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The Cascade Theory of Handedness Development suggests that an individual's hand preference results from a developmental history of cascading manual asymmetries for a variety of actions throughout infancy (Michel, 1983). Infants who consistently use their preferred hand for a variety of actions would gain proficiency using that hand and, consequently, could perform more effectively on other challenging manual tasks, such as object construction. Object construction ability has been linked with the development of a number of cognitive abilities, including spatial abilities and language. Therefore, linking infant handedness with object construction could provide insight into how the behavioral proficiency derived from a hand preference could affect cognitive development. This project tests the relation between infant handedness and object construction ability for 131 infants (70 males) who were assessed monthly for the development of a hand preference (6-14 months) and the development of construction skill (10-14 months). Of these 131 infants, 65 toddlers (30 males) were tested for their toddler hand preference (18-24 months) and their construction ability. The results generally supported the prediction that infants with a consistent hand preference were better at construction during both age periods than those infants without a preference. Also, toddlers with a hand preference demonstrated more sophisticated construction skills than those without a preference. The results are related to the development of infant cognition with a particular emphasis on embodiment theory.

HOW DOES HANDEDNESS AFFECT THE DEVELOPMENT

OF CONSTRUCTION SKILL FROM 10-24 MONTHS?

by

Emily Marcinowski

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Approved by

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Committee Chair

To my husband, Shawn. I couldn't have done this without you.

APPROVAL PAGE

This dissertation written by Emily Marcinowski and has been approved by the following committee of the Faculty of the Graduate School at The University of North Carolina at Greensboro.

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PREFACE

This dissertation was a part of a larger longitudinal project conducted by George F. Michel and dedicated to studying the development of infant handedness from 6-14 months of age. I, Emily Marcinowski assisted with the creation of the toddler handedness task. I was also integral to the pilot testing and creation of the infant and toddler construction tasks under the supervision of George F. Michel. I also performed all analyses for this dissertation and assisted with data collection, management and coding.

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CHAPTER I

INTRODUCTION

How children interact with objects changes across early childhood. Initially, infants will visually inspect objects (e.g., 7 weeks of age: von Hofsten, 1982, 1984). Next, young infants begin engaging in object-directed actions, by reaching for, touching, grasping or swiping at objects (2-5 months; Bushnell & Boudreau, 1993; Ennouri & Bloch, 1996; von Hofsten, 1982, 1984). These older infants can modify their manual actions in a way that matches the affordances of objects and adjusts for the constraints of their posture (Lobo, Kokkoni, de Campos, & Galloway, 2014). When infants can acquire objects, they can perform a greater number of unimanual actions with them, such as banging, shaking or inserting them into their own mouths (6-14 months; Campbell, Marcinowski, Babik & Michel, 2015; Lockman, Ashmead, & Bushnell, 1984; Thelen, 1979). By 12 months, infants begin to relate objects to other objects or to the specific properties of various substrates more effectively (Greenfield, Nelson, & Saltzman, 1972; Morgante & Johnson, 2011). Year old infants begin to examine relative differences among different materials and the consequences of these differences. Infants scratch textured surfaces, draw on paper and scoop sand, because these actions are conducive to exploration of these substrates (Morgante & Johnson, 2011). Infants also perform object-on-object interactions, or interactions involving multiple objects acting upon one another. Infants begin inserting objects into other objects, rubbing objects against one another or clacking them together (Campbell et al., 2015; Greenfield et al., 1972). By their first year, infants have become capable of using their bodies to elicit a specific consequence from manipulating objects.

The ability to create new structures from the manipulation of objects begins to appear during late infancy. By 14 months, infants can build structures using objects (DeLoache et al., 1985; Marcinowski, 2013; Greenfield et al., 1972; Goodson & Greenfield, 1975; Greenfield & Childs, 1977; Greenfield & Schneider, 1977; Greenfield, 1991). Object construction broadly refers to a merging of multiple objects into a single, hierarchically-arranged structure (with sub-components incorporated into larger components), including stacking blocks into a tower, nesting cups within each other, assembling magnets, or fitting together textured or complementary shapes[1]. Construction is unique in that it involves the creation of physical structures that are hierarchically-arranged (Greenfield, 1991). A hierarchically-organized structure is one whose elements are subordinate and/or superordinate to other elements (Bruner & Bruner, 1968). For example, a log cabin and a row of logs resting on the ground both create structures (a "cabin" or a "row"); but only a log cabin would be a hierarchically-organized structure, because the placement of the higher logs depends on the placement of lower logs. A "row" of logs only has a simple organization where logs only pair with the adjoining logs, while other logs in the row are unaffected by placement. Infants can create hierarchies of their own behavioral responses as early as 5 weeks (Bruner & Bruner,

[1] Although there are multiple types of construction (e.g., sentence construction), construction will refer only to creating structures composed of physical objects in this dissertation.

1968); but hierarchically-arranged physical structures cannot be created until after 12 months (Marcinowski, 2013) and hierarchical strategies for combining objects do not emerge until after 3 years of age (Greenfield et al., 1972). Construction is not simply combining objects into a visually- or physically-attached structure; instead the resulting structure is hierarchically-organized and composed of more than 2 objects.

After 18 months, children are not only combining more objects into hierarchically-arranged structures, but they are using different strategies to combine objects and these strategies enable the creation of more complex structures (Greenfield et al., 1972; Goodson & Greenfield, 1975; Greenfield & Childs, 1977; Greenfield & Schneider, 1977; Greenfield, 1991). Thus, during development, not only are infants increasing the number of objects combined within a structure, but also they are employing different strategies to combine the objects during the first two years.

Defining Object Construction

Although several actions contribute to object construction, the most commonly studied is stacking, which refers to placing an object on top of another object. To examine stacking ability, researchers often use cubes (Chen, Keen, Rosander & von Hofsten, 2010; Gesell & Amartruda, 1941) or a variety of shapes with flat edges (Hanline, Milton & Phelps, 2001; Largo & Howard, 1979a, 1979b) composed of a hard material (e.g., wood; Hanline et al., 2001). Stacking is typically studied to establish "normal" developmental milestones during late infancy (e.g., Gesell & Amartruda, 1941), differentiating between developmentally-atypical and typical populations (e.g., Specific

Language Impairment; Kamhi, Ward & Mills, 1995). Stacking is also considered to be an engaging motor precision task for infants and toddlers, because they will perform it without instruction (e.g., Chen et al., 2010).

Nesting is also used to measure construction and refers to one object being placed within another object. Nesting is almost exclusively studied using seriated cups (e.g., Greenfield et al., 1972); but it has also been conceptualized more broadly as "insertion" – where objects are inserted into container objects (e.g., bead into a cup; Lifter & Bloom, 1989, Bloom, 1993; one cup nested within another cup; Greenfield et al., 1972). Typically, seriated nesting is used as a measure of hierarchical structuring ability in young children, since nesting seriated cups produces a hierarchically-organized structure without requiring great manual proficiency to achieve. Also, strategies for seriation and error correction strategies can be observed through seriated cup nesting (DeLoache, Brown, & Sugarman, 1985; Greenfield et al., 1972). As with stacking, young children will spontaneously nest seriated cups without encouragement or instruction from a researcher (DeLoache et al., 1985).

Another construction action is "affixing", which refers to attaching one object to another by use of special materials or shapes (e.g., Velcro, magnets, chain links). The majority of researchers use fitted-piece puzzles or blocks primarily as a measure of spatial ability (e.g., Levine, Ratliff, Huttenlocher, & Cannon, 2011; Verdine et al., 2014; Sacrey, Arnold, Whishaw, & Gonzalez, 2013) rather than construction ability. Similar to nesting seriated cups, some affixing tasks can also be used as a measure of hierarchical structuring (using straws: Greenfield & Schneider, 1977; Kamhi et al., 1995) allowing for more complex hierarchies, Others have used a method of assembly (e.g., building a bridge or propeller; Goodson & Greenfield, 1975; Kamhi et al., 1995; Labarthe, 1997) to assess hierarchical structuring. Some of these other activities can be equated approximately to affixing, including forming structures from clay (Price-Williams, Gordon & Ramirez, 1967) or stringing beads (Price-Williams, 1961). The "affixing" category is a much more heterogeneous grouping of actions (fitting, stringing, adhering, etc.), than stacking or nesting.

Although researchers rarely investigate the development of these skills as a single construct (except for Takeshita, 2001). Indeed, the actions responsible for forming a structure may differ from one another. These varied actions are unified in that multiple pieces become a single, new structure (e.g., blocks become a block tower, nested cups become a seriated cup structure). The properties of the newly-created structure differ from the original objects comprising it and these new characteristics have a consequence on what additional actions can be performed on the structure.

Since very few researchers study multiple actions of object construction as a single construct, it has yet to be determined, whether multiple constructive actions are distinct or are they derived from an underlying construct. For example, the motor planning involved in each action differs. Stacking is most likely to succeed, if the flat side of the placed block is parallel to the top, flat side of the tower; therefore *how* an object is acquired may have an impact on the success or the efficiency of the stack. A block that is acquired with the corner facing downward will be challenging to stack successfully, while a downward-facing flat side will be easier to place. The way in which a child acquires the block prior to the stack has an impact on the success or efficiency of the stack; thus "motor planning" (i.e., action planning prior to the action's occurrence: Claxton, Keen, & McCarty, 2003) may have an impact on the success of a construction.

Also, unstudied is whether similarities in the deployment of construction actions change depending on developmental timing. During infancy, infants might not yet exhibit the type of motor planning relevant to successful combination of objects. Therefore, the strategies for combining different types of objects may be initially similar across all action types and may be less successful object combination. Infants might use similar tactics to combine multiple object types, regardless of how conducive the tactic is to any possible structures for that object. Alternatively, infants might use a variety of strategies when attempting to combine objects. Later certain strategies can be attributed to successes for certain objects (e.g., pressing magnets together) and can be discontinued for other objects following failure (e.g., pressing wooden blocks together). Once appropriate strategies are identified, then children can develop the ability to plan for that strategy. Thus, the developmental timing of construction abilities is a relatively unexplored domain of infancy.

How Might Handedness Affect the Development of Object Construction Ability?

Undoubtedly, motor development also plays a role in the development of object construction, particularly the development of manual control. Motor development is inextricably linked to infant cognitive development (Campos et al., 2000), in part, because having control of their body *enables* infants to acquire information by exploring their environment (Iverson, 2010). Therefore, motor development affects how infants can explore their environment (Soska & Adolph, 2014), how social partners interact with infants (Walle & Campos, 2013), and how infants represent objects symbolically (Kotwica, Ferre & Michel, 2008).

Infants use their hands to acquire a great deal of information about the properties of objects and object relations through manual exploration. Manipulating objects enables infants to internalize the presence of objects no longer registered by the senses (abstract representation; Bruner, 1973), object characteristics (the unseen back of objects: Soska, Adolph, & Johnson, 2010), causal relations (e.g., the effect of manipulating one object on another), object categories (a cup can be a container, while a block cannot: Iverson, 2010), and, eventually, representations of the physical environment (Brunyé, Gardony, Mahoney, & Taylor, 2012; Casasanto, 2009; Michel et al., 2013). In essence, manual exploration likely both *enables and facilitates* the infant's acquisition of environmental information, particularly the properties of objects and object relations that can be generalized to social objects and social relations.

