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Unimanual hand preference is a behavior in which one hand is used more often than the other when single-handedly manipulating objects. The progressive lateralization theory (Michel, 2002) of handedness proposes that handedness gradually concatenates during infancy as a cascade from initially a preference for contacting objects to acquiring them, to their unimanual manipulation, to the eventual emergence of a hand preference for role-differentiated bimanual manipulation (RDBM). Together, these behaviors represent the individual's handedness expressed across most manual skills. Thus, the theory posits that an early hand preference for object acquisition will predict a later preference for single-handed object manipulations. This proposal was examined by describing the development of hand-use preferences for unimanual manipulation of objects for 90 infants (57 males) tested monthly from 6 to 14 months. These 90 infants were obtained from a larger sample of 380 infants: 30 infants from a group of 45 with left hand-use preferences for acquiring objects were matched for sex and development of locomotion skills with 30 infants with a right hand-use preference and 30 with no hand preference for acquiring objects. Results showed that the frequency of unimanual manipulations is stable during the 6-14 month period. Multilevel modeling of unimanual manipulation trajectories for the three acquisition hand-preference groups revealed that hand-use preferences for unimanual manipulation become more prominent with age and the preference is predicted by the hand-use preference for object acquisition. Also, infants with a right-hand preference for object acquisition develop a hand-use preference for

unimanual manipulation sooner than those with a left preference and infants without a preference for acquisition remain without a preference for manipulation.

THE RELATION BETWEEN HANDEDNESS FOR REACHING

AND UNIMANUAL HANDEDNESS

FROM 6 TO 14 MONTHS

by

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APPROVAL PAGE

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The general consensus is that handedness represents an intrinsic aspect of hemispheric specialization of function (similar to the left-hemisphere control of speech) whose development is controlled by genes as evidenced by many genealogical studies of familial handedness (e.g., Annett, 1985; McKeever, 2000; McManus & Bryden, 1992, Medland, et al. 2009; but see Laland, Kumm, Van Horn, & Feldman, 1995 for an alternative interpretation). According to this consensus, what may appear to be the development of manual preferences is not a development of hemispheric specialization but rather, as manual skills develop, they become complicated enough to require the asymmetric processing and control abilities intrinsic to the differences between hemispheres (Kinsbourne, 1976; Witelson, 1985). Because of the contralateral control of the limbs (Lemon, 2008), the activated hemisphere will manifest an apparent hand-use preference. Since many manual skills require fine motor control and since the left hemisphere appears to enable such programming, a right hand preference will most likely predominate (Serrien, Ivry, & Swinnen, 2006).

Thus, hand-use preferences *per se* do not develop; rather, as any manual skill develops more complexity, it eventually requires the processing and control abilities of one hemisphere (most often the finely-timed, sequentially-organized, motor programming capabilities of the left hemisphere). Indeed, within this theoretical frame, all instances of lateralized hand-use represent the manifestation of the same underlying asymmetry of manual control; each example of a hand-use preference represents the same handedness factor – left-hemisphere control. Unfortunately, it is difficult to account for left hand-use preferences in this invariant lateralization theory without invoking some separate disruptive factor. Indeed, invoking such a disruptive factor is used to account for the typically reported association of left-handedness (or at least non-right-handedness) with many medical and mental problems.

Given the similarity of hemispheric specialization for handedness and speech, investigations of the development of either should provide some insight into the development of the other. This dissertation uses the development of hand-use preferences during infancy not only as an example of how to examine the development of any sensorimotor character of infants but also as an example of how to study the development of hemispheric specialization for the control of speech.

Theories Relating to the Development of Hand Preference

There are many theories pertaining to the development of cerebral lateralization that have been applied to the study of hand preference development. Lenneberg's progressive lateralization theory (1967) suggested that there is a critical period for language acquisition and as such, hemispheric specialization of function for language occurs during that same period of development. Since hemispheric specialization for language is highly related to specialization for handedness (Knecht, et al. 2000), Lenneberg's theory could be applied to the development of handedness, as well. According to Lenneberg, both hemispheres start out with little or no lateralization, and gradually, through processes of maturation, become lateralized differentially for different functions. Lenneberg's theory fits with a common notion that there is no handedness during the early ages but that it begins to be manifest as the maturation of cerebral differences emerges. Many researchers have considered infant handedness to be non-existent and that it only develops later (Dubois, et al., 2009).

However, Kinsbourne (1975) and Witelson (1985a, 1987) independently proposed an invariant lateralization theory in contrast to Lenneberg. The invariant lateralization theory suggests that lateralization is present in the brain before birth, and that the apparent development of any behavioral or psychological laterality is actually only a result of the lag in the development of more complex functions. As more complex functions develop they require the special processing and programming abilities of a specific hemisphere. Therefore, as the individual develops the ability to engage in more complex processing within different functional domains (e.g., manual skills, reasoning, language, and visuospatial orientation), the functions would appear to become lateralized as the processing and programming required for their manifestation becomes allocated to the different processing or programming abilities of the two hemispheres. Within this invariant lateralization theory, a lateralized ability like handedness would always be present but constrained to appearing early in development only within easily manifested skills (e.g., holding a rattle). Hence, Caplan and Kinsbourne (1976) demonstrated that newborn infants exhibited a handedness according to the hand that was able to hold a rattle longest (a skill neonates can manifest). Since there was other evidence of lateralized functioning in young infants, the invariant lateralization theory seemed to be confirmed and supplanted Lenneberg's progressive lateralization theory.

In 1983, Michel proposed a modified progressive lateralization theory, to account for early appearing (primitive) forms of lateralization, present even before birth, but also to account for subsequent changes in lateralized abilities as development proceeds. In this theory, early asymmetries of hand-use can cascade via self-generated experiences into expanded hand-use preferences across a variety of manual skills. The progressive lateralization theory fits with dynamic systems theory which proposes that a newly emerging behavior is built upon previously lateralized behaviors.

Although three theories of the development of handedness have been proposed, most investigations have ignored them because recent work has questioned the relevance of handedness to hemispheric specialization of function for language (Knecht, et al. 2000). Most modern researchers agree with the early work of Gesell (Gesell & Ames, 1947) and dismiss the likelihood of any early manifestation of handedness (e.g., Corbetta & Thelen, 1999). Dubois et al. (2009) illustrated this point in the following quote: "[i]nfants initially use both hands indifferently (Corbetta & Thelen, 1999; Rönnqvist & Domellöf, 2006), then preference for one hand becomes clear generally from 18 months of age on (Fagard & Marks, 2000) and is more and more pronounced during the following years (Ingram, 1975)" (p. 414). This quote clearly represents the notion that most handedness researchers have come to the conclusion that there is no hand preference in infancy and that hand preference is only apparent after toddlerhood. However, if hand preference does not become apparent until after toddlerhood, from where does this sudden behavioral phenomenon appear? Is it a hemisphere maturational event (as proposed by Lenneberg)? Or is it a consequence of the manual actions of children becoming more sophisticated and then having their control distributed to the processing of one hemisphere (as proposed by Kinsbourne and Witelson)? Or have we missed the early development of handedness and those early biases that feed into the development of later handedness (as proposed by Michel)?

Studies which Illustrate the Cascade Theory in Hand Preference Development

Michel's (1983) theory of hand preference development incorporates an explicitly developmental perspective in which infants will manifest hand-use preferences. Michel and colleagues (2002) demonstrated that the right shift in handedness may be the result of asymmetries of prenatal and postnatal postures of the infant that bias different perceptual-motor experiences between the hands. Specifically, these authors theorize that the head orientation preference of neonates (distributed similarly to handedness, with a predominance of infants exhibiting a rightward orientation preference) leads to a hand preference for the ipsilateral hand because it is more frequently in the neonate's field of vision when the head is turned and because the head turn activates asymmetrical actions from the right face-side hand.

This visual and motor bias created more effective eye-hand and proprioceptive actions schemes for the face-side hand. Since the head orientation bias activates asymmetric brainstem and spinal actions that result in different activity of the face-side limb (compared to the skull-side limb), this creates proprioceptive and haptic-tactile feedback asymmetries between the limbs. This, in turn, establishes a proprioceptive "map" that is aligned with the visual-spatial map asymmetry created by the differential hand-regard imposed by the head orientation preference. These combine to provide a bias for the face-side hand to be more active, better controlled, and more effective in reaching for visually presented objects.

In Michel's theory, many structural and functional asymmetries are present at conception, which among other factors, may reflect epigenetic maternal and grandparent effects and uterine asymmetries (Michel, 1983, 1988, 1998, 2002). Thus, the development of hand preference begins with *in utero* fetal position and neonatal motor asymmetries, which concatenate into a newborn head orientation preference (Michel & Goodwin, 1979). These early asymmetries develop into early hand-use preference for swiping at and reaching for objects which can be observed early in infant development (Michel, 1981; Michel & Harkins, 1986). The ways in which these emerging behaviors progress have been proposed by Michel & Harkins (1986) to be a result of a concatenation of influences of early behavioral asymmetries on the development of subsequent behavioral asymmetries. Thus, in their view, handedness is a result of self-generated experiences (e.g., differential hand-regard) as well as other exogenous factors.

Direct examination of the progressive cascade theory of the development of hand preference was conducted by Hinojosa, Sheu, and Michel (2003). They used a measure of unimanual hand preference in which a one hand *manipulates* an object. In this research, infants age 7, 9, and 11 months were identified and grouped according to their preferred handedness for acquiring objects which were presented to infants on a table. Also, during these three months, different toys were presented on a table to the infants, and the frequency of unimanual manipulations were recorded. The results supported the notion that the infants' hand-use preference for acquisition predicted a later developing hand-use preference for unimanual manipulation. Specifically, infants who displayed a right hand preference for acquisition at 7-11 months, subsequently displayed a right-hand-use preference for unimanual manipulations, but only at 11 months. Moreover, infants with a left hand preference for acquisition at 7-11 months, displayed a left-hand-use preference for unimanual manipulation, again only at 11 months. Those displaying no preference for reaching slightly increased in right handed unimanual manipulations from 7 to 11 months.

An important aspect of this study was that the types and frequency of unimanual manipulations did not differ between the 7 and 11 month ages. Therefore, the increase in a hand-use preference for unimanual manipulation between 7 and 11 months was unlikely to be due to an increasing facility with or complexity of the infants' unimanual skills, as would have been predicted by the invariant lateralization theories of Kinsbourne or Witelson. Only the infant's preference for acquiring objects predicted the infant's preference for unimanual manipulation at 11 months of age, whereas acquisition preferences were apparent as early as 7 months. The intervening four months permitted the hand-use preference for acquiring objects to concatenate into the same hand-use preference for unimanual manipulation of objects. The Hinojosa, et al. (2003) results are also difficult to fit into the dynamical systems theory of Corbetta and Thelen which proposed that infant hand preferences are a consequence of the development of certain forms of postural control and the impact of contextual influences. For infants in the Hinojosa, et al. (2003) study the context was essentially the same and the manifestation of unimanual manipulations was the same at both 7 and 11 months of age. Although the infant clearly was developing during the intervening four months (their hand-use preference for acquiring objects did not change). The only change was in their hand-use preference for manipulating them, as was predicted by the cascade theory.

The Hinojosa et al. (2003) study provides only one piece of the developmental cascade of hand preference development during infancy. In order to verify that the development of hand preference derives from a concatenation in which earlier appearing forms of hand-use asymmetries contribute to the development of later forms of hand-use asymmetries, the developmental relation among each form of such hand-use asymmetries must be examined. Additional studies must be conducted if we want to provide support for the notion that handedness development in infancy is a complex cascade of developmental processes involving sequences of hand-use asymmetries.

These developmental processes include contingencies involving prenatally influenced (Fong, Savelsbergh, van Geijn, & de Vries, 2005; Michel & Goodwin, 1979) congenital postural asymmetries (Kurjak et al., 2004; Michel, 1981) that feed into the establishment of sensorimotor asymmetries of the action systems underlying the use of the arms and hands in early infancy (Michel & Harkins, 1986). These systems begin with hand-use preferences being reliably observed initially in acquiring objects (Michel & Harkins, 1986; Ferre, Babik, & Michel, 2010), subsequently in unimanual manipulation (Hinojosa et al., 2003) and finally in the establishment of handedness preferences for role differentiated bimanual manipulation and tool-use (Michel, 2002).

Additional support for the cascade theory of hand preference development occurred in a study by Nelson, Michel, and Campbell (2013). They studied infant's hand preference for acquiring objects monthly during infancy from 6 to 14 months, and the hand preference for role-differentiated bimanual manipulation (RDBM) for the same infants from 18 to 24 months. During lab visits, infants were presented with 32 items while sitting on their parent's lap at a table. Handedness status was assigned according to the latent classes identified via group based trajectory model analysis (Jones, Nagin, & Roeder, 2001) of the assessment of asymmetries of hand use for 323 infants tested monthly during the nine month period from 6 to 14 months of age (cf., Michel, Babik, Sheu, and Campbell, 2013). This analysis revealed three latent classes: 37% of the sample of infants with a consistent right hand-use trajectory; 14% of infants with a consistent left hand-use trajectory; 49% of infants showing a consistent trajectory without significant use differences between the right and left hands. During toddlerhood, the hand use preferences for role-differentiated bimanual manipulation of objects was examined monthly from 18 to 24 months of age, using 29 trials, for a much smaller convenience sample (n=38) of these children. This study examined whether an earlier manifestation of hand preference for acquiring objects was related to a later developing hand-use preference for RDBM.

