**
	HS1	β_{11}	-1.918***
	HS2	β_{12}	-1.294**
$(AGE)^2$, π_{2i}	Intercept	β_{20}	-0.048**
	HS1	β_{21}	0.086***
	HS2	β_{22}	0.066**
	Random Effects		
Level 1:	Within-person, ε_{ij}	σ_ε^2	2.394
Level 2:	Intercept, δ_{0i}	σ_0^2	1.743**
	AGE, δ_{1i}	σ_1^2	0.017**

Note. ** $p < .01$. *** $p < .001$

A non-significant random effect for the quadratic trend of change was dropped from the model. As mentioned above, dummy-coded handedness status variable HS1 compares right-handers to left-handers, whereas HS2 compares right-handers to infants without a stable hand-use preference.

Figure 3. Observed (Mean and SE) and estimated trajectories of toy acquisition handedness in infants with different handedness status; NP = no preference



The multilevel analysis revealed significant quadratic trends of change in right- and left-handed infants as well as infants without a stable hand-use preference (Table 2 and Figure 3). Thus, right-handers increase their right-handedness during the period from 6 to 11 months and decrease thereafter, whereas left-handers increase their left-handedness until the age of 11 months and slightly decrease thereafter. Moreover, infants initially without a stable hand-use preference increase their right-hand use during the entire 6-14 month interval.

Another hypothesis in this study predicted a decrease in the proportion of infants lateralized for toy acquisition (right- and left-handers) at the age of approximately 12 months. In order to test this hypothesis, monthly z-scores for toy acquisition hand-use were coded as being left-handed if they are less than -1.65 ($z = 1.65$ for $\alpha = .05$ in one-tailed testing), right-handed if they are more than +1.65, and reflecting no hand-use preference otherwise. The number of infants lateralized for toy acquisition increases from 6 to 9 months, reaches its maximum (49%) at the age of 9 months, and starts decreasing thereafter (Table 3).

Table 3. Distribution of infants among the three handedness groups for toy acquisition with age; NP = no preference

Age	Left	NP	Right
6	13	55	20
7	15	48	26
8	13	45	30
9	22	41	27
10	16	45	29
11	14	49	27
12	14	49	27
13	12	54	24
14	14	51	25

However, the chi square analysis showed that the observed changes in handedness distribution were not statistically significant ($\chi^2(16, N = 805) = 10.589$, $p = .834$).

Development of Handedness for Unimanual Manipulation

The number of toy acquisitions tends to increase with age until reaching the ceiling at the age of approximately 10 months. Interestingly, similar pattern of change was observed for unimanual manipulations. Thus, multilevel analysis revealed that the number of unimanual manipulations increases with age from 9 to 12 months, and decreases thereafter (Table 4 and Figure 4). There are no significant differences in the trajectories of change in the number of unimanual manipulations with age among the three handedness groups (HS1: $t(87) = -0.237$, $p = .813$; HS2: $t(87) = -1.087$, $p = .280$). The final multilevel model is presented below. In this model, n_UNI_{ij} represents the number of unimanual manipulations for child *i* at time *j*.

Level 1 model: $n\_UNI_{ij} = \pi_{0i} + \pi_{1i}*(AGE)_{ij} + \pi_{2i}*(AGE)^2_{ij} + \varepsilon_{ij}$

Level 2 models: $\pi_{0i} = \beta_{00} + \delta_{0i}$

$\pi_{1i} = \beta_{10} + \delta_{1i}$

$\pi_{2i} = \beta_{20}$

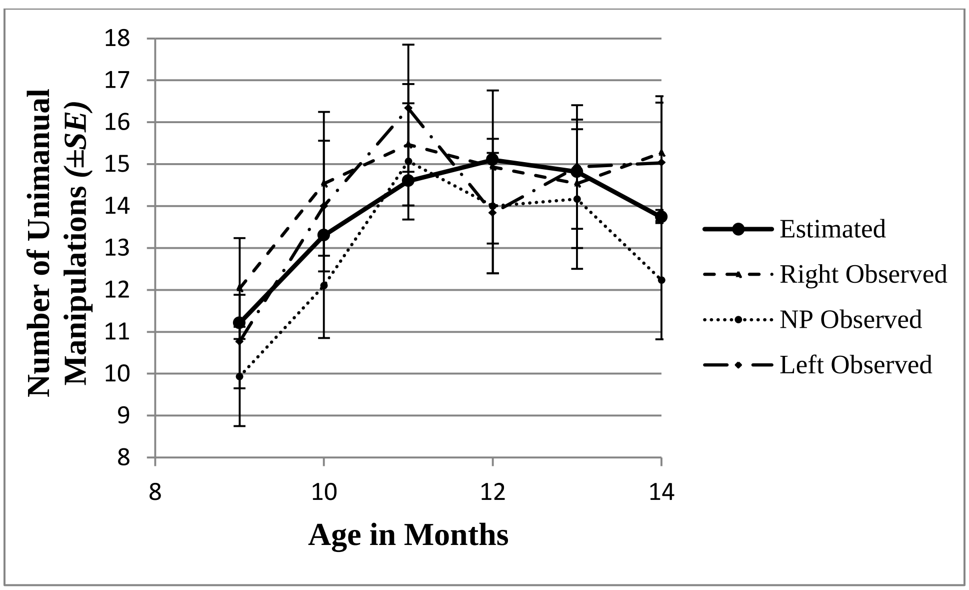
Handedness for unimanual manipulation was predicted to become more pronounced with age. Moreover, significant differences in hand-use for unimanual manipulation were predicted among different handedness status groups.

Table 4. Estimated fixed and random effects for the number of unimanual manipulations

Level 1 Effects	Level 2 Effects	Parameters	Model Estimates
	Fixed Effects		
Initial status, π_{0i}	Intercept	β_{00}	-43.230**
AGE, π_{1i}	Intercept	β_{10}	9.613***
$(AGE)^2$, π_{2i}	Intercept	β_{20}	-0.396***
	Random Effects		
Level 1:	Within-person, ε_{ij}	σ_ε^2	33.494
Level 2:	Intercept, δ_{0i}	σ_0^2	233.010***
	AGE, δ_{1i}	σ_1^2	1.703***

Note. ** $p < .01$. *** $p \leq .001$

Figure 4. Observed (Mean and SE) and estimated trajectories of change in the number of unimanual manipulations



In order to test these hypotheses, the change in the hand-use preference for unimanual manipulation with age was analyzed using the multilevel analysis. The final multilevel model of change in handedness for unimanual manipulation of toys is presented below, and its estimated parameters are displayed in Table 5. The observed and estimated trajectories of handedness for unimanual manipulation are illustrated in Figure 5. In this model, z_UNI_{ij} represents the hand-use preference for unimanual manipulation estimated in z-scores for child *i* at time *j*.

Level 1 model: $z\_UNI_{ij} = \pi_{0i} + \pi_{1i}*(AGE)_{ij} + \varepsilon_{ij}$

Level 2 models: $\pi_{0i} = \beta_{00} + \beta_{01}* HS1_i + \beta_{02}* HS2_i + \delta_{0i}$

$\pi_{1i} = \beta_{10} + \beta_{11}* HS1_i$

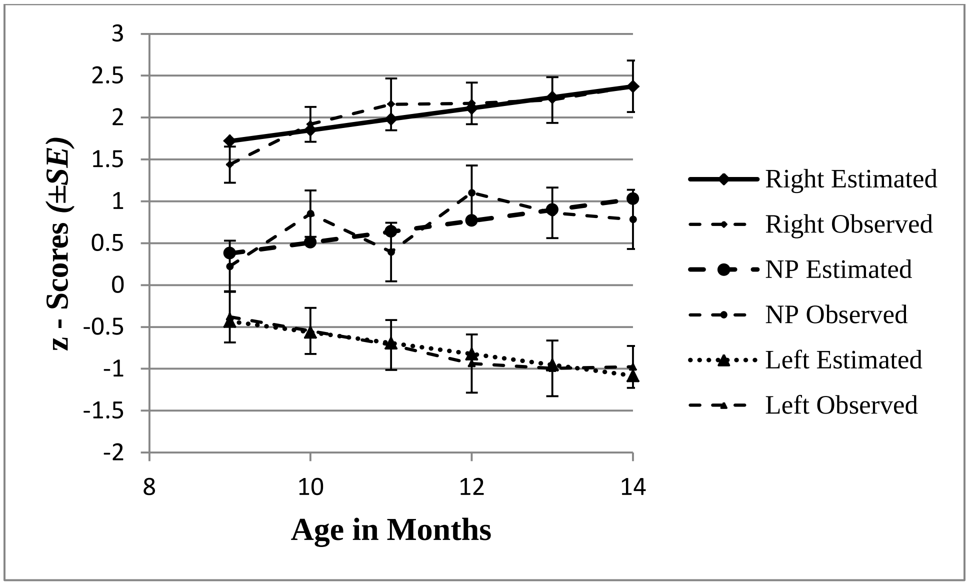
Table 5. Estimated fixed and random effects for unimanual manipulation handedness

Level 1 Effects	Level 2 Effects	Parameters	Model Estimates
	Fixed Effects		
Initial status, π_{0i}	Intercept	β_{00}	0.550
	HS1	β_{01}	0.186
	HS2	β_{02}	-1.342***
AGE, π_{1i}	Intercept	β_{10}	0.130**
	HS1	β_{11}	-0.260***
	Random Effects		
Level 1:	Within-person, ε_{ij}	σ_ε^2	2.040
Level 2:	Intercept, δ_{0i}	σ_0^2	0.574***

Note. ** $p < .01$. *** $p \leq .001$

The multilevel analysis revealed a significant linear, but not quadratic, trend of change for right- and left-handed infants as well as infants without a stable hand-use preference (Table 5 and Figure 5). Thus, for unimanual manipulation, right-handers and no preference infants increase their right-handedness during the period from 9 to 14 months, whereas left-handers increase their left-handedness during this age period.

Figure 5. Observed (Mean and SE) and estimated trajectories of handedness for unimanual manipulation in infants with different handedness status; NP = no preference



A significant increase in the proportion of infants lateralized for unimanual manipulation (right- and left-handers) was predicted at the age when unimanual manipulation peaks in the infant's manual repertoire with objects. The multilevel analysis revealed that the maximum number of unimanual manipulations is performed on average at the age of 12 months. Thus, a significant shift towards more lateralization of unimanual handedness might be expected at 12 months. To test this hypothesis, monthly z-scores were coded into categorical handedness status (right, left and no preference) using z = 1.65 as a cut-off point. The number of infants lateralized for unimanual manipulation increases from 9 to 12 months, decreases at 13 months, and then increases again at 14 months (Table 6). However, this trend of change in the distribution of handedness for unimanual manipulation is not statistically significant ($\chi^2(10, N = 540) = 9.635$, $p = .473$).