Manual asymmetries, such as handedness, have been related to infant cognitive development, as well. One example involves object management skills (the ability to store more than two objects; Bruner, 1972). When an infant stores more than two objects, overflow objects are placed in a location which will permit the infant to regain possession of the object and enables the infant to engage with the object later (e.g., lap, beside them, etc.). Such storage implies the symbolic representation of the object, because the object is not present but its location is readily available to the infant (Bruner, 1973). An object that is still "possessed" by the infant but not currently in use requires a mental representation of the object; therefore, the manual skill of storage implies the representation of the object so that it may be retrieved later for incorporation into the manipulation of other objects (Bruner, 1973). For this reason, Bruner (1973) suggested that object management skill demonstrates an early incidence of abstract representation of objects. Interestingly, infants with a hand preference can more skillfully perform object storage, particularly intermanual transference and placing an object in a nearby location at earlier ages than infants without a preference (Kotwica, Ferre, & Michel, 2008). By manipulating more objects and transferring objects to both hands more often, infants with a hand preference gain additional, self-directed experience with objects, than do infants without a hand preference. Having a hand preference during infancy may permit additional experience with object manipulation and may promote an earlier understanding of abstract representations.

Historically, the origin of handedness in humans has been proposed to be *a consequence of innate or genetic mechanisms* (e.g., Annett, 1970, 1995; Caplan & Kinsbourne, 1976; Kinsbourne, 1975a, 1975b, 1975c, 1976; McManus, 1985; McManus & Bryden, 1992). The invariant lateralization theory proposes that a rightward asymmetry manifests in early infancy and occurs as a result of a gene (Caplan & Kinsbourne, 1976; Kinsbourne, 1975b, 1976). Newborn infants look and orient rightward four times as often, as leftward (Turkewitz, Gordon, & Birch, 1968), and 3-month-old infants preferentially use their right hands to hold a rattle (Caplan & Kinsbourne, 1976). Since this right preference occurs at such an early age and it was believed that it could not have been affected by practice or societal influences, asymmetrical hand use was proposed to emerge from an innate source (Caplan & Kinsbourne, 1976; Kinsbourne, 1975b). A hand preference does not progress slowly or develop, instead asymmetrical hand use for a manual skill will manifest as soon as the infant is capable of performing the manual action (Kinsbourne, 1975b, 1976). In sum, according to the invariant lateralization theory handedness does not *develop*, rather it emerges from an asymmetry in the functioning of the cerebral hemispheres derived from gene-controlled brain development. For this reason, lateralization is *invariant* throughout development.

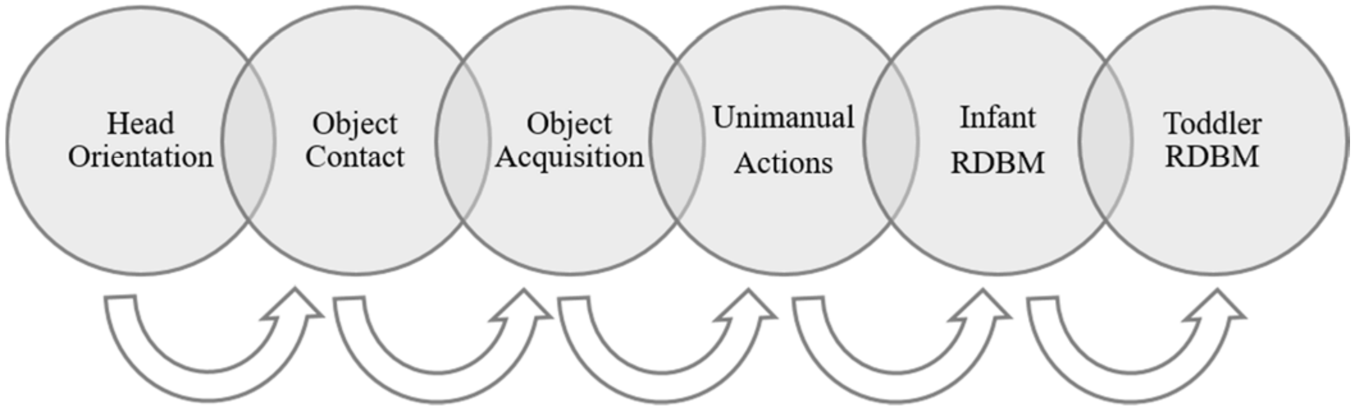
There are some problems surrounding interpretation and study of the invariant lateralization theory. Relying on terms like "innate" or "universality" as explanations for development can be misleading, because it is difficult to define what these particular terms actually mean or how development actually occurs (Lickliter & Honeycutt, 2003; Michel, Marcinowski, Babik, Campbell, & Nelson, 2015; Turkewitz & Devenny, 1993). Innate behaviors have been characterized as stemming from genetic or inherited origins (Bateson & Mameli, 2007). However, genetic or inherited explanations are not sufficiently specified enough to describe the development of behavior (Gottlieb, 1992, 2007). An organism can be examined from different levels of functioning – molecular, genetic, neural, structural, behavioral, societal – and their interactions. So, it is short-sighted to think that only a single level of functioning (i.e., genetic) could control or account for the development of behaviors (Gottlieb, 1992; Wahlsten, 1999, 2012), even those characteristics considered to be innate or species-typical.

For example, sexual behavior is often considered to be an innate characteristic (Michel & Tyler, 2007); however some evidence demonstrates that masculine sexual behavior emerges through a developmental process (Moore, 1984, 1992; Moore & Morelli, 1979). Rodent dams preferentially lick the anogenital region of their male pups more so than their female pups. Increased tactile stimulation of the anogenital region in males leads to greater control over copulation (Moore, 1984) and increases the number of motoneurons responsible for penile function (Lenz & Sengelaub, 2006). In fact, ovariectomized females who experienced elevated levels of maternal licking as pups (like a typical male pup) displayed masculine sexual behaviors as adults (Moore, 1984). Other examples come from research on well-established relations between candidate genes and behavioral phenotypes revealing that they are likely exaggerated or the consequence of Type I error (e.g., Chabris et al., 2012). Thus, explanations of behavioral development in terms of "inherited" or genetic control may be overly-simplistic.

Innate behaviors have also been characterized as developmental processes which stem from non-malleable or non-acquired origins (Bateson & Mameli, 2007). Negative descriptors, such as *non*-malleable or *non*-acquired origins, rely on the *absence* of other explanations, which is not a theoretically sound method of investigating a phenomenon. A number of reasons might explain why a behavior does not appear to be malleable or acquired across development (e.g., poor measurement, Type II error). For example, the invariant lateralization theory claims that an early infant right asymmetry was "little affected by practice, or indeed, by societal labeling" (p. 534, Caplan & Kinsbourn, 1976). However, research since then has shown that hand use asymmetries during early infancy can be affected by other developmental processes, such as intrauterine position (Michel & Goodwin, 1979; Michel & Harkins, 1986), neonatal head orientation (Domellöf, Hopkins & Rönnqvist, 2005; Michel, 1981), and environmental influences, such as presence of a toy (Lynch, Lee, Bhat, & Galloway, 2008) or parent interaction (Michel & Harkins, 1986). Again, innateness is used to explain an absence of a mechanism ("no practice or societal labeling"), when instead the unique processes associated with early handedness development should have been investigated. Thus, in part, the claim of the invariant lateralization theory that handedness manifests from an innate source relies on faulty reasoning.

Handedness has also been suggested to *develop*, as a result of changing asymmetries throughout development. Michel (1983, 2002) proposed that handedness results from a cascade of motor asymmetries that are carried throughout early childhood (Figure 1). Initially, a fetus' position *in utero* affects the infant's supine head orientation preference, postnatally (Michel & Goodwin, 1979). A head orientation preference leads to increased visual regard of the preferred-side limb and, thus, greater hand-eye coordination with the preferred-side limb. This early asymmetry develops into an early reaching handedness (Michel, 1981; Michel & Harkins, 1986). Subsequently, this hand preference for object acquisition affects preferences for later object manipulations (unimanual: Campbell et al., 2015; role-differentiated bimanual manipulation: Nelson et al., 2013). Because a hand preference emerges from a cascade of earlier developing asymmetries affecting the development of later asymmetries, an infant acquires a great deal of information through manual exploration of the environment using a preferred hand (particularly for objects). By way of this cascade, the infant is an active participant in the development of their own handedness development and handedness need not be attributed to innate processes or training (Michel & Harkins, 1986).

Figure 1. Michel's (1983, 2002) Cascade Theory of Handedness.



Interestingly, proponents of the Cascade theory of handedness have found evidence, which seems to contradict the invariant lateralization theory's account (Campbell et al., 2015; Hinojosa, Sheu & Michel, 2003). Kinsbourne (1975) predicted that infants would immediately manifest a hand preference for a particular manual action as soon as they were capable of competently performing the action. In contrast, Michel (1983, 2002) predicted that infants would initially exhibit no hand preference for the manual action and a preference would develop as the preference was transferred from the preference manifested in an earlier manual skill. To test these contrary predictions, infants across 9 monthly visits (6-14 months) were tested for their hand preferences for object acquisition and unimanual handedness (Campbell et al., 2015). Although infants were capable of competently performing unimanual actions at all tested ages, differences between preference groups for unimanual actions did not begin to appear until after 11 months. This "delay" in an infant's preference provides evidence in favor of the cascade account of handedness, rather than the invariant lateralization theory.

So, how might handedness relate to the development of object construction during infancy and toddlerhood? One influence of handedness on object construction abilities could derive from the affordances associated with having a stable hand preference. That is, a stable hand preference likely affects the development of proficiency for the manipulation of objects. A hand preference is one case of an asymmetry of manual proficiency. By definition, when an infant has a hand preference, one hand (i.e., the preferred) is used preferentially over the other (i.e., the non-preferred hand); as a result, an infant derives more manual proficiency for the preferred hand as a result of the differential "practice" associated with the preference. In contrast, an infant without hand preference uses both hands equivalently and neither hand establishes greater proficiency, assuming that infants with or without a preference manipulate objects equivalently (not an unlikely assumption). Consequently, an infant with a hand preference *may have an advantage* over infants without a preference because they can explore objects in their environment more deftly using their proficient, preferred hand. Although a majority of infants exhibit a consistent hand preference during the 6 to 14 month age period, many do not (Michel, Babik, Sheu, & Campbell, 2013). Therefore, if infants with a hand preference do have an advantage for exploring objects in their environment, then they may develop manual and cognitive abilities more quickly or, at least, differently from infants without a hand preference.

