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Lateralized hand-use is an easily observable sensorimotor skill that can be used as a model for the exploration of the development of differential functioning between the two cerebral hemispheres, or hemispheric lateralization. However, it has been argued that handedness is not a stable trait, and it cannot be reliably identified until 6 years of age or later. Many studies of infants report variability as the prominent characteristic of infant manual asymmetries. However, other studies have reported significantly consistent hand-use preferences for infants. Perhaps, the hand-use preferences in infants are somewhat different from their lateralized hand-use. Some researchers have tried to explain high variability in the development of lateralized hand-use using a dynamic systems perspective. From this perspective, the emergence of new motor skills such as sitting, crawling and walking imposes new constraints on the development of lateralized hand-use but not necessarily on the development of hand-use preferences. The current large scale (108 infants) longitudinal (from 6 to 14 months) study explored the relationship between the development of gross motor skills and lateralized hand-use. Our goal was to explore possible fluctuations in lateralized hand-use development at the onset of sitting, crawling, and walking among infants with and without clear hand-use preferences (as assessed by a valid and reliable measure) and controlling for gender. The multilevel analysis performed in HLM program showed that only the onset of walking significantly influences the trajectory of lateralized hand-use, however this trajectory differ between males and females, and also depends on infant’s handedness status.

POTENTIAL POSTURAL CONSTRAINTS ON THE DEVELOPMENT OF LATERALIZED HAND-USE IN INFANCY

by

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APPROVAL PAGE

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CHAPTER I

INTRODUCTION

Background

Handedness is an easily observable sensorimotor skill that can be used as a model for exploration of differential functioning between the two cerebral hemispheres. As with left hemisphere predominance in the control of speech, right-handedness predominates in the human population. Thus, both lateralized asymmetries have a population level distributional asymmetry combined with an interesting minority (those with right hemisphere control of speech or no clear asymmetry in speech control, as well as those with left handedness or no clear handedness). Given that atypical patterns of handedness (e.g., left-handedness or variable handedness) and right hemisphere specialization for fine motor movements and language have been associated with particular neurobehavioral dysfunctions such as learning disabilities (Narbona-García, 1989), autism (Kleinhans et al., 2008), dyslexia (Hugdahl et. al, 1998), stuttering (Costa & Kroll, 2000), and schizophrenia (Ribolsi et al., 2009); the exploration of early trajectories of lateralized hand-use (or, in other words, the distinctiveness of the difference between hands in their use) might have important implications for our understanding of the development of afore-mentioned neurobehavioral dysfunctions.

It has been argued that infant handedness is not a stable trait, and cannot be reliably identified until 6 or even 10 years of age (Janssen, 2004). Although handedness appears to be unstable during infancy, its fluctuation may be due to assessment limitations and not to the lack of the underlying hemispheric lateralization. Moreover, there is a growing evidence that the majority of infants manifest relatively stable handedness for reaching by the age of 7 to 13 months (Michel et al., 2006) and the high variability in the development of handedness exposed in other studies may be explained using a dynamic systems perspective (Thelen, 1986).

From a dynamic systems perspective, the emergence of new motor skills, such as sitting, crawling or walking, can modify established patterns of infant handedness (Corbetta & Bojczyk, 2002; Corbetta & Thelen, 1996; Corbetta & Thelen, 2002; Goldfield, 1993; Rochat, 1992). This modification may occur because the limbs are part of a system in which the control of the forelimbs is partially coupled to the control of the hind limbs. Thus, alterations in the developmental transitions occurring with locomotion may affect the pattern of activity of the forelimbs. Thus, exploration of postural changes occurring with the developmental process of locomotion on the development of handedness may shed light on why handedness appears to be an unstable trait during infancy. It is hypothesized that the developmental trajectories of lateralized hand-use should be affected by the milestones of gross motor development, particularly those examining the development of locomotion.

Handedness and Lateralization

Handedness is usually defined as a preference to use one hand more than other, or that one hand performs faster or more skillfully on certain manual tasks that are not likely to have been practiced. For humans, there is a remarkable asymmetry in the distribution of handedness with no more than 12% of the population ever showing a left hand preference (Annett, 1985; Ramsay, 1980). Since the precise control of movements of the hands and fingers derives from the activity of neurons in the contralateral hemisphere, the predominance of right handedness in the population likely means that the left hemisphere is controlling the expression of right handedness. Moreover, neurological evidence from anatomical, physiological, and behavioral studies reveals that for the majority of people the left hemisphere is responsible for controlling other fine motor movements, including those involved in speech production. Therefore, handedness and hemispheric control of speech and other language characteristics as well as other fine motor skills typically are related in research investigations.

Since handedness represents an easily observable sensorimotor skill that involves differences in functioning between the two cerebral hemispheres, the development of handedness can serve as a model for the development of hemispheric lateralization. Hemispheric lateralization refers to the ability of the two cerebral hemispheres to operate and process information differently. Research shows that although for the majority of individuals the left hemisphere is responsible for speech production, "the processing of the emotional content of language (called emotional prosody) appears to be right lateralized" (Gazzaniga, Ivry & Mungun, 2009, p.458). Davidson (1992) also observed greater activation in the frontal region of the left hemisphere in response to "positive, approach-related emotions", and arousal in the frontal region of the right hemisphere in response to "negative, withdrawal-related emotions" in infants and adults (p. 39). In the area of visuospatial processing, the right hemisphere is considerably better at the perception and recognition of faces, but only the "dominant left hemisphere can generate voluntary facial movements" (Gazzaniga et al, 2009, p.459). Moreover, in complex cognition, the right hemisphere is more effective in causal inference while the left hemisphere excels in causal perception (Roser et al., 2005). Another difference in cognition between the two hemispheres is that the left hemisphere is more likely to look for patterns of events and built hypotheses while the right hemisphere tends to approach problem solving in the simplest possible way (Wolford, Miller, & Gazzaniga, 2000).

Therefore, different functions are unequally distributed (lateralized) between the two hemispheres and handedness is one of them. Although handedness is a continuous trait varying from the strong right-handedness to the strong left-handedness, it is very common in research to treat handedness as a categorical variable and study "right-handed" vs. "left-handed" subjects, or "right-handed" vs. "non-right-handed" individuals (Dragovic, Milenkovic, & Hammond, 2008; McManus, 1985). For example, Dragovic, Milenkovic, and Hammond (2008), using latent class analysis on a 7-item questionnaire given to two independent samples of size 1224 and 787 subjects, found that the continuum of handedness manifestation in the population can be categorized into three independent clusters – consistent right-handedness, inconsistent right-handedness, and left-handedness. Annett (1970), using association analysis for several hundred subjects' responses to a 12-item handedness inventory, found that only a minimum eight clusters could represent the handedness continuum.

Consequently, different questionnaires have different cut-off points, and create different handedness subgroups such that a researcher might find different proportion of left-handers and right-handers in the same sample using different inventories. Bishop et al. (1996) argued that assessment of handedness with questionnaire inventories might result in a limited understanding of the complexity of the trait and mislead to the categorical approach in the exploration of handedness.

It should be noted that even when manual tasks are used to estimate handedness, results often depend not only on an underlying lateralization of the cerebral hemispheres, but also on task constraints, manner of stimuli presentation, affordances of stimuli, complexity of a task, subject's neuromotor state, etc. (Gabbard & Helbig, 2004; Leconte & Fagard, 2006; Pryde, Bryden, & Roy, 2000). Peters & Murphy (1992) also argued that when a researcher estimates handedness and divides subjects into different handedness categories, it is difficult to demonstrate that those categories truly represent underlying differences in hemispheric lateralization.

Hemispheric Lateralization in Right- and Left-Handers

So, how do right-handers differ from left-handers on patterns of hemispheric lateralization? It has been reported that for the majority of right-handers (90-95%), verbal skills are lateralized to the left-hemisphere while much smaller proportion of left-handers

(60-80%) is left-hemisphere lateralized for language (Annett & Alexander, 1996; Kimura, 1983). Gonzalez and Goodale (2009) note that "the remaining 20–30% of left-handers appear to have language bilaterally represented or atypically represented in the right hemisphere" (p. 3182).

Interestingly, this relation is not straight-forward so that right-handers are left-hemisphere lateralized for language, and left-handers are just a mirror image of right-handers. Gonzalez and Goodale (2009) found that right-hand preference for precision grasping was related to the left-hemisphere lateralization for language (tested with dichotic listening procedure). However, the left-handedness group (determined by the Edinburgh handedness and the Waterloo questionnaires) was much less homogenous than right-handedness group. Gonzalez and Goodale (2009) identified two groups of left-handers: 1) left-right-handers (who showed similar patterns of grasping and language lateralization as right-handers) and; 2) left-left-handers "whose performance was the mirror image of that of right-handers" (p. 3182). Levy and Gur (1980) state that:

> variations in laterality of hemispheric specialization within handedness groups is almost certainly due to the fact that in some left- and right-handers the control pathways from the language hemisphere lead, directly or indirectly, to the ipsilateral hand and in others, to the contralateral hand (p. 202).

Since frontal eye-fields in the cortex control eye movements, Gur, Gur, and Harris (1975) explored direction of eye movements as a function of task type in subjects with right-hand preference (N = 28), and those with left-hand preference (N = 13). The researchers explored the movement of eyes according to the type of a task; theory predicted the left shift of eyes in response to spatial questions, and right shift in response to verbal questions. The results of the study indicated that the majority of left-handers (11 out of 13) were "nondiscriminators", so that their response did not depend on the problem type, while the other two left-handed subjects showed the response suggesting that their right hemisphere is specialized for language while the left hemisphere is specialized for spatial processing. Thus, the researchers concluded that left-handers on average had a weaker specialization of hemispheres.

Zenhausern and Kraemer (1991) investigated "the validity of lateral eye movements (LEM) as a measure of the individual differences and task demands" on different spatial, verbal tasks as well as tasks without "clear hemispheric locus" in fifty subjects, and concluded that "LEM are a reliable individual difference measure and are sensitive to task differences" (p. 169).

It is very important to address not only uniqueness of left-handers as a group, but also the heterogeneity among the members of this group. Gur, Gur, and Harris (1975) found that the responses of left-handed subjects tested with "eye movements" procedure in general were less homogenous than responses given by right-handed subjects. Gonzalez and Goodale (2009) also support this notion in their research.

It is noteworthy that the pioneer research on hemispheric lateralization for verbal and spatial skills was almost exclusively conducted on male samples of the population (Levy, 1974). However, she reported that the left hemisphere is specialized for language in right-handed population for 96-99% males, but only for 88-90% females. Levy and Reid (1978) suggested that "the estimates of the proportion of dextrals with right-hemispheric language derived from the neurological literature are valid for males, but greatly underrepresent the true proportion in females" (p. 206). Thus, if both sexes are equally represented in a given study, it is expected that an interaction between handedness status and sex in the trajectories of lateralized hand-use would exist.

Following this hypothesis, Herron (1980) analyzed processing of verbal and visual stimuli in right- and left-handers using the EEG technique and controlling for the gender of participants. Herron (1980) found that, in general, right-handers are more lateralized than left-handers. However, when she controlled for the participant's sex, Herron found "sex related differences in hemispheric specialization among left-handers, but not among right-handers" (p. 240). That is, left-handed females had less differentiation between the two hemispheres than left-handed males (as well as right-handed males and females). Unfortunately, researchers study differences in lateralization development between groups with different handedness status, or between males and females, with little emphasis put on the exploration of the possible interaction between handedness status and gender.

Some recent studies point out to the problem of "complex interactions among gender, handedness, and brain organization" (Eviatar, Hellige, & Zaidel, 1997, p. 562). Eviatar, Hellige, and Zaidel (1997) found that interaction of handedness and gender is task-dependent. When interhemispheric flexibility was assessed with a letter-matching task, "measuring *quantitative* differences in hemispheric abilities", left-handed subjects were found to "have less flexible callosal function than right-handers", and no sex differences between males and females were observed on this task (p. 574). However, the interaction between handedness and gender was observed in the "consonant-vowelconsonant… identification task measuring… *qualitative* differences in hemispheric strategies": left-handed males had higher scores on this test than did right-handed males while left- and right-handed females did not significantly differ from each other (Eviatar, Hellige, & Zaidel, 1997, p. 567). Moreover, Welcome et al. (2009) also emphasized "the importance of considering brain/behavior relationships within sub-populations, as relationships between behavioral asymmetry and callosal anatomy varied across subject groups" (p. 2427).

Sex Differences in Lateralization

Although handedness is an aspect of hemispheric specialization of functions, its patterns of sex differences seem somewhat disparate. There is a conflicting evidence of the differential lateralization between males and females. For example, Annette (1985), based on handedness questionnaires, reported that females seem to be more lateralized in handedness than males, whereas the majority of pioneer studies on hemispheric specialization using the diversity of methodologies like clinical studies, dichotic listening, tachistoscopic presentation, and electrophysiology frequently reported that females are less lateralized than males (Lake & Bryden, 1976; Lansdell, 1962; McGlone, 1978; Van Dyke et al., 2009; Witelson, 1976).

In the exploration of sex differences in relation to lateralization of cognitive functions, linguistic and spatial abilities are usually emphasized. There is some evidence which demonstrates that girls score on average higher on tests from the linguistic domain while boys outperform girls in spatial domain (Burstein, Bank, & Jarvik, 1980; Gaddes &

Crockett, 1975; Kirk, 1992; Maccoby and Jacklin, 1974; McGuiness & Morley, 1991; Ray et al., 1981; Voyer, 1996). However, Spreen, Risser and Edgell (1995) noted that age plays significant role in these differences so that "before age 8 and after adolescence girls generally seem to outperform boys in measures of verbal skills" while "male superiority in tests of spatial ability" is evident as early as at the age of 4 (pp.107-108).

While there is at least some consensus about the differential specialization of cognitive functions between the two hemispheres in males and females, there are many conflicting viewpoints as to the degree and the origin of cerebral lateralization in both sexes. For instance, Buffery and Gray (1972) stated that verbal and spatial abilities achieve a stage of complete lateralization in females while males remain to be more bilateral in these skills. Knowing that males show better results on spatial tests while females outperform males on verbal tests, Buffery and Gray concluded that it is beneficial for an individual when verbal skills are lateralized, but spatial skills are expressed bilaterally. In contrast, Levy and Reid (1978) and Witelson (1976) concluded stronger lateralization of males for spatial as well as verbal functions. The researchers also suggested that bilateral language representation is beneficial and might lead to higher verbal abilities.