When the relation of infant hand preference for acquiring objects to toddler hand preference for role-differentiated bimanual manipulations was examined, it was discovered that 93% of the participants who were right-handed during infancy were also right-handed during toddlerhood. Amongst those participants who had no preference for object acquisition during infancy, 65% of them manifested a right hand-use preference for RDBM as toddlers. Of those infants without a preference for acquiring objects, 30% exhibited a left hand-use preference for RDBM as toddlers, and the remaining 5% had no preference for RDBM.

These results indicate several things about handedness development: First, for this relatively small sample, the majority of infants develop a hand preference for RDBM by 18-24 months of age. This is much sooner than many researchers have previously hypothesized (Ingram, 1975; Corbetta & Thelen, 1999; Rönnqvist & Domellöf, 2006). Second, the proportion of observed left-handedness which was observed for RDBM in toddlerhood was much greater than the 8 - 12% that is traditionally observed in the adult population (Annett, 1985, 2002). This high percentage of left-handedness for toddlers is consistent with other reports (Marschik et al., 2008; Ramsay, Campos & Fenson, 1979; Tirosh, Stein & Harel, 1999). However, there is a gap in the literature on the development of left-handedness. More empirical work on the development of left-handedness might reveal how the incidence of left-handedness eventually decreases to between the reported rates of 8% (McManus, 1991) to 10-18% (Annett, 2002; Marchant, McGrew, & Eibl-Eibesfeldt, 1995) that has been observed in the adult population.

Third, the Nelson et al. (2013) provides additional support for the Michel theory of the development of hand preference. The majority of those infants who had a stable hand preference for acquiring objects during infancy used the same hand preference to perform a role-differentiated bimanual manipulation during toddlerhood. This is consistent with the notion that previous forms of hand preference in early manual skills lead to the development of emergent forms of hand preference during the development of novel manual skills. Thus, early handedness development is likely a spreading cascade across different manual skills rather than simply an increase in handedness within a skill. Moreover, the asymmetries within any skill can interact with the caregiver's handedness to further shape the individual's hand-use (Harkins & Michel, 1988; Michel, 1992) such that by 18 months, most children have a hand-use preference across a range of unimanual and bimanual skills that will form the basis of all future hand actions and hence their "handedness" (Michel, 2002).

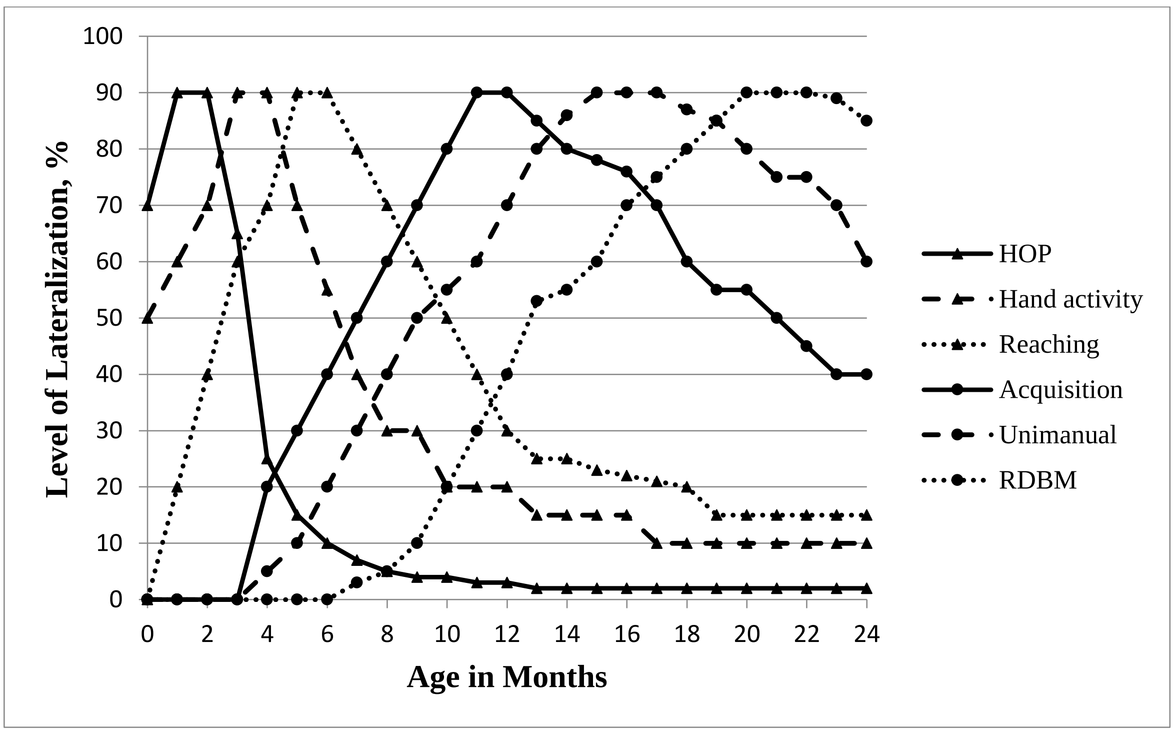
In all phases of this handedness cascade, the above referenced studies (i.e. Hinojosa et al., 2003) find the sharp right-shift (predominance of right-handedness) and the minority polymorphism (left-handedness) as predicted by Annett's model. However, these studies involved relatively small samples of infants tested only a few times during their development and may have poorly estimated the pattern of handedness development. Support for Annett's theory can be found in a study conducted by Michel et al. (2013). This study examined whether there are latent groups underlying infant hand-use preferences for acquiring objects that match the rs+ distributions predicted from Annett's model. The hypothesis for this study was that three handedness groups would exist in the infant sample similar to Annett's conclusion that the majority of the population falls into a right-hand preference group.

The Michel et al. (2013) study identified the hand-preference of 328 infants (182 males, 146 females) as they acquired objects for examination during nine monthly visits (from 6 to 14 months of age). While infants were seated on their parent's lap at a table, a research assistant presented items on the table either at the infant's midline or two matching items were presented simultaneously shoulder width apart. The hand that was used to pick up, or acquire, objects was recorded. Hand preference was determined by the number of times an infant picked up objects with each hand. A group based trajectory model (Jones, Nagin, Roeder, 2001) was used to determine the number of distinct groups that were present in the data. The analysis revealed that three groups of infant hand preference were identifiable in the trajectory data. The individual infants in these groups were then examined using an HLM model and the trajectories of the three groups were revealed to have a rate of growth that was significantly different across all groups. Each group's trajectory was quadratic. One group exhibited a right-hand preference with an asymptote at 10 months, one group exhibited no preference (although they display a trend toward right-hand preference increasing across the 6 to 14 month time period), and one group was identified as left-handed with an asymptote at 11 months.

Michel et al. (2013) showed that the quadratic trends that were identified increased across the 6 – 11 month age period, then declined from 11 – 14 months of age demonstrate that object acquisition is a prevalent (and sufficiently challenging) manual skill in the infant's repertoire during this period. Also, object acquisition develops after establishment of the skills of swiping at and contacting objects (Michel & Harkins, 1986) and it is incorporated into all other manual skills involving object manipulation (e.g., tool use and artifact construction). Handedness for acquiring objects is related to and predicts the later development (at about 10 to 12 months) of handedness for unimanual object manipulation (Hinojosa et al., 2003) and handedness for role differentiated bimanual manipulation (Babik & Michel, submitted), which appears at about 13 to 14 months. Thus, this study supports the idea that observed fluctuations in one type of hand preference is reflected in other types of hand preference across the months and development of hand preference for any one skill will be influenced by hand preference in other manual skills.

The identification of an increase in hand preference for a skill at a particular age, followed by a decrease in the skill indicates that the development of hand preference for different skills have different onset times and trajectories of expression (Michel et al., 2013). This cascading behavioral emergence is illustrated in figure 1. This figure shows a hypothetical illustration of how each of six behaviors develops from birth to 24 months of age. As one behavior reaches its peak of lateralization, another behavior is just beginning to become lateralized. It is important to consider the timing of each of these types of lateralized behaviors in order to describe the construct that one is attempting to study.

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)).



Note: HOP = head orientation preference; RDBM = role-differentiated bimanual manipulation

The timing, or the onset of hand preference was addressed in a study by Fennell et al. (1983) in which 208 children were assessed for hand preference at 66 (5.5 years), 92 (7.6 years), and 130 (10.8 years) months of age. Hand preference was assessed using the Harris Tests of Lateral Dominance (Harris, 1947), which consists of subjects performing 10 unimanual tasks, such as throwing a ball (unfortunately, all of the tasks are common tool-using tasks that are not only acquired through imitation and training but are also highly practiced). The results show that while hand preference appears to be stable between age 92 months and 130 months, between the ages of 66 and 92 months, hand preference changed for 8.6% of the sample. We can infer from the results of this study that hand preference for the unimanual tasks that were measured by these authors is continuing to stabilize during the 66 to 92 month age range. If change in unimanual hand preference is observed during this period, it is possible that greater instability in hand preference would be observed at earlier ages. Similarly, McManus et al. (1988) identified stable hand preference in their sample by 36 months, however, they report that the strength, or degree of hand preference increased from 3 to 7 years. Both Fennell (1983) and McManus (1988) provide evidence which support a cascading theory of handedness development which says that a stable hand preference increases in association with increasing age.

Defining Unimanual Manipulation

When engaging with objects, infants use their arms and hands in a variety of ways: swiping, grasping, unimanual manipulation (e.g., banging, shaking, hitting, and throwing), role-differentiated bimanual manipulation (one hand supports the active manipulation of the object by the other hand), tool-use (using an object to affect change in other objects), artifact construction (building an object with other objects). According to Uzgiris and Hunt (1975), unimanual manipulation of objects is a sensorimotor skill that develops from earlier developing skills, such as reaching for and grasping (acquiring) objects. Therefore, a hand-use preference for acquiring objects could transfer into a preference for manipulating them.

Of course, how handedness is characterized has important implications for investigating the development of handedness. For adult humans, the construct "handedness" often is characterized as a trait or an aspect of self-identity (similar to "gender" or "ethnic" identity) with a limited number of categories (e.g., right, left, and some expression of ambilaterality). As such, handedness of adults may be assessed via self-assignment or via left versus right answers on a questionnaire. However, even a simple 12 item questionnaire, with a sufficiently large enough sample, creates a minimum of eight distinct categories of handedness as determined by the pattern of how the answers relate to one another (Annett, 1972, 2002). Moreover, tests of handedness for unimanual proficiency do not match well with handedness revealed by questionnaire (Cavil & Bryden, 2003; Steenhuis & Bryden, 1989; Todor & Doane, 1977). Tests of unimanual proficiency reveal differences between the hands which distribute across individuals more like the construct "stature" rather than like a categorical trait (Annett, 1972). That is, each of several different unimanual tasks show differences in performance skill between the hands but the size of those differences varies continuously across individuals, albeit distinctly shifted to a majority with a right-hand advantage in proficiency (Annett, 1972; Bryden & Steenhuis, 1991). If handedness is a construct similar to stature, then assigning categories of "right" and "left" (like assigning categories "tall" and "short" to stature) can only be done relative to membership in a particular population or sample rather than as identifying aspects intrinsic to the individual.

In contrast, for infants and children, hand-use preferences can be identified only by observing differential use in particular situations or via testing procedures that permit assessment of differences between the hands in their proficiency to perform certain unimanual skills (e.g., dotting circles, moving pegs from one set of holes to another). Under these conditions, the differences in proficiency between the hands may be distributed continuously across infants. Thus, the size of the differences between the hands in proficiency distributes continuously across individuals more like the construct "stature" than like a categorical trait (Annett, 1972). That is, each of several different unimanual tasks show differences in performance skill between the hands but the size of those differences varies continuously across individuals, albeit distinctly shifted to a majority with a right-hand advantage in proficiency (Annett, 1972; Bryden & Steenhuis, 1991). If handedness is a construct similar to stature, then assigning categories of "right" and "left" (like assigning categories "tall" and "short" to stature) can only be done relative to membership in a particular population or sample rather than as identifying something intrinsic to the individual.

As Michel's (2002) cascade theory proposes: during development, infant hand-use preferences concatenate across prehensile manual skills (beginning with visually-elicited swiping at objects, extending to visually-guided acquisition of objects, to unimanual manipulation, and eventually to role-differentiated bimanual manipulation) and this concatenation permits infant hand-use preferences to match the proficiency measures of differences in hand skill characteristic of the handedness of adults. The preferences manifested in earlier skills create lateralized sensorimotor experiences which bias the organization of actions of later developing skills. Thus, each instance of a lateralized asymmetry of hand-use for each manual skill manifested during infancy represents a separate manual preference that is built upon an earlier asymmetries (preferences) and the combination of these various manual preferences eventually represent the individual's general handedness "trait" and forms the basis of their categorical identity. As such, preferences for acquiring objects will concatenate into a preference for manipulating them.

The current study is designed to assess the hypothesis that an earlier hand-use preference for acquiring objects biases unimanual manipulation of objects and results in the latter manifestation of a hand-use preference for manipulation that matches the acquisition hand-use preference. As a result of such concatenation during development, the individual eventually has a relatively consistent preference across many manual skills which can form the basis of the trait-like character of handedness. The advantage of the concatenation notion is that a separate disrupting factor need not be assumed for the occurrence of left handedness. As with the right preference, the left hand-use preference transfers from a left preference in earlier skills which transfer from an earlier left-biasing asymmetry (Michel & Harkins, 1986).