One example of object construction skill that seems to be related to manual proficiency is the ability to stack (e.g., blocks into a block tower). Chen et al. (2010) found that 18-21 month-olds who were able to stack tall block towers early employed more refined and controlled motor strategies, than those who could not build tall towers. Toddlers who could build tall towers exhibited kinematic differences in their stacking actions, such that the arm greatly slowed near the tower (Chen et al., 2010). This slowed movement likely allowed these toddlers an opportunity to place a block more precisely, which permits the toddler to correct the placement more effectively using visual and haptic feedback. In contrast, toddlers who could only build short towers exhibited an increase in the action speed during the middle of the reach and slowed the rate of speed much later in the movement trajectory. These toddlers were less successful at tower-building using this action strategy, since it is less conducive to precise block placement. At 18-21 months, motor precision of the stacking action seems to be important to stacking blocks successfully.

Although a measure of handedness was not included in this study, it is likely that infants with a hand preference would perform better on this stacking task, than infants without a hand preference. However, this might only be likely if the preferred hand is used during stacking. It has been reported that right-handed children are more likely to use their preferred hand for stacking (Marchik, Einspieler, Strohmeier, Garzarolli & Prechtl, 2007). Infants with a hand preference who use their preferred hand to stack might create taller towers than infants without a hand preference.

If a hand preference was to be relevant for successful object construction skill, then the cascade theory of handedness would predict that an early infant hand preference should promote object construction ability. As a consequence of additional practice, a preferred hand should be more capable of exploring object properties in the environment and more proficient at performing actions relevant to object construction (e.g., acquisition, placement, etc.). Thus, an infant with a hand preference should have an advantage over infants without a preference for object construction. If infants with a preference do indeed have an advantage for achieving object construction, then any manual skills or cognitive abilities that are related to object construction could also be affected by infant handedness. The current study examines the relation of infant hand preferences to the development of object construction skills.

Could Object Construction Affect the Development of Cognition?

A number of researchers have connected the development of construction ability to cognitive development, including spatial skill (Caldera et al., 1999; Levine et al., 2011; Verdine et al., 2014) and mathematical ability (Nath & Szucs, 2014; Wolfgang, Stannard, & Jones, 2003). Children who engaged in more spontaneous block play were better at copying block structures and could better identify embedded geometric shapes (Caldera et al., 1999). Also, block construction skill predicted a child's ability to copy block structures and re-create color patterns within block towers. Advanced visuospatial skills gained from object construction have been associated with greater mathematical ability. Children who could build more complex Lego structures were more advanced in their mathematical achievement; however this relation was mediated by visuospatial ability (Nath & Szucs, 2014). No relation was found between object construction ability and reading or verbal achievement, suggesting that object construction is more closely tied to visuospatial development. Since object construction and visuospatial skill appear to be related, the development of object construction could alter the development of visuospatial abilities. Construction play could provide children with additional experience in the visuospatial manipulation of objects, and so, early object construction ability could affect cognitive development, particularly for those skills dependent on visuospatial ability.

One way in which object construction could affect visuospatial ability is through the embodiment of our actions upon the physical environment. Infants could embody the associated sensorimotor skills involved in the creation of object structures within their nervous system. Embodiment theory suggests that physical interactions in the environment guide how we develop cognition and abstract concepts (e.g., Barsalou, 2008; Lakoff & Johnson, 1999; Oppenheimer, 2008). Prior sensorimotor manipulation of the environment guides our comprehension of events, situations or symbols. Through increasingly specialized exploration, infants develop a more specific and comprehensive mental meaning assigned to objects, object relations and actions (Bloom, 1993; Iverson, 2010). Infants transduce sensory information about objects or structures, which then influence cognition; hence physical structures produced within the environment are "embodied" into the infant's nervous system. According to embodiment theory, to understand cognition, one must first understand the development of motor skills (Lakoff & Johnson, 1980).

Infant handedness is a previously unexplored domain of motor development affecting the development of object construction ability. Since infants with a stable hand preference show a unique developmental trajectory for manual skills, they might also have a unique trajectory for object construction and subsequent cognitive development (Michel et al., 2013). If infants with a preference are lateralized early in development, then sensory stimulation from preferred hand manipulation might reinforce neural pathways to the related hemisphere (i.e., right or left). These reinforced neural pathways gained through environmental stimulation might then contribute to the neural pathways important for the development of cognition.

What Are the Aims of this Project?

The first aim of this dissertation is to *describe* the development of construction ability across late infancy (10-14 months) and toddlerhood (18-24 months). Despite the development of object construction skills being a theoretically-interesting behavior manifesting in early childhood, very few studies include infants (18 months or younger) (e.g., Chen et al., 2010; DeLoache et al., 1985; Greenfield et al., 1972; Marcinowski, 2013) and only one researcher has investigated the emergence of infant construction longitudinally (Marcinowski, 2013). In order to make predictions about the factors influencing the development of construction skill (such as, handedness), it is important to *describe* a behavior's development (Kagan, 2013; Michel et al., 2013; Michel et al., 2015; Tinbergen, 1963). This study will begin with a description of the developmental process of object construction for future study.

The second aim of this dissertation is to assess whether handedness and hand use affect the development of construction ability. Since a preferred hand is more practiced and proficient, I predict that infants with a hand preference, regardless of direction, will exhibit a more rapid development and better building skills, than infants without a consistent hand preference. However, this relation will only be likely if infants with a hand preference use their more proficient, preferred hand for constructing objects. Infants with a preference who do not use their preferred hand to build structures will not be more advanced in their object construction ability. As with infant handedness, toddler handedness is also predicted to affect the development of toddler construction ability. Toddlers with a hand preference, regardless of direction, are predicted also to develop object construction skills more rapidly and exhibit better building skills, than toddlers without a hand preference.

CHAPTER II

METHOD

Participants

Participants (n=380) were recruited from Guilford County birth records to come to the Infant Development Center at UNCG for 9 monthly visits during the age period from 6 to 14 months and for 8 monthly visits during the 18 to 24 month period for a sub-sample of the 380. All visits occurred within 1 week of their birth date. Participants for this project were tested during the 10-14 month age period with mean ages of 9.835, 10.793, 11.806, 12.781, and 13.786 months, respectively. The participants for the 18-24 month visits were tested at mean ages of 17.704, 18.710, 19.709, 20.708, 21.607, 22.683, and 23.601 months, respectively. The sample was composed of 2% Asian, 56% Caucasian, 24% African American, 8% Hispanic, and 16% multiracial infants. One hundred and eighty-nine infants (56%) were male and 146 were female (44%).

All infants had full-term pregnancies and births without complications. Procedures for recruitment, obtaining informed consent, and data collection were in accordance with the regulations set by the UNCG Institutional Review Board for the protection of human subjects. For each visit, parents were given a $10 Target gift card. During these visits, infants were administered a reliable handedness assessment from 6-14 months (Michel, Ovrut, & Harkins, 1985) and the analyses on infant handedness classification were conducted on the larger sample (n=380).

There were 2 “waves” of data for the assessment of the development of object construction ability: infant (10-14 months) and toddler “waves” (18-24 months). The **infant construction sub-sample** was a convenience sample of 131 infants (a sub-sample of the 380 infants) born after March, 2010 and who had missed 2 visits or less across the 6-14 month ages with no more than 1 of those in the 10-14 month ages (excluding, 249 infants). During these 10-14 month visits, infants were administered an object construction assessment task (Table 1). This infant sub-sample was composed of 58% Caucasian, 24% African American, 3% Hispanic, 2% Middle Eastern, 1% Asian, and 13% multiracial infants, which is roughly representative of both the overall study sample (Michel et al., 2013a) and Guilford County’s ethnic demographics (US Census Bureau, 2010). Families’ median yearly household incomes were $60,000-$69,999 (range: $10,000-$150,000+). The mothers’ and fathers’ education levels ranged from high school graduate to professional degree. The median education level for both was a bachelor’s degree. The primary language spoken in the home was English for all participants, except in 5 cases: 3 Spanish, 1 Arabic, and 1 French. Seventy infants (53%) were male and 61 were female.

Table 1. Ages and Sample Sizes Available for Each Task.

Task	Administered at Ages	Sample Size	Sample name
Handedness	6-14 months	n=380	Overall Infant Sample
Construction	11-14 months	n=131	Infant Construction Sub-Sample
Handedness	18-24 months	n=101	Toddler Sample
Construction	18-24 months	n=65	Toddler Construction Sub-Sample

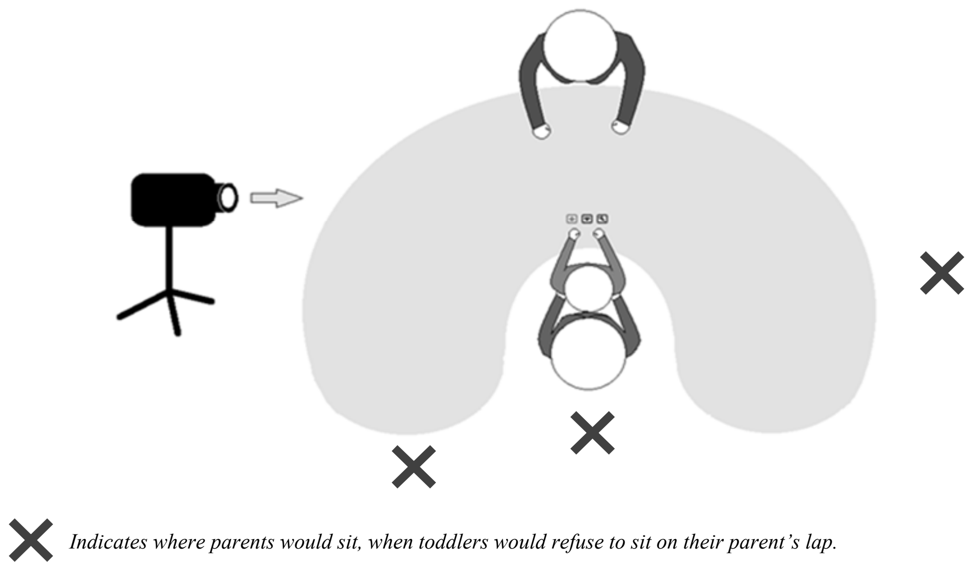
From the overall infant sample, some participants were brought back to the lab for an additional 7 monthly visits (**toddler sample**: Table 1). Across the 18-24 month visits, toddlers were given a handedness task and some were given an additional object construction task (n=61). To be included in the **toddler construction sub-sample**, toddlers also must have been born after March, 2010, missed 2 visits or less across infant ages, missed 2 visits or less across the 18 to 24 months age period and received the toddler construction task (excluding, 70 toddlers). Thus, these toddler participants could not have missed more than 4 visits across the 6-24 month ages. The toddler construction sub-sample was composed of 63% Caucasian, 29% African American, and 8% Hispanic. Families' median yearly household incomes was $60,000-$69,999 (range: $10,000-$150,000+). The mothers' and fathers' education levels ranged from some high school/no diploma to a doctorate degree. The median education level for both was a bachelor's degree. The primary language spoken in the home was English for all participants, except in 3 cases: 2 Spanish and 1 French. Thirty-five toddlers (54%) were male and 30 were female (46%).