Table 6. Distribution of infants among the three handedness groups for unimanual manipulation with age; NP = no preference

Age	Left	NP	Right
9	11	57	22
10	11	48	31
11	13	44	33
12	13	42	35
13	13	43	34
14	16	39	35

Development of Handedness for RDBM

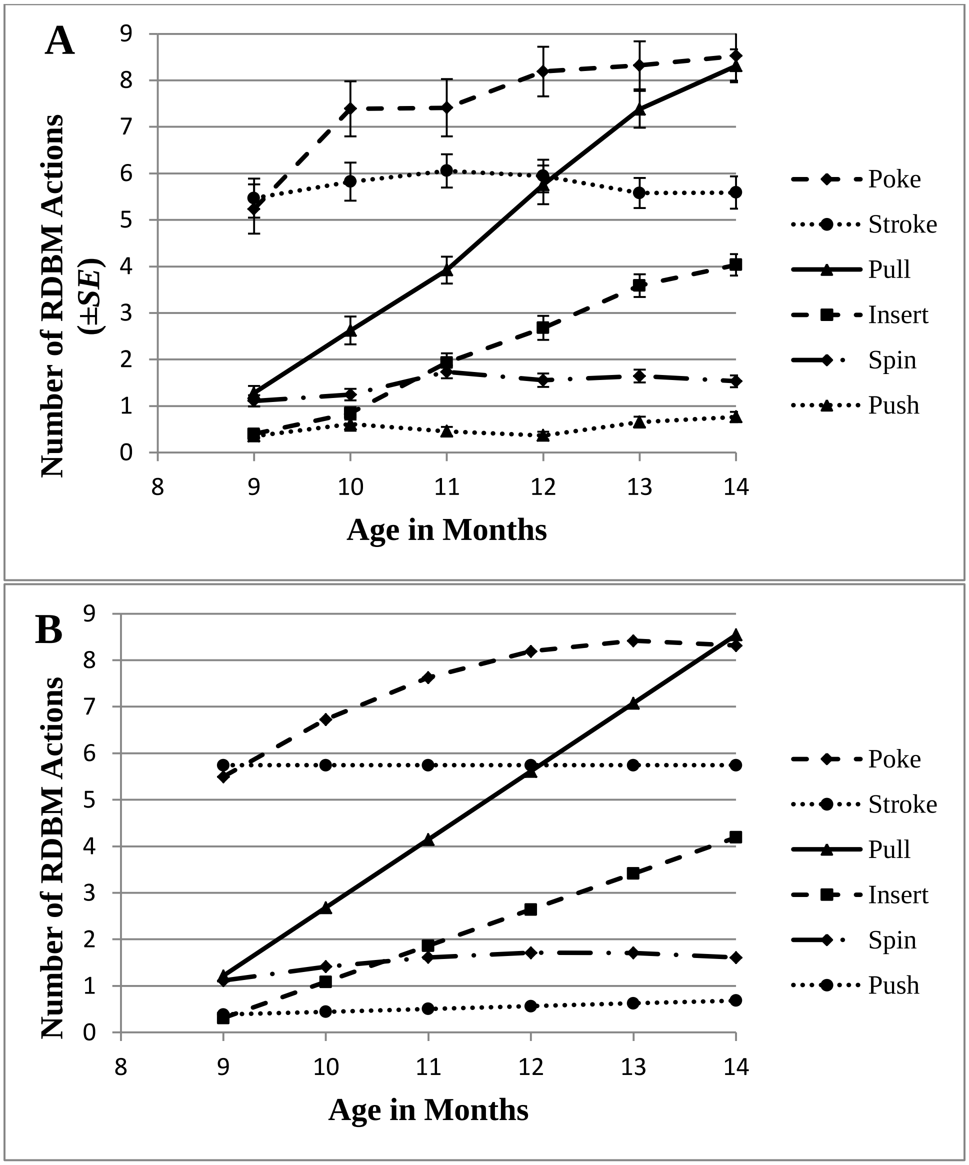
One of the hypotheses in the current study was that handedness for earlier appearing (simple) role-differentiated bimanual manipulation skills may not change with age and might not be significantly different between infants with different handedness status for toy acquisition, whereas handedness for later developing (difficult) RDBM skills might become more pronounced with age, and would differentiate right-handers, left-handers, and no preference infants. In order to test this hypothesis, separate multilevel analyses were conducted for the trajectories of the number of RDBM actions for each of the six observed RDBM skills (poke, stroke, pull, spin, insert, push). Simple RDBM skills are predicted to appear much sooner than the difficult ones.

The multilevel analysis showed a significant quadratic trend of change in the number of pokes and spins with age (POKES: Intercept: $\beta = -20.623$, $t(89) = -2.951$, $p =$

.004; AGE: β = 4.405, t(89) = 3.552, p < .001; $(\text{AGE})^2$: β = -0.167, 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; $(\text{AGE})^2$: β = -0.050, t(448) = -2.486, 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 = 0.776, t(449) = 16.937, p < .001; PUSHES: Intercept: β = -0.155, t(89) = -0.423, p = .673; AGE: β = 0.060, t(89) = 2.012, p = .047). In contrast, the number of strokes did not change significantly with age (Intercept: β = 5.743, t(89) = 23.281, p < .001). The observed mean trajectories of different role-differentiated bimanual manipulation skills are presented in Figure 6A, whereas the estimated trajectories are illustrated in figure 6B.

The multilevel analysis of change in the number of different types of role-differentiated bimanual manipulation revealed that relatively high numbers of pokes and strokes are 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 is negligible at the age of 9 months, but on average tends to increase with age. Thus, one might assume that pokes and strokes represent early (simple) RDBMs while pulls, inserts, spins and pushes represent late (difficult) RDBMs.

Figure 6. Observed (A) and estimated (B) trajectories of change in the mean number of different types of RDBM actions



It was hypothesized that infants with an established hand-use preference for toy acquisition (both right- and left-handers) would perform more RDBM actions (especially difficult RDBMs) at the early age of 9 months, as well as throughout the 9-14 month age interval as compared to infants without a distinct hand-use preference for toy acquisition. Thus, all RDBMs, and separately simple and difficult RDBMs were combined together in order to explore changes in trajectories of their frequencies with age and possible differences in these trajectories between infants with different handedness status.

The final multilevel model for the number of all role-differentiated bimanual manipulations is presented below, and its estimated parameters are provided in Table 7 (Model 1). The model revealed no significant differences in the trajectories of the number of all RDBMs between infants with different handedness status according to the latent class (HS1: $t(87) = -0.980$, $p = .330$; HS2: $t(87) = -1.025$, $p = .308$). In this model, n_ALL_{ij} represents the total number of all role-differentiated bimanual manipulations for child *i* at time *j*.

Level 1 model: $n\_ALL_{ij} = \pi_{0i} + \pi_{1i}*(AGE)_{ij} + \pi_{2i}*(AGE)^2_{ij} + \varepsilon_{ij}$

Level 2 models: $\pi_{0i} = \beta_{00} + \delta_{0i}$

$\pi_{1i} = \beta_{10} + \delta_{1i}$

$\pi_{2i} = \beta_{20}$

The final multilevel model for the number of simple RDBMs is presented below, and its estimated parameters are provided in Table 7 (Model 2). In this model,

n_SIMPLE_{ij} represents the total number of simple role-differentiated bimanual manipulations for child *i* at time *j*.

Level 1 model: $n\_SIMPLE_{ij} = \pi_{0i} + \pi_{1i}*(AGE)_{ij} + \pi_{2i}*(AGE)^2_{ij} + \varepsilon_{ij}$

Level 2 models: $\pi_{0i} = \beta_{00} + \delta_{0i}$

$\pi_{1i} = \beta_{10} + \delta_{1i}$

$\pi_{2i} = \beta_{20}$

Table 7. Estimated fixed and random effects for handedness for all (Model 1), simple (Model 2), and difficult (Model 3) role-differentiated bimanual manipulations

Level 1 Effects	Level 2 Effects	Parameters	Model 1	Model 2
		Fixed Effects		
Initial status, π_{0i}	Intercept	β_{00}	-49.478***	-24.324*
AGE, π_{1i}	Intercept	β_{10}	9.683***	6.092***
$(AGE)^2$, π_{2i}	Intercept	β_{20}	-0.292**	-0.240***
		Random Effects		
Level 1:	Within-person, ε_{ij}	σ_ε^2	35.820	19.663
Level 2:	Intercept, δ_{0i}	σ_0^2	217.497***	90.147***
	AGE, δ_{1i}	σ_1^2	1.496***	0.356*

Level 1 Effects	Level 2 Effects	Parameters	Model 3
		Fixed Effects	
Initial status, π_{0i}	Intercept	β_{00}	-18.354***
AGE, π_{1i}	Intercept	β_{10}	2.390***
$(AGE)^2$, π_{2i}	Intercept	β_{20}	
		Random Effects	
Level 1:	Within-person, ε_{ij}	σ_ε^2	12.570
Level 2:	Intercept, δ_{0i}	σ_0^2	50.776***
	AGE, δ_{1i}	σ_1^2	0.726***

Note. * $p < .05$. ** $p < .01$. *** $p \leq .001$

The model revealed no significant difference in the trajectories of the number of simple RDBMs between infants with different handedness status (HS1: $t(87) = -0.406$, $p = .686$; HS2: $t(87) = -1.038$, $p = .302$).

The final multilevel model for the number of difficult RDBMs is presented below, and its estimated parameters are provided in Table 7 (Model 3). Similar to the Models 1 and 2, Model 3 reveals no significant difference in the trajectories of the number of difficult RDBMs between infants with different handedness status (HS1: $t(87) = -0.774$, $p = .441$; HS2: $t(87) = -0.959$, $p = .340$). In this model, n_DIF_{ij} represents the total number of difficult role-differentiated bimanual manipulations for child *i* at time *j*.

Level 1 model: $n\_DIF_{ij} = \pi_{0i} + \pi_{1i}*(AGE)_{ij} + \varepsilon_{ij}$

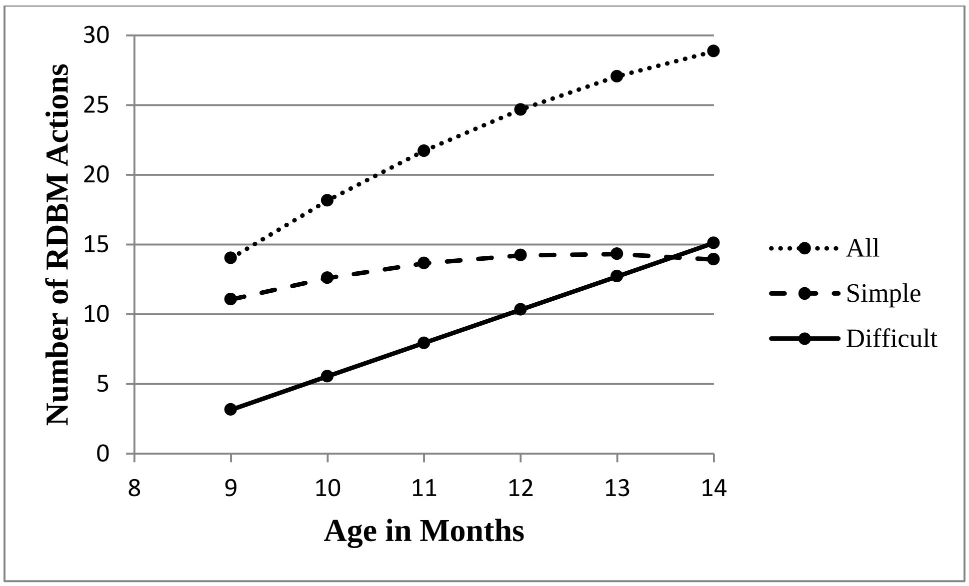
Level 2 models: $\pi_{0i} = \beta_{00} + \delta_{0i}$

$\pi_{1i} = \beta_{10} + \delta_{1i}$

Estimated trajectories of the number of all, simple, and difficult RDBMs in relation to the infants' handedness status are represented in Figure 7. In contrast to the hypothesis predicting differences in the number of performed RDBMs between lateralized and non-lateralized infants, no such differences were detected.