As noted above, Hinojosa et al., (2003) provided some support for this concatenation hypothesis when they assessed unimanual manipulation at 7 and 11 months for infants with different hand-use preferences for acquiring objects. At 7 months, few infants had a hand-use preference for manipulating objects (Hinojosa et al., 2003). However, by 11 months, infants who manifested a consistent right hand-use preference for acquiring objects at 7, 9, and 11 months exhibited a right hand-use preference for unimanual manipulation. Infants with a consistent left hand-use preference for acquisition at 7, 9, and 11 months had a left hand-use preference for unimanual manipulation at 11 months. The infants without a hand-use preference for acquiring objects did not exhibit a hand-use preference for manipulation at either 7 or 11 months. Thus, there appeared to be a predictive relation between a hand-use preference for acquiring objects and the subsequent development of a hand-use preference for unimanual manipulation.

Unfortunately, the study by Hinojosa and colleagues had some design problems: First, the sample of 25 infants (10 with a right preference and 8 with a left preference for acquiring objects) was rather small and the infants were tested only at 7, 9, and 11 months of age. Recent literature shows that developmental changes in hand preference for object acquisition fluctuate somewhat across the 6 to 14 month age period (Michel, Babik, Sheu, & Campbell, 2013). Indeed, reliable estimates of acquisition hand preference trajectories could not be identified using fewer than 6 months of data (Ferre, Babik, & Michel, 2010). Thus, it would be important to gather more months of assessment data of unimanual hand preference. Michel et al. (2013) conclude that by collecting nine time points from 6 to 14 months, they were able to identify 3 latent groups in the developmental trajectories of infant hand preference (right, left, and no preference).

Another limitation in the Hinojosa et al. (2003) study was that the procedure allowed the infant to acquire the object from the surface of the table for manipulation. Thus, those infants with a hand-use preference for acquiring objects would likely have initiated unimanual manipulation with their preferred hand for acquiring objects. This would likely bias any association of the unimanual manipulation hand-use preference with the preference for acquisition. By conducting their study in this way, it is possible that the preference of the infant for acquiring objects could bias the hand preference for unimanual manipulation. In order to disentangle an infant's preference for acquiring objects from the preference for unimanual manipulation, the same infants would have to be assessed separately on both an acquisition task and a unimanual manipulation task. The absence of a relation between the two preferences at seven months likely indicates the independence of the hand-use preferences for these two skills. However, it is important to ensure that the hand-use preference for acquiring objects does not directly bias the assessment of a hand-use for unimanual manipulation.

In the current study, we avoid confounding a hand-use preference for acquiring object with the assessment of a preference for unimanual manipulation by placing pairs of identical objects simultaneously in each of the infant's hands, thereby promoting manual symmetry for object acquisition for the assessment of unimanual manipulation. This type of procedure eliminates the action of the infant picking the toy up, and isolate the unimanual manipulations from any acquisition preference. Thereafter, any differences between the hands in manipulation frequency (e.g., shake, bang) are not a consequence of a preference for acquiring the object. With this procedure, the infant's "choice" of the hand for unimanual manipulation is not confounded by a hand-use preference for object acquisition. Finally, we assess the hand preference of a fairly large sample of 90 infants monthly (nine times) from 6 to 14 months of age.

Previous research suggested that the frequency of manual actions may be used as a marker for evaluating the development of unimanual manipulation skill (Hinojosa et al., 2003; Kimmerle, Mick, & Michel, 1995; Kimmerle, Ferre, Kotwica, & Michel, 2010). Throughout this paper, we will use the term "unimanual manipulation skill" to refer to the number of unimanual actions that are performed on an object. Hinojosa et al. (2003) reported no significant change in frequency of unimanual manipulation actions between ages 7 and 11 months for 25 infants. Similar results were found by Kimmerle et al. (2010), who defined unimanual manipulations as manual movements performed with one hand on an object(s). They found no change in the frequency of the performance of unimanual manipulation actions (or the proportion of unimanual actions in the manual repertoire of the infants) during the 7 to 13 month period in 14 infants tested bimonthly during play with 6 toys.

According to Ramsay (1980), the earliest instance of unimanual manipulation of objects is usually observed at the age of about 5 months. Of course, some unimanual actions, such as manipulation of the infant's body parts (other hand, feet, lips, ears) and clothing, appear very early after birth. However, these actions seem to be more like primary and secondary circular reactions (Baldwin, 1894; Piaget, 1952) than like controlled actions on objects. Primary circular reactions have been described by Piaget (1952) as occurring when two actions or schemata become complementary to one another and occur without intention. Secondary circular reactions are repetitions of primary circular reactions and are actions that an infant carries out in response to reactions that were produced by chance. Ramsay (1980) defined unimanual action as an attempt to manipulate any movable part of the toy while the other hand was not in a supporting role. He observed infants' unimanual actions with four toys in a cross-sectional design at 5, 7 and 9 months (n = 16 at each age). Ramsay (1980) reported that the total number of unimanual actions increased significantly between 5 and 7 months of age but not thereafter (5 month *M* = 6.2; 7 month *M* = 17.6; 9 month *M* = 18.1).

Since Ramsay (1980) observed no change in frequency of unimanual manipulation actions from seven to nine months and others found no change from 7 to 11 months (Hinojosa et al., 2003) or 7 to 13 months (Kimmerle et al., 2010; Kimmerle, et al., 1995), unimanual actions appear to be a relatively stable component of the infant's manual repertoire during the latter half of the first year. A hand-use preference for acquiring objects seems to appear as early as six months of age (e.g., Ferre et al., 2010; Michel, Babik, Sheu, & Campbell, 2014). Therefore, if a unimanual preference is simply the manifestation of the same underlying factor that creates the manifestation of an acquisition preference, we might expect that a unimanual hand-preference would appear soon after six months of age. Also, if a hand-use preference in a manual action depends upon that action acquiring a sufficient degree of complexity to be challenging enough to access hemispheric differences in processing or programming ability, then we might expect that the complexity of a unimanual action would be related to the manifestation of a hand-use preference rather than related to a preference for acquisition.

Rationale for the Current Study and Hypotheses

In contrast to previous longitudinal research on unimanual manipulation skills and handedness which collected data relatively infrequently during the 6 to 14 month age period, the current study assesses unimanual actions monthly during this age period for a group of 60 infants whose hand-use preference for acquiring objects remained consistent during that age period (30 with a right hand-use preference and 30 with a left preference) and a group of 30 infants who exhibited no hand-use preference for acquiring objects during this age period. Hinojosa et al. (2003) found that infants with different hand-use preference status for acquiring objects did not exhibit a hand-use preference for unimanual manipulation at 7 months, but did at 11 months despite there being no significant differences in their frequency of unimanual manipulations performed at these two ages. However, Hinojosa et al. (2003) did not track any changes in unimanual hand-use preference. According to Ramsay's (1980) cross-sectional study, a hand-use preference for unimanual manipulation only begins to be manifest at seven months and seems not change at nine months. At both months, infants contacted movable parts of toys with the right hand more often than with the left hand.

Michel, Ovrut, and Harkins (1985) explored unimanual manipulation in a cross-sectional study of 96 infants (12 infants for each of eight monthly assessments from 6 to 13 months of age) using a set of 21 different toys (28 presentations). They evaluated infants' hand-use preferences for several unimanual actions (e.g., transfer, shake, hold, bang, throw, scrape, push, pull, and reorient). These actions were combined to calculate a hand-use preference score for each infant at each age. Michel et al. (1985) found that the percentages of infants with right and left hand-use preference for unimanual manipulation did not change across the 6 to 13 month age period. However, this cross-sectional study with a relatively small sample of infants tested at each month does not permit confident conclusions about the developmental consistency of hand-use preferences for unimanual manipulation.

The current study assesses unimanual actions monthly during the 6 to 14 month age period for a group of 90 infants with either a left (30) or right (30) or no consistent hand preference (30) for acquiring objects during this age period. The development of differences between the hands in their frequency of performance of eight unimanual manipulation actions are examined monthly. Hand-use preference categories are identified in two ways. First, at each month of age, the relative frequency of left and right hand-use for that assessment (which distributes continuously across infants within an age) is categorized into "right" or "left" hand preference according to the significance of the difference in frequency of use between the hands ($\alpha < .01$). Differences that do not differ from chance are assigned to a "no preference" category. Second, infants are categorized into "right", "left", and "no preference" according to the latent classes revealed via the analysis of the trajectories of their relative hand-use across the nine monthly assessments from 6 to 14 months of age.

The prediction was made that hand preferences for unimanual manipulation will become more distinctive with age. A prediction was also made that a transfer of the preference from acquisition to unimanual manipulation would occur. Thus, those infants with a right hand preference for object acquisition will develop a right hand preference for unimanual manipulation. Similarly, those with a left hand preference for object acquisition will develop a left hand preference for unimanual manipulation. Infants without a preference for acquiring objects will be unlikely to exhibit a preference for unimanual manipulation and likely represent the early development of those adults who exhibit rather small differences between their hands in manual proficiency. Thus, by 14 months, hand preferences for unimanual manipulation are predicted to become consistent with the hand preferences for object acquisition.

CHAPTER II

METHOD

Subjects

The sample of 90 infants (57 males, 33 females) used for this study is a subsample of 380 infants tested in the Infant Development Center at the University of North Carolina at Greensboro. All infants had a normal gestation period and birth weight, and came from uncomplicated single births. The current sample is ethnically diverse: 71% White, 22% African American, 5% of Hispanic or Latino, and 2% of multi-ethnicity. All subjects were tested monthly, within +/-7 days from infants' monthly birthdays, from 6 to 14 months (total 9 visits) on object acquisition and unimanual manipulation. Infants' mean age was 6.13 months (*SD* = 0.15 months) at the beginning of the study, and 14.25 months (*SD* = 0.16 months) at the end of the study. From the sample of 380 infants, 45 exhibited a consistent developmental trajectory with a left hand-use preference for acquiring objects during the age period of 6 to 14 months. Of these 45, 30 infants (19 males, 11 females) were selected for study and then matched for sex and the level of postural control and locomotion (onset of sitting, crawling, and walking assessed using the Touwen's scale, 1976) with 30 infants with a consistent developmental trajectory of a right hand preference and 30 infants without a distinct hand-use preference. Their hand-use preference for acquiring objects was identified from the latent classes revealed by The Group Based Trajectory Model (Nagin, 2005) for all 380 infants (see Michel et al., 2014 for details). A power analysis was conducted to confirm the number of infants that must be randomly selected in order to be 95% sure that the sample mean is within the margin of error of the population mean. Using the mean (-0.16) and the standard deviation (.21) of the sample of the 45 left handed infants, it was then calculated that 30.21 infants would be required in order to achieve a sample mean that is within the margin of error of the population mean. Right preference and no preference infants were then matched to these left preference infants.

Procedure

Infants' hand-use preference for object acquisition and unimanual manipulation was assessed in the Infant Development Center every month. Enrollment of participants, informed consent, data collection and storage were completed in compliance with IRB regulations for the protection of human subjects. At each monthly visit, parents received a $10 gift card.

Object Acquisition. In the current study, object acquisition was defined as an action of lifting an object from the surface of the table. Hand-use preference for object acquisition was evaluated monthly from 6 to 14 months. Infants' manual activity during the play with 34 single-part infant toys was recorded using two synchronized cameras which provided both an overhead and a side view of the infant's hands. While infants sat on their parents' laps, parents were asked to stabilize the infant's waist to maintain a steady posture during play. Once the infant was seated at the table, a research assistant would present the items on the table directly in front of the infant. Toys were presented to infants as either one toy on the table (19), one toy suspended in the air (5), a pair of identical toys on the table (7) or a pair of identical toys suspended in the air (3). Identical pairs were presented in line with the infant's shoulders, and single toys were presented to the infant's midline on the table. The entire object acquisition procedure lasted 20-25 minutes. Infants were allowed to pick up the toys and explore the objects for up to 30 seconds before the research assistant removed the item and presented the next item.

Acquisition hand-use preference was coded in the Observer® XT (Noldus Information Technology, Wageningen, Netherlands) which permitted a frame-by-frame account of the hand used for an object acquisition. The hand used to acquire each toy initially was coded for all toys at each visit. Twenty percent of all coded videos were re-coded by another coder for inter-rater reliability (Cohen's Kappa *M* = 0.91, *Mdn* = 0.91, range = 0.82 to 0.99). Another 20% of the videos were re-coded for intra-rater reliability (Cohen's Kappa *M* = 0.94, *Mdn* = 0.94, range = 0.88 to 0.99). Coders were unaware of infants' hand preference.

The primary goal of this study was to determine whether an infant's earlier appearing hand-use preference for grasping (acquiring) objects predicts the later development of a hand-use preference for manipulating them with one hand. For the current study of infant hand-use, hand-use preference categories were identified in two ways. First, at each month of age, the relative frequency of left and right hand-use for that assessment (which distributes continuously across infants within an age) was categorized into "right" or "left" hand-use preference according to the significance of the difference in frequency of use between the hands ($\alpha = .05$). Differences that do not differ from chance are assigned to a “no preference” category. Second, infants were categorized into “right”, “left”, and “no preference” according to the latent classes revealed via the analysis of the trajectories of their relative hand-use across nine monthly assessments from 6 to 14 months of age.