One unfortunate problem with this sample is the large decrease in sample size from the infant handedness sample (n=380), infant construction sub-sample (n=131), and toddler construction sub-sample (n=65). This decrease does not represent participant attrition; rather it is a function of extensive piloting work with the original 380 and the loss of funding that affected the toddler sample size. Despite this problem, there were no significant differences between the infant handedness sample and the infant construction sub-sample for sex (χ^2=0.440, p=0.213) or infant handedness (χ^2=4.043, p=0.116). No differences were found for race (Caucasian, African-American, or Other) between these samples for mother (χ^2=3.358, p=0.153), father (χ^2=3.902, p=0.146), or infant race (χ^2=3.362, p=0.153). There were also no differences between the infants who were or were not recruited for the toddler portion on sex (χ^2=0.030, p=0.862) or infant handedness (χ^2=2.549, p=0.467). No differences were found for race (Caucasian, African-American, or Other) between the infant-only and infant-toddler participants for mothers (χ^2=3.140, p=0.154), fathers (χ^2=2.857, p=0.154), or infants (χ^2=4.597, p=0.132). Thus, there are no systematic differences between the demographic characteristics of participants within the infant handedness sample, infant construction sub-sample, and the toddler construction sub-sample.

Procedure (Infant Visits)

The experimenter sat directly across from the infant on the convex side of a rounded crescent-shaped table, while the infant sat on the concave side. The infant sat on the parent's lap and held the infant on either side of the infant's waist to maintain a stable posture. A camera (Panasonic WV-CP240) was placed to the side and directly above the infant's hands, allowing two views for coding accuracy (Figure 2). Each visit was recorded in its entirety for later data coding. If the child became irritable during the session, a short break was taken or another appointment was scheduled within 5 days (the interrupted task was restarted at the second visit). Both the stacking and the handedness tasks were in the same setting.

Figure 2. The Set-up for All Measures from the Top Camera View.



Indicates where parents would sit, when toddlers would refuse to sit on their parent's lap.

Infant Handedness (6-14 Months)

The infant handedness assessment (6-14 months) comprised 32 objects of varying shapes and sizes were presented to infants, one-by-one. The objects were presented either singly (26 objects) or in pairs (6 objects). Single objects were presented either on the table (29 objects) or in the air (3 objects) to the infant's midline. Paired objects were two identical objects placed on the table in line with the baby's shoulders. The presenter allowed the infants to manipulate each object until it was acquired or after 20 seconds (whichever occurred first). The entire handedness assessment lasted approximately 15 minutes. Videos were coded using Noldus © Observer XT 10.1, which allows coders to stop or slow down the videos for coding accuracy. On 20% of randomly-selected videos, the overall inter-rater agreement was 93.22% and the overall intra-rater agreement was 97.9%.

An infant's hand preference for acquisition was ascertained using Group-based trajectory modeling (GBTM; Michel et al., 2013). GBTM is a statistical technique which clusters similar patterns of trajectories together, and identifies sub-groups whose members follow a similar developmental trend (Haviland, Nagin, Rosenbaum, & Tremblay, 2008). Sub-groups may be qualitatively different within a population, but relatively homogeneous within the sub-group; since it assumes that the observations are drawn from a population with distinct sub-groups (Michel et al., 2014; Michel, Sheu, & Brumley, 2002). When the analysis finds sub-groups, it creates a posterior probability of group membership in all groups for each infant. The infant is assigned to the group where the posterior probability is the highest. For example, if an infant has a posterior probability of 0.02 for the left group, 0.8 for trending right, 0.13 for stable right and 0.05 for the no preference group, that infant would be assigned to the trending right group, since they have the highest probability of belonging to that group. The GBTM analysis was performed on the larger dataset (n = 380) prior to creating the sub-sample (n = 131), so that group assignment would be more accurate.

Infant Construction Task (10-14 Months)

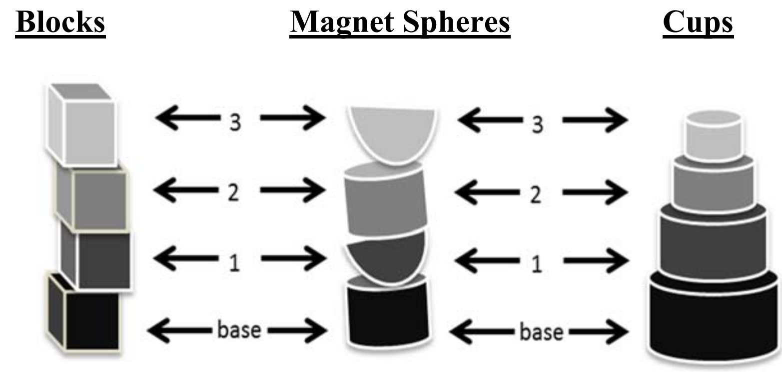
The stacking task comprised 7 sets of objects which afforded at least 1 of 3 construction actions (Figure 4): 1) four cylinder blocks ("Round blocks" – 2 red, 2 purple), 2) five cubic blocks with alphabet letters painted with multiple colors on all sides

("ABC blocks"); 3) four stacking cups painted to look like cakes (2 brown, 2 white) presented twice ("Stacking/Nesting Cakes); 4) 3 magnetic sticks ("Magnet sticks" – 1 blue, 1 yellow, 1 red); 5) 5 magnetic round spheres ("Magnetic Spheres" – 1 red, 2 blue, 1 green, 1 orange); and 6) rings and a stand ("Rings and stick" – 1 red, 1 blue, and 1 orange ring with a yellow stand). Before presenting the task to the infant, the presenter demonstrated how the task could be constructed and de-constructed. Then, the task was presented using both hands to the infant in a completely deconstructed state. For example, the cubic blocks were stacked one-by-one into a tower using all the blocks, then the blocks were removed one-by-one and all of the de-constructed blocks were simultaneously pushed to the infant. The cakes were presented to infants in two ways: once to demonstrate stacking and once to demonstrate nesting. Thus, infants had two, independent opportunities to demonstrate stacking with the cakes. The infant engaged with a task for at least 20 seconds. The entire assessment of construction took approximately 6 minutes.

The three coded actions were stacking, nesting, and affixing, although each object hand only 1 or 2 actions which were possible (see Table 3). Stacking was defined as "placing an individual object on top of another" (ABC blocks, Round blocks, Stacking/nesting cakes, Stacking rings). Nesting was defined as "placing or settling an individual object inside another object" (Stacking/Nesting cakes). When an object had an open end (as with the cakes), stacking could only be observed when the base object has a solid side facing up. Nesting can only be observed when the open end of the base object is facing up, and cannot be observed when its solid side is facing up. Finally, affixing was defined as “joining or attaching an individual object to another” (Magnet sticks, Magnet spheres, Stacking rings). A ring within the stacking rings toy was only counted as a stacking action, if the rings were stacked on one another without the stand. Affixing was counted, if the rings were affixed onto the stand.

In addition, only successful constructions are counted towards this analysis (Figure 3). Only when the object in the infant’s hand was built upon the base object and the infant removes his/her hand without the object immediately losing its placement is an action considered successful. If the object fell out of place once the infant let go of the object, then this is not considered a successful construction (e.g., the infant places a block onto a tower, and it falls off the tower immediately). A successfully nested object is when all included objects were completely settled within each other; that is, the objects must be nested in the correct order based on descending size. A magnetic object could be affixed in one of two ways. First, the infant could affix two magnets using two hands. Second, an infant with one hand could move one magnet to the other magnet which resulted in adherence. If another magnet rolls toward their hand and adheres to a magnet in the infant’s stationary hand, this is not considered a successful affix. The Stacking Rings could be affixed by the infant placing the rings over the stick stand, and the ring maintains its position after the infant’s hand is removed.

Figure 3. Image of Potential Structures.



Videos of the infant construction tasks were coded using Noldus © Observer XT 10.1. On 20% of stratified-randomly selected videos, inter-rater reliability had an overall agreement of 96.6%. In addition, intra-rater reliabilities for 20% of another set of stratified-randomly selected videos had an overall agreement of 97.9%.

Procedure (Toddler Visits)

The configuration of the testing site for toddlers was the same as for the infant visits. The only difference is that some toddlers insisted upon sitting by themselves, rather than on their parent's lap. In these cases, a different chair that afforded freedom of upper limb movement for the toddler was used. The parent would sit on the right side of the table (perpendicular to the toddler), next to the toddler, or directly behind the toddler in a different chair. The parents in this project were instructed not to interact with children during testing either with their hands or verbally. This situation occurred enough to be mentioned, yet it still was a relatively rare occurrence and only if the toddler insisted.

Ideally, parents would have been assigned to sit equally on the right and left sides, but the testing set-up made this impossible. The left side has monitors, recording equipment and cameras blocking spots for parents to sit; therefore parents could not have sat on the left side without interfering with data collection. Counterbalancing could not have been done, because the research set-up might have to be completely altered when the toddler first indicated a preference to sit alone (potentially leading to additional frustration) and the incidence of toddler obstinacy cannot be predicted prior to the visit. This right-bias in parent location might have drawn the toddler's attention towards the right side. Parents have been shown to influence their child's behavior, such as conduct (e.g., Wittmer & Honig, 1994) and hand use (Michel, 1992). Yet, most studies focus on active manipulation. Michel (1992) *did* find an effect of maternal hand use on infant handedness development; but these parents were specifically instructed to play with their infants. The parents in the current project were instructed not to interact with their toddlers. Certainly, the possibility exists that a parent's location could have biased activation and right hand use, simply from their presence on the right side. It has been suggested that hemispheric specialization is partially a consequence of differential allocation of attentional resources (Kinsbourne, 1974, 1975b). Thus, the parent's presence on the right side could have influenced the assessment of toddler handedness and construction. It is not *expected* that it did, given the infrequent occurrence of the phenomenon; but it is enough of a concern to warrant mention within this project.

Toddler Handedness (18-24 Months)

The toddler handedness task (18-24 months) comprised 6 objects presented twice and 9 objects presented once. Each object afforded role-differentiated bimanual manipulations (RDBM). RDBM is a bimanual action for which one hand (the non-preferred hand) supports the manipulation and/or exploration of the object by the other (preferred) hand. For example, when unzipping a bag, the non-preferred hand would be used to hold the bag and the preferred hand would be used to move the zipper. RDBM was used to assess toddler handedness, rather than acquisition because RDBM has been demonstrated to a better indicator than acquisition of toddler hand preferences (Fagard & Marks, 2000). Children are already proficient at acquiring objects with either hand by a year of age, but the ability to perform RDBMs begins to be manifest after 13-14 months of age (Kimmerle, Ferre, Kotwica, & Michel, 2010). Since object acquisition is such a well-practiced skill by a year of age, the preferred hand does not need to be used. However, as RDBM begins to develop as a skill, the more preferred hand will be more proficient and will take the active role in an RDBM. Indeed, longitudinal study has demonstrated that RDBM reliably measures toddler handedness and infant hand preference for acquisition has been shown to predict toddler hand preference for RDBM (Nelson, Campbell, & Michel, 2013). Acquisition preference also appears to relate to bimanual preferences in cross-sectional studies (e.g., Fagard & Lockman, 2005; Fagard & Marks, 2000; Michel Ovrut, & Harkins, 1985; Ramsay, 1980).