Furthermore, Waber (1977, 1979) presented a theory in which it was suggested that the timing of physical and sexual maturation might be the key to the degree of lateralization in males and females so that later and slower maturation (which is typical for males) facilitates greater asymmetry of functions in the brain while earlier and faster maturation (typical for females) results in more symmetrical distribution of functions between cerebral hemispheres. In agreement with this theory, Witelson (1976) using a test of tactual perception (dichaptic stimulation test) found that hand and sex interacted significantly so that boys performed significantly better with their left hand than with the right one while there was no significant difference between hands in girls.

Interestingly, Waber's theory about maturation influencing lateralization can be expanded, and related not only to males and females but to the developing individuals in general. In her research, Waber (1979) partially supported this theory by showing that disregarding of sex, late-maturing individuals (Tanner scale was used to assess maturation) performed significantly better than early-maturing individuals on spatial tests. However, this difference disappeared in verbal tests.

It seems intuitive to explore differences in brain structure between males and females in order to understand differences in their behavior in general, and their lateralization patterns in particular. It was noticed that females on average have bigger callosal size, and it was shown that the latter correlates negatively with cerebral volume (Welcome et al., 2009). Thus, we might expect to find sex differences between males and females in the size of corpus callosum only because females on average have smaller brains than males. Leonard, et al. (2008) demonstrated that when brain size of participants was controlled in the analysis, no statistically significant effect of gender on lateralization was found. This research emphasized the importance of further exploration of sources of sex differences.

According to Johnson (1997), "differential timing of development between the two hemispheres in early infancy may be sufficient to bias each of them to process particular types of inputs" (p. 170). Expanding this idea, it can be stated that lateralization of functions is a dynamic system that has great potential for plasticity, but with development certain sensory inputs become more effectively processed by one hemisphere and it becomes dominant in some functions rather than others. The timing is important, and it is possible that sex differences in hemispheric lateralization are consequences of differential rates of maturation between males and females. As interesting as these results are, now we need to understand what is governing the process of maturation and how it can be observed and measured. We consider that the development of gross motor skills might be a potent indicator of differential rates of maturation between males and females (the issue of maturation and age as a marker of development is elaborated further in the text).

It is also important to emphasize that "there is typically more individual variation within a sex than between sexes" (Spreen et al., 1995, p. 102). This fact might explain the contradicting findings in the research on sex differences in hemispheric lateralization.

Origins of Lateralization

Differences between right-handed and left-handed individuals as well as between males and females do not reveal much about the origin of such differences. For more than four decades, two competing theories of the developmental origins of hemispheric lateralization have been explored in research. Lenneberg (1967) proposed the progressive lateralization theory and argued that an individual brain develops progressively from a point of little or no lateralization toward stages of greater and more complete lateralization. The continuous character of this development was used to explain a relationship among patterns of lateralization at different ages.

In contrast, the invariable lateralization approach (Kinsbourne, 1975; Witelson, 1980) proposed that infants' brains are already lateralized at birth, and observed changes reflect not progressive lateralization, but as the individual develops more complex and sophisticated cognitive and emotional abilities, the latter subsequently get distributed to the appropriate hemisphere for processing. Thus, it only appears that lateralization develops because the psychological characteristics develop. Moreover, the notion of the invariant lateralization hypothesizes is that only complex functions require lateralized processes. Therefore, as individuals develop more complex functions, these functions will now exhibit the influence on of the existing lateralization.

While these theories represent two extreme points of view on the development of lateralization, many researchers argue that although asymmetries in the development are present at the moment of conception, they continue to develop and reorganize throughout the life span (Morgan, 1977; Michel, 1988; Michel & Moore, 1995). Thus, Michel (2002) argues that handedness development should be perceived as a complex cascade of different developmental contingencies. The development of lateralization begins at the time of conception when the asymmetry of the fertilized egg combines with the asymmetry of the uterus (Morgan, 1977).

In the last trimester of pregnancy, when the uterine space becomes very limited and restricts fetus' movements, the asymmetry of the uterine space and the specific gravity of the fetus combine to make the left occiput anterior presentation position (fetal head in vertex position with the face turned towards mother's right side) the most probable one (Michel, 1983). This position allows the right ear to receive different sensory input (more often speech sounds) than the left with consequent differences in stimulation to the left hemisphere. Moreover, this common fetal presentation results in asymmetric stimulation of the vestibular system associated with upright walking. This means that after birth, the vestibular system will be equalized only if the head is turned in the same direction as in utero (Previc, 1991). Thus, fetus' in utero position might predict postnatal postural asymmetries (Michel, 1981; Michel & Goodwin, 1979) which include a preferred head orientation position and a consequent influence on vestibular and stretch reflex which further influence limb and trunk positions. These postural preferences, in turn, lead to asymmetries in the tactile, visual and proprioceptive feedback of the infant's hands and arms (Michel & Harkins, 1986).

After birth, the vast majority of infants turn their heads to the right side when placed on the back (Michel, 1983). In this position, an infant's visual field is shifted to the right side, and the right hand gets more visual exploration, and the actions of the right hand (controlled by the left hemisphere) are mapped more distinctly with visual experiences of the position of that hand in space than those of the left hand. Note that this would be reversed for infants that prefer to turn their heads to the left side.

As the right hand becomes more active, it provides more stimulation to the brain. As a result, the left hemisphere receives much more eye-hand coordinated proprioceptive, visual, and corrollary discharge stimulation than the right one. Moreover, infants' relatively underdeveloped functional state of the corpus callosum does not allow the effective communication between the two hemispheres, and confines the sensory information to only one hemisphere, thus promoting the lateralization of hemispheres (Michel, 1988; Springer & Deutsch 1981).

These early sensorimotor asymmetries facilitate the formation of "action systems" that underlie the use of forelimbs (Michel, 1988; Michel & Harkins, 1986). The head orientation, inducing associations between the hand in space and the visual map of space, encourages more effective transport of that hand to a position in space than the other hand. According to this view, hand-use preferences for object manipulation would be (and are) initially observed in reaching and acquisition patterns (Michel, 1983). Acquisition preferences would build into manipulation preferences and these both would build into preferences for role-differentiated bimanual manipulation or RDBM (when two hands perform different but complementary movements on one or many objects), which forms the foundation of adult handedness in tool-use and construction (Vauclaire, 1984).

Michel and colleagues has demonstrated that hand-use preference for acquisition predicts subsequent hand-use preferences for unimanual manipulation when each hand independently manipulates a single toy (Hinojosa, Sheu, & Michel, 2003). It remains to be determined whether hand-use preferences for reaching, acquisition and unimanual manipulation might contribute to the development of hand-use preferences for role-differentiated bimanual manipulation. Such transformations in how handedness is expressed may change the observed handedness for reaching (the most frequently assessed manipulation pattern for infant handedness) and might lead to the observation of high intra-individual variability and frequent fluctuations in the development of handedness and lateralized hand-use. Thus, handedness does not start out as non-lateralized nor does it start out lateralized in the same manner as it will be in adults. Handedness, as an example of the development of lateralization, exhibits a clear developmental trajectory specified by neither of the two main theories of the developmental origins of lateralization.

Postural Constraints on the Development of Infant Handedness and Lateralized Hand-use

For some studies of infants, variability has been reported to be a prominent characteristic of infant manual asymmetries and interlimb coordination development (Corbetta & Thelen, 1999; Corbetta, & Thelen, 2002; Fagard, 1998; Fagard & Lockman, 2005; McCormic & Maurer, 1988; Piek, 2002; Thelen, 1995; Thelen, Corbetta, & Spencer, 1996). From one observation to another, infants often appear to change their preferences in hand use for reaching and manipulation of objects as well as the choice of unimanual versus bimanual strategies for reaching, acquisition, and manipulation (Fagard & Lockman, 2005).

Fagard and Lockman (2005) argued that fluctuations in handedness development could be explained from a dynamic systems perspective as being a function of other developing skills, such as sitting, crawling and walking. According to the dynamic systems perspective,

> movement patterns emerge from both the cooperative coupling of the ensemble of components that constitute the behavior itself (i.e., the collective activity of the neural, muscular, skeletal, and vascular components of the body segments involved in the movement), and the interaction of this natural cooperative coupling with specific environmental constraints (Corbetta & Thelen, 1996, p.503).

Since the emergence of sitting, crawling, and walking change infant's posture, influences balance control, and demands new adaptations in perception, the onset of each postural milestone would naturally lead to reorganization of infant's perception-action system.

To understand how the onset of milestones of gross motor development might facilitate changes in lateralized hand-use, we need to explore patterns of lateralized hand-use at the onset of reaching, long before the onset of sitting and locomotion. At the onset of reaching, between 3 and 4 months of age, infants exhibit two different types of reaching – unimanual and bimanual. Interestingly, while adults usually choose between unimanual and bimanual reaching depending on the perceptual information about the size of an object, in infants, size of an object does not relate to the type of reaching (Corbetta & Thelen, 1996; Fagard & Jacquet, 1996; Newell et al. 1989). White, Castle and Held (1964) argue that at the onset of reaching the majority of infants perform mostly symmetrical bimanual movements disregarding an object's properties. Although infants considerably improve their reaching skills throughout the first year of life, there are frequent fluctuations between unimanual and bimanual reaching.

Gesell and Ames (1947) were the first to report infants' regression to the bimanual reaching by the end of the first year of life. Gesell (1946) suggested that observed fluctuations between periods of unimanual and bimanual reaching might be the consequences of undergoing neuromotor reorganizations and are the "functional expressions of transient but necessary stages in the organization of the neuromotor system" (p. 307). However, he failed to specify the developmental origins of before-mentioned "neuromotor reorganizations".

Other researchers tried to treat handedness as a component of a larger dynamic system involving postural control of all limbs. Corbetta and Thelen (2002) have shown that the development of crawling skills may play a significant role in disrupting the stability of lateralization in infants. As infants acquire new skills like sitting, crawling and walking, they learn to control their posture and movements, as well as explore new ways of using their hands which interferes with the established patterns of handedness. Rochat (1992) and Goldfield (1993) report that the mastery of sitting as well as the emergence of crawling shifts infants' handedness toward unimanual reaching thereby increasing the lateralized hand-use. Goldfield (1989) also examined the transition from rocking to crawling and argued that infants rock during a period when they show mostly bimanual reaching, and crawl when they have developed a strong hand preference.

Corbetta and Thelen (2002) argued that the emergence of crawling alone is not sufficient in explaining the entire range of variability in handedness development. Rather, they have suggested that infants might become less handed by the end of the first year because they undergo continuous postural changes as they develop from mainly a sitting position toward an upright posture. Corbetta and Bojczyk (2002) observed that infants significantly increase two-handed reaching when they are in the stage of active acquisition of walking skills. Interestingly, the proportion of both-hand reaches declines when walking develops and infants gain better balance control.

Corbetta and Thelen (2002) also found that arm coupling increases at the onset of independent upright locomotion around the end of the first year. This tendency to use both hands simultaneously is not specific to reaching preferences, but also applies to a considerable array of other motor tasks as well as spontaneous non-reaching movements (Corbetta & Thelen, 1999). Interestingly, learning to walk independently stimulates infants to hold their hands above waist level, and this pattern of posture persists during the period of unstable walking and uncertain balance control. Improvements in balance control cause changes in posture, when infants lower their arms to waist level or below (Corbetta & Bojczyk, 2002). This postural change coincides with the decrease of two-hand reaching. Thus, it was proposed that upright locomotion might impose new constraints on balance control, bimanual manipulation, head and arm control that may interfere with established reaching preferences.

Corbetta and Thelen (2002) note that since they did not follow their infants long enough after the onset of walking, they could not study the development of handedness after the acquisition of stable upright walking and confident posture control. However, they hypothesize that the decline of arm coupling will facilitate an increase in infants' lateralized hand-use. This hypothesis is consistent with the results of other studies. For example, Ramsay and Weber (1986) argue that infants do not show a significant increase in lateralization before 17 months of age, while Fagard and Marks (2000) report an increase in lateralized hand-use for role-differentiated bimanual manipulation (when two hands perform different, but complementary movements) consistently between 18 and 36 months. Thus, previous research suggests the dynamic systems approach may be appropriate in describing the interrelation between observed fluctuations in handedness and gross motor development during infancy.

Age as a Marker of Development

A key tenet of dynamic systems theory is that "patterns of change can only be understood as a function of time" (Corbetta, & Thelen, 2002). Consistent with this notion, many researchers try to map different manual skills as a function of time (age). In contrast, Wohlwill (1973) argued that although chronological age is widely used in research literature as a measure and predictor of brain maturation and lateralization, it is only a convenient marker of development; it does not help to explain developmental change. Different components of the physiological structure of an organism develop at different rates which may not correspond to the development of other components.

Moreover, some researchers consider age to be a poor predictor of change in infant development (Wohlwill, 1973; Michel & Moore, 1995). Here is how Bijou and Baer (1963) suggest treating the age variable:

> We expect that little of the changing behavior of a child is produced by the passage of time alone. *Therefore, a developmental analysis is not a relationship of behavior to age, but is a relationship of behavior to events which, requiring time*

> *in order to occur, will necessarily have some correlation with age* (p. 198, italics in the original).

Following this ideas, Touwen (1976) designed a scale of neuromotor development that highlighted important milestones of motor development. Touwen's neuromotor development assessment scale provides an alternative metric to age, because it includes a comprehensive evaluation of developmental change without ascribing age as a mechanism of this change (Touwen, 1976). Touwen suggests evaluation of the infant's posture and motility so that key points of motor development such as rolling over, sitting, crawling, standing and walking onsets are used as markers of development. It has also been proposed that the developmental transitions in neuromotor status, not age, may relate better to the developmental transitions observed in infants' lateralized hand-use (Corbetta & Thelen, 1999). Moreover, Touwen's (1976) evaluation of neuromotor development seems to be better associated with development of the nervous system than age.