The exploration of trajectories of change in the number of different types of RDBM allowed us to separate those into simple and difficult RDBMs. Now not only we can test the hypothesis that hand-use preference for role-differentiated bimanual manipulation becomes more pronounced with age, but also test whether later (difficult), rather than earlier (simple), developing RDBM skills would highlight differences between the handedness groups as specified by infants' handedness for toy acquisition.

Figure 7. Estimated trajectories of change in the mean number of all, simple, and difficult RDBM actions with age



These trajectories of change in the handedness for all, simple, and difficult role-differentiated bimanual manipulations are examined next. The final multilevel model of the development of handedness for all RDBMs is presented below, and its estimated parameters are displayed in Table 8 (Model 1).

Level 1 model: $z\_ALL_{ij} = \pi_{0i} + \pi_{1i}*(AGE)_{ij} + \varepsilon_{ij}$

Level 2 models: $\pi_{0i} = \beta_{00} + \delta_{0i}$

$\pi_{1i} = \beta_{10} + \delta_{1i}$

In this model, z_ALL_{ij} represents the hand-use preference for all role-differentiated bimanual manipulations estimated in z-scores for child *i* at time *j*. The multilevel analysis revealed a significant linear, but not quadratic, trend of change in handedness for all role-differentiated bimanual manipulations (Table 8 and Figure 8).

Table 8. Estimated fixed and random effects for handedness for role-differentiated bimanual manipulation

Level 1 Effects	Level 2 Effects	Parameters	Model 1	Model 2
		Fixed Effects		
Initial status, π_{0i}	Intercept	β_{00}	-2.183***	-0.603
AGE, π_{1i}	Intercept	β_{10}	0.296***	0.112**
		Random Effects		
Level 1:	Within-person, ε_{ij}	σ_ε^2	1.880	1.689
Level 2:	Intercept, δ_{0i}	σ_0^2	8.686***	3.588*
	AGE, δ_{1i}	σ_1^2	0.115***	0.045**

Level 1 Effects	Level 2 Effects	Parameters	Model 3
		Fixed Effects	
Initial status, π_{0i}	Intercept	β_{00}	-5.340
	HS1	β_{01}	15.149**
AGE, π_{1i}	Intercept	β_{10}	0.780
	HS1	β_{11}	-2.632**
AGE^2, π_{2i}	Intercept	β_{20}	-0.017
	HS1	β_{21}	0.104**
		Random Effects	
Level 1:	Within-person, ε_{ij}	σ_ε^2	1.438
Level 2:	Intercept, δ_{0i}	σ_0^2	
	AGE, δ_{1i}	σ_1^2	0.009***

Note. * $p < .05$. ** $p < .01$. *** $p \leq .001$

Moreover, no statistically significant differences among infants with different handedness status were found (HS1: $t(87) = -1.851$, $p = .068$; HS2: $t(87) = -0.355$,

p = .723). Thus, all infants tend to increase their right-handedness for all role-differentiated bimanual manipulations during 9-14 month interval.

The final multilevel model of change in the handedness for simple RDBMs is presented below, and its estimated parameters are provided in Table 8 (Model 2). In this model, z_SIMPLE_{ij} represents the hand-use preference for simple role-differentiated bimanual manipulations estimated in z-scores for child i at time j.

Level 1 model: $z\_SIMPLE_{ij} = \pi_{0i} + \pi_{1i}*(AGE)_{ij} + \varepsilon_{ij}$

Level 2 models: $\pi_{0i} = \beta_{00} + \delta_{0i}$

$\pi_{1i} = \beta_{10} + \delta_{1i}$

This model reveals a linear trend of change in the development of simple RDBMs with no significant difference in the trajectories between infants with different handedness status (HS1: $t(87) = -0.832$, p = .408; HS2: $t(87) = 0.122$, p = .903).

The final multilevel model of change in the handedness for difficult RDBMs is presented below, and its estimated parameters are provided in Table 8 (Model 3). In this model, z_DIF_{ij} represents the hand-use preference for difficult role-differentiated bimanual manipulations estimated in z-scores for child i at time j.

Level 1 model: $z\_DIF_{ij} = \pi_{0i} + \pi_{1i}*(AGE)_{ij} + \pi_{2i}*(AGE)^2_{ij} + \varepsilon_{ij}$

Level 2 models: $\pi_{0i} = \beta_{00} + \beta_{01}* HS1_i$

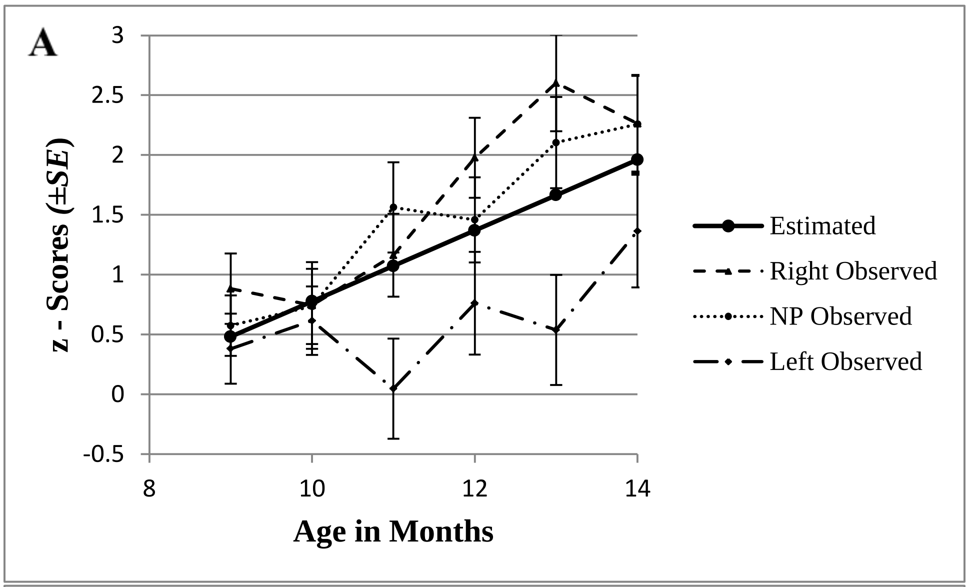
$\pi_{1i} = \beta_{10} + \beta_{11}* HS1_i + \delta_{1i}$

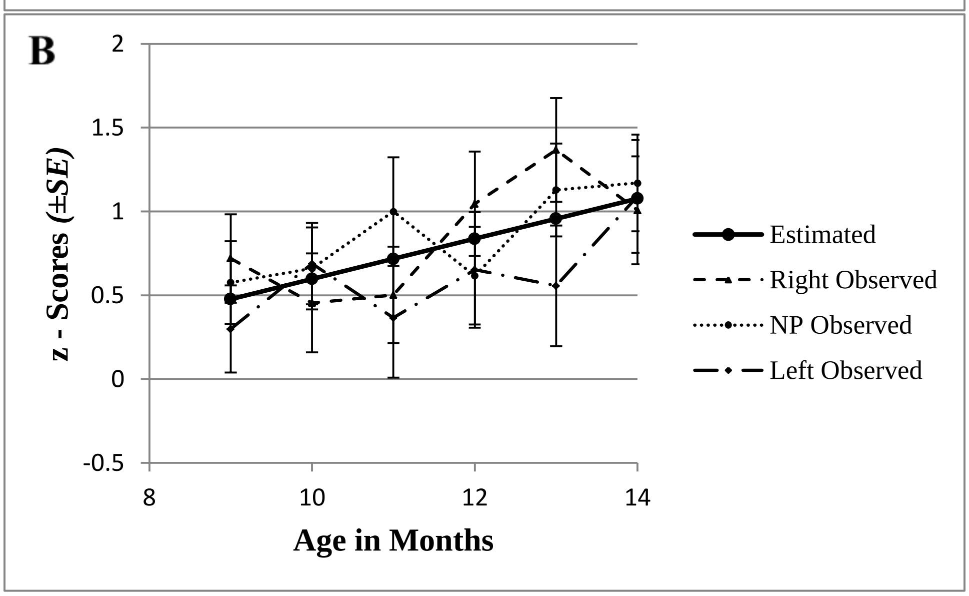
$\pi_{2i} = \beta_{20} + \beta_{21}* HS1_i$

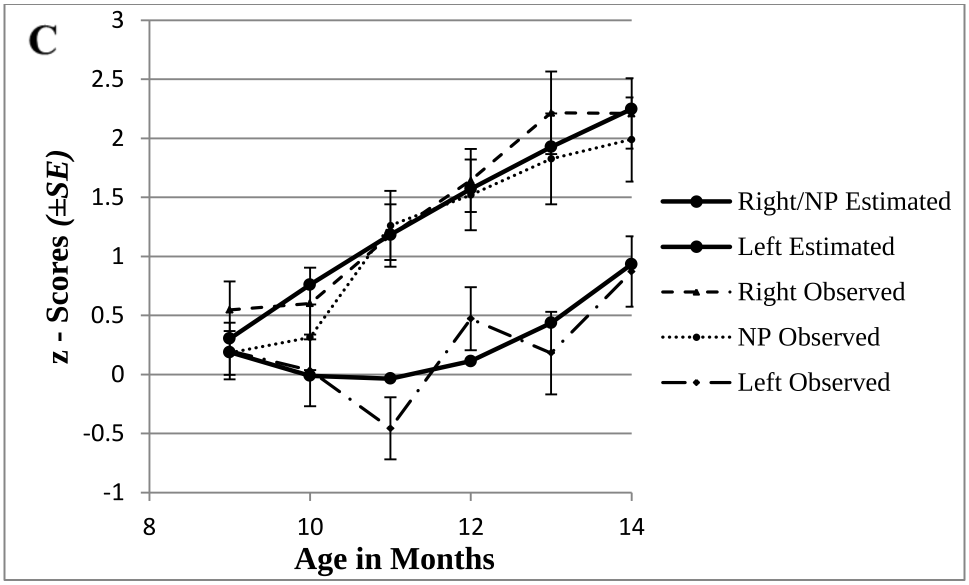
This model reveals no significant difference in the trajectories of handedness for difficult RDBMs between right-handed infants and no preference infants (HS2: $t(427) = -0.692$, $p = .489$), but a significant difference between these two groups and left-handers (see Table 8 for details). The observed and estimated trajectories of handedness for all, simple, and difficult role-differentiated bimanual manipulations are illustrated in Figure 8. Note that for difficult RDBMs, hand-use preference of right-handers and infants without a distinct hand-use preference becomes more right-handed with age, whereas hand-use preference of left-handers has a clear quadratic trend with the decrease in right-handedness from 9 to 11 months and steep increase thereafter. This unusual pattern of change in hand-use preference of left-handed infants warrants further investigation, and we will discuss possible explanations later in this paper.