There were multiple RDBMs which could be coded for each of the objects in the assessment task (see Table 2) and the total number of possible RDBM actions was 29.

The presenter would draw attention to the manipulative property (e.g., unlatching a container) and then place the object to the toddler's midline on the table. The presenter allowed the infants to manipulate each object until a RDBM manipulation occurred or after 30 seconds (whichever occurred first). At times, a toddler could not perform the first action in a two-part action which some of the RDBM objects afforded (e.g., unzipping bag, followed by removing the toy). In these cases, the presenter would perform the first action, so that the toddler could have the opportunity to perform the second action. The entire handedness task lasted approximately 10 minutes. Videos were also coded using Noldus © Observer XT 10.1. From 20% of stratified, randomly-selected set of videos, the overall inter-rater agreement was 96%. As with infant handedness, toddler hand preference was ascertained using a GBTM.

Table 2. Toddler Handedness Task.

Repetitions	Data points	Object	Components	Overarching Action	Passive Hand	Active Hand
2x	2	1. Ball-in-Tube	PVC tube with Velcro piece inside Cloth ball	Remove ball from tube	Stabilize tube	Remove ball
2x	2	1. Figure-in-Cup	Plastic cup with Velcro piece inside Figure	Remove figure from the cup	Stabilize cup	Remove figure
2x	2	2. Toy-in-Snack cup	Snack cup Small figure	Remove figure from snack cup	Stabilize cup	Remove figure
2x	2	3. Ring on column	Stand Plastic ring	Pull ring off of the stand	Stabilize column	Remove ring
2x	4	4. Worm-in-jar	Toothpick dispenser Fuzzy worm	a) Pull worm from toothpick dispenser b) Unscrew lid from toothpick dispenser	a) Hold toothpick dispenser b) Hold toothpick dispenser	a) Pull worm b) Unscrew lid
1x	3	5. Small Latch Container	Small latch container Fitted animal figure	a) Unlatch container b) Removing top from container c) Remove animal figure from container	a) Hold container b) Hold container c) Hold container	a) Unlatch b) Remove top c) Remove animal
1x	3	6. Large Latch Container	Large latch container	a) Unlatch container b) Removing top from container	a) Hold container	a) Unlatch b) Remove top c) Remove animal

			Large, fitted animal figure	c) Remove animal figure from container	b) Hold container c) Hold container	
1x	1	7. Foam peg block	Foam block with a circular cut-out Foam Cylinder	Remove foam cylinder from foam block	Hold foam block	Remove foam cylinder
2x	4	8. Zipper bag	Clear zipper m up bag Wind-up toy	Unzip bag Remove wind-up toy	a) Hold zipper bag b) Hold zipper	a) Unzip b) Remove wind-up toy
1x	1	9. Two Nested cups	Large cup Small cup	Remove smaller, nested cup from larger cup	Stabilize large cup	Remove small cup
1x	1	10. Bolt-in-box	Red box with a hole down the center Green bolt fitted into the red box	Remove green bolt from red box	Hold the red box	Remove the green bolt
1x	1	11. Phone-in-purse	Purple cloth purse Soft phone toy with inside squeaker	Remove phone from purse	Hold the purse	Remove the phone
1x	1	12. Brush-in-purse	Purple cloth purse Blue, plastic brush	Remove plastic brush from purse	Hold the purse	Remove the brush
1x	1	13. Peel large sticker	Large, rectangular sticker	Remove sticker from its paper	Hold the paper	Peel the sticker
1x	1	14. Peel small sticker	A square of 4 small, circular stickers	Remove one sticker from its paper	Hold the paper	Peel the sticker

Toddler Construction Task (18-24 Months)

As with the infant construction task, stacking, nesting and affixing were the three possible actions. The toddler construction task comprised 7 sets of objects (see Figure 4). Each set of objects afforded at least 1 of 3 construction actions: 1) ten 1 inch cubic blocks (“Small blocks” – 2 red, 2 orange, 2 yellow, 2 green, 2 blue), 2) ten 2 inch cubic blocks (“Large blocks” – 2 red, 2 orange, 2 yellow, 2 green, 2 blue); 3) 9 seriated cups colored to look like cakes (5 brown, 4 white) presented twice (“Stacking/Nesting Cakes”); 4) 10 magnetic round spheres (“Magnetic Spheres” – 3 green, 2 blue, 2 red, 1 teal, 1 yellow, and 1 orange); 5) 8 visually-seriated, hat-shaped cups (“Sombreros” – 2 yellow, 3 orange, 2 green, and 1 blue); 4 cauliflower pieces with Velcro (“Cauliflower” – 2 leaves, and 2 halves of a floret); 10 textured blocks (“Porcupine blocks” – 4 blue (2 large, 4 small), 2 green (large), 1 red (small), 3 yellow (small)); 8 orange pieces with Velcro (“Orange” – 4 peels, and 4 slices); 12 non-seriated, plastic bowls (“Bowls” – 3 green, 3 red, 3 orange, 3 teal); and 6) painted, wooden rings and a wooden stand (“Wood rings” – 3 red, 2 blue, 3 purple, and 1 unpainted stand). Before presenting the task to the toddler, the presenter demonstrated how the task could be constructed and deconstructed. Then, the task was presented using both hands to the infant in a completely de-constructed state. For example, a few porcupine blocks were combined into a structure, then the structure was disassembled and all of the de-constructed blocks were simultaneously pushed to the toddler. The entire assessment of construction took approximately 12 minutes.

Figure 4. Pictures of Construction Toys.

A) Infant Toys

B) Toddler Toys

As before, stacking, nesting and affixing were coded for the toddler construction objects and each object had only 1 or 2 possible actions (see Table 3). Also, the same rules and definitions for infant construction actions applied to toddler construction. Two sets of construction objects overlapped across the infant and toddler visits

(Stacking/Nesting cakes, Magnet Spheres); however these objects had more pieces during toddler visits.

Table 3. Description of the Infant and Toddler Construction Assessments.

Construction Object	Afforded Action	# pieces	Largest Possible Structure
Infant Visits			
Round blocks	Stack	4	3
ABC blocks	Stack	5	4
† *Stacking/Nesting Cakes*	Stack	4	3
(presented twice)	Nest	4	3
Stand with Rings	Affix	3 + stand	3
† *Magnet Spheres*	Affix	5	4
Magnet Sticks	Affix	3	2
Toddler Visits			
Small blocks	Stack	10	9
Large blocks	Stack	10	9
† *Stacking/Nesting Cakes*	Stack	9	8
(presented twice)	Nest	9	8
Wood Rings	Affix	8 + stand	8
Sombreros	Nest	8	7
Bowls	Nest	11	10
† *Magnet Spheres*	Affix	10	9
Porcupine blocks	Affix	11	10
Cauliflower	Affix	4	3
Orange	Affix	8	7

† *Presented at both infant and toddler visits*

Videos of the infant construction tasks were coded using Noldus © Observer XT 10.1. On 20% of stratified-randomly selected videos, inter-rater reliability had an overall agreement of 98.1% (90%-100%). In addition, intra-rater reliabilities for 20% of another set of stratified-randomly selected videos had an overall agreement of 97.4% (88.2%-100%).

CHAPTER III

RESULTS

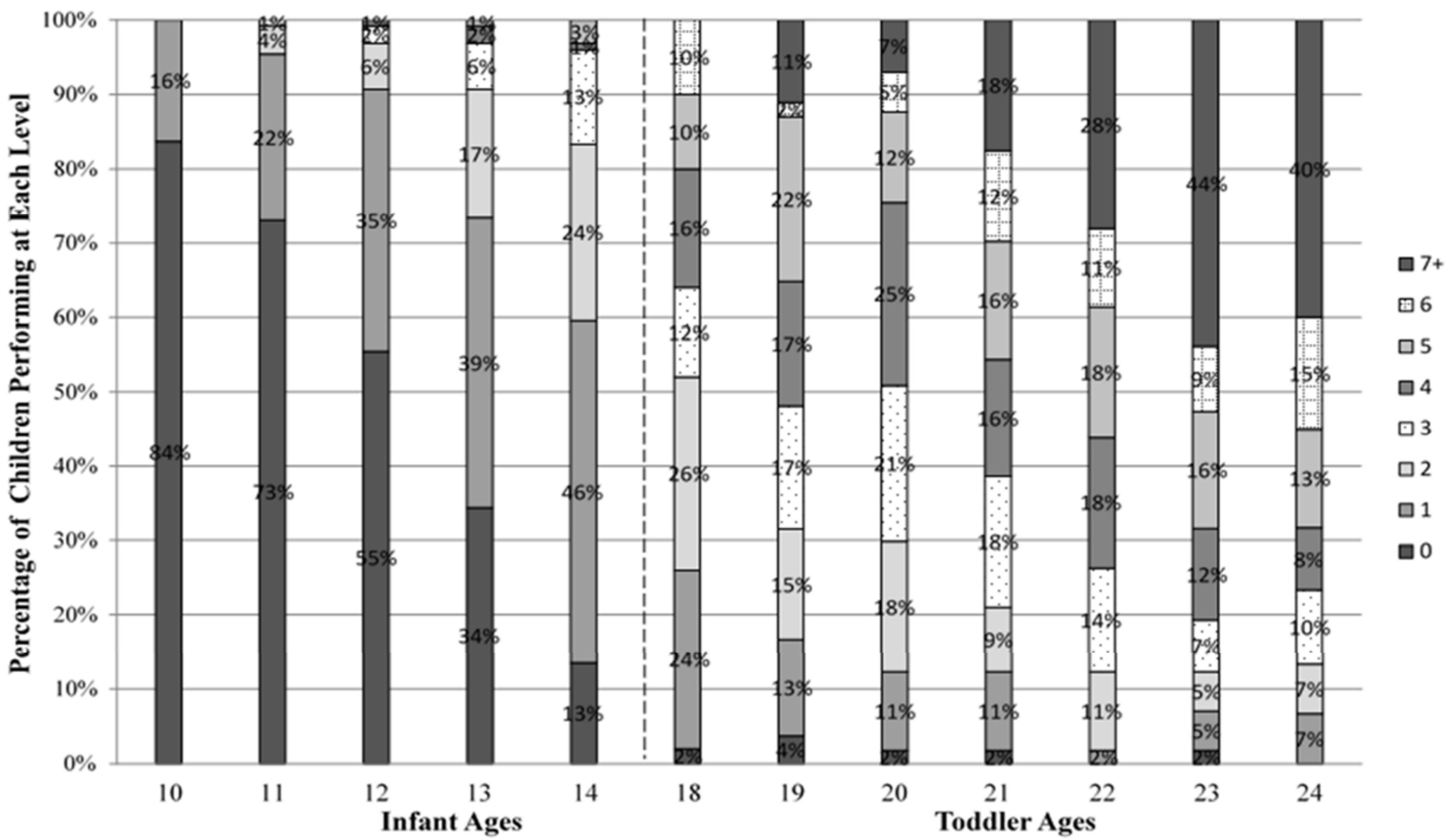
Descriptive Analyses of Construction

Construction skill was measured by summing all successfully constructed pieces across all construction toys for each action ("Sum of stacking/nesting/ affixing"). This "sum of" variable was meant to capture the total number of constructions the child was performing, regardless of actual achievement. For example, an infant that stacked 2 cakes, 3 Round blocks, and 0 of the other toys, would have a score of "5" on sum of stacking.