Therefore, it can be proposed that the expression of lateralization in readily observed handedness patterns may be better associated with neuromotor development than with age. To test such a theory, researchers would need to explore patterns of handedness development and neuromotor development longitudinally on large samples of infants.

Current Study

Unfortunately, the few studies that examined the influence of gross motor development and postural constraints on handedness development were small sample studies involving 4 to 10 subjects (Corbetta & Bojczyk, 2002: Piek, 2002). The current large-scale (108 subjects) longitudinal study (9 monthly visits from 6 to 14 months) is an attempt to determine different developmental trajectories that boys and girls with and without clear hand-use preference manifest during the first year of life, and to distinguish whether these handedness trajectories can be better related to infant's neuromotor development or infant's age.

The current study will explore the relationship between the development of gross motor skills (sitting, crawling, and walking) and lateralized hand-use development for the acquisition of objects in order to determine whether fluctuations in handedness are associated with the onset of sitting and locomotion.

It is hypothesized that:

1. Developmental trajectory of lateralized hand-use depends on the locomotor status of the infant so that significant fluctuations in lateralization are expected at the onset of sitting, crawling, and walking.
2. Since age is just a marker of developmental change, expression of lateralization in readily observed handedness patterns might be better associated with neuromotor development than with age.

3. The direction and magnitude of change in lateralized hand-use at the onset of sitting, crawling, and walking will depend on the handedness status of the infant (right-hand preference, left-hand preference, no distinct preference).
4. The direction and magnitude of change in lateralized hand-use at the onset of sitting, crawling, and walking depend on gender of the infant.

CHAPTER II

METHOD

Subjects

One hundred eight infants (58 males, 50 females) from full-term pregnancies (at least 37 weeks gestation) and uncomplicated single births were used for the assessment of handedness patterns as well as neuromotor development (otherwise described as the development of certain gross motor skills, see Table 1). The sample is ethnically diverse and representative of the North Carolina population: 53% of Caucasian, 28% of African American, 3% of Hispanic or Latino, 3% of Asian, and 13% of mixed ethnicity. All infants were divided into rolling cohorts of 20 to 40 subjects and tested nine times between 6 and 14 months of age at monthly intervals within +/-7 days from infants' monthly birthdays. Mean age (in months) at the beginning of the study was M = 6.13 (*SD* = 0.15) and at the end of the study M = 14.25 (*SD* = 0.16).

Procedure

Assessment of neuromotor development. For each observation, parents brought their infant to the Infant Development Center at the University of North Carolina at Greensboro where handedness patterns and neuromotor development were assessed. Upon arriving at the center, infants were tested on twelve items from Touwen's (1976)

Group III neurological assessment scale, but only three of them were used in this study: 1) duration of sitting; 2) locomotion in prone position (crawling); 3) walking (for the full description of the three items and their scoring see Table 1).

Table 1

The three items from Touwen's (1976) Group III neurological assessment scale

1. Duration of sitting: Raw scores: 0 – unable to sit without support; 1 – sits free for some seconds; 2 – sits free for 30 seconds; 3 – sits free for 1 minute; 4 – sits free for longer than 1 minute.
2. Locomotion in prone position: Raw scores: 0 – No equivocal change of spatial position; 1 – wriggling or pivoting movements; 2 – abdominal progression using the arms only; 3 – abdominal progression using arms and legs; 5 – creeping on all fours.
3. Walking: Raw scores: 0 – unable to walk; 1 – walks if held by both hands; 2 – walks if held by one hand; 3 – walks few (less than seven) paces; 4 – walks seven or more paces.

Group III items are composed of skills and actions that, in previous research, appeared to have a particular developmental course and showed differences in the rates of development between individuals for this age range. Touwen (1976) reported the first developmental changes on these twelve items starting at 6 months of age and progressing through 14 months of age. In the current study, the patterns and sequence of developmental transitions in these three items were examined in order to define whether infants with different handedness status (right-hand preference, left-hand preference, and no preference) have different patterns of neuromotor development. During the neuromotor assessment, the infant's performance was noted on paper forms filled-out by a researcher at the time of the visit, and then all scores were transferred to a single speadsheet file for subsequent analysis.

Handedness assessment. For the assessment of handedness, infants were seated on their parent's lap (at navel height to the table top) to permit unobstructed movements of infant's arms. The table had a concavity cut from the infant's side to enable it to partially surround the infant and mother. Parents were asked to hold the infant with both hands at the waist level so that the infant could maintain a steady posture. Parents were also asked not to interfere with infant's movements. In the instances of accidental parent's interference, this part of the video was excluded from the coding and analysis.

While infants were seated on their mothers' laps, a valid handedness assessment for prehension (the combination of reaching for, and acquisition of a toy) was administered (Michel, Ovrut, & Harkins, 1986). Assessment of handedness patterns consisted of separate presentations of thirty-four toys: ten double presentations involving two identical toys presented in line with the infant's shoulders (7 pairs of toys presented on the table and 3 pairs in the air), and twenty-four single toys presented in infant's middle line (19 toys presented on the table, and 5 toys presented in the air). The toys selected for the study were brightly colored, produced noise, or included movable parts that facilitated infants' interest and increased the likelihood of acquisitions. By the alternation of double and single presentations as well as air and table presentations researchers ensured that infants were not involved in any kind of biased repetitive response. After about every three presentations, or if the infant's postures became biased because she/he was slightly turned to one side or used one arm or one hand for support, the researcher played for a few seconds with infant's hands, and returned them in position straight with the table to achieve continued activation of both hands and to prevent any biases in reaching and acquisition of toys. This procedure also helped at least limit the influence of habituation in hand-use preferences as a result of repeated reaching with the same hand.

Each toy presentation lasted for about 15 seconds before the toy was removed and the next one was presented. The duration of a complete assessment was, on average, 20-25 minutes. All of the infant's manual actions were videotaped using two digital Panasonic cameras one located overhead and one to the right side of the infant. The cameras were connected to a Videonics mixer which provided the images from both cameras to mix as a split screen video. These recordings were then transferred to a computer having the Noldus Observer© software used for coding videos.

Measures

Neuromotor development. For the analysis of patterns of neuromotor development, we dummy-coded the raw scores obtained from the Touwen's Group III assessment. For the first scale, referring to the sitting status, we coded all raw scores less than four as 0, and the score of four as 1, thus the dummy code 0 is equivalent to "pre-sitting" status, and 1 refers to "post onset of sitting" status. For the second scale referring to the status of crawling, we coded all raw scores which were less than five as 0, and the score of five as 1, thus the dummy code 0 is equivalent to the "pre-crawling" status and 1 refers to attainment of "post crawling" status. For the third scale referring to the status of walking, we coded all raw scores which were less than four as 0, and the score of four as 1, thus the dummy code 0 is equivalent to "pre walking" status and 1 refers to "post onset of walking" status for each infant at each visit.

Hand use preference. For the hand-use preference analysis, the videotapes were coded using Noldus Observer© software which permitted precise millisecond frame-by-frame coding of reaching and manipulation behaviors. Coders viewed all recordings in real time and then in slow motion to define the moment when infant's fingers closed around the edge or a feature of a toy in a grasp-like motion (acquisition). During a single toy presentation, if an infant's two hands acquired a toy within an interval of less than 0.25 sec, we coded this action as bimanual, and otherwise we coded it as unimanual (the hand that acquired the toy first would get coded, but not the other one). During a double toy presentation, if infant's two hands each acquired a toy within an interval of less than 0.25 sec, we coded unimanual acquisition for both hands; otherwise we coded the action as unimanual only for the hand that was faster. Twenty percent of the videos were re-coded by a second coder for an assessment of inter-rater reliability, which reached a mean Cohen's Kappa of 91% (median K 0.91, and range K 0.82 to 0.99). A different twenty percent of the videos were re-coded by the same coder in order to check for the intra-rater reliability which reached a mean Cohen's Kappa of 94% (median K 0.94, and range K 0.88 to 0.99). All coding was done blindly to the predicted hand-preference of infants.

For each infant at each monthly visit, a ratio of number of right acquisitions divided by the sum of right and left acquisitions ((R/(R+L)) across the thirty-four toy presentations were supposed to provide an estimation of the infant's preference for acquisition at that month. The ratio of 0.5 was considered to be a base line of no preference.

We considered using the proportion of right acquisitions over the sum of right and left acquisitions as a continuous variable in our multilevel model, but the exploratory analysis showed that the majority of infants had individual slopes not statistically different from zero. Therefore, after calculating the proportion of right-hand acquisitions for each monthly visit of each infant, we estimated the 95% confidence interval on the proportion of right acquisitions collapsing across all nine visits. If this confidence interval for a particular infant crossed the "no preference" (0.5) base line, the subject was assigned to the "no preference" group. If the confidence interval was completely above the base line, the subject was assigned a "right-hand preference" status. Equivalently, if the confidence interval was completely below the base line, the subject was assigned a “left-hand preference” status. This classification allows separation of infants into three distinguished handedness status groups (right-handers, left-handers, and infants without a pronounced hand use preference) based on our confidence in their hand use over the nine visits. Although this classification tends to ignore the continuous character of handedness development, it was necessary for comparison of neuromotor development in connection with the handedness status. Moreover, the above-mentioned ratios were also used as continuously distributed scores without any categorization for the growth curve analysis performed in order to identify individual patterns in the development of handedness for acquisition.

Furthermore, to follow the change of lateralized hand-use level, we estimated a lateralization index – proportion of bimanual acquisitions to the total number of acquisitions for each visit subtracted from one:

$$\text{Lateralization Index} = 1 - \frac{\text{Both}}{(\text{Right} + \text{Left} + \text{Both})} = \frac{(\text{Right} + \text{Left})}{(\text{Right} + \text{Left} + \text{Both})}$$

In contrast with a handedness status proportion ((R/(R+L)), the lateralization index allows us to observe the change in lateralized hand-use for an infant, but does not have a normative base level for comparison. However, it can be stated that as the lateralization index increases, the lateralized hand-use of an infant also increases. Since in the current study we are particularly interested in the change of lateralized hand-use during continuous development of gross motor skills (sitting, crawling, and walking) during infancy, we will use the lateralization index as an outcome measure in our analysis.

CHAPTER III

RESULTS

Descriptive Statistics

The first analysis was the assessment of attrition rates and missing data in our sample. For each of nine visit/data points, at least 82% of the infants provided data. Attrition rate was very small since none of the infants had more than one visit missing from the nine visits and only two infants failed to show up for the final appointment.

Table 2 shows the description of the sample in terms of gender composition and rates of acquisition of gross motor skills like sitting, crawling and walking. Notice that not all infants acquired walking by the end of the study. Only 85.19% of infants (77.59% among males, and 94% among females) demonstrated walking by the age of 14 months. When only the data from infants who were walking by the end of the study was included into analysis, there were no significant sex differences in the mean ages of acquisition of sitting ($t = -1.015$, $p = 0.313$), crawling ($t = 1.067$, $p = 0.289$), and walking ($t = -1.112$, $p = 0.269$). However, the developmental data for males is somewhat biased since 22.4% of male infants did not start walking (as comparing to 6% of females) by the end of the study. If we try to correct this bias and assume that the onset of walking for all non-walking females and males will be at the age of 15 months, the new estimated mean ages for the onset of walking would be 12.98 and 12.30 months for males and females respectively, and ANOVA table shows that they significantly differ ($t = -2.481$, $p = 0.015$).

Table 2

Descriptive analysis of the development of gross motor skills

Motor Skills	Number of Infants	Minimum age of Skill Acquisition	Maximum age of Skill Acquisition	Mean age of Skill Acquisition	Standard Deviation
MALES					
Sitting	58	6	9	6.90	0.81
Crawling	58	6	13	8.91	1.44
Walking	45	11	-	12.40 *12.98*	1.01 *1.41*
FEMALES					
Sitting	50	6	8	6.70	0.74
Crawling	50	6	14	8.72	1.53
Walking	47	9	-	12.13 *12.30*	1.31 *1.45*
OVERALL					
Sitting	108	6	9	6.81	0.78
Crawling	108	6	14	8.82	1.53
Walking	92	9	-	12.26	1.18

Analysis of the simple correlations among the onset of sitting, crawling, and walking revealed a significant correlation between the onset of sitting and crawling ($r = 0.368$, $p < 0.01$), a significant correlation between sitting and walking ($r = 0.411$, $p < 0.01$), and a significant correlation between the onset of crawling and walking ($r = 0.557$,

$p < 0.01$). All correlations were estimated for the corrected data assuming that all not-walking infants started walking at the age of 15 months. Thus, the estimation of effects in our model might be biased because variables representing gross motor skills are not independent.

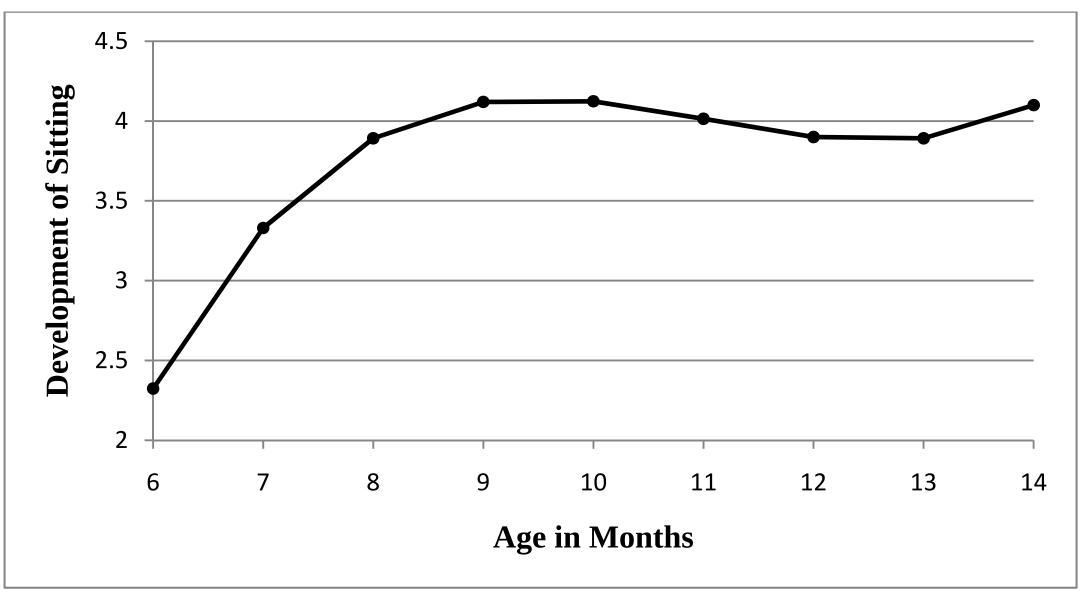
Although in our multilevel analysis the index of lateralized hand-use is a dependent variable while the onset of sitting, crawling and walking, along with age, gender and handedness status, were independent variables, for the purpose of the current exploratory analysis it is interesting to examine the development of locomotion as a dependent variable. Based on the literature review, we might expect that the rates of locomotor development might be different for infants from different handedness groups as well as for males and females.