To analyze developmental trajectories of hand-use preference for object acquisition, the infant’s monthly hand-use preferences for object acquisition were converted into Handedness Index HI-scores: $HI = (R–L)/(R+L)^{1/2}$, where R and L correspond to the total number of acquisitions performed by the right and the left hand. Next the GBTM (Nagin, 2005) and the SAS TRAJ procedure (Jones, Nagin, & Roeder, 2001) were used on hand-use preference HI-scores to derive hand-preference latent classes from 380 infants’ monthly (from 6 to 14 months) assessments (Michel, et al. 2014). GBTM is a statistical method that permits identification of distinct patterns in the distribution of a sample’s trajectories. Of a total of 45 infants, whose trajectory exhibited a significant and consistent left hand-use preference for acquiring objects, we randomly selected 30 infants and matched them (for sex and locomotor development) with 30 infants whose trajectory exhibited a significant right hand-use preference, and 30 infants without a hand-use preference throughout the 6 to 14 month age period. These 90 infants will serve as the subjects for the investigation of the relation of hand-use preference for acquiring objects to the hand-use preferences for unimanually manipulating objects.

Unimanual Manipulation. Unimanual manipulation is an action in which one hand has an active manipulating role on an object and the other is not even supporting the object. Unimanual manipulation was studied longitudinally during play with a set of 17 pairs of identical infant toys (Figure 2). Members of each pair was placed simultaneously in the infant's hands and unimanual manipulations (shaking, hitting, scraping, mouthing, rotating, scraping, clacking, picking up (only if an object was dropped), taking, refusing, and dropping) performed by each hand on each object were coded using the Noldus Observer® XT in real time for the following 20 seconds or until six manipulations had occurred. The hand used for each active manipulation was identified. "Shake" was coded for swinging of an object in a vertical orientation without a table contact; "hit" – several abrupt contacts of an object with the table (repetitive hitting was recorded as only one hit); "in mouth" – placing an object in the mouth; "rotate" – turning the wrist in a circular motion (repetitive rotation was recorded as only one rotation); "scrape" – more than one sliding movement of an object across the table (repetitive scraping was recorded as only one scrape; "clack" – lateral movement of an object against another object in the opposite hand while that hand was inactive); "pick-up" – lifting a dropped object off of the table; "take" – removing an object from an inactive hand; "refuse" – refusing to accept an object from the presenter by pulling the hand away from the object; "drop" – termination of contact between the hand and an object. Repetitive actions were recorded only once unless another action intervened. Thus, repetitive "shake" actions were recorded only once unless another action (e.g., "in mouth") occurred in between bouts of shaking. If an infant drops a toy and proceeds to engage the other toy with both hands, such bimanual manipulations will not be counted. Also, since there will be a toy in each hand, it will be possible for both hands to be active simultaneously with a toy in each hand. These will be recorded as “both” and will not be included in the analyses because we are interested in only unimanual actions.

Figure 2. The 17 Pairs of Items Used in the Unimanual Task.

Twenty percent of all coded videos were re-coded by another coder for inter-rater reliability. Another 20% of the videos were re-coded for intra-rater reliability. Coders were blind to infants’ predicted hand preference for acquisition.

The number of coded right- and left-handed unimanual manipulations were converted into monthly HI scores $(R-L)/(R+L)^{1/2}$ representing each infant’s hand-use preference at each monthly visit. Multilevel analyses, using Hierarchical Linear Modeling (HLM; Raudenbush, Bryk, Cheong, Congdon, & du Toit, 2004), was then performed to explore developmental trajectories of the number of unimanual manipulations and hand-use preferences for unimanual manipulation according to the three groups (right, left, and no) defined by their hand-use preference for acquiring objects. The hand-use preference variable was coded as two dummy variables, "Left" and "NP", with Right being the reference group.

Maternal Hand Preference. Maternal hand preference will be observed using the Briggs and Nebes (1975) version of the Annett handedness questionnaire (Annett, 1972). This questionnaire asks mothers to answer how each of twelve items are performed using the hands. Questions include such items as "Which hand do you use to hold a match when striking it?" and "Which hand is on the lid of the jar when opening it?" There are five options for answering: always right, usually right, no preference, usually left, and always left. Questionnaires are scored such that answers of always right receive +2; always left receive -2; usually right receives +1; usually left, -1; and no preference answers are scored as 0. Overall scores less than -9 or greater than +9 were categorized as left- and right-handed, respectively (as recommended by Briggs & Nebes).

CHAPTER III

RESULTS

Development of Unimanual Manipulation

One of the goals in the current study is to explore the developmental change in infants' skill of unimanual manipulation assessed by the frequency of performance of ten unimanual manipulations at each age. Previous research explored different types of unimanual manipulations, but failed to provide a detailed account of the developmental patterns for each type. It is expected that the mean number of unimanual manipulations at each age for each of the 10 unimanual actions would remain relatively steady across age based upon the findings presented by Hinojosa et al. (2003) in which the frequency of unimanual actions did not change from 7 to 11 months of age.

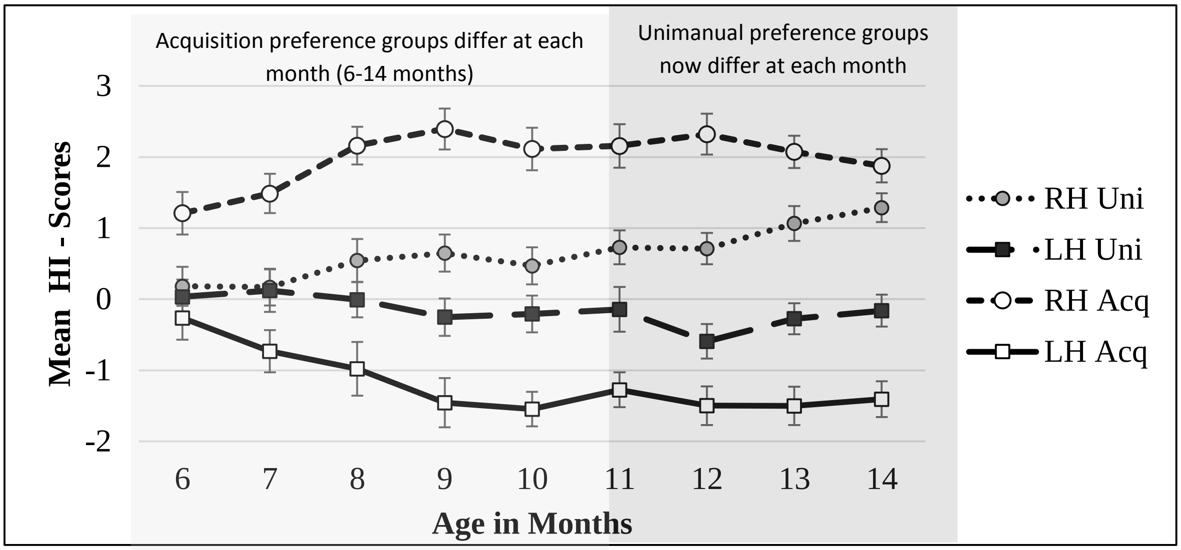
Preliminary Analyses

Before undertaking these analyses, it was important to determine whether the trajectories of hand-use preferences for object acquisition were significantly different between infants in the right and left hand-use preference categories according to their 6 to 14 month trajectories. Infants' object acquisition hand-use status was determined by the trajectory of hand-use preference scores across the 9 months (6 to 14) rather than by specific differences in their monthly scores. If there are no hand-use preferences for unimanual manipulation before 11 months of age (as was reported by Hinojosa et al., 2003) but there also are no object acquisition hand-use preferences before 11 months, then any identification of unimanual hand preferences after 11 months is unlikely to be the result of the influence of a hand preference for acquiring objects. If, however, there is a hand-use preference for acquiring objects before 11 months of age, but not a unimanual hand-use preference, then any later appearing unimanual hand-use preferences likely was influenced by the earlier hand preferences for acquiring objects.

T-tests (Bonferroni corrected) were conducted to investigate the differences between HI scores for right and left handers at each month. These t-tests were conducted in order to see whether infants are significantly different from one another at each month. This means that the GBTM classification for hand-use preference for acquiring objects is capturing significant differences in early left and right hand-use between infants from the left- and right-preference categories.

Figure 3 shows that the mean hand preference scores (HI-scores) for acquiring objects were significantly different between the right and left preference infants at each age from 6 to 10 months. This difference starts out significant and increases across the months, which is consistent with their classification via the GBTM analysis. These results confirm that object acquisition hand use preferences have been clearly established by 10 months of age. In order to support the concatenation theory, there would have to be no unimanual hand preference during this time. Note that the hand use scores for acquisition are significantly different between the two groups (t-test, Bonferroni corrected, $p < .01$) for each month.

Figure 3. Mean (and Standard Errors) HI Scores for Acquiring Objects for Unimanual Manipulation for Infants Classified by Their Latent Class Trajectory Analysis as Having Right and Left Hand Preferences for Acquiring Objects.



Amongst the ten unimanual actions that were observed, it is important to differentiate between unimanual manipulations that reflect the active use of one hand (shake, hit, in mouth, rotate, scrape, clack, pick-up, take) and those that reflect withdrawal from active unimanual manipulation (refuse, drop). These two types of actions highlight important differences in manipulation during infancy and were separated into “active unimanual manipulations” and “rejections” of unimanual manipulation. Therefore, in the following analyses, we calculated the total number of active unimanual manipulations as the sum of the number of actions – shake, hit, in mouth, rotate, scrape, clack, pick-up, and take.

In order to investigate the presence of a unimanual hand preference, we first conducted a multilevel analysis which revealed a significant quadratic trend of change in hand preference for unimanual manipulations (Table 1 and Figure 4). The unconditional growth model was first examined in which only age was in the model. Next the full model was run. This model included age, squared age, and cubic age, as well as hand preference as level 2 variables. Because the variance associated with cubic age was not significant, it was removed from the model. The fixed effect of cubic age was then removed. Next, the variance component of squared age was removed. Then the fixed effect of squared age was removed. The variance component for linear age was kept because it was significant. Although the fixed effect of linear age was not significant, it was retained in the model because of the significance of the variance component. Finally, the fixed effect of right on linear was removed as well as the variance component for linear age. Thus, the final model included age in level 1, and left and right hand group in level 2.

Note that linear, quadratic and cubic trends were analyzed in the model but only the significant trends are reported. Infants in each of the three hand preference groups for object acquisition (right, left, no preference) initially are not significantly different in their hand preference for unimanual manipulation (Tukey's HSD, $\alpha > .10$). However, all infants increase their hand preference (HI scores) with age. Infants in the left hand-preference group for object acquisition increase the use of their left hand for unimanual manipulation with age and infants in the right hand-preference group for object acquisition increase their right hand preference for unimanual manipulation.

The final multilevel model for unimanual manipulations according to hand preference for acquiring objects is presented below. In this model, UM_{ij} represents an infant's HI for unimanual manipulation for child *i* at time *j*. The estimated parameters are provided in Table 1.

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

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

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

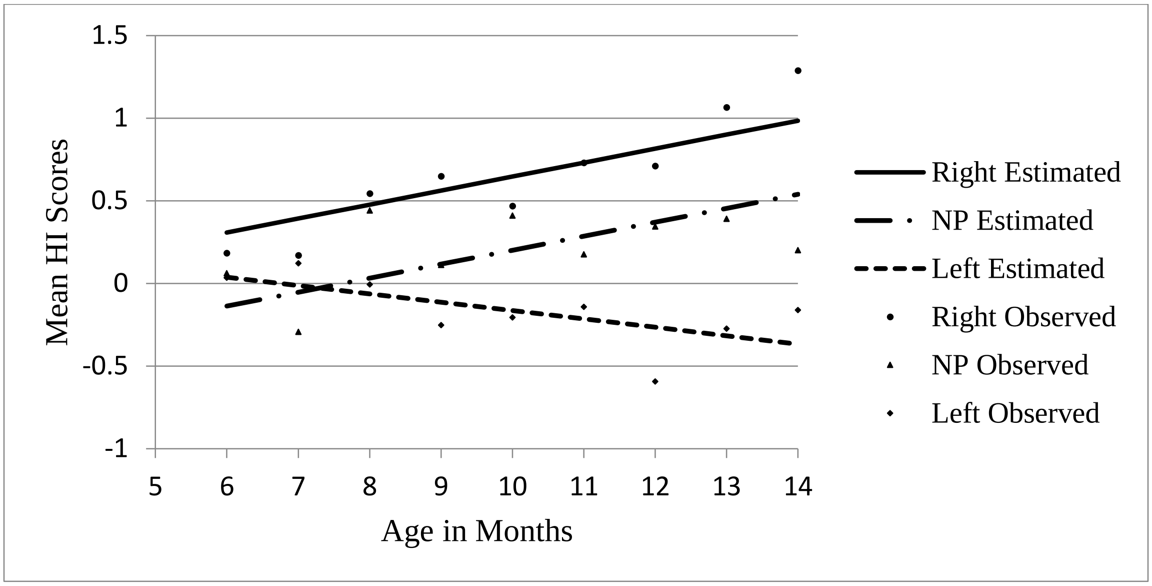
Table 1. Estimated Fixed and Random Effects for Active Unimanual Manipulations According to Hand Preference for Acquiring Objects.