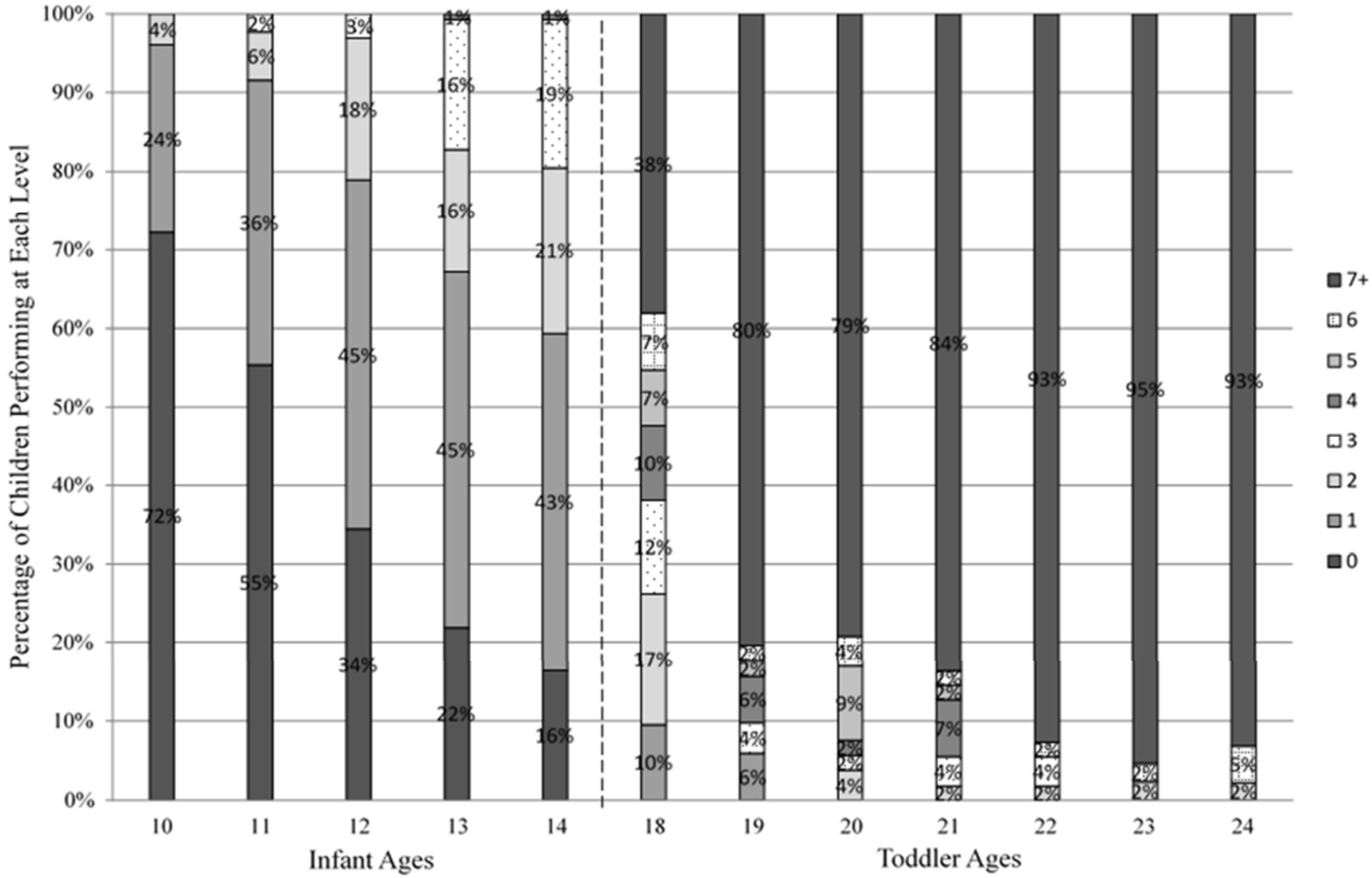
For descriptive purposes, the most complex structure (i.e., with the most items comprising the structure) was calculated for each action ("Max stack/nest/affix"; Figures 5 A-C). This "max" variable was meant to capture the child's highest level of achievement, not accounting for the number of constructions perforfmed. For example, an infant that stacked 2 cakes, 3 Round blocks, and 0 of the other toys, would have a score of "3" for max stack. These "Max" variables are only presented descriptively and not analyzed because they exhibited little variability, particularly during the 18-24 month period.

Figure 5. Cumulative Percentages of Infants Performing at Each Level by Age (Max Stacks/Affixes/Nests)

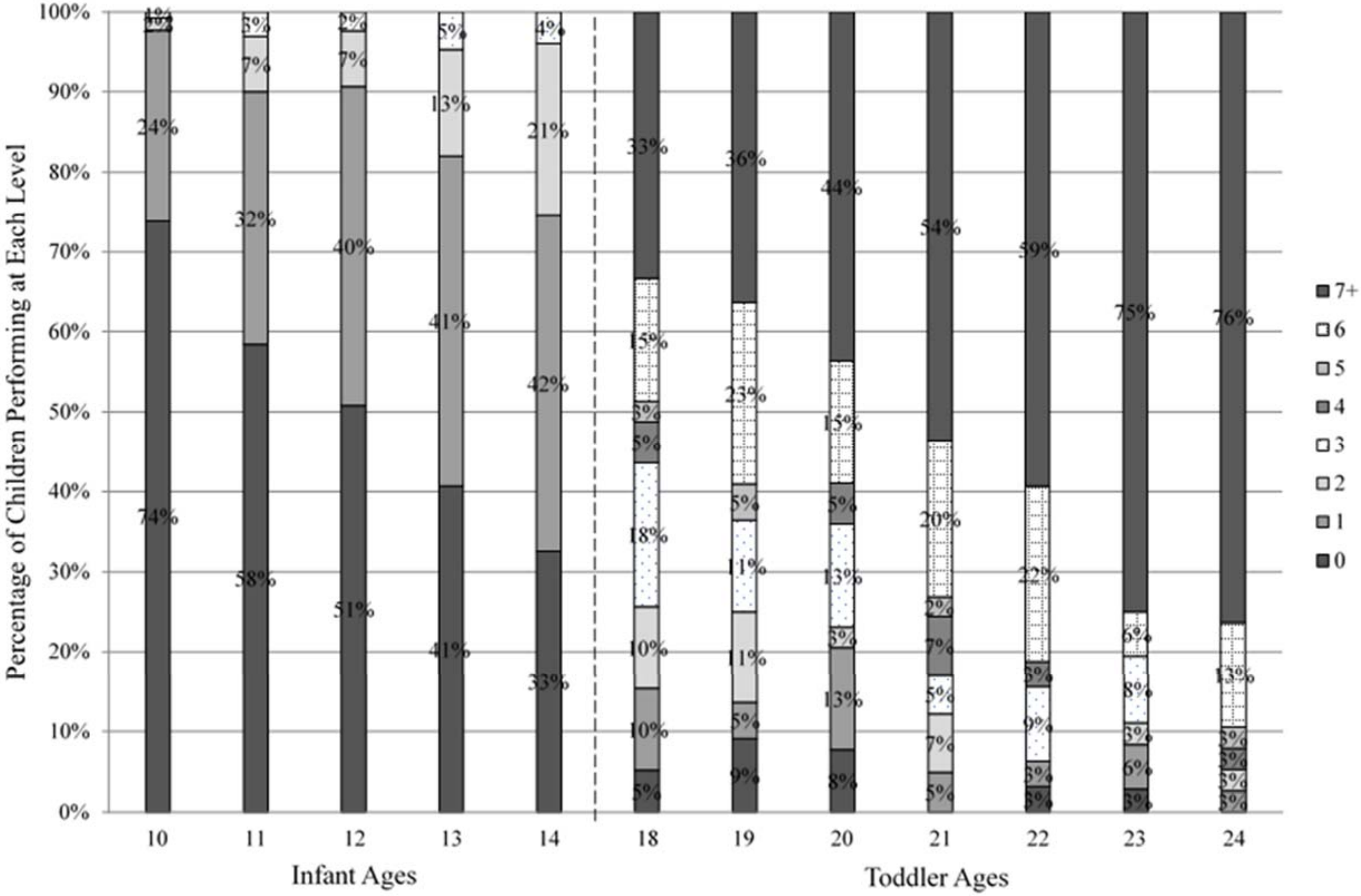
A) Stacking



B) Affixing


Percentage of Children Performing at Each Level
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
10
11
12
13
14
18
19
20
21
22
23
24
Infant Ages
Toddler Ages
7+
6
5
4
3
2
1
0
72%
24%
4%
55%
36%
6%
2%
34%
45%
18%
3%
22%
45%
16%
16%
16%
43%
21%
19%
10%
17%
12%
10%
7%
7%
38%
80%
79%
84%
93%
95%
93%

C) Nesting



Percentage of Children Performing at Each Level
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
10
11
12
13
14
18
19
20
21
22
23
24
Infant Ages
Toddler Ages
7+
6
5
4
3
2
1
0

Before testing models of the development of object construction skill, the type of distribution must be assessed for each dependent variable. In the past, infant construction has been shown to be Poisson-distributed (Marcinowski, 2013), and prior projects with toddler construction were also found to be Poisson-distributed (Marcinowski, Nelson, & Michel, 2014; Marcinowski, Soula, Nelson, & Michel, 2014). Using JMP 11, distributions for all ages for each action were analyzed for goodness of fit, using a Pearson Chi-Square. "Sum of stacking" was found to match an underdispersed Poisson model for infant and toddler ages (χ^2=0.493-49.557, *p*s .316-1.000)[2]. "Sum of Affixing" matched an underdispersed Poisson model from 10-22 months of age (χ^2=0.493-49.557, *p*s 0.316-1.000); but 23 (χ^2=973, *p*=0.230) and 24 months (χ^2=0.980, *p*=0.437) of age were distributed normally. "Sum of Nesting" met the assumptions of an underdispersed Poisson model across all infant and toddler ages (χ^2= 0.440-51.914 *p*s 0.240-0.997). Based on this information, sum of stacking, nesting, and affixing will be analyzed using an *underdispersed multilevel Poisson model*.