The development of sitting. We used the continuous scale of sitting (presented in table 1) as a dependent variable, and orthogonal age (up to the third power) and the handedness status as independent variables. Because the longitudinal assessments were time-structured, and for the purposes of reducing multicollinearity among the higher-order time terms, we coded infants' age using orthogonal polynomials (Kleinbaum, Kupper, Nizam & Muller, 2008). An exploratory analysis of time effects using the orthogonal polynomials suggested that the change in locomotion was adequately captured by cubic polynomial of time ($F(1, 88) = 33.92$, $p = 0.000$ for a linear trend; $F(1, 88) = 16.96$, $p = 0.000$ for a quadratic trend; and $F(1, 88) = 16.11$, $p = 0.000$ for a cubic trend). Thus, we decided to include in our model three time variables representing orthogonal polynomials for linear, quadratic and cubic age (in the exploratory analysis addressed as Age, Age^2, and Age^3). The handedness group affiliation was dummy-coded and represented by two variables since we had three levels of this variable. Infants with a right-hand preference were chosen as a reference group. The regression showed no significant effect of handedness status and no interactions between age and handedness status. The resulting reduced model included only age as an independent variable: (β_0 = 3.744; β_1 = 0.145; β_2 = -0.019; β_3 = 0.022):

$$\text{Sitting} = \beta_0 + \beta_1 * \text{Age} + \beta_2 * \text{Age}^2 + \beta_3 * \text{Age}^3$$

This model is graphically represented in figure 1.

Figure 1. The predicted development of sitting collapsing across three handedness groups and two sexes ("development of sitting" represents the continuous scale of sitting shown in table 1)



According to the ANOVA table, an effect of age was highly significant: linear age (t = 16.73, p = 0.000), quadratic age (t = -15.16, p = 0.000), cubic age (t = 10.12, p = 0.000). However, the effect of handedness status was not statistically significant: the first handedness status variable HP1 comparing right-hand preference group to the left-hand preference group (t = 0.69, p = 0.49), and the second handedness status variable HP2 comparing right-hand preference group to no-preference group (t = 0.11, p = 0.91). The final model accounts for 39% of the observed variability (R^2). Moreover, when the relation of sitting development across time was explored controlling for gender, no significant effects were found for the latter.

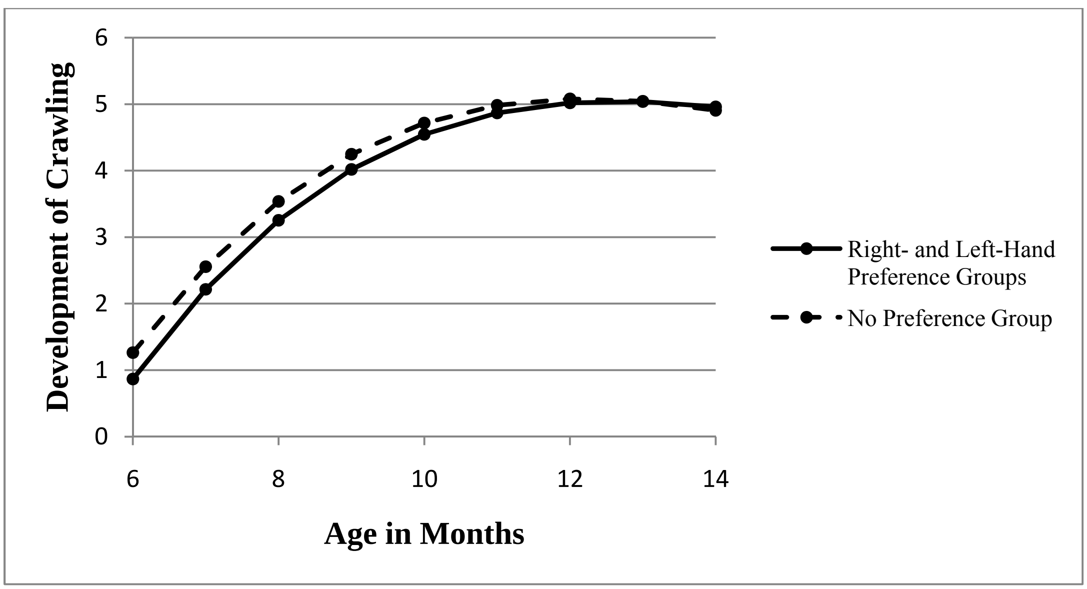
The development of crawling. We used the continuous scale of crawling (presented in table 1) as a dependent variable, and orthogonal age (up to the third power) and the handedness group as independent variables. The final reduced model is presented below (β_0 = 3.865; β_1 = 0.487; β_2 = -0.034; β_3 = 0.007; β_4 = 0.172; β_5 = -0.056):

$$\text{Crawling} = \beta_0 + \beta_1 * \text{Age} + \beta_2 * \text{Age}^2 + \beta_3 * \text{Age}^3 + \beta_4 * \text{HP2} + \beta_5 * \text{Age} * \text{HP2}$$

This model is graphically presented in figure 2.

According to the ANOVA table, an effect of age was highly significant: linear age (t = 29.49, p = 0.000), quadratic age (t = -19.09, p = 0.000), cubic age (t = 2.23, p = 0.026). Moreover, the effect of handedness status was statistically significant, but only for the second handedness status variable HP2 (t = 2.75, p = 0.006). Since HP1 was not significant, we might conclude that the development of crawling did not significantly differ between right-hand preference group and left-hand preference group. In this case, we can collapse right- and left-handers into one group, and then the HP2 variable would describe differences between infants with no distinct hand preference and infants with a hand preference (right or left).

Figure 2. The predicted development of crawling in groups of infants with a different handedness status collapsing across two sexes ("development of crawling" represents the continuous scale of crawling shown in table 1)



The slope of the HP2 variable $\beta_4 = 0.172$ means that across time, infants without a distinct hand preference have a slightly larger intercept than infants with a hand-use preference, or, in other words, their score on the crawling scale is 0.172 points larger at the age of 6 months. However, we also found a significant interaction between linear age and HP2 variables ($t = -2.28$, $p = 0.023$), and the slope $\beta_5 = -0.056$ means that with each month the no preference group will become closer and closer to infants with distinct handedness. This makes sense since by the age of 14 months all of normally developing infants have acquired crawling skills irrespective of their handedness status. The final model accounted for 66% of the observed variability (R^2). Again, when the relation of crawling development across time was explored controlling for gender, no significant effects were found for the latter.

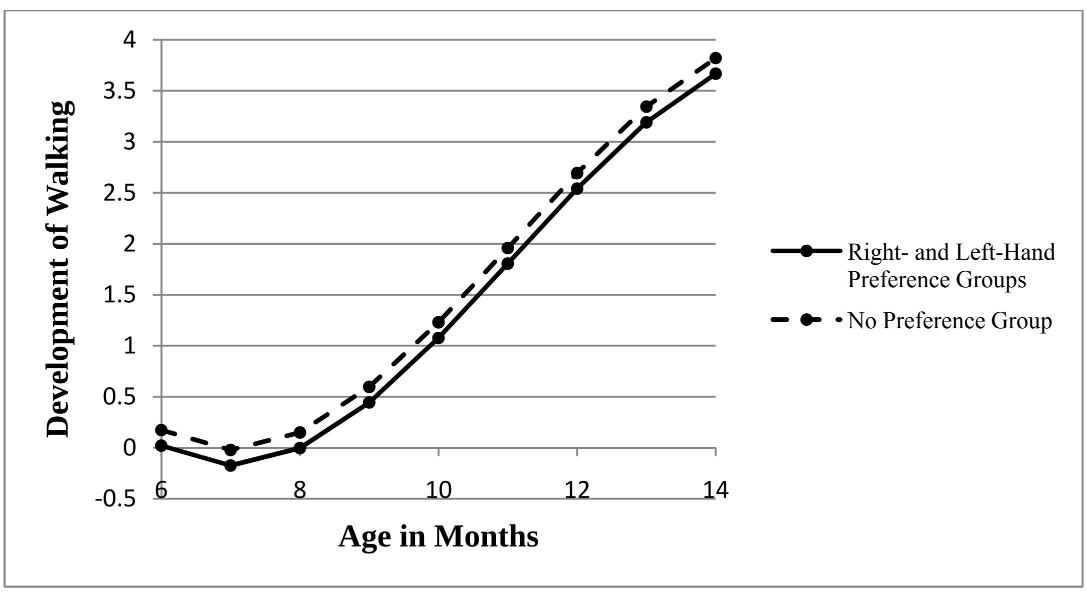
The development of walking. The continuous scale of walking (presented in table 1) was used as a dependent variable while orthogonal age (up to the third power) and the handedness group represented independent variables. The final reduced model is presented below ($\beta_0 = 1.396$; $\beta_1 = 0.519$; $\beta_2 = 0.016$; $\beta_3 = -0.018$; $\beta_4 = 0.153$):

$$\text{Walking} = \beta_0 + \beta_1 * \text{Age} + \beta_2 * \text{Age}^2 + \beta_3 * \text{Age}^3 + \beta_4 * \text{HP2}$$

This model is graphically presented in figure 3.

According to the ANOVA table, an effect of age was highly significant: linear age ($t = 43.53$, $p = 0.000$), quadratic age ($t = 9.36$, $p = 0.000$), cubic age ($t = -6.03$, $p = 0.000$). Moreover, the effect of handedness status was statistically significant, but only for the second handedness status variable HP2 ($t = 2.49$, $p = 0.013$). Since HP1 was not significant, we might conclude, as we did in the analysis of the development of crawling, that the development of walking did not significantly differ between right-hand preference group and left-hand preference group. In this case, we can collapse right- and left-handers into one group, and then the HP2 variable would describe differences between infants with no distinct hand preference and infants with a hand preference (right or left). The slope of the HP2 variable $\beta_4 = 0.153$ means that infants without a distinct hand preference have a slightly larger intercept than infants with a hand-use preference, or, in other words, their score on the walking scale is 0.153 points larger at the age of 6 months. No significant interactions between age and handedness status were found. The final model accounts for 68% of the observed variability (R^2).

Figure 3. The predicted development of walking in groups of infants with a different handedness status collapsing across two sexes ("development of walking" represents the continuous scale of walking shown in table 1)



Furthermore, the development of walking skills with age was explored controlling for gender. The effect of gender was found to be statistically significant. The final reduced model is presented below (β_0 = 1.335; β_1 = 0.493; β_2 = 0.016; β_3 = -0.018; β_4 = 0.285; β_5 = 0.055):

$$\text{Walking} = \beta_0 + \beta_1 * \text{Age} + \beta_2 * \text{Age}^2 + \beta_3 * \text{Age}^3 + \beta_4 * \text{Sex} + \beta_5 * \text{Age} * \text{Sex}$$

This model is graphically presented in figure 4.

Figure 4. The development of walking in males and females collapsing across the three handedness groups ("development of walking" represents the continuous scale of walking shown in table 1)

According to the ANOVA table, an effect of age was highly significant: linear age ($t = 30.64$, $p = 0.000$), quadratic age ($t = 9.40$, $p = 0.000$), cubic age ($t = -6.09$, $p = 0.000$). Moreover, the effect of gender was statistically significant ($t = 4.69$, $p = 0.000$). The slope of the sex variable $\beta_4 = 0.285$ might be interpreted as females having a slightly larger intercept than males at the age of 6 months. Moreover, a significant interaction between linear age and gender was found ($t = 2.32$, $p = 0.021$). The slope of the interaction term $\beta_5 = 0.055$ means that with time females become even more skillful in walking than males. The final model accounts for 69% of the observed variability (R^2).

In summary, exploring the development of gross motor skills, we found that the rates of the development of crawling and walking differ significantly between infants with and without hand-use preference with the latter group developing locomotion faster, and between sexes with females acquiring walking skills faster. Although this difference in the development of locomotion is very interesting, we need to look at the distribution of males and females in groups with different hand preference status since if we find any skew in those distributions, it might introduce a bias in our evaluation. Table 3 reveals that while the number of males and females is equal in the left-hand preference group they appear to be considerably different in the group of infants without hand preference, and in the group of right-handers.

A two-way contingency table analysis using crosstabs resulting in χ^2 (2, N = 108) = 4.234, $p = 0.12$ revealed that our three handedness groups are not significantly different from each other in gender distribution.