	Unimanaul Manipulation		
	Unconditional Growth	Full Conditional Growth	Final Conditional Model
Fixed Effects†	*Coefficient*	*Coefficient*	*Coefficient*
Intercept (γ_{00})	0.072	0.031	-0.153
Age (γ_{10})	0.039	0.043	0.085***
Left (γ_{01})	-	0.008	0.192
Left*Age (γ_{11})	-	-0.094	-0.135**
Right (γ_{02})	-	0.114	0.478**
Right*Age (γ_{12})	-	0.083	-
Random Effects†	*Variance Component*	*Variance Component*	*Variance Component*
Intercept (δ_{0i})	0.391***	0.387***	0.410***
Age (δ_{1i})	0.010**	0.005	0.006*
Level-1 (σ_{ε}^2)	1.682	1.683	1.683

† For all fixed and random effects, *df* = 87

* $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$

Figure 4. Estimated and Observed Trajectories of Change in Hand Preference for Active Unimanual Manipulations; NP = No Preference.



Only by 11 months of age, are the unimanual hand preference scores for infants in the right hand-preference group for acquisition significantly different from the unimanual preference scores of infants in the left hand-preference group for acquisition (Tukey's HSD, $\alpha < .05$). Thereafter, infants with a right hand-preference for acquiring objects are always significantly different from left hand-preference infants in their hand preference for unimanual manipulation. By 13 and 14 months of age, the three acquisition preference groups (right, left, and no) are significantly different from one another in their hand preference for unimanual manipulation of objects (Tukey's HSD, $\alpha < .05$) with infants having no acquisition preference exhibiting no preference for unimanual manipulation.

As predicted, unimanual manipulation hand preference becomes more distinctive with age in all infants, meaning that infants show more extreme HI scores across age. Infant unimanual manipulation is predicted by their object acquisition hand preferences. Moreover, the infants in the left and right hand preference groups for acquiring objects are significantly different in their preference scores for acquisition at 6 months and on; whereas, they are only significantly different in their unimanual manipulation preference scores at 11 months – five months later. Only at 14 months were infants with no preference significantly different from both the left- and right-hand preference groups.

Did each group differ significantly in their right and left unimanual hand use from an expected zero difference in right and left hand use from 11 months on? Single sample t-tests were performed at 11, 12, 13, and 14 months of age to determine whether the mean HI for manipulation for each of the acquisition handedness groups differed from a population mean of zero. A conservative $\alpha = 0.01$ was Bonferroni corrected for the four multiple comparisons for each group ($\alpha = 0.0025$). The Ts for those infants with a right-hand preference for acquisition were significant only for 13 and 14 months (11 month T = 2.9, $p = 0.0035$; 12 month T = 3.02, $p = 0.0026$; 13 month T = 3.97, $p < 0.001$; 14 month T = 5.86, $p < 0.0001$). Thus, only for the last two months of assessment was the right hand was used significantly more often than would be expected if the hands were used equivalently. None of the T values for those infants with a left-hand preference for acquisition were significant for any of the four months (11 month T = -0.46, $p = 0.326$; 12 month T = -2.45, $p = 0.01$; 13 month T = -1.25, $p = 0.11$; 14 month T = -0.72, $p = 0.24$). Thus, for all four months, the left hand was not used significantly more often than would be expected if the hands were used equivalently. Again, none of the T values were significant for those infants with no hand preference for acquisition (11 month T = 0.68, *p* = 0.25; 12 month T = 2.08, *p* = 0.02; 13 month T = 1.71, *p* = 0.098; 14 month T = 0.92, *p* = 0.18). Thus, with the exception of infants who preferred their right hand for acquiring objects, infants in each of the other two groups exhibited no significance difference between the use of their right and left hands.

To obtain more details about the development of lateralization for unimanual manipulation during 6 to 14 month period, we converted the relative hand scores (HI-scores) for each infant for each month into a categorical hand preference status for that infant at that month by using HI = +/-1.7 (as described in footnote 1). Thus, if use of the right or the left hand for active unimanual manipulations was more frequent than would be expected by chance (HI = +/-1.7, $\alpha < .01$, two-tailed), then the infant's hand preference status for manipulation was categorized as "right" or "left", respectively. If the difference in use of the two hands in active manipulations was not different from chance, then the infant's unimanual manipulation status was categorized as "no preference".

Table 2 shows the monthly unimanual hand preference status for infants relative to their hand preference status as defined by their latent class trajectory. The results reveal that at the ages 6 through 14 months, the majority of infants in each of the three groups with a hand preference status for object acquisition do not have a distinct hand preference for unimanual manipulation, even by 14 months of age. In addition, no significant differences among those with a right-preference, left-preference, and no preference for object acquisition are detected during six through 11 month period (6 months: $\chi^2(4, N = 88) = 0.920$, $p = .922$; 7 months: $\chi^2(4, N = 89) = 0.915$, $p = .922$; 8 months: $\chi^2(4, N = 88) = 4.879$, $p = .300$; 9 months: $\chi^2(4, N = 90) = 2.081$, $p = .721$; 10 months: $\chi^2(4, N = 88) = 8.345$, $p = .080$; 11 months: $\chi^2(4, N = 90) = 3.198$, $p = .525$). Note that occasionally (7 of 27 instances) an infant did not provide any usable data for assessing their unimanual manipulation preference.

Table 2. Number (percent in parentheses) of Infants in each Hand Preference Category According to Their Acquisition Hand Preference (from the Latent Class Analysis of Developmental Trajectories Across the 9 Months) and Unimanual Hand Preference (from the HI-Score Classification of Hand-Use for each Month).

Infant Age in Months	Hand Preference for Acquiring Objects								
	Right (n = 30)			Left (n = 30)			No Preference (NP) (n = 30)		
	Hand Preference for Unimanual Manipulation								
	Right	NP	Left	Right	NP	Left	Right	NP	Left
6	4 (13)	22 (74)	4 (13)	5 (17)	23 (76)	2 (7)	4 (14)	21 (75)	3 (11)
7	5 (17)	21 (70)	4 (13)	5 (17)	20 (69)	4 (14)	4 (13)	22 (74)	4 (13)
8	8 (28)	18 (62)	3 (10)	2 (7)	24 (83)	3 (10)	7 (23)	20 (67)	3 (10)
9	6 (20)	21 (70)	3 (10)	3 (10)	23 (77)	4 (13)	6 (21)	18 (62)	5 (17)
10	10 (34)	17 (59)	2 (7)	2 (7)	24 (83)	3 (10)	5 (17)	23 (77)	2 (6)
11	5 (17)	24 (80)	1 (3)	5 (17)	20 (66)	5 (17)	4 (13)	24 (80)	2 (7)
12	8 (27)	22 (73)	0 (0)	1 (3)	22 (73)	7 (23)	3 (10)	27 (90)	0 (0)
13	10 (33)	18 (60)	2 (7)	0 (0)	26 (87)	4 (13)	4 (13)	25 (84)	1 (3)
14	14 (47)	16 (53)	0 (0)	2 (7)	23 (77)	5 (16)	0 (0)	29 (97)	1 (3)

After 11 months, statistically significant differences (all Bonferroni corrected) in the distribution of infants are identified for unimanual hand preferences for the three different hand preference groups for object acquisition (12 months: $\chi^2(4, N = 90) = 21.204, p < .0001$; 13 months: $\chi^2(4, N = 90) = 14.509, p = .006$; 14 months: $\chi^2(4, N = 90) = 30.182, p < .0001$). Note that at 12 months, the distribution of the three hand preference groups for unimanual manipulation across the three hand preference classes for object acquisition does not differ between right-handers and infants with no preference ($\chi^2(2, N = 60) = 2.783, p = .090$), but differs significantly between right- and left-handed infants ($\chi^2(2, N = 60) = 12.444, p < .002$).

At 13 months, we also observed no significant difference between right-handers and no preference infants ($\chi^2(2, N = 60) = 4.044, p = .132$) and a significant difference between right-handers and left-handers ($\chi^2(2, N = 60) = 12.121, p < .002$). In contrast, at the age 14 months, not only do right-handers differ from left-handers ($\chi^2(2, N = 60) = 15.256, p < .0001$), but right-handers also become significantly different from infants with no hand preference ($\chi^2(2, N = 60) = 19.273, p < .0001$). Again, these patterns suggest that the action of unimanual manipulation is developing during infancy from the stage of less lateralization towards increased lateralization and the direction of lateralized preference is predicted by their hand preference for acquisition.

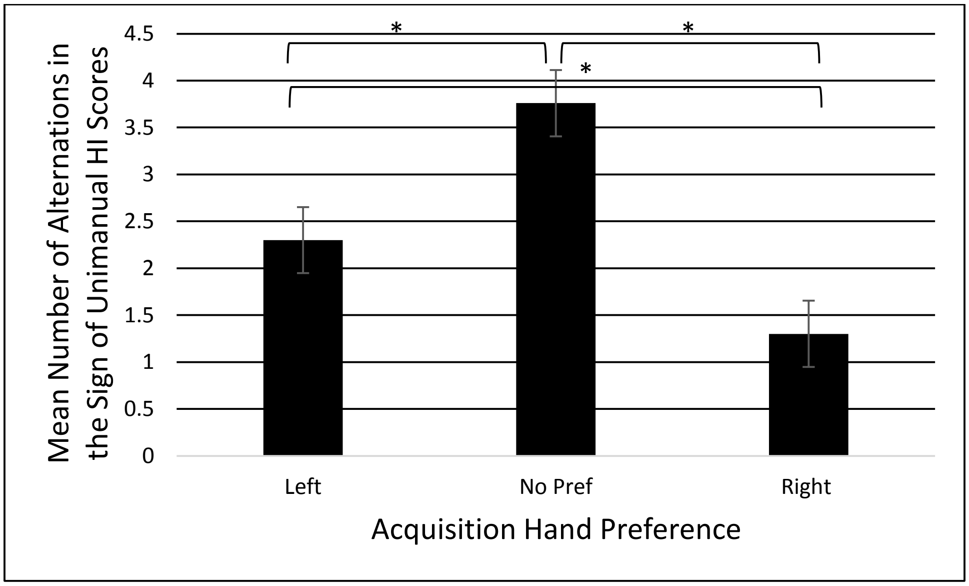
We found no statistically significant change in hand preference distribution across the ages 7 months to 11 months (contrary to the results of Hinojosa et al., 2003). The number of infants (grouped according to their acquisition hand preference) are not significantly changing their unimanual hand preference category (right-preference infants

($\chi^2(2, N = 60) = 2.00, p = .368$), infants with no hand preference for object acquisition ($\chi^2(2, N = 60) = 0.591, p = .744$), left-preference infants ($\chi^2(2, N = 59) = 0.574, p = .750$). Thus, these results support the proposal that the hand preference for unimanual manipulation only begins to develop after the age of 11 months.

Finally, to test the consistency of the infant's unimanual hand use, four single factor analyses of variance were conducted on acquisition hand preference groups (between) and four dependent variables (within) provided by the infant's HI score for unimanual manipulation: 1) The number of times an infant alternated between positive and negative HI scores across the nine months (more frequent alternations indicates greater inconsistency and we expected that infants without a preference for acquisition would be less consistent than either infants with a right or left preference for acquisition); 2) The number of positive HI scores observed for unimanual manipulation (more positive scores indicates more right hand use and we expected that infants who preferred to use their right hand for acquisition would have more positive HI scores than both infants who had no preference for acquisition and those with a left preference); 3) The number of alterations between significant HI scores (we predicted that infants without a hand preference for acquisition would show more alternations in their significant HI scores for unimanual manipulation than infants with either a right or left hand preference); 4) The number of significant HI scores for unimanual manipulation that an infant exhibited from 6 to 14 months (we expected that infants without a hand preference for acquisition would have fewer significant HI scores for unimanual manipulation than infants with either a right or left preference).

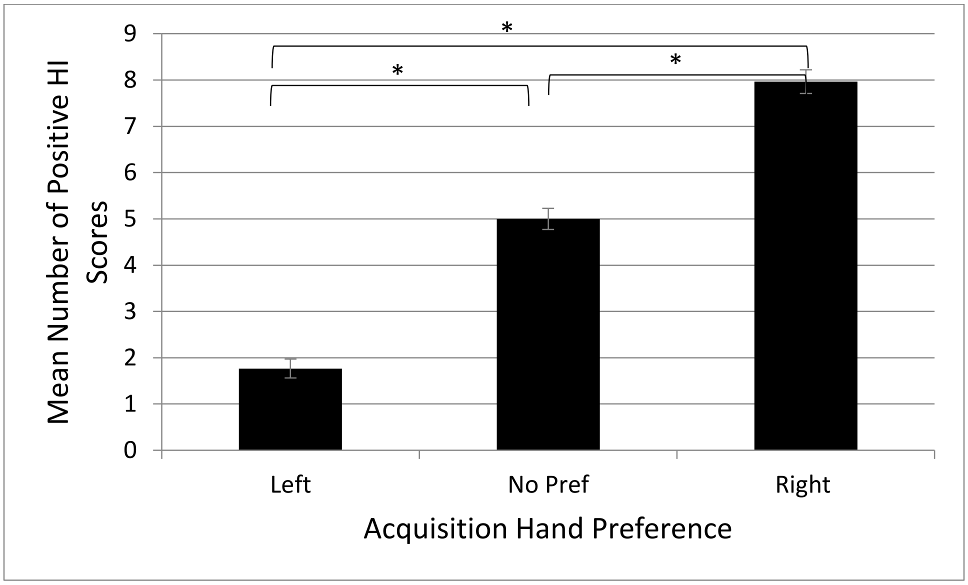
We found that infants with a right hand preference for acquiring objects exhibit the fewest alternations in HI sign (*M* = 1.3, *SD* = 1.1) and no preference have the most (*M* = 3.76, *SD* = 1.4) with left in between (*M* = 2.3, *SD* = 1.6). This frequency of alternations is significantly different for all three groups (Figure 5, Bonferroni corrected $p = .003$) indicating that those infants with a right or left preference for acquisition are more consistent in their unimanual hand use than those without a preference ($F(2, 87) = 24.67$, $p < .0001$). A Bonferonni post hoc test revealed that there were significant differences between the left hand preference group and the no preference group, between the right group and the no preference group, and between the left and right group ($p < .0001$).