What is a Multilevel Poisson Longitudinal Model?

A *multilevel longitudinal model* describes both change over time and how these changes vary separately for individuals and groups (Raudenbush & Bryk, 2002; Singer & Willett, 2003). A multilevel model, like a typical regression or ANOVA, models the effect of a dependent variable (e.g., log(λ)) on time-sensitive and -insensitive independent

[2] A significant χ^2 indicates a violation, while a non-significant χ^2 indicates that a distribution falls within accepted bounds of the tested distribution.

variables (See Appendix A and B). Within a multilevel model, each parameter (π) has fixed effects (γ) and random effects (i.e., a variance component; δ). Fixed effects describe average values (γ_{00}, γ_{20}, etc) or the effect of a Level-2 variable (γ_{03}, γ_{12}, etc) on the average value. When multiple dummy-coded variables are included in a model, the values (e.g., γ_{00}) provide the reference group's values, while the effect of a Level-2 variable (e.g., γ_{01}) provides the amount of linear/quadratic/etc. change attributable to the Level-2 variable. For example (see Appendix A), if a longitudinal model is created with no level-2 variables, then the fixed effect of the intercept (γ_{00}) becomes the average sample mean at the 0 value visit. If a dummy-coded "Sex" variable (female=1) is introduced to the intercept, then the "γ_{00}" is defined as the average mean of males (i.e., the reference group) at the 0 value visit and the "γ_{01}" now means the average change to the intercept from being female. If the "γ_{01}" is not significant, then females are no different from males and "Sex" can be dropped from the intercept of this model.

Variance components indicate whether significant variability exists in an individual's initial status or slopes (see Appendices 1 and 2). In essence, a multilevel model partitions within subjects variability into separate variance components, so that variability can be attributed to specific elements of the model. The traditional "error" variance term (ε) still describes variability not explained by the model; however person variance components describe variability within the intercept and all slopes. If a variance component for a parameter is significant, it denotes that significant variability exists for the parameter and the average estimates of that parameter do not sufficiently capture the sample data. For example, if a linear slope had a significant variance component but the intercept does not, then it can be concluded that infants begin at roughly the same point (intercept) but there is significant variability in the way that infants initially change (linear). Because of their treatment of variability, multilevel models do not assume homogeneity of variance, in the same way that an ANOVA model might. Instead, differing levels of variability across visits, groups or individual change *are a core feature of multilevel models*. The addition of these variance components (δ) provides a more nuanced way of understanding whether individuals change in unique ways or if the "average" change adequately captures individuals.

There are two additional benefits to using a multilevel longitudinal model over traditional methods of longitudinal analysis, particularly for modeling developmental data. First, missing Level-1 data points do not eliminate a participant from analyses, as with least squares regression repeated measures analyses (Howell, 2008). Missing data are accommodated more effectively than in other longitudinal methods (such as repeated measures ANOVA). More specifically, an individual's trajectory is calculated using all available data points, because participants' data are mapped as trajectories as a function of time. Second, the time variable can be included in the model as a continuous variable, as opposed to a categorical variable (e.g., "10.78 months", rather than "11 months"). Continuous time variables allow for a more accurate measure of the effect of change over time, because time is measured more accurately and any variability associated with actual age will be explained. Thus, unequal sequencing of observations can be accounted for by modeling a child's unique age for each assessment.

The models included in this dissertation are further unique, because they account for data that are positively-skewed and require Poisson regression model. A *Poisson* regression model is a method of analysis commonly used to model count data, as opposed to continuous data (Raudenbush & Bryk, 2002). Count variables (e.g., frequency data) are integers (i.e., whole numbers with values > 0); therefore these variables are often positively-skewed. Within a Poisson model, the mean is expected to equal the variance (Dobson & Barnett, 2008); although this assumption is frequently violated by datasets (Avant, Gazelle, & Faldowski, 2011). Over- and underdispersed Poisson models were developed to account for this discrepancy. An overdispersed model exhibits more variability than might be expected under a standard Poisson (i.e., variability > mean), while an underdispersed model exhibits less (i.e., variability < mean). In HLM, longitudinal Poisson models allow for over/underdispersion by estimating the level 1 variance parameter. If the model's Level 1 variance is <1, it is underdispersed; whereas if it is >1, it is overdispersed[3]. Underdispersed models are commonly found in datasets with a large number of zeroes. Because construction is a newly-developing skill across these infant and toddler ages, it would be expected for models to display underdispersion.

Poisson regression models also allow for *variable exposure*, or variability in the amount of opportunities for the dependent variable to occur. Because a Poisson regression model tests the rate of constructions occurring; the exposure variable incorporates the differences in opportunity at each visit into the model. Conceptually-

[3] Theoretically, the variance of an over- or underdispersed model will be greater than or less than the mean, respectively; however, the software program, HLM, standardizes the Level 1 variance to equal 1 for ease of interpretation.

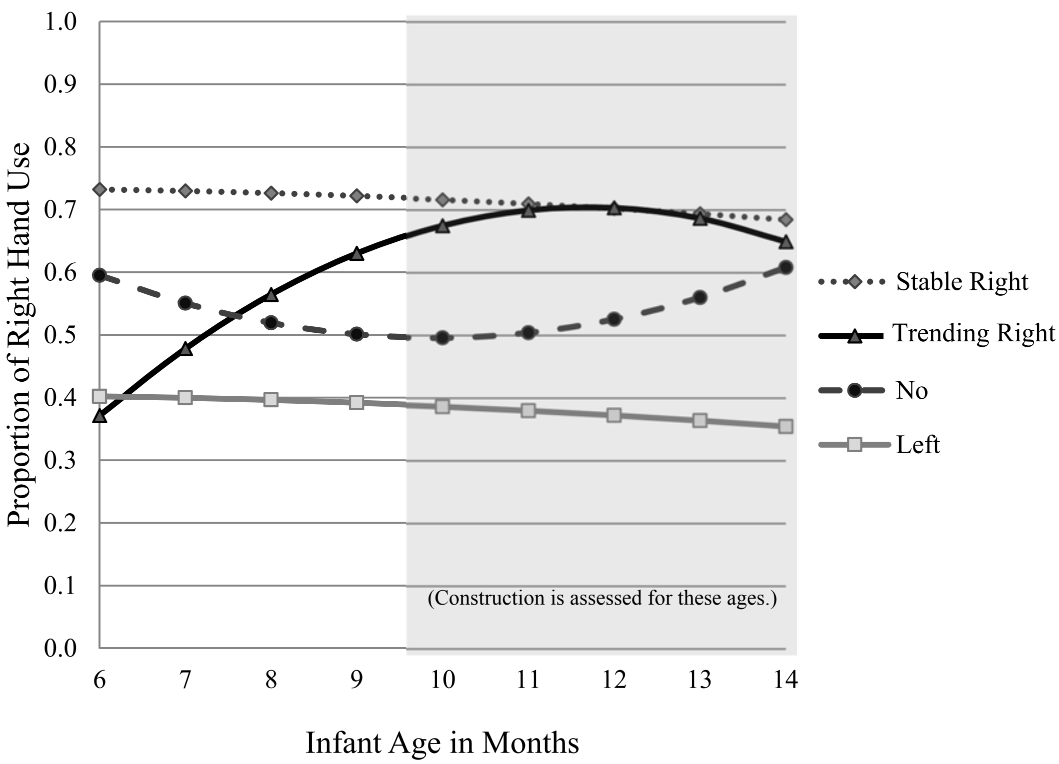
speaking, Poisson regression transforms the dependent variable into a log rate parameter (λ_i), which is linear to the predictors. The dependent variable/rate parameter can be conceptualized as the rate by which the dependent variable changes, relative to the total number of opportunities. Variable exposure within the current project's dataset will be discussed in greater detail later.

Handedness Classification

Infant. The hand(s) initially used to pick-up object(s) were coded for each toy presentation (i.e., 32 codes per visit). Data from the handedness task at each age were used to compute this formula: Proportion of Acquisition Hand use$_{age}$ = (Σ(Right pick-ups))/(Σ(Right pick-ups)+Σ(Left pick-ups)). Next, the handedness of each infant was determined through GBTM using the SAS TRAJ procedure (Jones, Nagin, & Roeder, 2001; Babik, Campbell, & Michel, 2013) on the entire sample (n=380), and the sub-sample's handedness classification from the larger analysis was used for the current study. Four groups were found from these analyses within the larger sample (n=380): Stable right (32.2%), Trending right (25.4%), Left (12.2%), or No stable handedness (30.2%)(see Figure 6). From these data, a subsample (n=131) completed the construction task, 38 infants (29%) had a stable right hand preference, 38 infants had a trending right hand preference (29%), 23 infants (18%) were left-handed and the remaining 32 (24%) were classified as having no stable handedness throughout the 6-14 month ages. Infants with a trending right preference and infants without a preference had significant quadratic trajectories, while left-handers and stable right-handers had only significant linear trends.

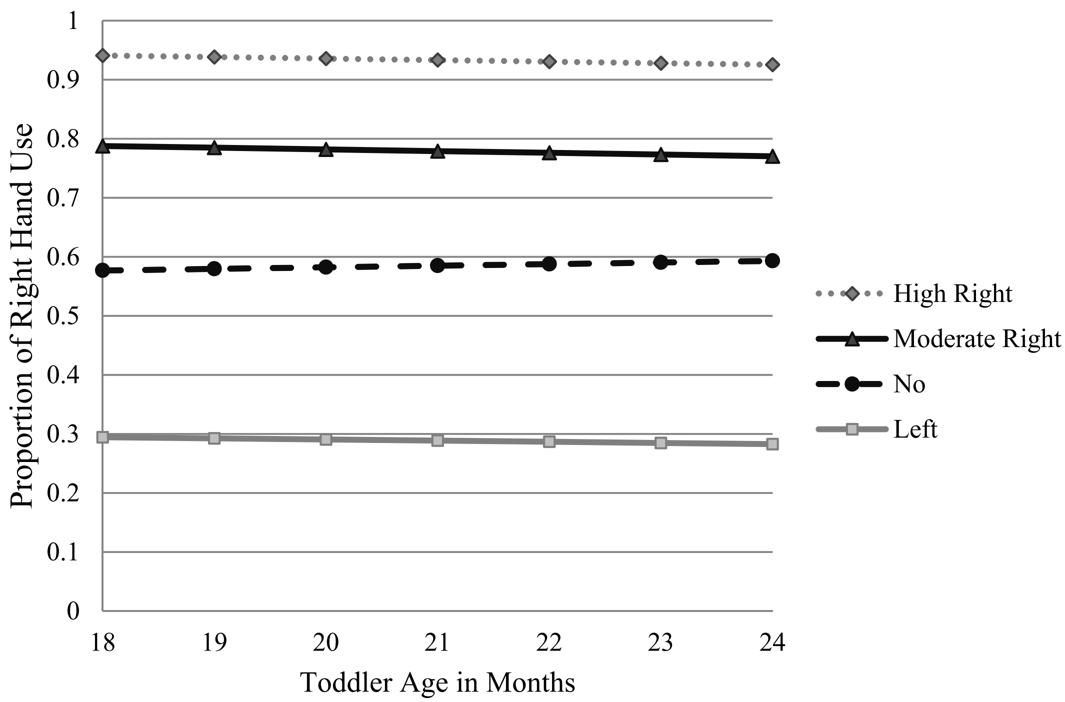
The average posterior probability for the association of the infants with the groups was 0.800 (Left = 0.849, Trending = 0.753, No = 0.798, Stable Right = 0.821).