Thus, as it was predicted, there are no differences in handedness for simple RDBMs among infants with different handedness status, whereas difficult RDBMs differentiate left-handers and the other two handedness groups (right-handers and no preference infants). 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 handedness trajectories among infants with different handedness status for toy acquisition.

Figure 8. Observed (Mean and SE) and estimated trajectories of handedness for all (A), simple (B), and difficult (C) RDBM; NP = no preference infants; Right/NP = right-handers and no preference infants







Furthermore, handedness for simple RDBMs was predicted to appear sooner than handedness for difficult RDBMs. A significant increase in the proportion of infants lateralized for RDBM (right- and left-handed) was expected around the age of 13 months. To test this hypothesis, monthly z-scores were coded into categorical handedness status (right, left, and no preference) using z = 1.65 as a cut-off point. The average distribution of handedness for both simple and difficult RDBMs changes significantly across 6 monthly visits (simple: $\chi^2(10, N = 540) = 28.156$, $p = .002$; difficult: $\chi^2(10, N = 522) = 78.313$, $p < .0001$) (Table 9).

Multiple comparisons were performed separately for simple and difficult RDBMs in order to explore the significance of change in the number of left-handed, right-handed and no preference infants from month to month. Five comparisons for each type of RDBM would lead to the Bonferroni corrected α-level being set at $a = .01$.

Table 9. Distribution of infants among the three handedness groups for simple and difficult role-differentiated bimanual manipulation with age; NP = no preference

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

For simple RDBMs, the significant change in increase of lateralized infants occurred only between 10 and 11 months ($\chi^2(2, N = 180) = 9.216, p = .010$). For difficult RDBMs, the significant change in increase of lateralized infants occurred only between 12 and 13 months ($\chi^2(2, N = 177) = 8.986, p = .011$). Thus, chi square analysis revealed that a statistically significant change in lateralization for simple RDBMs occurs two months sooner than a significant change in lateralization for difficult RDBMs (10 to 11 months vs. 12 to 13 months). These results can be interpreted to support the cascade theory of lateralization development with simple skills becoming lateralized sooner than more difficult skills.

Latent Classes in RDBM Handedness

According to the Figure 8C, one might conclude that all infants in the current sample increase their right-handedness for role-differentiated bimanual manipulation with age. If this is the case, then where does left-handedness for RDBM observed in adults come from? To explore in more detail the development of RDBM handedness, we decided to identify possible latent classes among the developmental trajectories of infant handedness for RDBM. However, we intended to explore not only the entire period of 9-14 months, but also (and even more importantly) the age period when the skill of RDBM becomes more pronounced (later in the development), while at the same time taking into account enough data points to adequately capture the observed change in RDBM handedness.

We have demonstrated above that infants become significantly more lateralized for simple RDBMs at the age of 11 months, and for difficult RDBMs – at the age of 13 months. Thus, we wanted to explore how the trajectory of handedness for RDBM would change if we considered the sequence of 11-12-13-14 months (Model 1, Table 10), 12-13-14 months (Model 2, Table 10), and only ages of 13 and 14 months (Model 3, Table 10). All the following analyses were done for the difficult RDBM since this 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 three and four month sequences, but no statistically significant change in RDBM handedness during 13 and 14 months (Figure 9). We concluded that 13-14 month data is insufficient to show the change in RDBM handedness and cannot be used for subsequent analysis. Also, the pattern of change suggested by the three month model is not substantially different from the pattern of change shown by the more complex four month model; thus, the three month sequence (12-13-14) would adequately represent the change in RDBM handedness during the period when RDBM presumably becomes a well-developed skill. As a result, the subsequent latent class analyses were performed separately for the 9 to 14 month sequence that includes the period before the RDBM becomes a skill, as well as for 12-13-14 month period featuring the development of RDBM as a new skill in the infant's repertoire.

Table 10. Estimated fixed and random effects for RDBM handedness for the sequences of four (Model 1), three (Model 2) and two (Model 3) months

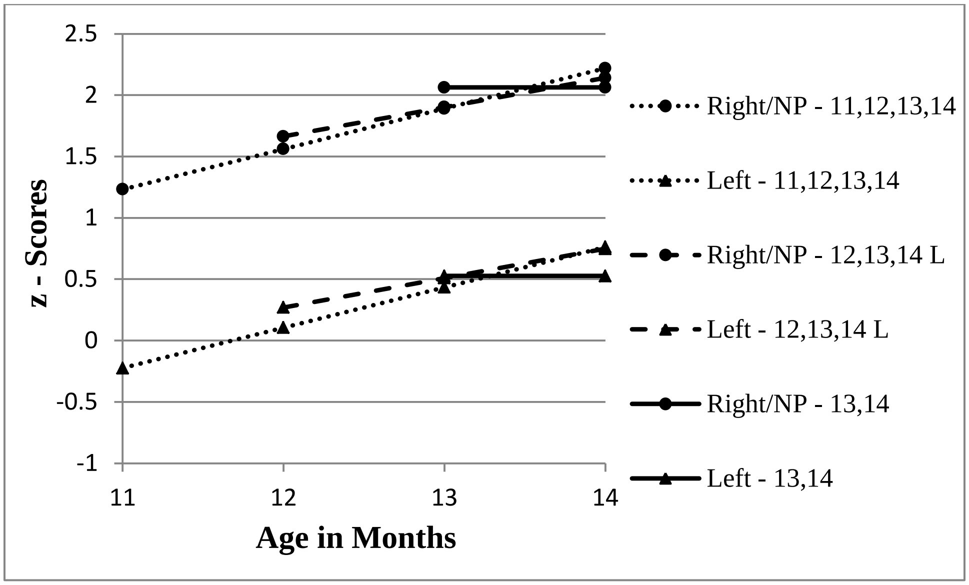
Level 1 Effects	Level 2 Effects	Parameters	Model 1	Model 2
		Fixed Effects		
Initial status, π_{0i}	Intercept	β_{00}	-2.387**	-1.205
	HS1	β_{01}	-1.456***	-1.393***
AGE, π_{1i}	Intercept	β_{10}	0.329***	0.239**
		Random Effects		
Level 1:	Within-person, ε_{ij}	σ_{ε}^2	1.481	1.574
Level 2:	Intercept, δ_{0i}	σ_0^2	1.590***	1.743***

Level 1 Effects	Level 2 Effects	Parameters	Model 3
		Fixed Effects	
Initial status, π_{0i}	Intercept	β_{00}	2.062***
	HS1	β_{01}	-1.535***
		Random Effects	
Level 1:	Within-person, ε_{ij}	σ_{ε}^2	1.777
Level 2:	Intercept, δ_{0i}	σ_0^2	1.906***

Note. ** $p < .01$. *** $p \leq .001$

The group-based trajectory modeling (Nagin, 2005) using SAS TRAJ procedure (Jones, Nagin, & Roeder, 2001) allowed us to identify the number of latent classes in the trajectories of RDBM handedness in the period of 12-13-14 months, as well as 13 to 14 months. Since previous multilevel analyses suggested a significant quadratic, but not cubic, trend of change in RDBM handedness with age, the mixture model trajectories were assumed to follow a second-order polynomial function.

Figure 9. Estimated trajectories of RDBM handedness for the sequences of four, three and two months; NP = no preference



The Bayesian information criterion (BIC) was used to identify the number of groups in the model (Schwarz, 1978). Specifically, 2ΔBIC, twice the difference between the BIC for the full model (larger number of groups) and that for the reduced model (smaller number of groups), is interpreted as the degree of evidence for the full model. This interpretation is justified because 2ΔBIC is approximately $2\ln B_{10}$, where B_{10} is the Bayes factor (Kass & Raftery, 1995). A value of $2\ln B_{10}$ greater than 10 is interpreted as very strong evidence against the reduced model which can be replaced in favor of the more complicated model (Kass & Wasserman, 1995). The GBTM assigns infants to latent classes according to the highest associated classification probabilities. 2ΔBIC criterion suggested that the best fitting model has three latent classes underlying RDBM handedness for the entire 9 to 14 month age period (Table 11, Model 1), and only two latent classes in RDBM handedness when we took into consideration handedness z-scores for only 12-13-14 month period (Table 11, Model 2). The estimated parameters for both models are presented in the Table 12, and the models are illustrated in Figure 10 (A – Model 1; B – Model 2).

Table 11. Tabulated BIC and 2 Delta BIC for the Models 1 and 2 from the latent class analysis

	Model 1		Model 2	
Number of classes	BIC	2ΔBIC	BIC	2ΔBIC
1	-1033.26	–	-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

Since our model is a mixture of censured normals, after defining the latent classes we ensured that z-scores for each of the obtained three (Model 1) and two (Model 2) latent classes do not show any considerable departure from normality. We examined monthly q-q plots and conducted Kolmogorov-Smirnov test of normality for each of the months by each of the three/two latent classes and concluded that data is normally distributed.