Table 3

Distribution of males and females in groups with different hand preference status

Gender	No Hand Preference Group	Right-Hand Preference Group	Left-Hand Preference Group
Male	22	31	5
Female	28	17	5

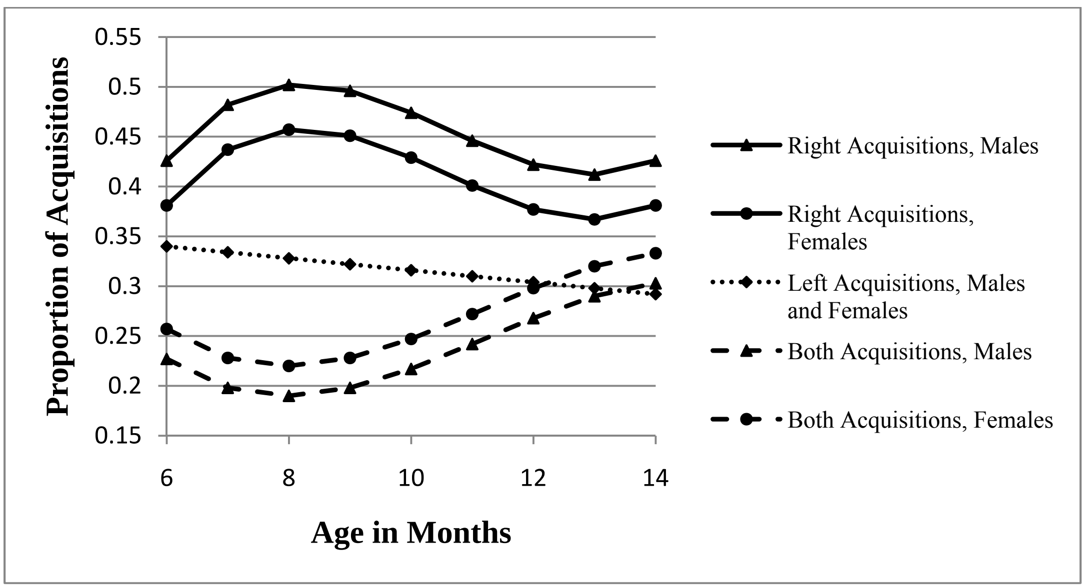
Moreover, additional analyses were performed to estimate whether proportions of males and females in right-hand preference group and no hand preference group are significantly different from 50%. Binomial test showed that with $p = 0.48$ the null hypothesis of equal proportion of males and females in right-hand preference group cannot be rejected. Moreover, bimanual test for infants without hand preference resulted in $p = 0.059$, which suggests not to reject the null hypothesis about equal proportion of males and females at $p = 0.05$ level, but reject it at $p = 0.1$ level. Thus, the proportion of males is not statistically different from the proportion of females for right-handed infants and infants without a hand preference at the $p = 0.05$ level.

To explore the development of lateralization in our sample, we first plotted the predicted proportions of right-hand, left-hand, and both-hand acquisitions in our sample collapsing the three handedness groups, but controlling for gender (figure 5).

As we see in figure 5, the effect of gender was found to be statistically significant only in the change of the proportion of right-hand acquisitions and both-hand acquisitions. The final reduced model for the proportion of right-hand acquisitions is presented below (β_0 = 0.454; β_1 = -0.007; β_2 = -0.001; β_3 = 0.002; β_4 = -0.045):

$$\text{Proportion of Right} = \beta_0 + \beta_1 * \text{Age} + \beta_2 * \text{Age}^2 + \beta_3 * \text{Age}^3 + \beta_4 * \text{Sex}$$

Figure 5. The predicted change in average proportions of right-hand, left-hand, and both-hand acquisitions with age separately for males and females, but collapsing across different handedness groups



According to the ANOVA table, an effect of age was statistically significant: linear age ($t = -3.005$, $p = 0.003$), quadratic age ($t = -2.241$, $p = 0.025$), cubic age ($t = 2.635$, $p = 0.009$). Moreover, the effect of gender was highly significant ($t = -3.565$, $p = 0.000$). The slope of the sex variable $\beta_4 = -0.045$ might be interpreted as females having lower proportion of right-hand acquisitions across age. The final model accounts for

3.5% of the observed variability (R^2).

The final reduced model for the proportion of left-hand acquisitions is presented below ($\beta_0 = 0.316$; $\beta_1 = -0.006$):

$$\text{Proportion of Left} = \beta_0 + \beta_1 * \text{Age}$$

According to the ANOVA table, only the effect of linear age was statistically significant ($t = -2.718$, $p = 0.007$). The effect of gender was not significant. The final model accounts for 0.8% of the observed variability (R^2).

The final reduced model for the proportion of both-hand acquisitions is presented below ($\beta_0 = 0.237$; $\beta_1 = 0.013$; $\beta_2 = 0.001$; $\beta_3 = -0.001$; $\beta_4 = 0.03$):

$$\text{Proportion of Both} = \beta_0 + \beta_1 * \text{Age} + \beta_2 * \text{Age}^2 + \beta_3 * \text{Age}^3 + \beta_4 * \text{Sex}$$

According to the ANOVA table, an effect of age was statistically significant: linear age ($t = 7.589$, $p = 0.000$), quadratic age ($t = 4.448$, $p = 0.000$), cubic age ($t = -3.473$, $p = 0.001$). Moreover, the effect of gender was highly significant ($t = 3.368$, $p = 0.001$). The slope of the sex variable $\beta_4 = 0.03$ might be interpreted as females having slightly higher proportion of both-hand acquisitions or, in other words, being less lateralized across age. The final model accounts for 9.7% of the observed variability (R^2).

Thus, the analysis of the change in the proportions of right-hand, left-hand and both-hand acquisitions shows that on average (in our sample) females are more likely to use both hands for acquiring objects across age; they have a lower proportion of right-hand acquisitions, and higher proportion of the both-hand acquisitions than males.

Moreover, figure 5 appears to show that the proportion of right-hand acquisitions is almost complementary to the proportion of both-hand acquisitions, while the proportion of left-hand acquisitions only slightly declines with time. In this case, observed lateralized hand-use decreases with the decrease in the proportion of right-hand acquisitions (not left) and an increase in bimanual acquisitions.

Figure 5 showed the average change in proportions of right-hand, left-hand, and both-hand acquisitions across age separately for males and females, but collapsing across different handedness groups. However, we might want to look at the distribution of hand-preference status in our sample where infants with no hand preference represent 46.30% of our sample (50 infants), while right-handed infants contribute another 44.44% (48 infants), and the remaining 9.26% are infants with left-handed status (10 infants). Since right-handers and infants without a stable hand preference dominate the sample, collapsing across handedness groups can create a biased perspective of the data. If we plot the average change in proportions of right-hand, left-hand, and both-hand acquisitions with age separately for all three handedness groups controlling for gender, we might obtain a more robust and adequate picture (figures 6, 7, 8).

The final reduced model for the proportion of right-hand acquisitions in the right-hand preference group is presented below ($\beta_0 = 0.516$; $\beta_1 = -0.011$; $\beta_2 = -0.001$):

$$\text{Proportion of Right} = \beta_0 + \beta_1 * \text{Age} + \beta_2 * \text{Age}^2$$

According to the ANOVA table, an effect of age was statistically significant: linear age ($t = -3.254$, $p = 0.001$), quadratic age ($t = -2.867$, $p = 0.004$). The slope of the cubic trajectory of age was not significant as well as a slope of the sex variable. The final model accounts for 4.2% of the observed variability (R^2).

In the trajectory of the proportion of left-hand acquisitions in the right-hand preference group, the effects of age and sex were not significant. According to the ANOVA table, the intercept is $\beta_0 = 0.237$. The final model accounts for 0.4% of the observed variability (R^2).

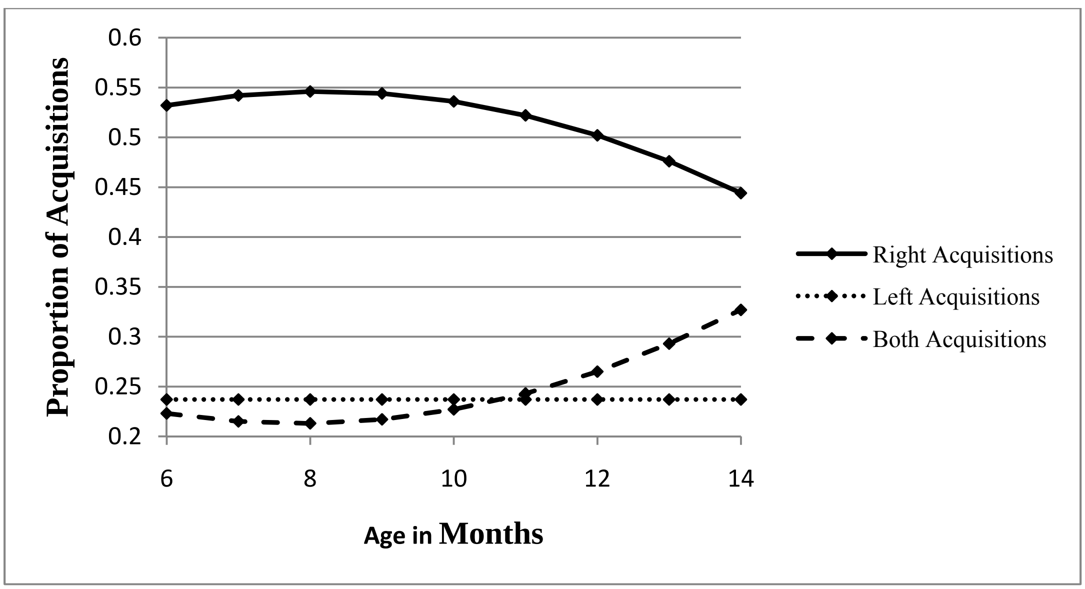
The final reduced model for the proportion of both-hand acquisitions in the right-hand preference group is presented below ($\beta_0 = 0.247$; $\beta_1 = 0.013$; $\beta_2 = 0.001$):

$$\text{Proportion of Both} = \beta_0 + \beta_1 * \text{Age} + \beta_2 * \text{Age}^2$$

According to the ANOVA table, an effect of age was statistically significant: linear age ($t = 4.702$, $p = 0.000$), quadratic age ($t = 3.081$, $p = 0.002$). The slopes of the cubic age and the sex variable were not significant. The final model accounts for 6.9% of the observed variability (R^2). All three afore-mentioned models are presented simultaneously in figure 6.

In summary, figure 6 reveals that an average right-handed infant acquires toys considerably more frequently with her right hand (45 to 55% of acquisitions), while using her left hand only about 20-25% of the time. Interestingly, the proportion of acquisitions by the preferred hand changes over time (having a quadratic trend) with the pick of the maximum lateralization in this group at 9 months, and minimum lateralization at the age of 14 months. However, the proportion of acquisitions with a non-preferred hand (left in this case) does not change significantly with time. Thus, in the group of right-handed infants, the proportion of both-hand acquisitions is completely complementary to the proportion of the right-hand acquisitions. Moreover, in this group, males do not differ from females in terms of their proportions of right-, left-, and both-hand acquisitions.

Figure 6. The predicted change in the average proportion of right-hand, left-hand, and both-hand acquisitions with age in infants with the right-hand preference

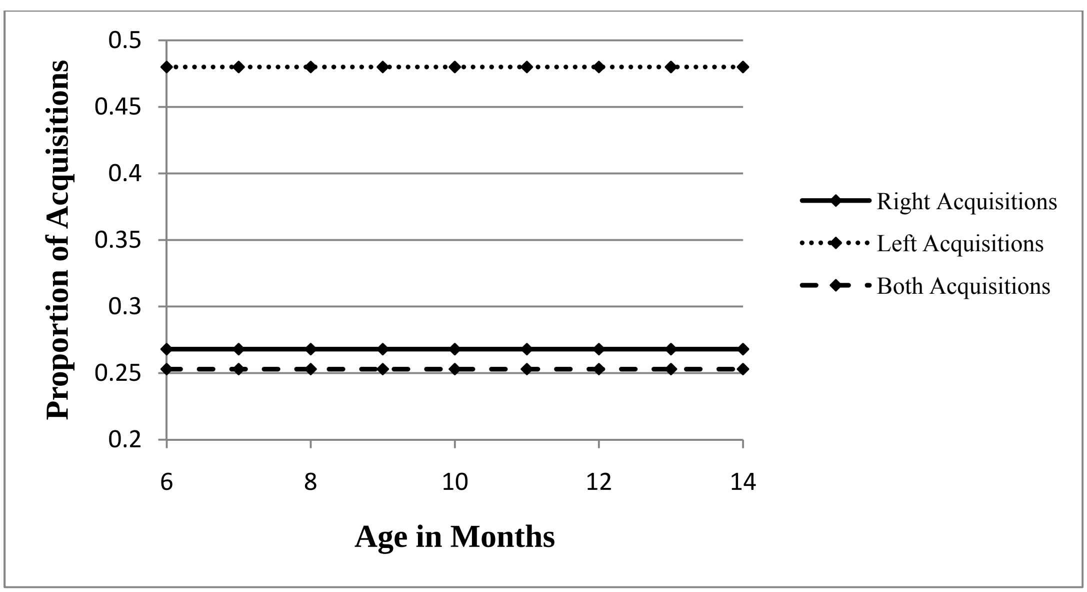


In the trajectory of the proportion of right-hand acquisitions in the left-hand preference group, the effects of age and sex were not statistically significant. According to the ANOVA table, the intercept is $\beta_0 = 0.268$. The final model accounts for 2.3% of the observed variability (R^2).

In the trajectory of the proportion of left-hand acquisitions in the left-hand preference group, the effects of age and sex were not statistically significant. According to the ANOVA table, the intercept is $\beta_0 = 0.48$. The final model accounts for 2.4% of the observed variability (R^2).

In the trajectory of the proportion of both-hand acquisitions in the left-hand preference group, the effects of age and sex were not statistically significant. According to the ANOVA table, the intercept is $\beta_0 = 0.253$. The final model accounts for 2.8% of the observed variability (R^2). All three afore-mentioned models are presented in figure 7.

Figure 7. The predicted change in the average proportion of right-hand, left-hand, and both-hand acquisitions with age in infants with the left-hand preference



Thus, figure 7 shows the average change in the proportion of right-hand, left-hand, and both-hand acquisitions with age in infants with the left-hand preference. We can observe that although the proportion of left-hand acquisitions (45-50%) is considerably higher than the average proportion of right-hand acquisitions (25-30%), both proportions do not significantly change over time. Moreover, in the group of left-handed infants, males do not differ from females in terms of their proportions of right-, left-, and both-hand acquisitions.

The final reduced model for the proportion of right-hand acquisitions in infants without hand preference is presented below ($\beta_0 = 0.387$; $\beta_1 = -0.004$; $\beta_2 = -0.001$; $\beta_3 = 0.002$):

$$\text{Proportion of Right} = \beta_0 + \beta_1 * \text{Age} + \beta_2 * \text{Age}^2 + \beta_3 * \text{Age}^3$$

According to the ANOVA table, effects of linear and quadratic age were not statistically significant: linear age ($t = -1.118$, $p = 0.264$), quadratic age ($t = -1.122$, $p = 0.262$), however the effect of cubic age is significant ($t = 2.217$, $p = 0.027$). Since the significant effect of cubic age explains variability in our data above and beyond the portions of variability explained by linear and quadratic age, linear and quadratic terms should be included in the model. The final model accounts for 1.7% of the observed variability (R^2).