Figure 5. Mean Number of Alternations of the Signs for HI Scores for Unimanual Hand Preference According to Each Acquisition Hand Preference Group. The No Preference Group Exhibits the Most Shifts Indicating the Least Consistency in Their Unimanual Preference.



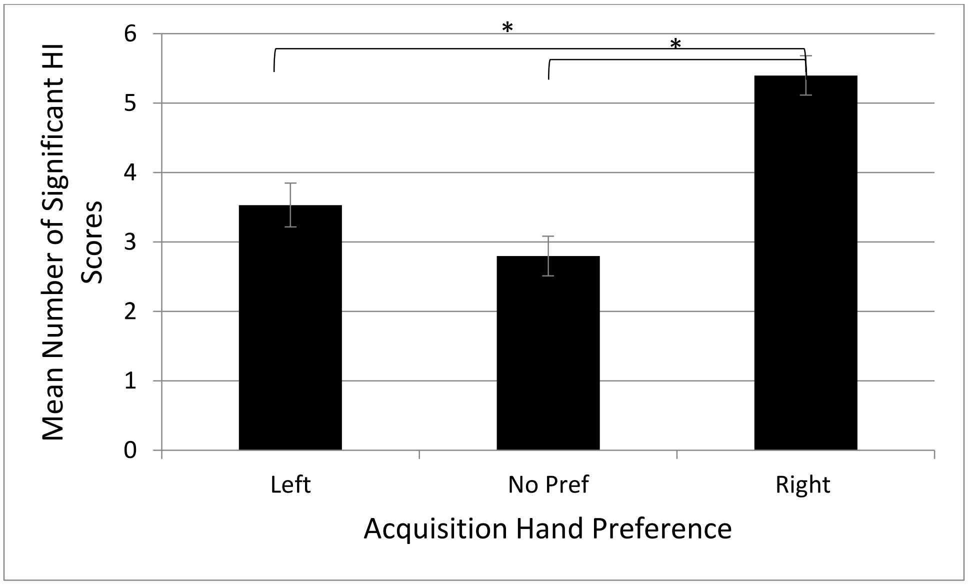
As can be seen in Figure 6, infants with a right preference for acquisition also have the greatest number of positive HI scores (*M* = 8.0, *SD* = 1.4) and those with a left preference for acquisition have significantly fewer positive (more negative) HI scores (*M* = 1.8, *SD* = 1.1) than either those with a right preference or no preference ($F(2, 87) = 181.43$, $p < .0001$). Bonferroni post hoc tests reveal that there were significant difference between the left hand preference group and the no preference group, between the right group and the no preference group, and between the left and right group ($p < .0001$).

Figure 6. Mean Number of Positive HI Scores for Unimanual Hand Preference According to Each Acquisition Hand Preference Group.



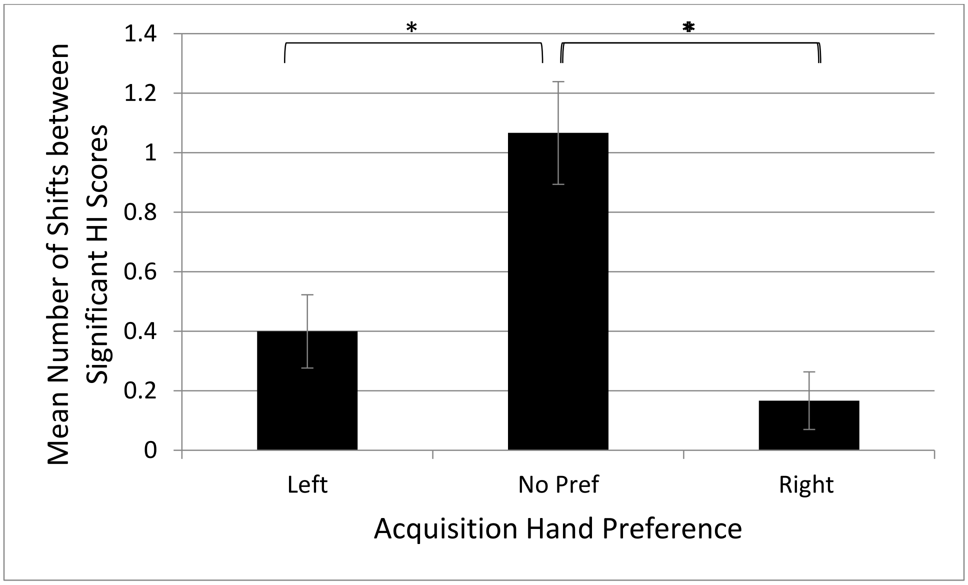
Also, infants with a right preference for acquisition have significantly more HI scores which fall outside of the critical score indicating significance, than those with either a left or no preference for acquisition ($F(2, 87) = 12.05$, $p < .0001$). We observed that infants in the left preference group have a less distinctive hand preference for unimanual manipulation than infants in the right preference group. Figure 7 illustrates the significant differences between the left hand preference group and the right hand preference group, as well as between the right preference group and the no preference group that were identified by a Bonferonni post hoc analysis ($p < .0001$).

Figure 7. Mean Number of Significant HI Scores for Unimanual Hand Preference According to Each Acquisition Hand Preference Group.



Finally, as expected, infants in both the right and left acquisition preference groups exhibit significantly fewer alterations between significant HI scores (HI > |1.7|) than those without a preference ($F(2, 87) = 20.62$, $p < .0001$). Thus, infants with either a right or left hand preference for acquisition exhibit more stable unimanual HI scores and these scores are consistent with their hand preference for acquisition. Figure 8 show the significant differences between the left hand preference group and the no preference group and the difference between the right group and the no preference group which was identified by a Bonferonni post hoc analysis ($p < .0001$). We conclude that the unimanual manipulation assessment identified relatively consistent hand-use that was consistent with the infant's acquisition preference.

Figure 8. Mean Number of Shifts Between Significant HI Scores for Unimanual Hand Preference According to Each Acquisition Hand Preference Group.

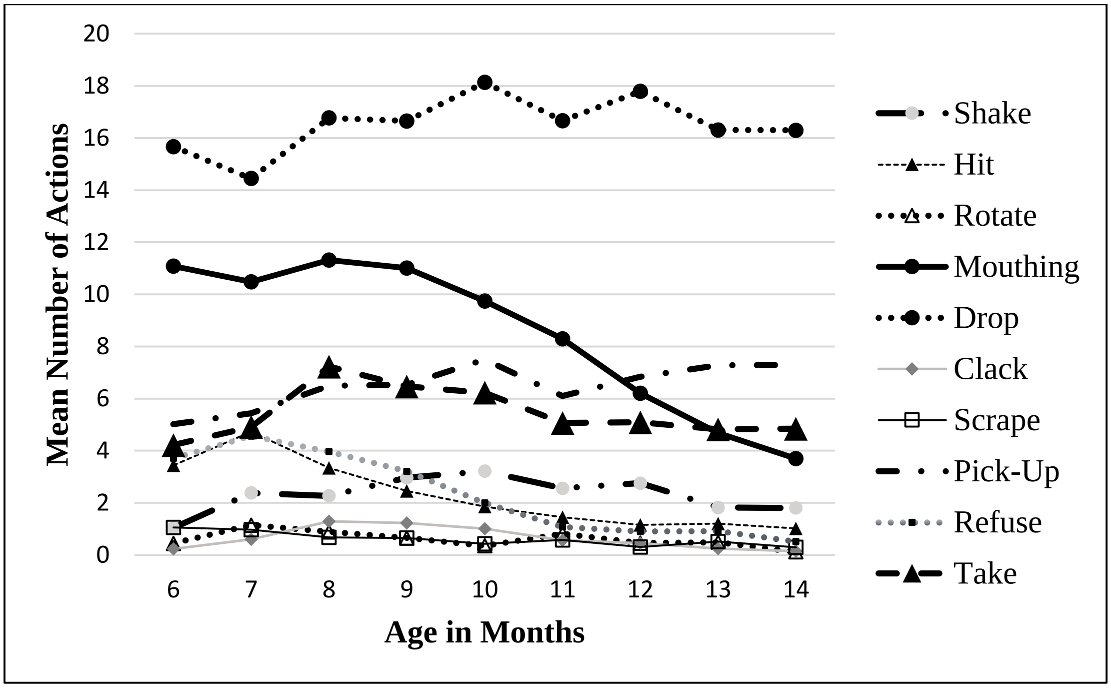


In order to account for the finding that left hand acquisition infants do not have distinctive unimanual HI scores, we examined mother's hand preference using the Briggs and Nebes (1975) modification of the Annett handedness questionnaire (Annett, 1972). Scores less than -9 or greater than +9 were categorized as left- and right-handed, respectively (as recommended by Briggs & Nebes). These scores identified 86% right-handers and 9% left-handers in a reference group of 1599 adults (48% females). Amongst mothers of infants with a left hand preference, 85% were found to have a right hand preference, while only 8% were found to have a left preference. Amongst mothers of infants with a right hand preference, 78% were found to have a right hand preference, while only 9% were found to have a left preference. Previous research has reported that infant left-hand preference scores can be weakened by object play patterns with right-handed mothers (Michel, 1992).

Development of "Active" and "Rejection" Unimanual Manipulation

In addition to an examination of the relation between hand preference for acquisition and hand preference for unimanual manipulation, an examination of the developmental trajectories of individual actions was conducted. In order to do this, the "active" and "rejection" categories were once again used to distinguish between unimanual manipulations that show engagement with an object (shake, hit, in mouth, rotate, scrape, clack, pick-up, take) and those that show disengagement (refuse, drop). These two types of actions highlight important differences in manipulation during infancy and were separated into "active unimanual manipulations" and "rejections" of unimanual manipulation (Figure 10). In the following analyses, the total number of active unimanual manipulations were calculated as the sum of the number of actions – shake, hit, in mouth, rotate, scrape, clack, pick-up, and take, as before and the total number of rejections as the sum of the number of refuses and drops.

Figure 9. Mean Number of Unimanual Actions Across Months for Each of the 10 Types of Unimanual Actions that were Coded.



The multilevel analysis of the number of unimanual manipulations revealed significant differences in trajectories between active unimanual manipulations and rejection actions (Table 3 and Figure 7). Both the total number of manipulations and active unimanual manipulations increase to asymptote between nine and 11 months of age and decrease thereafter. In contrast, rejections increase linearly with age.

The final multilevel model for the number of unimanual manipulations is presented below. In this model, NUM_{ij} represents the number of unimanual manipulations performed for child *i* at time *j*. The estimated parameters are provided in Table 3.

The final multilevel model for the number of active unimanual manipulations is presented below. In this model, A_UM_{ij} represents the number of unimanual manipulations performed by child *i* at time *j*. The estimated parameters are provided in Table 1.

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

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

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

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

The final multilevel model for the number of rejection unimanual manipulations is presented below. In this model, R_UM_{ij} represents the number of unimanual manipulations performed by child *i* at time *j*. The estimated parameters are provided in Table 1.

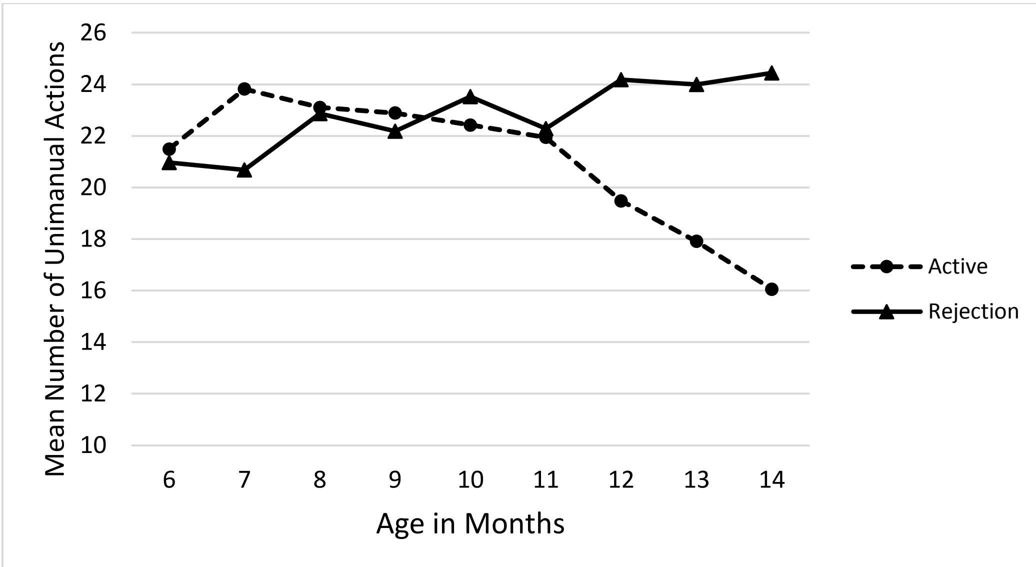
Level 1 model: $R\_UM_{ij} = \pi_{0i} + \pi_{1i}*(AGE)_{ij} + \pi_{2i}*(AGE)^{2}_{ij} + \varepsilon_{ij}$

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

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

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

Figure 10. Mean Number (and Standard Errors) of Active Unimanual Actions and Rejections Across Age.