Table 12. Estimated fixed and random effects from the latent class analysis (Model 1 for 9-14 month period, Model 2 for 12-14 month period)

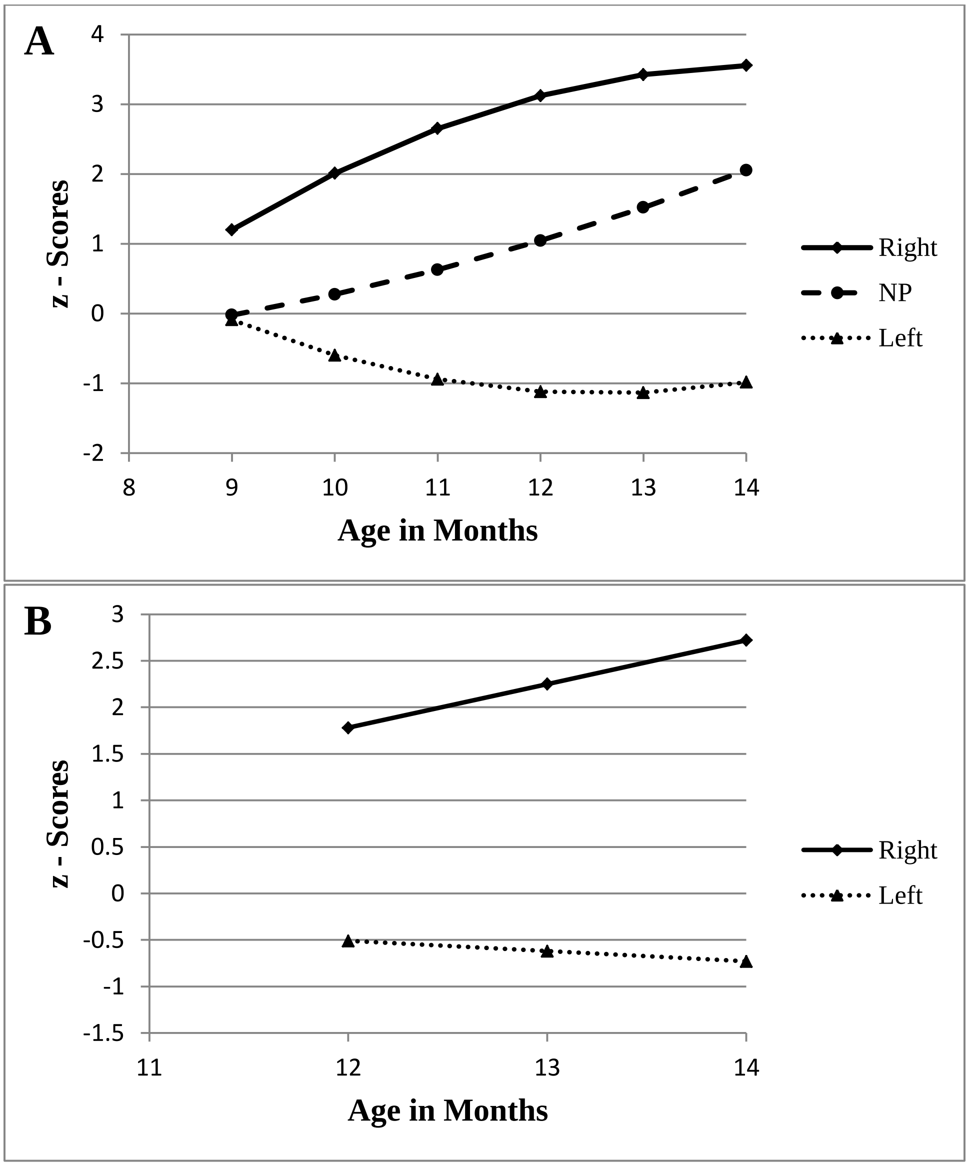
Level 1 Effects	Level 2 Effects	Parameters	Model 1	Model 2
Fixed Effects				
Initial status, π_{0i}	Intercept	β_{00}	-13.750**	-3.862***
	HS1	β_{01}	25.603***	4.666***
	HS2	β_{02}	13.773*	
AGE, π_{1i}	Intercept	β_{10}	2.426**	0.468***
	HS1	β_{11}	-4.491***	-0.582***
	HS2	β_{12}	-2.701**	
AGE^2, π_{1i}	Intercept	β_{20}	-0.085*	
	HS1	β_{21}	0.167**	
	HS2	β_{22}	0.115**	
Random Effects				
Level 1:	Within-person, ε_{ij}	σ_ε^2		1.318
Level 2:	Intercept, δ_{0i}	σ_0^2		0.559***

Note. * $p < .05$. ** $p < .01$. *** $p \leq .001$

According to Figure 10A, we can assume that the three latent classes estimated form RDBM handedness for the 9-14 month period represent “right-handed” infants (22.2% of infants, *SE* = 5.53), “left-handers” (21.1% of infants, *SE* = 5.17) and infants initially without an identifiable hand-use preference (56.7% of infants, *SE* = 6.38).

The latent class analysis revealed significant quadratic trends of change for all three handedness groups (Table 12, Model 1) with “right-handers” and ‘no preference” infants increasing their right-handedness and ‘left-handers” increasing their left-handedness during the 6-14 month age period (Figure 10A).

Figure 10. Estimated trajectories of RDBM handedness for the three classes defined by the latent class analysis for 9-14 month period (A); as well as the two class solution for 12-14 month period (B); NP = no preference



Furthermore, from Figure 10B, we infer that the two latent classes estimated form RDBM handedness for the 12-14 month period represent “right-handed” infants (71.1% of infants, *SE* = 5.96) and “left-handers” (28.9% of infants, *SE* = 5.96). The latent class analysis revealed significant linear, but not quadratic trends of change for the two handedness groups (Table 12, Model 2) with “right-handers” increasing their right-handedness and ‘left-handers” increasing their left-handedness during the 12-14 month age period (Figure 10A).

Next, we explored the distribution of infants among the three latent classes for RDBM handedness (estimated from 9-14 month age period) according to their handedness status for acquiring objects (Table 13). Right-handers for object acquisition tend to fall into no preference or right-handed latent classes for RDBM handedness, left-handers for object acquisition tend to remain left-handed or show no handedness for RDBM. In contrast, infants without a stable hand-use preference for object acquisition tend to exhibit no preference status for RDBM handedness.

Table 13. Distribution of infants among the three RDBM latent classes according to their acquisition handedness

Latent Class for Acquisition	Latent Class for RDBM		
	Left	NP	Right
Right	2	17	11
NP	4	19	7
Left	13	15	2

The distribution of infants among the two latent classes for RDBM handedness (estimated from 12-14 month age period) according to their handedness status for object acquisition is even more revealing.

Whereas right-handers and no preference infants for object acquisition tend to become right-handed for RDBM during the 12 to 14 month period, left-handers show higher heterogeneity with approximately half of the group becoming left-handed for RDBM and the other half becoming right-handed for RDBM (Table 14).

Table 14. Distribution of infants among the two RDBM latent classes according to their acquisition handedness

Latent Class for Acquisition	Latent Class for RDBM	
	Left	Right
Right	4	26
NP	8	22
Left	14	16

Thus, the group of infants who exhibit left-hand-use preferences for RDBM is composed of 46.7% of infants who exhibited a left-hand-use preference for object acquisition, 26.7% of infants with no preference for object acquisition, and 13.3% of infants with a right-hand-use preference for acquiring objects.

Does the Change in Bimanual Acquisition Relate to the Development of RDBM Skill?

Previous research suggested that a significant decrease in the proportion of infants' bimanual reaches/acquisitions will be observed just before the significant shift towards more lateralization in role-differentiated bimanual manipulation. So far, we have established that a significant increase in lateralization of handedness for simple RDBMs occurs between the age of 10 and 11 months, whereas a significant increase in lateralization for difficult handedness occurs between ages 12 and 13 months.

The multilevel analysis of developmental trajectories of change in the proportion of infants' bimanual acquisitions revealed a significant quadratic trend of change. The final multilevel model is presented below, and its estimated parameters are provided in Table 15.

Level 1 model: $pr\_BIM_{ij} = \pi_{0i} + \pi_{1i}*(AGE)_{ij} + \pi_{2i}*(AGE)^2_{ij} + \varepsilon_{ij}$

Level 2 models: $\pi_{0i} = \beta_{00} + \beta_{01}* HS2_i + \delta_{0i}$

$\pi_{1i} = \beta_{10} + \beta_{11}* HS2_i + \delta_{1i}$

$\pi_{2i} = \beta_{20}$

In this model, pr_BIM_{ij} represents the proportion of bimanual toy acquisitions over the total number (right-handed, left-handed and bimanual) of acquisitions for child *i* at time *j*. The observed and estimated trajectories of change in the proportion of bimanual acquisitions in infants with different handedness status are illustrated in Figure 11.

Figure 11. Observed (A) and estimated (B) trajectories of change in the mean proportion of bimanual acquisitions in infants with different handedness status; NP = no preference; Right/Left = right-handed and left-handed infants

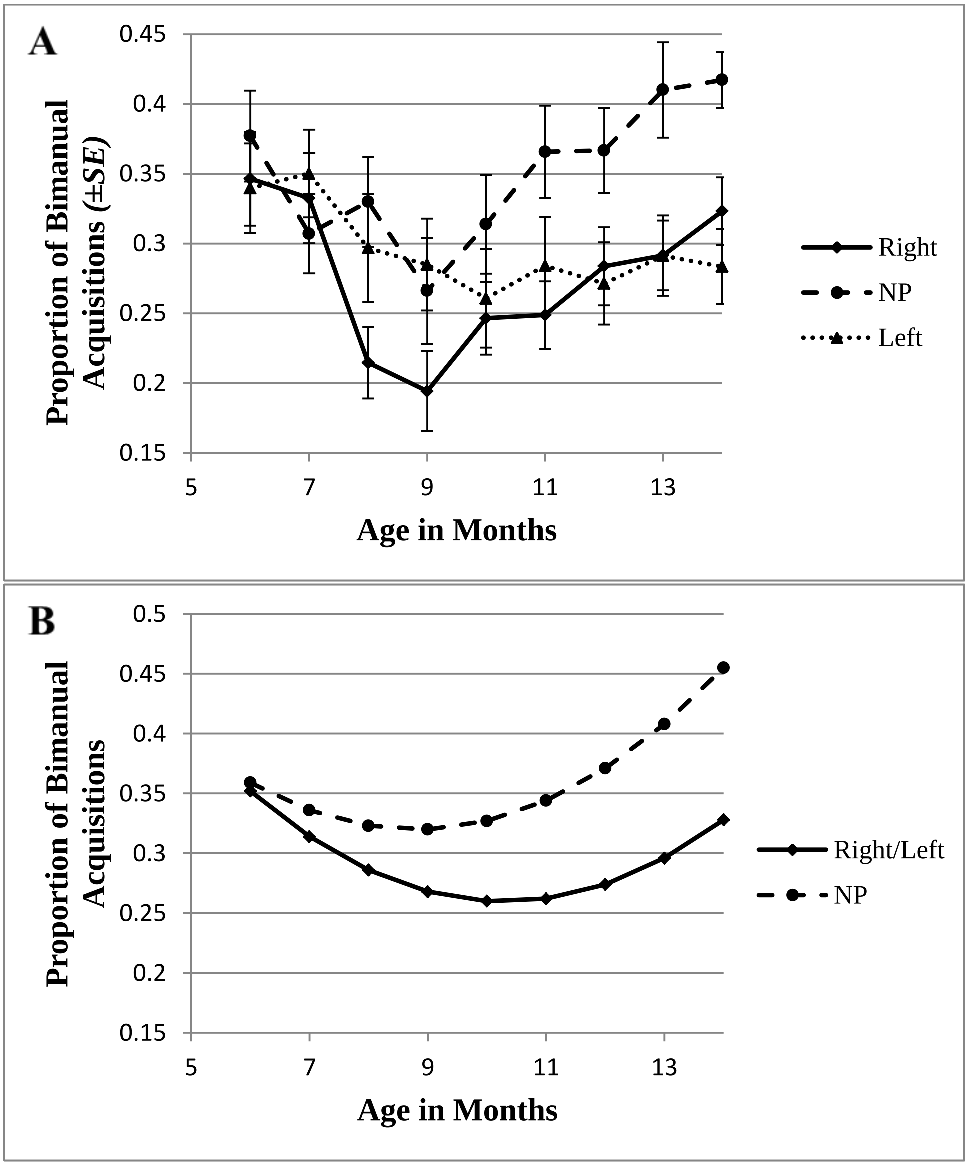


Table 15. Estimated fixed and random effects for the proportion of bimanual acquisitions

Level 1 Effects	Level 2 Effects	Parameters	Model Estimates
	Fixed Effects		
Initial status, π_{0i}	Intercept	β_{00}	0.790***
	HS2	β_{02}	-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. ** $p < .01$. *** $p \leq .001$

Developmental Cascade of Handedness

The final hypothesis in this study was that handedness for toy acquisition would predict handedness status for unimanual manipulation, which, in its turn, would predict handedness manifested during role-differentiated bimanual manipulation. Also, handedness for toy acquisition was hypothesized to predict handedness for RDBM.