The final reduced model for the proportion of left-hand acquisitions in infants without hand preference is presented below ($\beta_0 = 0.36$; $\beta_1 = -0.011$):

$$\text{Proportion of Left} = \beta_0 + \beta_1 * \text{Age}$$

According to the ANOVA table, only the effect of linear age was statistically significant: linear age ($t = -3.57$, $p = 0.000$). The final model accounts for 2.8% of the observed variability (R^2).

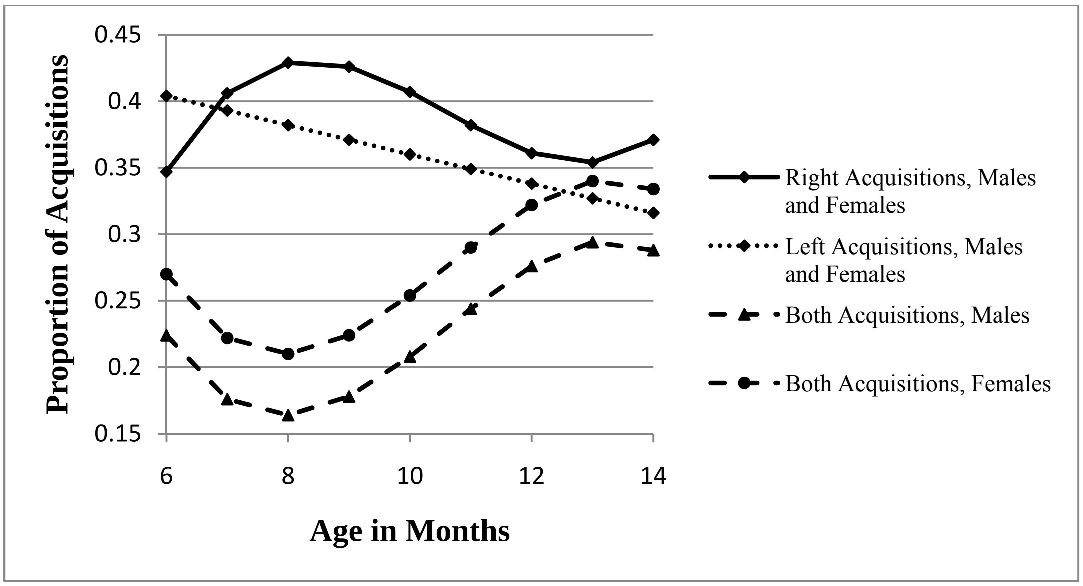
The final reduced model for the proportion of both-hand acquisitions in infants without hand preference is presented below ($\beta_0 = 0.228$; $\beta_1 = 0.015$; $\beta_2 = 0.001$; $\beta_3 = -0.002$; $\beta_4 = 0.046$):

$$\text{Proportion of Both} = \beta_0 + \beta_1 * \text{Age} + \beta_2 * \text{Age}^2 + \beta_3 * \text{Age}^3 + \beta_4 * \text{Sex}$$

According to the ANOVA table, an effect of age was statistically significant: linear age ($t = 6.046$, $p = 0.000$), quadratic age ($t = 3.284$, $p = 0.001$), cubic ($t = -3.429$, $p = 0.001$). Moreover, the effect of gender was also highly significant ($t = 3.704$, $p = 0.000$). The final model accounts for 14.6% of the observed variability (R^2). All three afore-mentioned models are presented simultaneously in figure 8.

In summary, figure 8 shows that infants that we earlier categorized as having no hand preference have similar proportions of right (35-43%) and left (32-41%) acquisitions, however, while the proportion of right-hand acquisitions has a cubic trend of developmental change and decreases starting at age 9 months, the proportion of left-hand acquisitions decreases all the way from 6 to 14 month having a linear developmental trend. The proportion of both-hand acquisitions has a cubic trend, and reaches its minimum at the age about 8 months, and then increased up to 14 months. Interestingly, males have similar developmental trend in the change of bimanual reaches as females; however, they are more lateralized than females across all ages.

Figure 8. The predicted change in the average proportion of right-hand, left-hand, and both-hand acquisitions with age in infants without stable hand preference controlling for gender



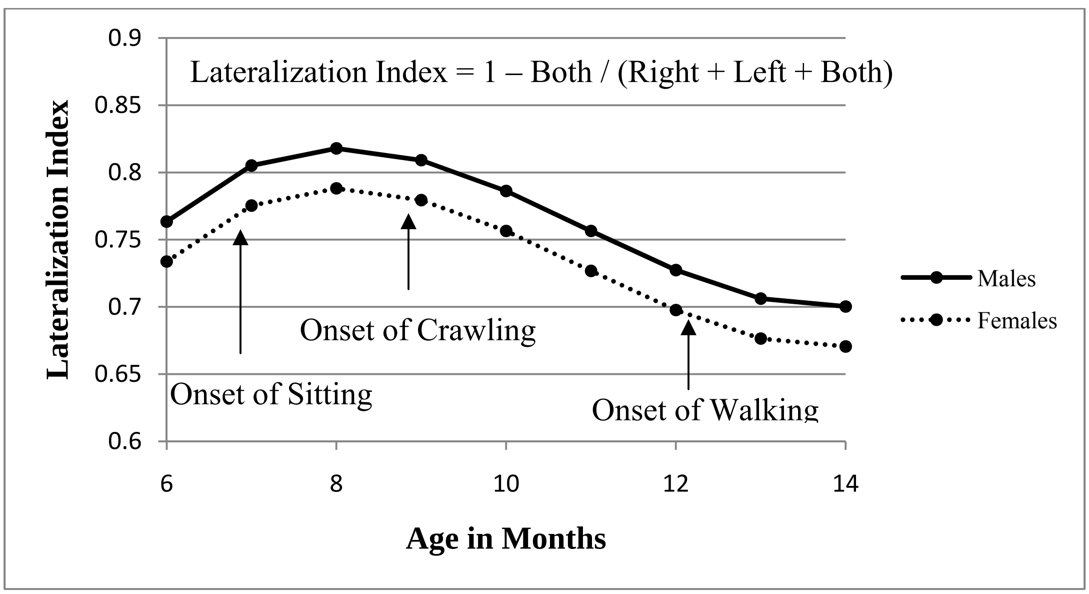
In order to better understand the shape of the lateralization trajectory, the predicted change in the development of lateralization in our sample was plotted collapsing across the three handedness groups, but controlling for sex (figure 9). The final reduced model for the change in lateralized hand-use is presented below ($\beta_0 = 0.764$; $\beta_1 = -0.013$; $\beta_2 = -0.001$; $\beta_3 = 0.001$; $\beta_4 = -0.03$):

$$\text{Lateralization Index} = \beta_0 + \beta_1 * \text{Age} + \beta_2 * \text{Age}^2 + \beta_3 * \text{Age}^3 + \beta_4 * \text{Sex}$$

According to the ANOVA table, an effect of age was statistically significant: linear age ($t = -7.577$, $p = 0.000$), quadratic age ($t = -4.470$, $p = 0.000$), cubic age ($t =$

3.475, p = 0.001). Moreover, the effect of gender was highly significant (t = -3.343, p = 0.001). The slope of the sex variable $\beta_4 = -0.03$ might be interpreted as females having slightly lower lateralized hand-use across time. The final model accounts for 9.7% of the observed variability (R^2).

Figure 9. The predicted development of lateralization in our sample collapsing across the three handedness groups controlling for gender



Interestingly, the analysis showed that the development of lateralization has a cubic trend over time with lateralization increasing on the interval between 8 to 9 months and decreasing between 12 and 14 months. From the average onset of sitting, crawling and walking in our sample (presented in table 2 and marked on figure 6), we can suspect that the increase in lateralization coincides with the onset of sitting and crawling while the decrease in handedness coincides with the onset of walking. Thus, visual exploration of the predicted trend in the change of lateralized hand-use suggests that our data might support the results of previous research about the relationship between the onset of crawling and increase in lateralized hand-use, and decrease in handedness after the onset of walking.

Multilevel Model of Change in Lateralized Hand-Use

Individual growth modeling was used to analyze our longitudinal data for the change in lateralized hand-use in infancy. Our dependent variable, LATERALIZATION, was calculated for each data point (each observation) for each infant by using the proportion of both-hand acquisitions subtracted from 1. Increases in this measure represent increases in lateralized hand-use, whereas decreases in this measure represent decreases in lateralized hand use.

In the current study, all multilevel analyses were conducted using HLM program. Multilevel models of change allow the simultaneous analyses of different research questions: 1) Level 1 describes within-person variability in the sample and focuses on the individual change over time in the lateralized hand-use; and 2) Level 2 describes between-person portion of variability and addresses question of how individual changes in lateralization vary across infants, and how grouping variables such as sex and hand-use preference can add to the explanation of this change (Singer & Willett, 2003).

Initial exploratory analysis of individual growth curves for each of one hundred eight infants indicated variations in the rates of change as well as functional forms for individual trajectories suggesting strong non-linear components of change. As in the exploratory analysis, we coded infants' age using orthogonal polynomials (Kleinbaum, Kupper, Nizam & Muller, 2008). An exploratory analysis of time effects using the orthogonal polynomials suggested that the change in lateralized hand-use was adequately captured by cubic polynomial of time ($F(1, 88) = 33.92$, $p = 0.000$ for a linear trend; $F(1, 88) = 16.96$, $p = 0.000$ for a quadratic trend; and $F(1, 88) = 16.11$, $p = 0.000$ for a cubic trend) with about 90% of subjects having very high fitting R^2 values of more than 0.87. Thus, we decided to include in our multilevel model three time variables representing orthogonal polynomials for linear, quadratic and cubic age (ORT_AGE, $(\text{ORT\_AGE})^2$, and $(\text{ORT\_AGE})^3$).

Moreover, we included in the final multilevel model three time-varying predictors defining gross motor development in infancy: the dummy-coded variables SIT, CRW and WLK representing the onset of sitting, crawling and walking respectively for each infant. Thus, our final multilevel model has six variables representing change over time on the within-person level. On the between-person level, to explain variability between infants, we included dummy-coded sex variable SEX, dummy-coded handedness preference variable HP representing differences between infants with a right-hand preference, left-hand preference, and without distinct hand preference. Since we have three levels of HP, we end up with two dummy-coded variables: the first handedness variable HP1 comparing right-hand preference group to the left-hand preference group, and the second handedness variable HP2 comparing right-hand preference group to no-preference group (infants with a right-hand preference were chosen as a reference group). The interactions between SEX and hand preference (HP1 and HP2) variables were included to explore whether change in the lateralized hand-use for each of hand-preference groups depends on the level of the SEX variable.

Model 1: unconditional means model. We started our analysis with the unconditional means model (Singer & Willett, 2003).

Level 1 model:

$$\text{LATERALIZATION}_{ij} = \pi_{0i} + \varepsilon_{ij}$$

Level 2 model:

$$\pi_{0i} = \beta_{00} + \delta_{0i}$$

In Model 1, $\text{LATERALIZATION}_{ij}$ represents the proportion of both hands acquisitions over the total number of acquisitions subtracted from 1 for child *i* at time *j*. The residual ε_{ij} represents the portion of infant *i*'s lateralization that is unpredicted at time *j*. Estimated fixed and random effects for the Model 1 are presented in table 4.

Interclass correlation for the unconditional means model was equal to 0.2858, suggesting that 28.58% of total variability is attributable to differences between individuals, and 71.42% is attributable to within-subjects factors.

Model 2: unconditional growth model. We proceeded by fitting an unconditional growth model including the three time variables in level 1 model along with random effects.

Level 1 model:

$$LATERALIZATION_{ij} = \pi_{0i} + \pi_{1i}*(ORT\_AGE)_{ij} + \pi_{2i}*(ORT\_AGE)^2_{ij} + \pi_{3i}*(ORT\_AGE)^3_{ij} + \varepsilon_{ij}$$

Level 2 models:

$$\pi_{0i} = \beta_{00} + \delta_{0i}$$

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

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

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

Estimated fixed and random effects for the Model 2 are presented in table 4. Each of the time effects is significant alone with the variance components for the intercept, linear, and quadratic change suggesting that all three age variables are needed to describe change in lateralized hand-use. Moreover, we can state that infants are heterogeneous in their intercepts, as well as in linear, quadratic, and cubic components of change since random effects were statistically significant. The proportional reduction in variance in level 1 of the model with the transition from model 1 to model 2 was estimated to be equal to 0.3643, which means that addition of age variables to the unconditional means model allows us to explain additional 36.43% of level 1 variability (linear age contributes 22.27%, quadratic age adds another 7.52%, and cubic age adds 6.64%).

Model 3: full level 1 model. With the next step, we added the three time-varying variables in level 1 model (Singer & Willett, 2003). The data did not support inclusion of random effect for those gross motor development variables (the algorithm did not numerically converge), thus the random effects associated with the time-varying variables were dropped from the model.

Level 1 model:

$$LATERALIZATION_{ij} = \pi_{0i} + \pi_{1i}*(ORT\_AGE)_{ij} + \pi_{2i}*(ORT\_AGE)^2_{ij} + \pi_{3i}*(ORT\_AGE)^3_{ij} + \pi_{4i}*SIT_{ij} + \pi_{5i}*CRW_{ij} + \pi_{6i}*WLK_{ij} + \varepsilon_{ij}$$

Level 2 models:

$$\pi_{0i} = \beta_{00} + \delta_{0i}$$

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

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

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

$$\pi_{4i} = \beta_{40}$$

$$\pi_{5i} = \beta_{50}$$

$$\pi_{6i} = \beta_{60}$$

Estimated fixed and random effects for the Model 3 are presented in table 4. The analysis of model 3 suggests that the effects of the onset of sitting and crawling variables are not significant. However, in order to address possible interactions between level 1 and level 2 variables in the model, all variables representing the development of gross motor skills were retained in the model for additional testing. The proportional reduction in variance in level 1 of the model with the transition from model 2 to model 3 was estimated to be equal to 0.0032, which means that addition of gross motor development variables to the unconditional growth model allows us to explain additional 0.32% of level 1 variability. Interestingly, if the variables representing gross motor development are included in the model first, their addition to the unconditional means model allows us to explain additional 26.13% of level 1 variability. Thus, the variables representing gross motor development are important, but their potency to explain within-subject variability is masked by age variables (and the fact that the age variable correlates with the onset of sitting, crawling, and walking).