Multilevel analysis of active unimanual manipulations and rejections according to infant hand-use preference for acquisition (Table 4) revealed that infants with a consistent right hand-use preference for object acquisition exhibit a significantly different trajectory in the development of unimanual manipulations during the 6 to 14 month period as compared to infants without a consistent hand-use preference for acquisition (Figure 8A).

The final multilevel model for active unimanual manipulations according to hand preference for acquiring objects is presented below. In this model, A_UM_{ij} represents the number of unimanual manipulations performed by child *i* at time *j*. The estimated parameters are provided in Table 1.

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

Level 2 models: $\pi_{0i} = \beta_{00} + \beta_{01} * (Right)_i + \delta_{0i}$

$\pi_{1i} = \beta_{10} + \beta_{11} *(Right)_i + \delta_{1i}$

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

The final multilevel model for rejection unimanual manipulations according to hand preference for acquiring objects is presented below. In this model, R_UM_{ij} represents the number of unimanual manipulations performed by child *i* at time *j*. The estimated parameters are provided in Table 1.

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

Level 2 models: $\pi_{0i} = \beta_{00} + \beta_{01} *(Left)_i + \beta_{02} *(Right)_i + \delta_{0i}$

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

Table 3. Estimated Fixed and Random Effects for Active Unimanual Manipulations According to Hand Preference for Acquiring Objects.

	Active Unimanaul Manipulation		
	Unconditional Growth	Full Conditional Growth	Final Conditional Model
Fixed Effects†	*Coefficient*	*Coefficient*	*Coefficient*
Intercept (γ_{00})	22.187***	26.671***	23.509***
Age (γ_{10})	0.982	-1.296*	0.730**
Age^2 (γ_{20})	-0.224***	-0.035	-0.223***
Left (γ_{01})	-	-5.265	-
Left*Age (γ_{11})	-	3.059*	-
Right (γ_{02})	-	0.114*	-3.956
Right*Age (γ_{12})	-	3.733*	0.754*
Right (γ_{21})	-	-0.266	-
Right*Age^2 (γ_{22})	-	-0.297*	-
Random Effects†	*Variance Component*	*Variance Component*	*Variance Component*
Intercept (δ_{0i})	112.300***	101.683***	112.300***
Age (δ_{1i})	13.015***	10.536***	13.015***
Age^2 (δ_{2i})	0.105***	0.088**	0.105***
Level-1 (σ_{ε}^2)	65.598	65.536	65.598

† For all fixed and random effects, *df* = 87

* $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$

Table 4. Estimated Fixed and Random Effects for Rejection Unimanual Manipulations According to Hand Preference for Acquiring Objects.

	Rejection Unimanaul Manipulation		
	Unconditional Growth	Full Conditional Growth	Final Conditional Model
Fixed Effects†	*Coefficient*	*Coefficient*	*Coefficient*
Intercept (γ_{00})	20.780***	20.044***	22.268***
Age (γ_{10})	0.614	1.898*	0.608
Age^2 (γ_{20})	-0.022	-0.140	-0.021
Left (γ_{01})	-	1.136	-2.036*
Left*Age (γ_{11})	-	-1.810	-
Left*Age^2 (γ_{22})		0.164	
Right (γ_{02})	-	1.030	-2.391**
Right*Age (γ_{12})	-	-2.023	-
Right*Age^2 (γ_{22})	-	0.188	-
Random Effects†	*Variance Component*	*Variance Component*	*Variance Component*
Intercept (δ_{0i})	19.620***	19.540***	21.606***
Age (δ_{1i})	6.025***	5.202***	6.030***
Age^2 (δ_{2i})	0.086***	0.079**	0.086***
Level-1 (σ_ε^2)	45.528	45.505	45.547

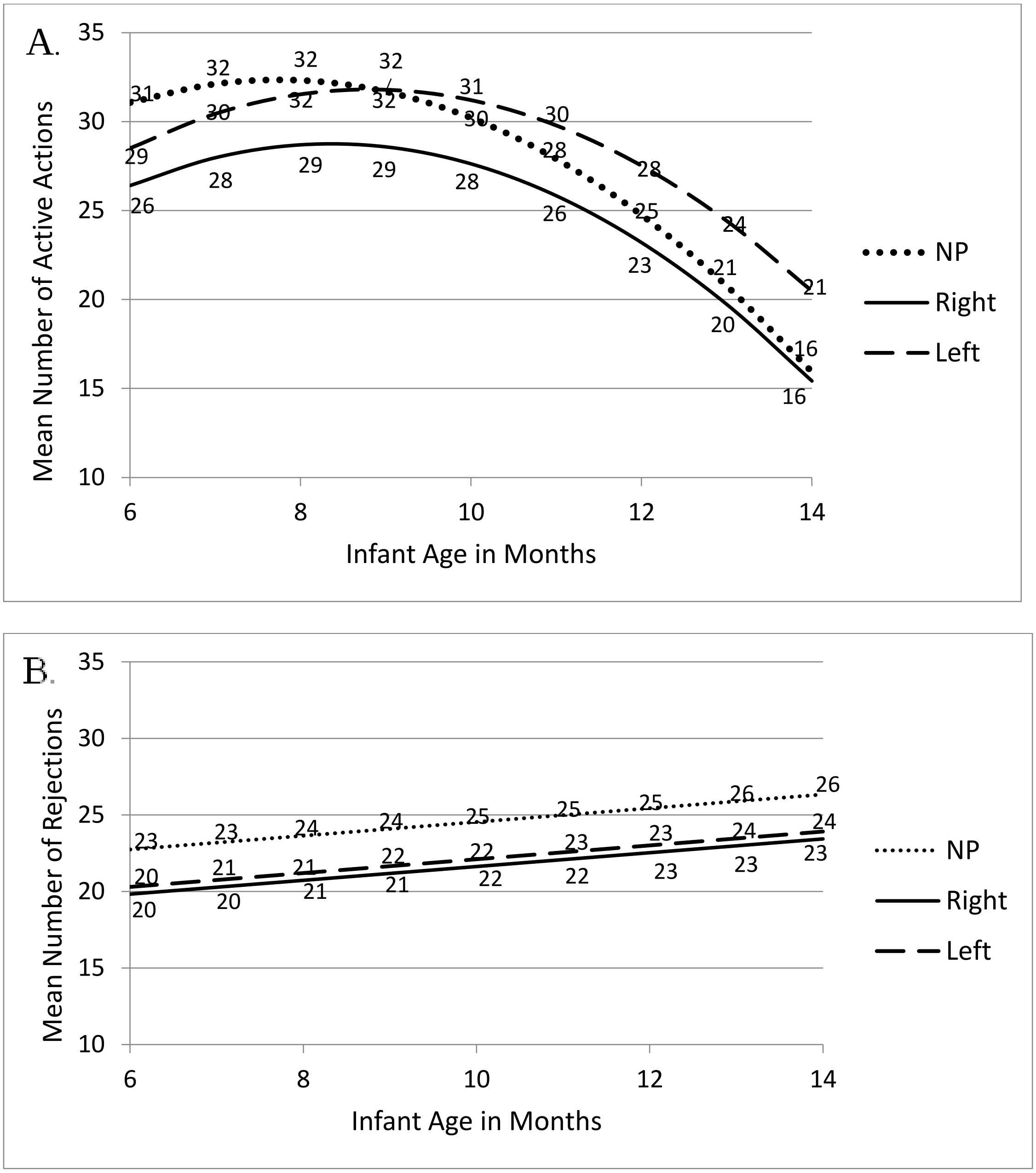
† For all fixed and random effects, $df = 87$

* $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$

Independent samples t-tests (Bonferroni corrected) showed that infants with a left and right hand-use preference for acquisition begin with no significant differences in the number of active unimanual manipulations at 6 months (t (86) = -1.49, p = .138; right preference M = 24.13, SD =12.38; left preference M = 26.39, SD = 12.52) and at 7 months (t (87) = -1.97, p = .052; preference M = 25.92, SD =12.61; left preference M =

28.57, *SD* = 13.13). In contrast, at 13 months and 14 months, infants who have a consistent left hand-use preference for acquiring objects, do significantly more active unimanual manipulations (13 month t (88) = 2.29, $p < .03$; 14 month t (88) = 2.01, $p < .05$) than infants with a right preference (13 month left preference *M* = 25.23, *SD* =11.33; right preference *M* = 19.97, *SD* = 7.67; 14 month left preference *M* = 19.40, *SD* =10.91; right preference *M* = 14.93, *SD* = 7.54). Thus, not only do those with and without a consistent hand-use preference for acquiring objects exhibit a difference in the developmental expression of their active unimanual manipulations but by 13 months, those with a left hand-use preference for acquiring objects are doing more active unimanual manipulations than those with a right hand-use preference (Figure 11A).

Figure 11. Estimated Trajectories of Change in the Mean Number of Active Unimanual Manipulations (A) and Rejections (B).



As Figure 11B shows, the mean number of rejections of unimanual manipulation tends to increase with age in all infants (Table 4). Thus, younger infants are less likely to refuse objects presented to both hands and less likely to drop them as compared to older infants. Note that infants with a hand-use preference for acquiring objects perform fewer refuse and drop actions (indicating that they withdraw less frequently from active unimanual manipulation) as compared to infants without a preference to acquire objects (Table 4).

Finally, the multilevel analysis of hand-use preference for rejections revealed a significant linear trend of change in all infants. No significant differences were found in the trajectories of hand-use preference for rejections of unimanual manipulation between right-handers and infants without a consistent hand-use preference, whereas these two groups together are significantly different from left-handers (Figure 12). Although the trajectory analysis shows significant differences in the shape of the trajectories, Tukey's HSD ($\alpha = .05$) reveals no significant differences in rejections among the acquisition hand-use preference groups for any of the monthly comparisons.

The final multilevel model for rejection unimanual manipulations according to hand preference for acquiring objects is presented below. In this model, R_UM_{ij} represents an infant's HI for rejection unimanual manipulation for child *i* at time *j*. The estimated parameters are provided in Table 5.

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

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

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

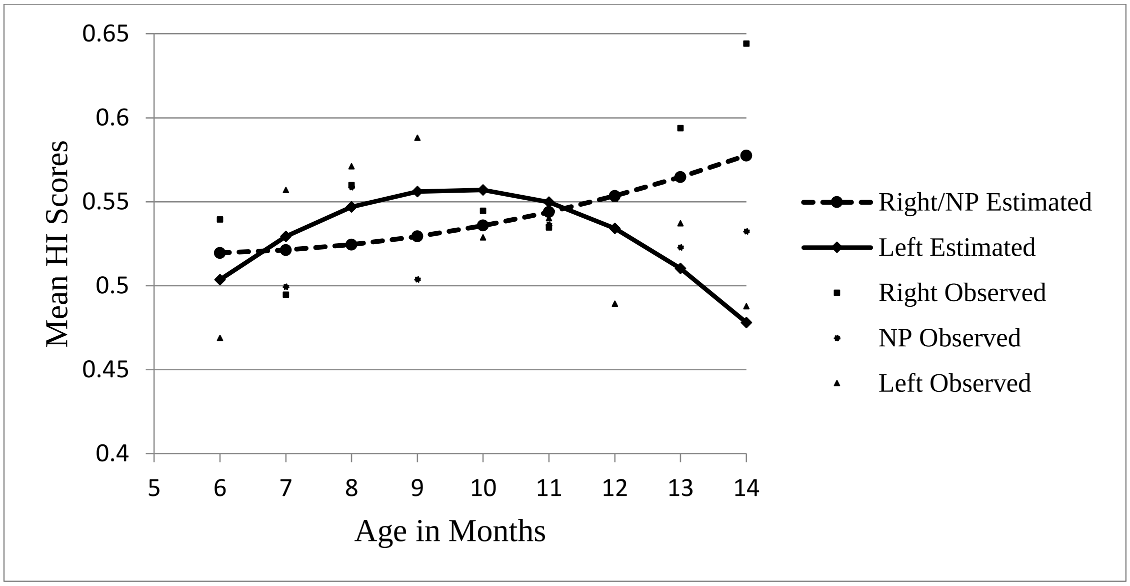
Table 5. Estimated Fixed and Random Effects for Hand-Use Preference for Acquiring Objects on Unimanual Rejections.

	Rejection Unimanual Manipulation		
	Unconditional Growth	Full Conditional Growth	Final Conditional Model
Fixed Effects†	*Coefficient*	*Coefficient*	*Coefficient*
Intercept (γ_{00})	0.220*	0.118	0.132
Age (γ_{10})	0.024	0.026	0.056*
Age^2 (γ_{20})	-	-	-
Left (γ_{01})	-	0.278	0.263
Left*Age (γ_{11})	-	-0.065	-0.095**
Left*Age^2 (γ_{21})		-	-
Right (γ_{02})	-	0.030	-
Right*Age (γ_{12})	-	0.060	-
Right*Age^2 (γ_{22})	-	-	-
Random Effects†	*Variance Component*	*Variance Component*	*Variance Component*
Intercept (δ_{0i})	-	-	-
Age (δ_{1i})	0.007***	0.006***	0.006***
Age^2 (δ_{2i})	-	-	-
Level-1 (σ_{ε}^2)	1.523	1.518	1.518

† For all fixed and random effects, *df* = 87

* $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$

Figure 12. Estimated and Observed Trajectories of Change in Hand Preference for Rejection Unimanual Manipulations, NP = No Preference.