The multilevel analysis revealed that the hand-use preference for unimanual manipulation is significantly positively related to the hand-use for toy acquisition. The final multilevel model of change in the handedness for unimanual manipulation in relation to handedness for toy acquisition is presented below, and its estimated parameters are provided in Table 16. In this model, z_UNI_{ij} represents the hand-use preference for unimanual manipulation estimated in z-scores for child *i* at time *j*, whereas z_ACQ_{ij} represents the hand-use preference for toy acquisition estimated in z-scores for child *i* at time *j*. Figure 12 illustrates the estimated trends of change in unimanual manipulation handedness.

Level 1 model: $z\_UNI_{ij} = \pi_{0i} + \pi_{1i}*(z\_ACQ)_{ij} + \varepsilon_{ij}$

Level 2 models: $\pi_{0i} = \beta_{00} + \delta_{0i}$

$\pi_{1i} = \beta_{10}$

Figure 12. Estimated trajectory of handedness for unimanual manipulation in relation to the handedness for toy acquisition

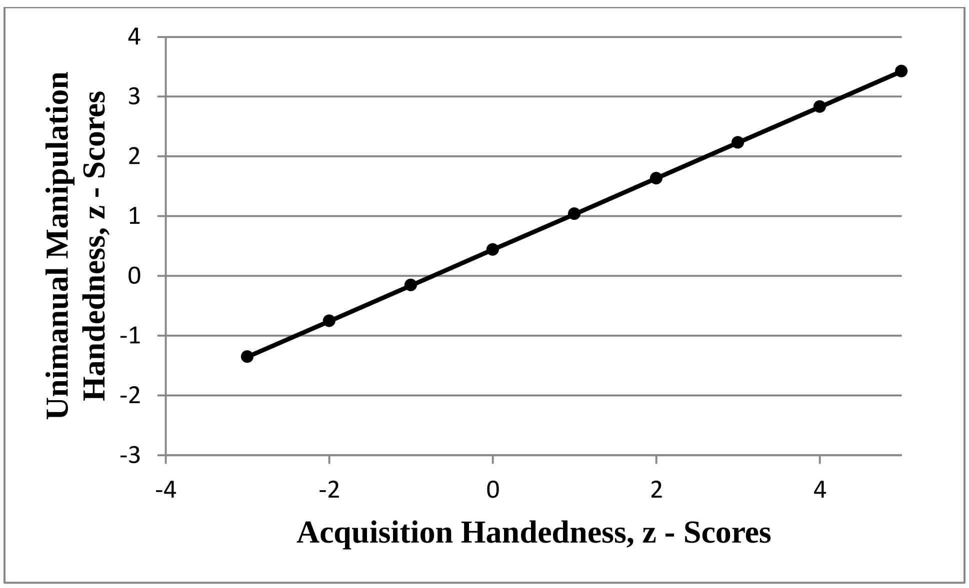


Table 16. Estimated fixed and random effects for unimanual manipulation handedness in relation to acquisition handedness

Level 1 Effects	Level 2 Effects	Parameters	Model Estimates
	Fixed Effects		
Initial status, π_{0i}	Intercept	β_{00}	0.439***
(z_ACQ), π_{1i}	Intercept	β_{10}	0.597***
	Random Effects		
Level 1:	Within-person, ε_{ij}	σ_{ε}^2	1.517
Level 2:	Intercept, δ_{0i}	σ_0^2	0.463***

Note. *** $p < .001$

Furthermore, handedness for simple RDBMs was not significantly related to the handedness for unimanual manipulation (z_UNI: $t(449) = 1.731$, $p = .084$), whereas handedness for difficult RDBMs was significantly and positively related to the handedness for unimanual manipulation. The final multilevel model is presented below and its estimated parameters are provided in Table 17. In this model, z_DIF_{ij} represents the hand-use preference for difficult role-differentiated bimanual manipulations estimated in z-scores for child *i* at time *j*, whereas z_UNI_{ij} represents the hand-use preference for unimanual manipulation estimated in z-scores for child *i* at time *j*. The estimated trajectory of handedness for difficult role-differentiated bimanual manipulation in relation to the handedness for unimanual manipulation is illustrated in Figure 13.

Level 1 model: $z\_DIF_{ij} = \pi_{0i} + \pi_{1i}*(z\_UNI)_{ij} + \varepsilon_{ij}$

Level 2 models: $\pi_{0i} = \beta_{00} + \delta_{0i}$

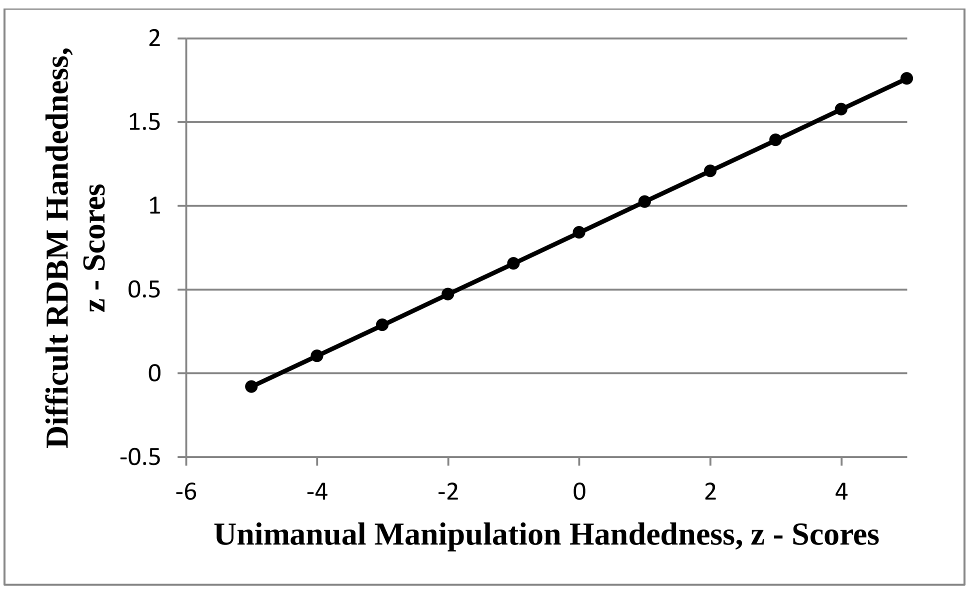
$\pi_{1i} = \beta_{10}$

Table 17. Estimated fixed and random effects for difficult RDBM handedness in relation to unimanual manipulation handedness

Level 1 Effects	Level 2 Effects	Parameters	Model Estimates
	Fixed Effects		
Initial status, π_{0i}	Intercept	β_{00}	0.840***
(z_UNI), π_{1i}	Intercept	β_{10}	0.184***
	Random Effects		
Level 1:	Within-person, ε_{ij}	σ_{ε}^2	1.875
Level 2:	Intercept, δ_{0i}	σ_0^2	1.050***

Note. *** $p \leq .001$

Figure 13. Estimated trajectory of handedness for difficult role-differentiated bimanual manipulation in relation to the handedness for unimanual manipulation



Finally, the multilevel analysis revealed that handedness for toy acquisition does not significantly predict handedness for simple RDBM (z_ACQ: $t(449) = -0.535$, $p = .593$), but it does predict handedness for difficult RDBM. The final multilevel model is presented below and its estimated parameters are provided in Table 18, and the estimated trajectory of handedness for difficult role-differentiated bimanual manipulation in relation to the handedness for unimanual manipulation is illustrated in Figure 14.

Level 1 model: $z\_DIF_{ij} = \pi_{0i} + \pi_{1i} * (z\_ACQ)_{ij} + \varepsilon_{ij}$

Level 2 models: $\pi_{0i} = \beta_{00} + \delta_{0i}$

$\pi_{1i} = \beta_{10}$

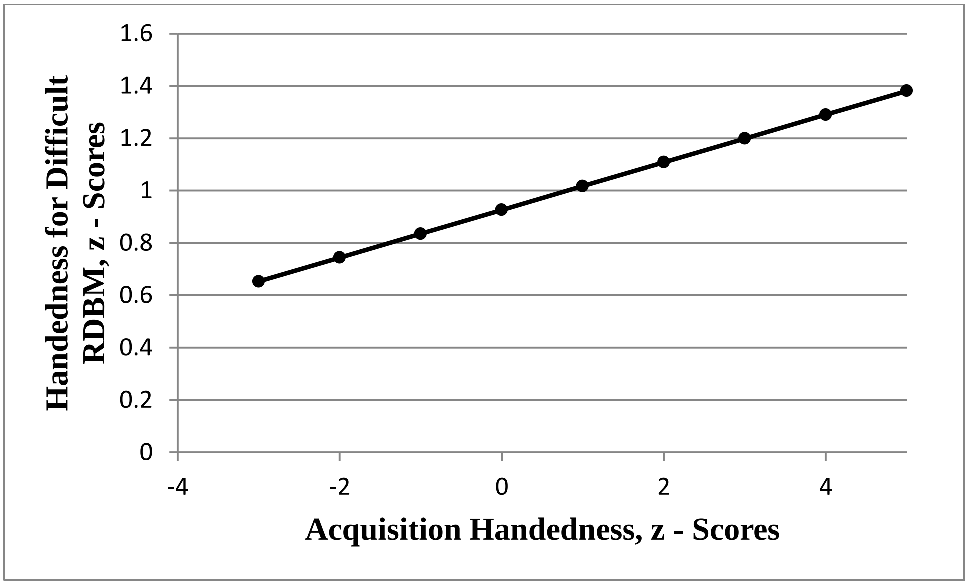
Table 18. Estimated fixed and random effects for difficult role-differentiated bimanual manipulation handedness in relation to acquisition handedness

Level 1 Effects	Level 2 Effects	Parameters	Model Estimates
Fixed Effects			
Initial status, π_{0i}	Intercept	β_{00}	0.926***
(z_ACQ), π_{1i}	Intercept	β_{10}	0.091*
Random Effects			
Level 1:	Within-person, ε_{ij}	σ_{ε}^{2}	1.890
Level 2:	Intercept, δ_{0i}	σ_{0}^{2}	1.214***