Model 4: full level 1 and level 2 model. At this step, all level 1 and level 2 fixed effects are present in the model along with all necessary random effects (Singer & Willett, 2003).

Level 1 model:

$$LATERALIZATION_{ij} = \pi_{0i} + \pi_{1i}*(ORT\_AGE)_{ij} + \pi_{2i}*(ORT\_AGE)^2_{ij} + \pi_{3i}*(ORT\_AGE)^3_{ij} + \pi_{4i}*SIT_{ij} + \pi_{5i}*CRW_{ij} + \pi_{6i}*WLK_{ij} + \varepsilon_{ij}$$

Level 2 models:

$$\pi_{0i} = \beta_{00} + \beta_{01}*SEX_i + \beta_{02}*HP1_i + \beta_{03}*HP2_i + \beta_{04}*SEX*HP1_i + \beta_{05}*SEX*HP2_i + \delta_{0i}$$

$$\pi_{1i} = \beta_{10} + \beta_{11}*SEX_i + \beta_{12}*HP1_i + \beta_{13}*HP2_i + \beta_{14}*SEX*HP1_i + \beta_{15}*SEX*HP2_i + \delta_{1i}$$

$$\pi_{2i} = \beta_{20} + \beta_{21}*SEX_i + \beta_{22}*HP1_i + \beta_{23}*HP2_i + \beta_{24}*SEX*HP1_i + \beta_{25}*SEX*HP2_i + \delta_{2i}$$

$$\pi_{3i} = \beta_{30} + \beta_{31}*SEX_i + \beta_{32}*HP1_i + \beta_{33}*HP2_i + \beta_{34}*SEX*HP1_i + \beta_{35}*SEX*HP2_i + \delta_{3i}$$

$$\pi_{4i} = \beta_{40} + \beta_{41}*SEX_i + \beta_{42}*HP1_i + \beta_{43}*HP2_i + \beta_{44}*SEX*HP1_i + \beta_{45}*SEX*HP2_i$$

$$\pi_{5i} = \beta_{50} + \beta_{51}*SEX_i + \beta_{52}*HP1_i + \beta_{53}*HP2_i + \beta_{54}*SEX*HP1_i + \beta_{55}*SEX*HP2_i$$

$$\pi_{6i} = \beta_{60} + \beta_{61}*SEX_i + \beta_{62}*HP1_i + \beta_{63}*HP2_i + \beta_{64}*SEX*HP1_i + \beta_{65}*SEX*HP2_i$$

Estimated fixed and random effects for the Model 4 are presented in table 4.

Model 5: final reduced model. Taking a full multilevel model as a starting point, a model comparison framework was used to reduce the fixed effects in the model, beginning with higher order interactions and working down to lower order interactions and main effects (Appelbaum & Cramer, 1974; Cramer & Appelbaum, 1980).

Level 1 model:

$$LATERALIZATION_{ij} = \pi_{0i} + \pi_{1i}*(ORT\_AGE)_{ij} + \pi_{2i}*(ORT\_AGE)^2_{ij} + \pi_{3i}*(ORT\_AGE)^3_{ij} + \pi_{6i}*WLK_{ij} + \varepsilon_{ij}$$

Level 2 models:

$$\pi_{0i} = \beta_{00} + \beta_{01}*SEX_i + \beta_{02}*HP1_i + \beta_{04}*SEX*HP1_i + \delta_{0i}$$

$$\pi_{1i} = \beta_{10} + \beta_{11}*SEX_i + \beta_{12}*HP1_i + \beta_{14}*SEX*HP1_i + \delta_{1i}$$

$$\pi_{2i} = \beta_{20} + \beta_{21}*SEX_i + \beta_{22}*HP1_i + \beta_{24}*SEX*HP1_i + \delta_{2i}$$

$$\pi_{3i} = \beta_{30} + \beta_{31}*SEX_i + \beta_{32}*HP1_i + \beta_{34}*SEX*HP1_i + \delta_{3i}$$

$$\pi_{6i} = \beta_{60} + \beta_{61}*SEX_i + \beta_{62}*HP1_i + \beta_{64}*SEX*HP1_i$$

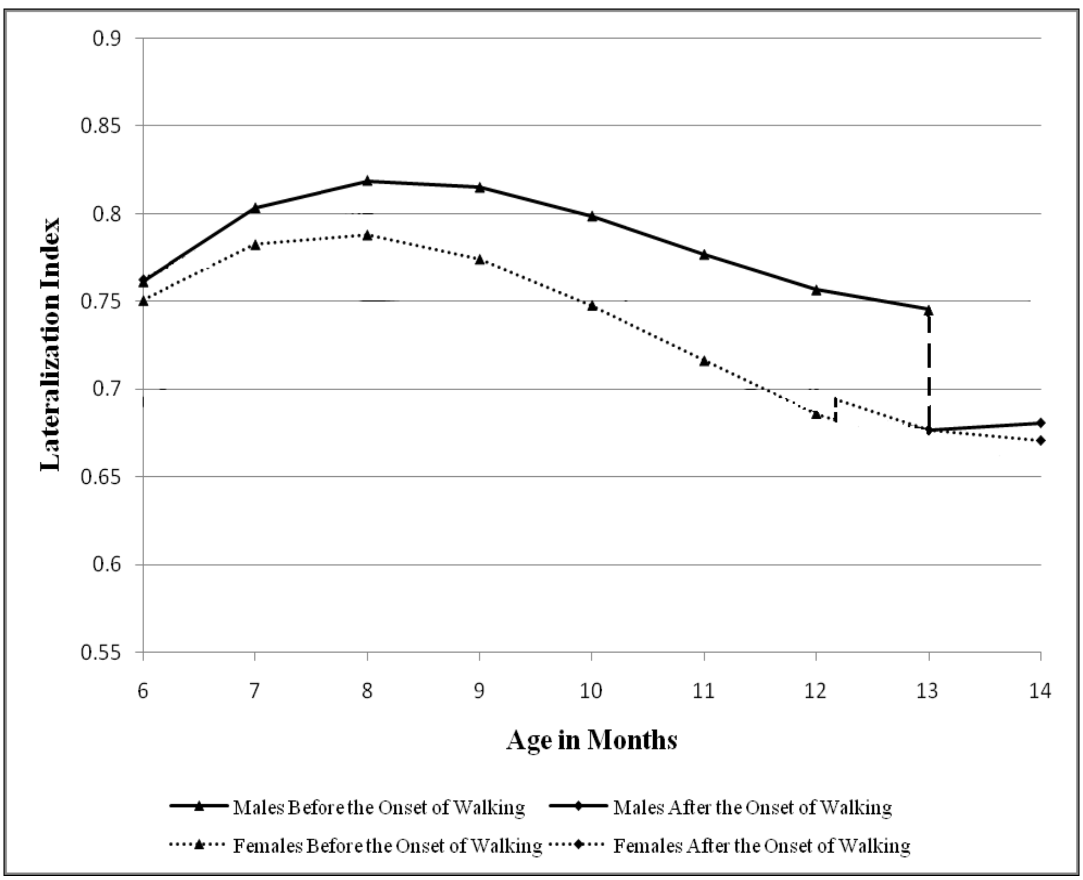
Among the benchmarks of the gross motor development, only the onset of walking was significant in the model while the sitting and crawling variables had to be dropped from the model. Among the background characteristics, handedness status variable HP1 was significant along with its interaction with the sex variable and a few cross-level interactions. The second handedness status variable HP2 turned out to be not statistically significant and was dropped from the model. Estimated fixed and random effects for the Model 5 are presented in table 4.

Of the specific interest in the current study was the relationship between lateralized hand-use, infants' ages, levels of development of their gross motor skills, like sitting, crawling and walking, as well as gender and hand preference. The model 5 shows the final equation that we are going to use for the interpretation of results. In model 5, we have a significant age effect, and we can argue that change in lateralized hand-use can be described as a cubic function. Moreover, the multilevel analysis showed that gender is a key variable for understanding developmental changes in lateralized hand-use since we found significant interactions between age and sex, the onset of walking and sex, as well as between sex and hand preference status (only HP1 comparing left-hand preference group to the right-hand preference and no preference groups). On the basis of these results, we can argue that developmental trend in lateralized hand-use differs significantly for boys and girls.

Furthermore, we found a significant effect for the variable referring to the onset of walking, which means that on average the onset of walking predicts a significant change in lateralized hand-use, and the initial point and the rate of this change is not the same for girls and boys. Moreover, the developmental change in lateralized hand-use does not differ for right-handed infants and infants without a stable hand preference, but those two groups together are different from left-handed infants.

To visually explore model 5 with all its implications, we plotted the fitted trajectories for average lateralized hand-use as a function of age for prototypical female and male infants with right-hand preference and without hand preference (figure 10) as well as for left-handed infants (figure 11).

Figure 10. Differences between males and females in fitted proportion of both-hand acquisitions before and after the onset of walking for infants with a right-hand preference and without hand preference

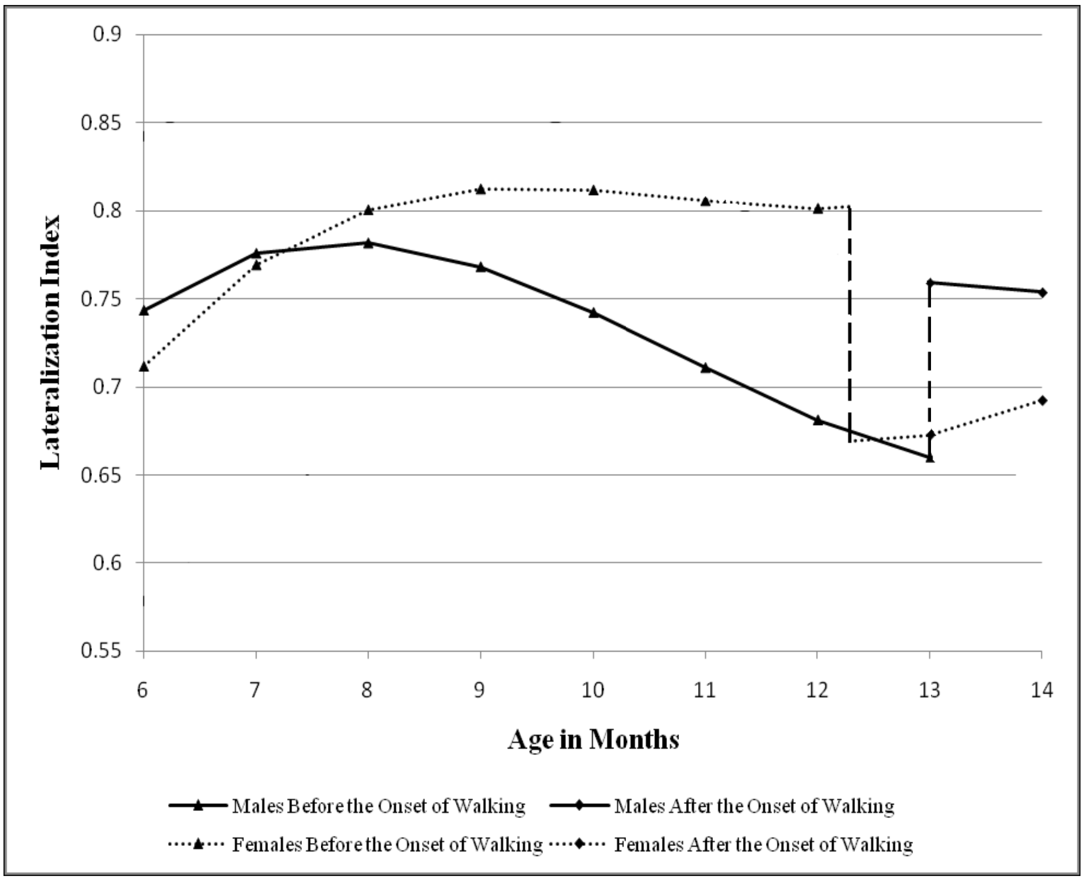


To emphasize the discontinuity of the development of lateralized hand-use, we showed the estimated change in lateralization for an average male with the onset of walking at 12.98 months, and an average female with the onset of walking at 12.30 months.

Figure 10 suggests that in right-handers and infants without hand preference, males and females start almost at the same point in terms of lateralized hand-use at 6 months of age; however males become more lateralized than females with age. Interestingly, the onset of walking has opposite effects on males' and females' lateralized hand-use – while males on average become less lateralized, females increase in their lateralization, and this change for males is more dramatic. It appears that males and females are considerably different in lateralized hand-use right before the onset of walking, but they become very similar after the onset of walking with males keeping the tendency to be slightly more lateralized in their hand use than females by the age of 14 months.

In figure 11, we see that patterns of change in lateralized hand-use for left-handers are strikingly opposite to what we observed in figure 10 for right-handers and infants without hand preference. Figure 11 suggests that among left-handed infants, males and females remain very similar in terms of lateralized hand-use up to the age 7 to 8 months, but then females keep sustaining the same level of lateralization all the way until the onset of walking while males decrease in their lateralization.

Figure 11. Differences between males and females in fitted proportion of both-hand acquisitions before and after the onset of walking for infants with a left-hand preference



At the onset of walking, we observe a dramatic shift for both males and females in their lateralized hand-use, but in contrast to what we observed in figure 10, left-handed males significantly increase while females decrease in their lateralization, and the magnitude of this shift is very similar for males and females. Moreover, left-handed males and females differ considerably not only before the onset of walking, but also after it.

One of the hypotheses that we were going to test was that age (as only a marker of development) might be not the best predictor of change in lateralized hand-use. Thus, it was hypothesized that the onset of sitting, crawling and walking would explain enough variability in our data so that we could eliminate the age variable (or variables) from the model. However, the multilevel analysis showed the significance of only the walking variable, and it was surprising since the shape of handedness development trajectory suggested that other gross motor skills might have significant effects.