CHAPTER IV

DISCUSSION

The goal of the current study was to examine the development of both unimanual manipulation and hand-use preferences for unimanual manipulation during 6 to 14 month period for infants with different hand-use preferences for acquiring objects. Although it was proposed long ago (Cohen, 1966; Hildreth, 1949) that an early hand-use preference for acquiring objects would facilitate the later development of the more sophisticated manual skills involved in manipulating objects, these results add to the relatively meager evidence for such an influence (cf., Kotwica, Ferre, & Michel, 2008) because the results reveal that the differences in hand-use preferences for unimanual manipulation are significant only after the differences between groups for hand-use preferences for acquisition have been identified.

The observation of a significant quadratic trend in the development of the action of active unimanual manipulations seems to contradict some of the previous research reporting no change in unimanual manipulation during infancy (Hinojosa et al., 2003; Kimmerle et al., 2010). However, in these previous studies, unimanual manipulation was assessed only at four ages (7, 9, 11, and 13 months) whereas the current study assessed unimanual manipulation at nine ages (6 through 14 months). The more frequent assessments permitted the detection of a quadratic trend of developmental change (cf., Ferre et al., 2010) with increases in unimanual manipulation achieving asymptote at a particular age. Thus, the results did confirm those of Hinojosa et al. (2003), since the mean number of unimanual manipulations in our study also did not significantly change between 7 and 11 months (36.2 vs. 37.4).

The results confirmed the predictions that hand preference for unimanual manipulation would become more distinctive with age and that a hand preference for acquiring objects would predict the hand preferred for unimanual manipulation. The results also confirmed the prediction that there would be a developmental delay in the expression of the preference for unimanual manipulation because the preference had to be transferred from acquiring objects to manipulating them. Infants with a right hand preference for acquiring objects (when compared to those with a left hand preference) initially are not significantly different in their hand use for unimanual manipulation. However, beginning at 11 months, those with a right hand preference for acquisition were significantly different from those with a left hand preference for acquisition in the hand used for unimanual manipulation.

Although infants without a consistent hand preference for acquiring objects have a rightward developmental trajectory for unimanual manipulation hand preference, they remain relatively non-lateralized for manipulation, even at 14 months. These results are consistent with those reported by Hinojosa et al. (2003). Thus, a hand preference for acquisition predicts a subsequent hand preference for unimanual manipulation whereas no hand preference for acquisition was associated with no hand preference for manipulation. Nevertheless, most infants had not established reliable hand preferences even by 14 months of age. I propose that hand preferences for unimanual manipulation are still developing during the infant's second year but that development is being biased by the influence of the infant's hand preference for acquiring objects on the hand used for unimanual manipulation during the first year. Since hand preference status for object acquisition corresponds well with hand preference for unimanual manipulation, these results support the cascade theory of hand preference development (Michel et al., 2013).

Given that most infants do not exhibit significant hand preferences for unimanual manipulation even by 14 months, systematic longitudinal investigations of hand preferences must be conducted throughout the second year of infancy. There are a few such studies of this age period, but they typically begin at 18 months (Nelson, Campbell, & Michel, 2013) or sample only sporadically during the 12 to 24 month period (Potier, Meguerditchian, & Fagard, 2013), or focus only a single manual skill. For example, Sgandurra et al. (2012) examined only prehension (reaching for objects and the adjustment of hand shape in preparation for different grip pattern and force control), whereas Kahrs, Jung, and Lockman (2013) examined the transition of banging into the functional skill of hammering. Unfortunately, in most studies of toddlers, hand-use preferences are ignored or not assessed systematically. Nelson et al. (2013) did report that infant right-hand preference for acquiring objects predicted right-hand preference for RDBM during the 18-24 month age period. This latter result is consistent with a cascading transfer across manual actions. However, the Nelson et al. (2013) study lacked infants with left-hand acquisition preferences and therefore, is not an adequate test of the cascade proposal.

So when and how might hand preferences develop for those without a unimanual preference by 14 months or, even more importantly, for those without a preference for acquisition? The cascade proposal would predict that nearly all of those with a hand preference for acquisition should eventually develop a preference for unimanual manipulation as the acquisition preference is transferred to unimanual manipulation. Of course, parental influences on imitation and hand-use (Harkins & Uzgiris, 1991; Michel, 1992) and other cultural practices (Michel, 2002) can affect the strength of offspring's hand preference. Although maternal left-handedness is related to offspring left-handedness (Harkins & Michel, 1988; McKeever, 2000), the vast majority of both potentially left-handed and right-handed offspring are likely to have right-handed mothers. Playful interaction between right-handed mothers and their infants will strengthen offspring right hand use and weaken left hand use (Michel, 1992; Mundale, 1992). Perhaps, this is the reason why there are so few left-handed adults at the extreme left-end of any measure as compared to high frequency of right-handed adults at the extreme right-end.

Since adult handedness is a continuously distributed variable, especially as measured by performance proficiency (peg-moving, dotting circles), many individuals will exhibit little or no differences between the hands even if they claim self-categorization into one of a few categories (e.g., right, mostly right, equilateral, mostly left, left). I would predict that the majority of the adults with minor differences in proficiency between their hands derive primarily from those with no consistent hand preference for acquiring objects during their first year. Clearly, the early development of handedness deserves more systematic longitudinal investigation.

Regarding the analysis of different kinds of unimanual actions, the analysis of active and rejections manipulations revealed that these actions develop along different trajectories. In contrast to active unimanual manipulations, rejections (“drop” and “refuse”) increase in frequency with age in all infants, with infants having a consistent hand-use preference for acquiring objects being more likely to accept an object with each hand and drop one of them less often than infants without a preference for acquiring objects. Thus, infants with a hand-use preference for acquiring objects have more opportunities to manipulate objects and explore their properties and likely increase their understanding of objects and object relations.

If a researcher were to combine both active and rejecting unimanual actions, many important aspects of the development of unimanual hand preference would be missed. One aspect that may be overlooked is that infants with a right acquisition preference are developing along different trajectories in their preference for “active” manipulations as compared to infants without a preference for acquisition. Additionally, infants with a lateralized hand preference for acquisition are performing fewer “rejections” than infants with no preference for acquisition. This may indicate that no preference infants are rejecting more often with the right and the left hand. Infants with a preference may be rejecting with only their preferred hand. Further investigation into which hand rejects in relation to the hand preference for acquisition is warranted. Rejecting items with the preferred hand may mean that infants are more likely to perform a role-differentiated bimanual manipulation (RDBM) with their preferred hand. An examination of how the development of unimanual preference relates to RDBM should be the next focus in this line of research.

Unimanual manipulation is a simple form of manual action that does not require any bimanual coordination involving interhemispheric transfer of information. Yet, unimanual manipulation may form the foundation of more advanced forms of manipulation, such as role-differentiated bimanual manipulation (Nelson, Campbell, & Michel, 2013) or object management skills (Kotwica et al., 2008). What is most intriguing about unimanual manipulation is that the handedness of adults and older children is assessed typically by proficiency differences between the hands in unimanual tasks. Only a few studies of children and adults have examined hand-use differences in proficiency with tasks that require role-differentiated bimanual actions (e.g., asynchronous and asymmetrical manual actions such as, for example, bimanual finger-tapping (Wolff, Michel, Ovrut, & Drake, 1990) or rotation of two cranks to draw lines (Fagard, 1987) which do involve colossal transfer of information between hemispheres for controlling between hand coordination. Some studies have examined hand-use preferences for RDBM during infancy (e.g., Fagard, 1998; Michel et al., 1985; Kimmerle et al., 1995; Kimmerle et al., 2010; Nelson et al., 2013; Potier, Meguerditchian, & Fagard, 2013). However, the early development of hand-use preferences has been relatively ignored when compared to the study of handedness in children and adults, in part, because the consensus is that handedness does not develop until after two years of age (Dubois et al., 2009).

Another detail that is gained by disentangling active and rejection types of unimanual actions is that infants with a consistent left hand-use preference for acquiring objects engage in more active unimanual manipulations than infants with a consistent right hand-use preference. Such differences in opportunities to discover object properties could contribute to the scaffolding of cognitive development and would be consistent with proposals that infant hand-use preferences can influence cognitive development (Michel, Nelson, Babik, & Campbell, 2013).

This study addresses problems that were present in the Hinojosa et al. (2003) study on unimanual hand preference. Namely, the bias of acquisition that was introduced in during the observation phase of the previous study when infants were allowed to pick objects up from the surface of the table. This problem was addressed by pressing the objects into the infants' palms during each trial in order to eliminate the need for the infant to first acquire the object before performing a unimanual manipulation.

Another problem in the Hinojosa et al. (2003) study was that unimanual manipulation was only observed at two time points (7 and 11 months of age). Previous research established that four or more observations are needed in order to establish reliable estimates of hand preference. This study addressed this issue by observing unimanual manipulation at nine time points (6 to 14 months of age).

Future studies examining the development of unimanual manipulation should focus on this behavior beyond 14 months of age. It is evident from the data that is presented in the current study that hand preference for unimanual manipulation is continuing to develop at the time point when the current study stopped observing unimanual manipulation. This is evidenced by the lack of a quadratic slope in the data. A quadratic slope would have indicated that infants had reached the asymptote of hand preference for the skill and infants have begun to perform the skill less often with their preferred hand. For this reason, it would be necessary to follow infants beyond 14 months of age when observing the development of hand preference for unimanual manipulation.

Other ideas for future studies include an examination of the relation between hand preference for unimanual manipulation and role differentiated bimanual manipulation (RDBM). In RDBM, the hands play complementary, but opposing roles in order to accomplish a goal. One hand stabilizes an object so that the other hand can manipulate the object in some way. The relation between hand preference between unimanual manipulaton and hand preference for RDBM may be such that the increase rejection unimanual manipulations that are observed in the current study may coordinate with the development of a hand preference for RDBM. The hand that rejects a toy in the unimanual manipulation procedure may then be the hand that is used to perform an RDBM on the object that is still retained in the non-preferred hand. Future studies would need to observe the actions that occur beyond the unimanual manipulation to follow the sequence of actions that precede a potential RDBM.

In conclusion, the frequency of unimanual manipulations increases during 6 to 14 month age period. Also, a hand preference for unimanual manipulation becomes more distinctive during this age period, with the infant's hand preference for object acquisition predicting the development of a hand preference for unimanual manipulation. Although the infant's hand preference for object acquisition predicts the development of a hand preference for unimanual manipulation, this hand preference for unimanual manipulation becomes significantly different between those infants with a right versus a left hand preference for acquiring objects only after 10 months. Moreover, the difference seems to be driven by the increasing use of the right hand for those with a right-hand acquisition preference. Although the frequency of unimanual manipulations increased with age, there were sufficient numbers of these actions to identify a hand preference (had there been a preference) for each assessment from 6 to 10 months. Therefore, the delay in the development of the relation of hand preferences for acquiring objects and hand preferences for unimanually manipulating them is consistent with the prediction that handedness development during infancy involves the transfer of the preference across these two manual skills. The results support a progressive lateralization notion for the development of handedness in which hand preferences transfer across manual skills in a cascading manner (c.f., Michel, 1983, 1988). I suspect that the transfer is stronger for the use of the right hand because most mothers are right handed and they play with their infant in ways that promote the infant's use of the right hand (Mundale, 1992).

The development of infant hand-use preferences for acquiring and manipulating objects is a complex process that deserves careful investigation, particularly its relation to the development of hand-use preferences for more sophisticated manual skills (e.g., RDBM, artifact construction, and tool use) during the infant's second year. Artifact construction and tool-use likely involve the coordination of both hands first manifested in RDBM. The development of hand-use preferences for object acquisition and unimanual manipulation during the infant's first year likely establishes the foundation for the development of a hand-use preference for RDBM in children. The development of hand-use preference during infancy also may contribute to the development of other sensorimotor and cognitive functions, including speech control (Michel, et al., 2014; Nelson, et al., 2013). A hand-use preference means that infants are more likely to manipulate objects and explore their properties differently, which would not only facilitate the development of their manual skills but also their knowledge of object properties, spatial relations, and logical relations (Langer, 1980).

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NOTES

[1] The HI is derived from binomial data and the z transformation of the binomial is $z = ((x+/-0.5)-(0.5N))/(.25N)^{1/2}$ (Siegel, 1956, p. 41). However, the formula $(R-L)/(R+L)^{1/2}$ creates a pattern for frequencies greater than 25 actions that make the difference between right and left hand-use of 9 or larger for a total of 25 actions to have a $z > 2.00$ with a $p < 0.01$ (8 is not possible for this odd number). For a total of 30 actions, a difference of 10 or larger (9 is not possible) yields a $z > 2.01$. Therefore, the formula $(R-L)/(R+L)^{1/2}$ which results in +/-1.7 is equivalent to the $z = 2.0$ for any total actions greater than 25. That is why we use > +/-1.7 as the decision criterion for assigning handedness.