Note. * *p* < .05. *** *p* ≤ .001

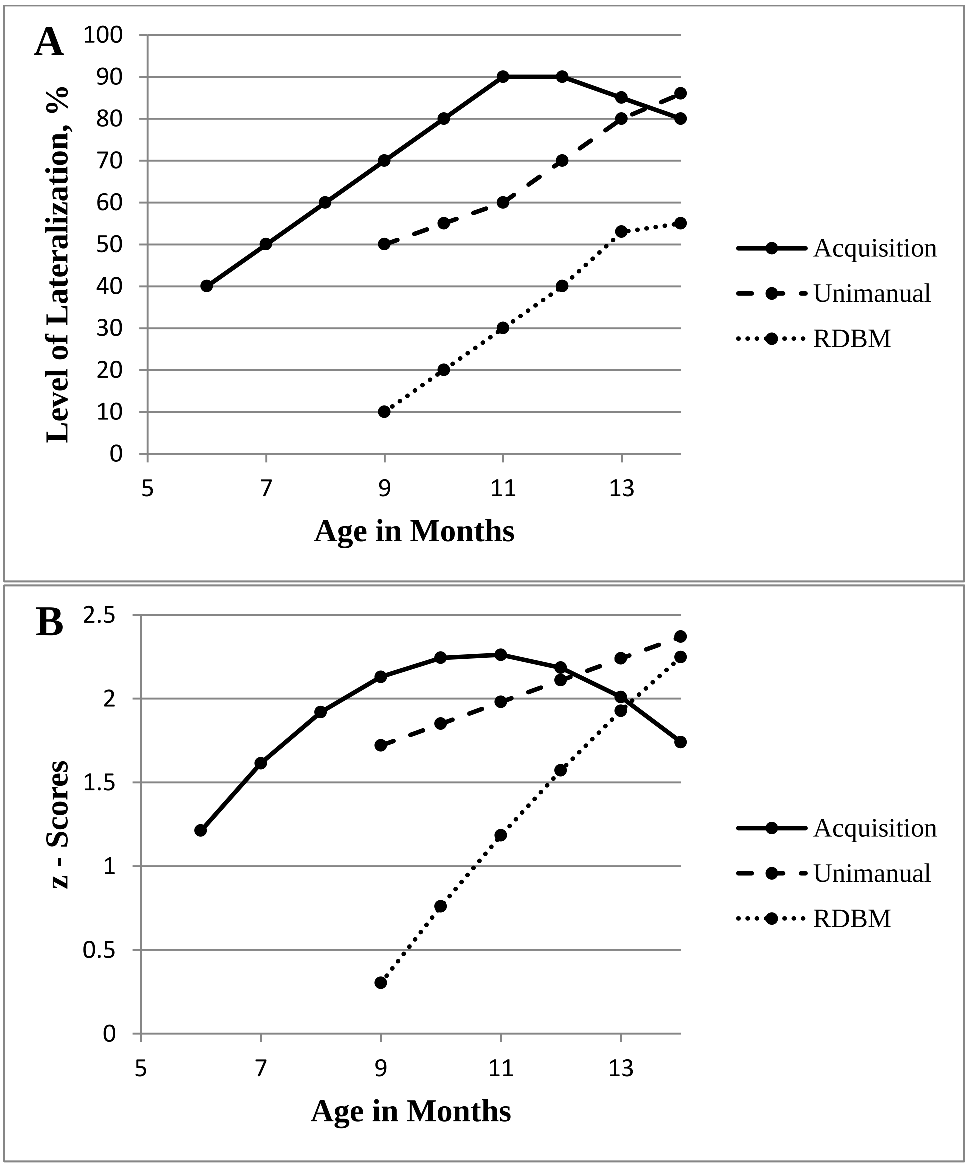
Thus, handedness for toy acquisition was found to be positively related to the handedness for unimanual manipulation, which, in its turn, is positively related to handedness for difficult, but not simple, RDBM. Moreover, handedness for toy acquisition is positively related to handedness for difficult (but not simple) role-differentiated bimanual manipulation. These results support the hypothesis about cascading nature of handedness development that suggests that lateralization of early developing manual skills influence lateralization of later developing manual skills.

Figure 14. Estimated trajectory of handedness for difficult role-differentiated bimanual manipulation in relation to the handedness for toy acquisition



Finally, let us re-examine Figure 1 depicting the cascading character of hypothetical handedness development. Does the observed data on the development of toy acquisition, unimanual manipulation and role-differentiated bimanual manipulation approximate this hypothetical model? Figure 15A recreates the theoretical trajectories for the hypothetical development of the three skills discussed in the current dissertation, and it reduces the time line to the 6 to 14 month period explored in this dissertation; other than that, Figure 15A preserves the locations of all hypothetical data points shown in Figure 1. Figure 15B shows the actual data for the development of toy acquisition, unimanual manipulation and RDBM. Interestingly, the two figures (15A and 15B) look very much alike even though one represents hypothetical trajectories of handedness development and the other shows the observed trajectories. Thus, we conclude that our data provide support for the cascading theory of handedness development.

Figure 15. Cascading character of handedness development – hypothetical (A) and observed (B)



CHAPTER IV

DISCUSSION

The goal of the current study was to examine the development of handedness for role-differentiated bimanual manipulation in relation to the developing handedness for toy acquisition and unimanual manipulation. Handedness development is proposed to be a cascade of handedness across different manual skills, each with its own time line, with handedness in earlier developing skills concatenating into handedness in later developing skills (Michel, 1983, 1988, 1998, 2002). Note that handedness that develops in each new skill is not derived from some underlying "unchanging" hemispheric specialization (as it was proposed by the invariable lateralization theory (Kinsbourne, 1975, 1981; Witelson, 1980). Simultaneously, handedness is not considered to be emerging independently in any succession of more complex manual skills. Thus, handedness in toy acquisition is predicted to influence the development of handedness for unimanual manipulation (Hinojosa et al., 2003), which, in its turn, would influence the development of handedness for role-differentiated bimanual manipulation (Michel, 1998; Michel et al., 1985; Ramsay, 1980b).

Furthermore, the cascade theory of handedness development proposes that lateralization of handedness might be weak in an emerging manual skill, increase as the skill is being mastered, and decrease when the skill becomes well-established and automatic. Therefore, in order to identify manual lateralization when assessing early handedness, a researcher must choose the manual task with the appropriate degree of challenge for infants at that phase of their development. For example, assessing handedness for toy acquisition is appropriate for one year old infants, but assessing handedness for role-differentiated bimanual manipulation may be more appropriate for two year olds.

In the current study, we identified three groups of infants (left-, right- and no hand-use preference) based on their latent classes derived from the trajectories of their development of a hand-use preference for toy acquisition assessed monthly from 6 to 14 months. Then, the trajectories of handedness development for each of the three initial handedness status groups were examined separately for toy acquisition, unimanual manipulation and role-differentiated bimanual manipulation. The change in the distribution of handedness status for each skill was examined by categorizing each infant's monthly hand-use z-score into right-hand, left-hand or no hand-use preference status. Finally, relations between the developmental trajectories of change in handedness for toy acquisition, unimanual manipulation and role-differentiated bimanual manipulation were explored.

Michel et al. (1985) reported that infants reduced their right-handedness for acquiring objects by the age of 13 months. Also, Ferre et al. (2010) showed an increase in infants' right-handedness for toy acquisition during 6-11 month interval and a decrease thereafter. Thus, in the current study, infants were predicted to increase in their lateralization of toy acquisition handedness during 6 to 12 month interval and decrease thereafter. Multilevel analysis of change in the development of handedness for toy acquisition with age showed that right- and left-handed infants increase in their lateralization of toy acquisition handedness during 6 to 11 month interval and decrease thereafter (as also noted by Ferre et al., 2010 in a separate group of infants). Although the shift in the trajectory of handedness was predicted to occur at 12 months, it was observed instead at 11 months. Infants without stable hand-use preference were found to increase in their handedness for toy acquisition during 6-14 month interval. Also, this change had a quadratic trend with the steeper increase in lateralization after the age of approximately 10-11 months.

Previous research suggested that the observed decrease in the lateralization of handedness for toy acquisition likely reflected the development of handedness for role-differentiated bimanual manipulation. That is, as RDBM is being mastered, infants might start acquiring toys with the non-preferred hand in order to immediately engage in RDBM with the preferred hand (Babik et al., 2014; Fagard & Pezé, 1997; Ferre et al., 2010; Goldfield & Michel, 1986). The decrease in the handedness for toy acquisition was predicted to relate to the significant shift towards more lateralization of handedness for RDBM. The current study showed that a significant increase in the proportion of infants lateralized for RDBM occurs on average at 11 months for simple RDBMs and at 13 months for difficult RDBMs. Therefore, it is likely that the change in toy acquisition handedness is related to the development of handedness for simple, but not for difficult RDBM or the transition between lateralization for simple and difficult RDBM.

Previous research found that infants significantly increased in their lateralization for unimanual manipulation from 7 to 11 months with right-handers and infants without a distinct hand-use preference for reaching becoming more right-handed for unimanual manipulation, and left-handers for reaching increasing their left-handedness for unimanual manipulation (Hinojosa et al., 2003). Therefore, in the current study handedness for unimanual manipulation was predicted to become more pronounced with age. Moreover, significant differences in hand-use preference for unimanual manipulation were predicted among different handedness status groups. The results showed an increase in the handedness for unimanual manipulation during 9-14 month interval, with right-handers being more right-handed for unimanual manipulation initially and developing toward more right-handedness, and left-handers being less right-handed for unimanual manipulation initially and developing toward left-handedness. Infants without a stable hand-use preference have the developmental trajectory of change in the unimanual manipulation handedness similar to that of right-handers, but with little initial lateralization. These results confirm those reported by Hinojosa et al. (2003).

A significant increase in the proportion of infants lateralized for unimanual manipulation (right- and left-handers) was hypothesized by the age of approximately 11 months when unimanual manipulation was predicted to peak in the infant's manual repertoire with objects. The current study showed that infants reach the peak of the number of unimanual manipulations at the age of 12 months. However, no significant increase in the proportion of infants lateralized for unimanual manipulation was found during this age or any other age during 9-14 month interval. Thus, this hypothesis was not supported.

Given the assumption that hand-use preferences appear initially with simple tasks and then later with more difficult tasks, all role-differentiated bimanual manipulation actions were divided into early developing simple RDBMs and later developing difficult RDBMs. Pokes and strokes represented simple RDBMs, whereas pushes, pulls, inserts, and spins represented difficult RDBMs. The total number of all, simple, and difficult RDBMs was found to increase during 9-14 month interval. Previous research (Goldfield & Michel, 1986; Kotwica et al., 2008; Michel, 2002) indicated that infants lateralized for object acquisition should perform more difficult RDBMs earlier than non-lateralized infants. In contrast, current results revealed no differences between the three handedness groups in the number of performed RDBMs across age. Thus, early establishment of hand-use preference does not seem to be beneficial in terms of the number of performed difficult RDBMs. These results do not support the notion that lateralized infants might be more efficient in complex manual skills (Goldfield & Michel, 1986; Kotwica et al., 2008; Michel, 2002), nor does it support the notion that less right-handed subjects are better in bimanual tasks (Fagard & Corroyer, 2003). Importantly, simple and difficult RDBMs should be distinguished in future research since researchers using a general category of RDBM actions (non-differentiated into simple and difficult ones) are unlikely to detect possible differences in RDBM handedness trajectories among infants with different handedness status for toy acquisition.