However, the exploratory analysis showed significant correlations between the onsets of our gross motor skills, and it may be that the most significant variable (probably the onset of walking) suppresses the influence of other variables which are collinear with walking. Thus, the follow-up analyses were performed separately for the onset of sitting and crawling variables including them in the model one at a time. The analyses showed no significant change in the developmental trajectory of lateralized hand-use at the onsets of sitting and crawling.

Table 4

Estimated fixed and random effects from Models 1 to 5 († $p < .10$; * $p < .05$; ** $p < .01$; *** $p < .001$)

Level 1 Effects	Level 2 Effects	Parameters	Model 1 Estimates	Model 2 Estimates	Model 3 Estimates	Model 4 Estimates	Model 5 Estimates
Fixed Effects							
Initial status, π_{0i}	Intercept	β_{00}	0.7499***	0.7502***	0.7451***	0.7537***	0.7804***
	SEX	β_{01}				-0.0458	-0.0497*
	HP1	β_{02}				0.1027	-0.0607
	HP2	β_{03}				-0.0149	
	SEX*HP1	β_{04}				0.0502	0.1258*
	SEX*HP2	β_{05}				0.0478	
ORT_AGE, π_{1i}	Intercept	β_{10}		-0.0134***	-0.0108**	-0.0106	-0.0068†
	SEX	β_{11}				0.0032	-0.0092†
	HP1	β_{12}				0.0018	-0.0080
	HP2	β_{13}				0.0014	
	SEX*HP1	β_{14}				0.0201	0.0331*
	SEX*HP2	β_{14}				-0.0124	
$(\text{ORT\_AGE})^2$, π_{2i}	Intercept	β_{20}		-0.0011***	-0.0008*	-0.0011*	-0.0012***
	SEX	β_{21}				0.0008	0.0006
	HP1	β_{22}				0.0006	0.0013
	HP2	β_{23}				0.0006	
	SEX*HP1	β_{24}				-0.0021	-0.0019
	SEX*HP2	β_{25}				-0.0011	

Level 1 Effects	Level 2 Effects	Parameters	Model 1 Estimates	Model 2 Estimates	Model 3 Estimates	Model 4 Estimates	Model 5 Estimates
Fixed Effects							
$(ORT\_AGE)^3$, π_{3i}	Intercept	β_{30}		0.0014***	0.0013***	0.0006	0.0011*
	SEX	β_{31}				0.0008	0.0008
	HP1	β_{32}				-0.0004	-0.0012
	HP2	β_{33}				0.0007	
	SEX*HP1	β_{34}				0.0012	0.0011
	SEX*HP2	β_{35}				0.0001	
SIT, π_{4i}	Intercept	β_{40}			0.0123	0.0185	
	SEX	β_{41}				0.0409	
	HP1	β_{42}				-0.1240	
	HP2	β_{43}				0.0130	
	SEX*HP1	β_{44}				0.0063	
	SEX*HP2	β_{45}				-0.0919	
CRW, π_{5i}	Intercept	β_{50}			0.0032	0.0041	
	SEX	β_{51}				-0.0319	
	HP1	β_{52}				-0.0477	
	HP2	β_{53}				0.0304	
	SEX*HP1	β_{54}				0.0589	
	SEX*HP2	β_{55}				0.0019	
WLK, π_{6i}	Intercept	β_{60}			-0.0318	-0.0613*	-0.0608**
	SEX	β_{61}				0.0453	0.0657*
	HP1	β_{62}				0.1458*	0.1463*
	HP2	β_{63}				-0.0050	
	SEX*HP1	β_{64}				-0.2632**	-0.2812**
	SEX*HP2	β_{65}				0.0288	

Random Effects							
Level 1:	Within-person, ε_{ij}	σ_ε^2	0.0148	0.0094	0.0094	0.0093	0.0092
Level 2:	Intercept, ζ_{0i}	σ_0^2	0.0059***	0.0065***	0.0065***	0.0069***	0.0067***
	ORT AGE, ζ_{1i}	σ_1^2		0.0003***	0.0003***	0.0003***	0.0003***
	$(\text{ORT AGE})^2$, ζ_{2i}	σ_2^2		0.000001***	0.000001***	0.000001***	0.000001***
	$(\text{ORT AGE})^3$, ζ_{2i}	σ_3^2		0.000001**	0.000001**	0.000001**	0.000001**

CHAPTER IV

DISCUSSION

The goal of the current study was to examine the change in lateralized hand-use longitudinally using a multilevel model approach. The study was designed not only to explore the change in handedness with time, but also to define the functional form of the trajectory, and between-subject differences taking into account handedness status and sex of participants. It was also suggested by previous research that age is a poor predictor of the developmental state of the nervous system (Wohlwill, 1973). Therefore, the multilevel model should include some other time-varying predictors associated with neural development. In the present study, the development of gross motor skills was used since fluctuations in lateralized hand-use were found to be significantly predicted by developmental transitions from before-sitting status to sitting, then to crawling, and eventually to the onset of walking (Corbetta & Thelen, 2002; Goldfield, 1993; Rochat, 1992). Thus, the current study explored the ability of neuromotor development (onset of sitting, crawling and walking) to predict changes in lateralized hand-use relative to age.

The exploratory analysis showed interesting patterns of the development of gross motor skills in infants with different handedness status, as well as between males and females. There are no differences between males and females as well as between infants with different handedness status on their rates of acquisition of sitting skills. However, crawling and walking skills in our sample were acquired with faster rates by infants without distinct hand preference. From the results of previous research (Corbetta & Bojczyk, 2002; Corbetta & Thelen, 2002), we would expect that since the onset of walking coincides with the decrease in lateralized hand-use, infants without hand preference might have an initial advantage: their motor system is already symmetrical and should not transform in any way to facilitate walking. Thus, it is intuitive that infants without hand preference benefit from their symmetry and acquire walking skills faster than infants with hand preference (left or right).

Previous research (Goldfield, 1993; Goldfield, 1989; Rochat, 1992) also suggested that the onset of crawling coincides with the increase in lateralized hand-use, and infants transit from the stage of rocking to the stage of crawling when their reaches become more asymmetrical. Thus, at the onset of crawling, infants are likely to be more lateralized. The results of our exploratory analysis suggest that infants without stable hand preference start crawling faster than more "lateralized" infants. Although these results seem to contradict previous research, they may not.

Since our categorizations of infants into different handedness status groups averages across all visits from 6 to 14 month, there is no way for us to infer from the handedness status that infants from a particular handedness group are more or less lateralized than others at a particular point in their development (right before the onset of crawling). In our research, infants without hand preference are very likely to be categorized into this group because they have roughly the same proportion of right- and left-hand acquisitions. Thus, we can assume that such infants alternate a lot between their hands while playing with toys, and this habit of alternation might help them to acquire crawling skills faster than do infants with a distinct hand preference.

Furthermore, the development of crawling skills had the same patterns for males and females, however, both genders differed in their rates of acquisition of walking skills. The exploratory analysis showed that females on average acquire walking skills faster than males, and with every passing month this difference becomes slightly larger. This fact explains why we have 22.4% of non-walking males (comparing to only 6% of females) by the end of the study at 14 months. Thus, if we accept that the rates of gross motor development might characterize some sort of "maturation" of the nervous system, we would conclude that females do not significantly differ from males on their rates of acquisition of sitting and crawling skills, and only the development of walking skills can capture that differential "maturation". If we argued that females have faster rates of "maturation", this argument would be based only on one measure of gross motor development. Moreover, in a subsequent aspect of the exploratory analysis, females on average showed to be less lateralized than males. If the hypothesis is that less lateralized hand-use facilitates the onset of walking, it could be argued that since females are on average less lateralized than males, they might have faster rates of acquisition of walking skills (which is true in our sample).

In the second part of the exploratory analysis, we examined patterns of development of lateralized hand-use among infants with different handedness status, as well as in males and females. The results suggested that females are less lateralized than males if we compare them without a relation to their handedness status. However, examining the patterns of lateralized hand-use across time in infants with different handedness status, there were striking differences between handedness groups. Right-handers are more similar to infants without hand preference in that both groups exhibited significant quadratic or cubic changes in the proportions of right- and both-hand acquisitions. However, the proportion of left-hand acquisitions is stable in the right-hand preference group, but declining through age for infants without a hand preference. In contrast, the left-hand preference group does not have a significant change in any type of acquisitions. They seem to alternate between left and right hand, using them with approximately equal frequency, but they do not show significant fluctuation in the proportion of bimanual acquisitions.

Although we did not find any differences between males and females in their patterns of lateralized hand-use in right- and left-handed infants, females without hand preference in our sample were significantly less lateralized than males, because they acquired toys bimanually more often than males from the same handedness group. It should be emphasized that all of the observed differences between different handedness groups are hard to interpret since the effect of handedness is very likely to interact with gender. Thus, differences in patterns of lateralized hand-use between infants with different handedness status are confounded with the sex of infants (males and females differ in their lateralization scores and the distribution of both genders is not equal in our handedness groups with smaller number of males in no preference group, and larger number of males in right-hand preference group). Thus, the multilevel analysis was expected to show more robust results.

The multilevel analysis showed significant effect of age, as well as significant interactions between age and sex, sex and the onset of walking, as well as sex and handedness status on the trajectory of change in lateralized hand-use. The analysis and subsequent graphical presentation of the final fitted model showed that males and females differ significantly on their trajectories of lateralized hand-use development, and their patterns of lateralization depend on handedness status. Analysis shows that right-handed infants have the same patterns of lateralized hand-use as infants without stable hand preference, but those two groups are considerably different from left-handed infants. In fact, their patterns of development of their lateralized hand-use are almost opposite. Among infants with right-hand preference and those without a hand preference, males seem to be more lateralized in their hand use than females across age, but at the onset of walking they significantly decrease in their lateralization, and males and females become virtually similar on lateralized hand-use after the onset of walking.

However, patterns of the development of lateralized hand-use in left-handed infants in our sample are absolutely different. While females and males have approximately same level of lateralization at the age 6 to 8 months, after this point, males decrease in their lateralization while females do not significantly change in their lateralized hand-use. Thus, after the age of 8 months, left-handed females were more lateralized than left-handed males. Interestingly, the onset of walking comes with a dramatic change in lateralization for both males and females: males dramatically increase while females dramatically decrease in their lateralization so that after the onset of walking females become less lateralized than males. Thus, males become more lateralized in their hand use than females after the onset of walking. The same result we observe for right-handers and infants without hand preference, but in left-handed infants the difference in lateralized hand-use between males and females after the onset of walking is much larger.

Although the multilevel analysis showed interesting differences in patterns of lateralized hand-use between the left-handed infants and the two other handedness groups, we cannot expect the results on left-handed infants to be stable and reliable since there are only ten left-handed infants in our sample (equally divided according to sex). Thus, it is difficult to interpret the patterns of lateralized hand-use in left-handed infants before more data is collected.

It is interesting that males in our sample were more lateralized in their hand use throughout the entire interval from 6 to 14 months, but at the onset of walking they significantly decreased in their lateralized hand-use and exhibited the same level of lateralization as females. It could be argued that since males and females “mature” at different rates, they might eventually come to the same point in the developmental trajectory for lateralized hand-use once the onset of walking occurs; hence the trajectories of lateralized hand-use for males and females before the onset of walking should not necessarily be the same. However, if we assume that females mature at faster rates than males, why are they less lateralized in their hand-use than males on the interval between 6 to 13 months? Does “faster maturation” imply less lateralized hand-use?

Interestingly, the analysis showed that the development of handedness has a cubic trend over time. The significance of age variables in our model suggests that age cannot be "substituted" by those factors of neuromotor development we chose to examine. However, some of them (e.g., the onset of walking) can help to improve the prediction of change in lateralized hand-use.

Furthermore, the shape of the developmental trajectory of lateralized hand-use shows increase in lateralization on the interval between 6 to 9 months, and the decrease in lateralization on the interval between 12 to 14 months. We noticed the same patterns of lateralization during the exploratory analysis, and argued that the increase in lateralized hand-use can be related to the onset of crawling, and the decrease in lateralization can be related to the onset of walking.

However, the multilevel analysis showed that only the onset of walking was a statistically significant predictor of change in lateralized hand-use. We hypothesized that since the onsets of gross motor skills considerably correlate with each other, the walking variable might work as a suppressor. Therefore, we tested the onsets of sitting and crawling separately on lateralized hand-use but found no effects. It was concluded that there is no significant change in the development of lateralization at the onset of sitting and crawling even when those two variables are tested in the model independently from each other and from the walking variable.

In summary, addressing our first hypothesis, the can conclude that although only the onset of walking was found to be a significant predictor of change in the trajectory of lateralized hand-use, the other benchmarks of the development of gross motor skills such as sitting and crawling ought to be controlled in the future research.

The second hypothesis suggested that since age is just a marker of developmental change, markers of neuromotor development ought to be better predictors of changes in lateralized hand-use. However, the multilevel analysis showed that age variables (up to the third power) in our model are highly significant; so age predicts an additional 36.43% of within-persons variability in lateralized hand-use. Thus, we cannot exclude age from the model. However, markers of neuromotor development should be included, since the addition of them might help to improve the prediction of change in lateralized hand-use.

The third hypothesis addressed the question of differences in lateralized hand-use among infants with different handedness status. The current study suggests that right-handed infants are not different in their trajectories of lateralization from infants without hand preference, but those two groups together are different from left-handed infants in our sample.

The forth hypothesis predicted differences in lateralized hand-use among males and females. Supporting it, our analysis showed significant differences between males and females, but it should be emphasized that the developmental trajectories of both males and females depend also on their handedness status.

One of the limitations of the current study is that not all infants showed walking skills by the end of the study, and according to the design of this study, we were not able to obtain important data. Thus, it is recommended that future research collect data on all infants up to the point of their confident walking. Moreover, the trajectories of males and females after the onset of walking in our sample indicate that they seem to keep changing, although it is difficult to predict their further trajectory. Thus, it will be important to follow infants further up to the age of 2-3 years old.

Finally, the multilevel analysis showed interesting patterns of development in left-handed infants, but these are difficult to interpret because there were only ten left-handers in our sample. Thus, these results may be neither stable nor reliable. Considering that left-handers usually represent about 10% of the general population, a large sample of about 250 infants ought to provide a large enough group of left-handed infants to observe true differential patterns of development in left-handers.

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