Based on the research done by Kimmerle et al. (1995), it was hypothesized that differences in the trajectories of handedness for role-differentiated bimanual manipulation among different handedness status groups for toy acquisition will be observed in difficult, but not in simple, RDBMs. This hypothesis was confirmed by finding differences in the trajectories of difficult, but not simple, RDBMs between infants with different handedness status. Interestingly, right-handed infants did not differ from infants without a stable hand-use preference, whereas these two groups differed from left-handed infants in their trajectories of handedness for difficult role-differentiated bimanual manipulation.

Whereas right-handers and infants without a stable hand-use preference for acquiring objects significantly increased in their preference to use their right hand for difficult RDBMs during 9-14 month interval, left-handers for acquiring objects slightly increased their preference to use their left hand for RDBM from 9 to 11 months, and thereafter, they increased their use of their right hand from 11 to 14 month. Although all infants increase their hand-use preference for role-differentiated bimanual manipulation, we did not observe left-handed infants increasing their preference to use their left hand for difficult RDBMs with age. Instead, rather counter intuitively, all infants increase their right hand use for difficult role-differentiated bimanual manipulation with age.

To explore in more detail the development of RDBM handedness, we decided to identify possible latent classes among the developmental trajectories of infant handedness for RDBM. When RDBM data for all 6 monthly visits was analyzed, three latent classes were identified in the trajectories of RDBM handedness. Within these classes, right-handers and infants without a distinct handedness increase their use of their right hand and left-handers increase their use of their left hand with age. Moreover, only two latent classes were revealed when data for 12 to 14 month period was used in the analysis: Right-handers who increase their use of their right hand with age and left-handers who increase their use of their left hand with age.

Importantly, the distribution of infants among the two latent classes for RDBM handedness (estimated from the 12-14 month age period) differ according to their handedness status for acquisition. The majority of right-handers and no preference infants for toy acquisition are right-handed for RDBM, whereas the group of left-handers is more heterogeneous in their hand-use 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. This heterogeneity of hand-use for RDBM among the group of left-handers, as defined by toy acquisition, contributes to the trend towards right hand-use in the developmental trajectory of their RDBM handedness.

This finding supports previous research that suggested that the group of left-handed infants is usually more heterogeneous in their handedness trajectories than the group of right-handers (Gonzalez & Goodale, 2009; Gur, Gur, & Harris, 1975). For example, Nelson, Campbell, and Michel (2013a) reported that the majority (15 out of 23, or 65.2%) of infants without a stable hand-use preference for toy acquisition during 6-14 month interval became right-handed for role-differentiated bimanual manipulation during 18-24 month interval, whereas the remaining no preference infants either became left-handed (7 out of 23, or 30.4%) or remained without a distinct hand-use preference (1 out of 23, or 4.4%). Perhaps, parental interaction patterns (Harkins & Michel, 1988; Michel, 1992; Mundale, 1992) make maintaining a left-hand use preference more difficult since the majority of infants have right handed mothers.

Kimmerle et al. (2010) suggested that hand-use preference in role-differentiated bimanual manipulation does not appear until about 13 months when this skill becomes mastered. In the current study, a significant increase in the proportion of infants lateralized for simple role-differentiated bimanual manipulation occurred at the age of 11 months, whereas similar significant change in manual lateralization for difficult RDBMs occurred, as it was hypothesized, at the age of 13 months. Thus, handedness for simple RDBMs appeared about two months sooner than handedness for difficult RDBMs. Again, the difficulty of the skill would define the timing of lateralization of the skill, which corresponds with assumptions of the cascade theory of handedness development.

Previous research suggested that role-differentiated bimanual manipulation becomes possible with a decrease in intermanual coupling. For example, Fagard and Pezé (1997) argued that a significant decrease in infants' bimanual reaches occurs just before the onset of first successful role-differentiated bimanual manipulations. This assumption was tested in the current study. The multilevel analysis showed that, according to the above-mentioned hypothesis, a significant decrease in the proportion of infants' bimanual acquisitions should occur at 11 months (considering only a significant change in handedness for simple RDBMs) or 13 months (considering only difficult RDBMs). The proportion of bimanual acquisitions was found to decrease in all infants from 6 to 9-11 months (9 months for right-handers and no preference infants; 11 months for left-handers) and increase thereafter. Thus, it appears that the decrease in the proportion of bimanual acquisitions for the majority of infants occurs just before the significant increase in lateralization of handedness for simple, but not for difficult, role-differentiated bimanual manipulations.

The cascade theory of handedness development also proposes that handedness in earlier developing skills would concatenate into handedness of the later developing skills. Thus, handedness for toy acquisition would be related to handedness for unimanual manipulation (Hinojosa et al., 2003). Handedness for toy acquisition and unimanual manipulation would be related to the handedness for role-differentiated bimanual manipulation (Michel, 1998; Michel et al., 1985; Ramsay, 1980b). The results of the current study partly confirmed these hypotheses.

Handedness for toy acquisition was found to be significantly and positively related to the handedness for unimanual manipulation, which, in its turn, is significantly and positively related to the handedness for difficult, but not simple, role-differentiated bimanual manipulation. Moreover, handedness for toy acquisition is positively related to handedness for difficult (but not simple) role-differentiated bimanual manipulation. Thus, it may be concluded that acquisition handedness concatenates into unimanual handedness, which, in its turn, cascades into handedness for role-differentiated bimanual manipulation. A similar relation between toy acquisition handedness and handedness for role-differentiated bimanual manipulation was shown by Nelson et al. (2013a). They found that 39% of their sample (n = 38) exhibited a consistent right hand-use preference for toy acquisition during 6-14 month interval that concatenated into the right hand-use preference for role-differentiated bimanual manipulation during 18-24 month interval.

When infants reach for a toy and acquire it with a particular hand, they are likely to immediately start unimanual manipulation of this toy with the same hand that was used for toy acquisition. In this case, handedness for toy acquisition and handedness for unimanual manipulation might be dependent, even when they are assessed in separate procedures. This dependency between handedness for toy acquisition and handedness for unimanual manipulation could be overcome by using pairs of identical toys and placing one toy in each of the infant's hands. The infant in likely to drop a toy from one hand and proceed with the unimanual manipulation of the toy in the other hand. In this case, infants "choice" of the hand for unimanual manipulation would not be confounded by the hand-use preference for toy acquisition. This alternative procedure is being currently tested in our lab (J. Campbell, unpublished data).

The cascade theory of handedness development proposes an increase in handedness manifested in each skill until the point when this skill is mastered and becomes more habitual and automatic. The number of actions performed in each skill might inform us about the development of the skill. Thus, according to the cascade theory of handedness development, an increase in the number of actions for a particular skill might be related to the increase in lateralization of handedness for this skill. Also, the peak in the number of performed actions might correspond to the peak in manifested handedness. Indeed, we observed the peak in the number of performed toy acquisitions at the age of approximately 10 months, which corresponded to a significant shift towards less lateralization of handedness for toy acquisition at approximately 11 months. Thus, the peak of performance corresponded to the peak of handedness lateralization for toy acquisition.

However, this relation did not hold for unimanual manipulation. The clear peak in the number of performed unimanual manipulations was observed at the age of 12 months, whereas trajectories of change in unimanual manipulation handedness showed an increase in handedness during 9-14 month interval in all infants. Moreover, it was hard to evaluate the relation between the peak of performance and the peak of lateralization in role-differentiated bimanual manipulation since the number of RDBM actions increases with age during 9-14 month interval, and this trend will possibly continue beyond 14 months. Support for this hypothesis comes from Nelson et al. (2013a) who found that 18 month children completed 71% of tasks using RDBM, whereas this number increased to 94% when these infants turned 24 months. Taking into account these results, we might predict that the skill of role-differentiated bimanual manipulation is still developing at 14 months, and further increase in RDBM handedness with age is expected.

Furthermore, the skill-lateralization relation was used in previous research to evaluate the invariable lateralization theory (Kinsbourne, 1975, 1981; Witelson, 1980) against the modified version of the progressive lateralization theory (Michel, 1983, 1988, 1998). Thus, Kimmerle et al. (1995) found no significant change in the frequency of unimanual manipulations from 7 to 11 months, and proposed that the skill of unimanual manipulation remains quite stable during this period. Hinojosa et al. (2003) also showed no change in unimanual skill but an increase in lateralization for unimanual manipulation.

Since the invariable lateralization theory predicts that the development of lateralization for each skill would occur while this skill is developing, Hinojosa et al. (2003) argued that showing no change in unimanual skill co-occurring with a significant change in the lateralization for this skill would result in rejection of hypotheses stated in the invariable lateralization theory and support of the modified version of the progressive lateralization theory.

The results of the current study provide additional support for the modified version of the progressive lateralization theory. In contrast to Kimmerle et al. (1995) and Hinojosa et al. (2003), we found a significant increase in the number of performed unimanual actions between 9 and 12 months, an a significant decrease thereafter. Thus, our conclusion was that the skill of unimanual manipulation is changing during this age period. Interestingly, whereas the number of unimanual manipulations reached its peak at 12 months, the lateralization of handedness for unimanual manipulation increases during the 9-14 month interval. Thus, similar to Hinojosa et al. (2003), we would reject assumptions of the invariable lateralization theory.

The cascade theory of handedness development might change researchers' notions about handedness development. For example, the observed variability in infant handedness (Corbetta & Thelen, 1999; Corbetta & Thelen, 2002; Fagard, 1998; Fagard & Lockman, 2005; McCormick & Maurer, 1988; Piek, 2002; Thelen, 1995; Thelen et al., 1996) made some researchers assume that handedness in infancy is not a stable trait, and cannot be reliably identified until the ages of 3-4 years (McManus et al., 1988) or even 8-9 years (Fennell, Satz, & Morris, 1983). Instead, it can be argued that the cascading transformations in handedness lateralization during infancy may change the manifestation of handedness for toy acquisition, unimanual manipulation, and role-differentiated bimanual manipulation, which would lead to the observation of fluctuations in the development of handedness (Michel, 2002). Clearly, identifying the infant's handedness requires systematic longitudinal investigation of a several manual skills exhibited by a large number of infants assessed many times during their first two years.

In summary, understanding of the developmental cascade of change in handedness lateralization may help a researcher to choose a correct time and task for handedness assessment, which would improve considerably the validity of studies relating handedness to other developing neuropsychological functions. Also, the cascade theory of handedness development is a valuable model of the development of lateralization in manual skills that can be used for studying the development of other forms of hemispheric specialization of function.

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