Figure 6. Infant Hand Preference Trajectories Determined by GBTM Procedure (n=380).



Toddler. The hand used to perform the action during an RDBM was coded for each toy presentation (i.e., 29 codes per visit). Data from the handedness task at each age were derived from this formula: Proportion of RDBM Hand use$_{age}$ = (Σ(Right RDBMs))/(Σ(Right RDBMs)+Σ(Left RDBMs)). Next, these RDBM data were analyzed using GBTM to identify the hand preference for each toddler, using the SAS TRAJ procedure (Jones, Nagin, & Roeder, 2001; Babik, Campbell, & Michel, 2013) on the entire sample (n=101). The toddler's handedness classification from this analysis was used for the subsample (n=65). Four groups were found from the analysis of the sample of 101 toddlers: “High” right (30.7%), “Moderate” right (28.9%), “Left” (20.0%), or “No” clear preference (20.4%)(see Figure 7). From the toddler subsample (n=65), 17 (26%) had a High right hand preference, 18 (28%) had Moderate right hand preference, 14 (22%) had a left preference, and the remaining 16 (25%) were classified as having no clear hand preference throughout the 18-24 month age period. All 4 handedness groups differed from 0 at their intercept (βs 0.295-0.941, *p*s < 0.000), which means that they exhibited a significant asymmetry. However, none of the groups had significant slopes (βs -0.003-0.003, *p*s 0.617-0.760). The average posterior probability for the association of the toddlers with the groups was 0.925 (Left = 0.995, No = 0.940, High Right = 0.906, Moderate Right = 0.886).

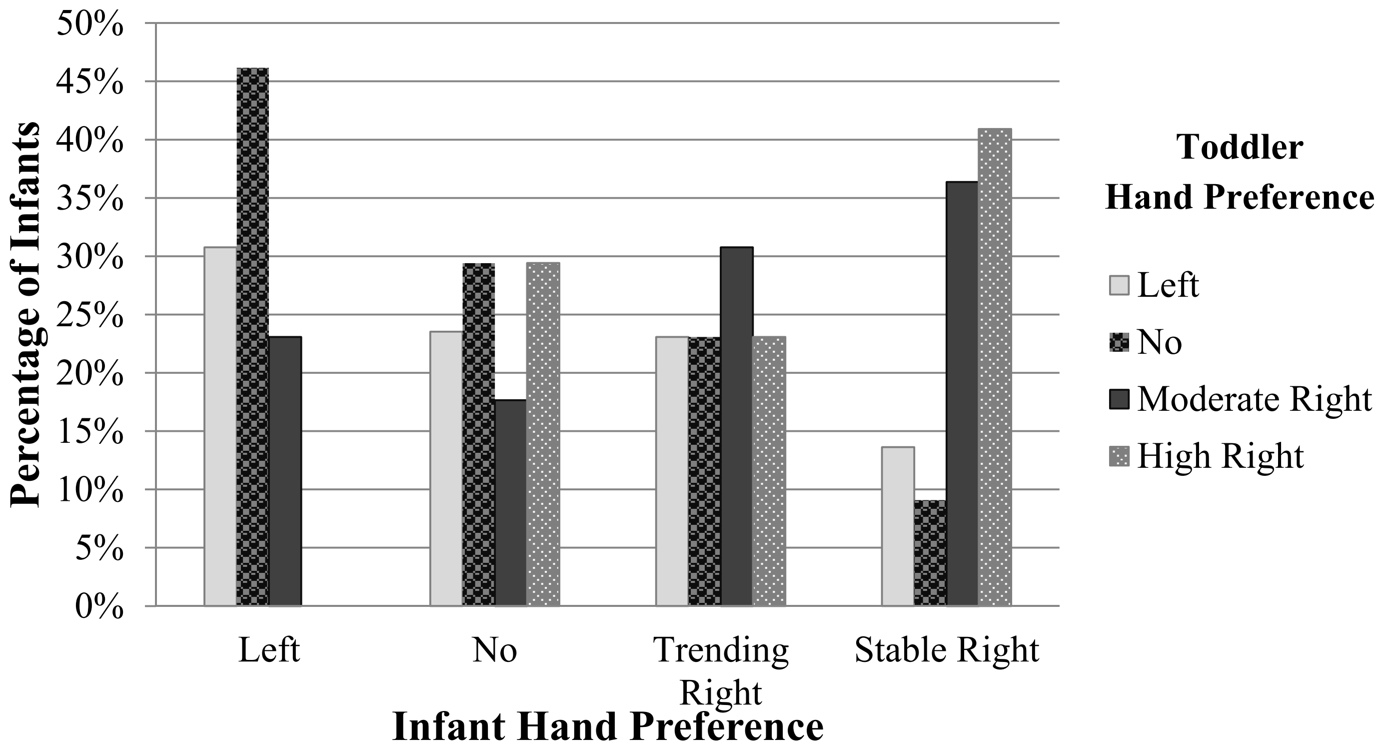
Figure 7. Toddler Hand Preference Trajectories Determined by GBTM Procedure (n=101).



Past research has found a significant relation between infant acquisition handedness and toddler RDBM handedness across these ages, even when using different analytic methods to classify toddlers (Nelson, Campbell, & Michel, 2013). For the current study, more infants with a stable right preference were right-handed as toddlers (either High or Moderate), using the GBTM method (Figure 8). Using a binomial test, infants with stable right-handedness were more likely to become right-handed (p<0.000) or high right-handers as (p=0.045) toddlers. Infant-toddler concordance handedness was not found for those infants with a left, trending right or no preference. However, nearly half of left-handed infants had no preference as toddlers (46%) and over 30% had a left hand preference as toddlers (more than any other group). Also, infants without a hand preference exhibit a remarkably even distribution of hand preferences among the four groups as toddlers; thereby demonstrating that their lack of a preference as infants is delaying their development of a preference as toddlers.

Other researchers have shown significant differences in proportions of handedness between infancy and toddlerhood, with particularly higher rates of left-handedness during toddlerhood (e.g., 20%: Vauclair & Imbault, 2006) than infancy (e.g., 14%: Michel, Babik, Sheu, & Campbell, 2014). These age differences may be a consequence of the influence of interactions with parents on hand preferences. Infants are more likely to have right-handed caregivers and social partners (Harkins & Michel, 1988). Because mothers tend to use their preferred (usually right) hand when interacting with their infant during object play and even left-handed mothers use their non-preferred hand much more often than do right-handed mothers during such play (Michel, 1992; Mundale, 1992), left-handed infants and those without a preference might develop a right bias in their hand use by toddlerhood as a consequence of such right-dominated social interactions during object play. Of course, such social interaction simply affirms the right preference of stable and (some) trending right-handers.

Figure 8. Overlap between Infant and Toddler GBTM Classifications.



Interestingly, trending right-handers likely have the same right bias during social and environmental interactions, yet they do not show a preponderance of right preferences as toddlers. Trending right-handers do have a right bias, as they are more likely to demonstrate a right preference as toddlers (54%), as compared to infants without a preference (43%); yet this bias is less pronounced as the stable right-handers (77%). Other factors may play a role in development for trending right-handers, above and beyond social and environmental biases (e.g., neuromotor development: Koucheki, Campbell, & Michel, 2015).

The Development of Infant and Toddler Construction

As described earlier, these data were analyzed with a multilevel Poisson longitudinal model (PMPLM), using the software program, Hierarchical Linear Modeling (HLM v.7). Although every attempt was made to give the infants a full set of items, items were occasionally missing (e.g., infant refusal). Infants had a mean of 11.39 items (s=1.40, 9-13 items) that could be stacked (out of 13 possible), 8.99 items (s=0.16, range: 5-9 items) that could be affixed (out of 9 possible) and 5.99 items (s=0.17, range: 3-6 items) that could be nested (out of 6 possible). Toddlers had a mean of 33.46 items (s=5.80, 20-34 items) that could be stacked (out of 34 possible), 36.27 items (s=4.37, range: 28-37 items) that could be affixed (out of 37 possible) and 30.49 items (s=5.84, range: 23-33 items) that could be nested (out of 33 possible). Available pieces did not correlate with stacking (ρ=0.052, p=0.196), nesting (ρ=-0.026, p=0.116), or affixing (ρ=-0.004, p=0.913) skill. Nevertheless, a variable exposure parameter was included into the model in an effort to accommodate differing opportunities to stack. The trajectory of the dependent variable can be conceptualized as the rate by which construction increased, relative to the total number of opportunities, at each visit.

The infant age variable, the toddler age variable, their squared slopes, and their cubic slopes were coded. The level-1 (time-varying) variables were Age, Age^2, and Age^3, while the level-2 (time-stable) variable was handedness group. The infant's actual age (i.e., continuous age) was centered on 10 months (Age = Age-10) to create a linear age variable. Quadratic ($Age^2 = (Age\text{-}Mean\ Age)^2$) and Cubic age ($Age^3 = (Age\text{-}Mean\ Age)^3$) were both coded orthogonally to Age to decrease multicollinearity (Bock, 1975). Infant handedness was coded as three dummy variables for "Stable Right", "Trending Right" and "Left". Infants with "No preference" served as the reference group. Toddler handedness was coded as three dummy variables for "High Right", "Moderate Right", and "Left". Toddlers with "No preference" served as the reference group.

On average, sum of *stacking* increased linearly across infant (γ_{11}=1.043, p<0.000) and toddler (γ_{11}=0.114, p<0.000) ages (see Table 4). Both ages' quadratic slopes and the infant cubic slope were not significant, but the variance components were. Although the sample on average does not exhibit quadratic or cubic change, variability in the quadratic and cubic slopes suggests that some children within the sample do have a quadratic and/or cubic slope. Toddlers were significantly variable to warrant a variance component for all parameters, except the linear slope. For parameters that have a significant variance component, toddlers exhibited significant variability in their scores at the initial visit (intercept) and changes of rate (quadratic and cubic slopes). Infants also had a variance component for the intercept, which means that infants exhibited significant variability at 10 months. Broadly-speaking, significant variance components denote that average scores (at the intercept) or average change (at slopes) do not adequately represent these data.

Sum of *affixing* increased quadratically across infant ages (γ_{21}=-0.116, p<0.000) and cubicly across the toddler ages (γ_{31}=-0.013, p<0.000). Infants and toddlers were significantly variable to warrant a variance component for their respective intercepts and linear slopes, but not for any higher order slopes. On average, sum of *nesting* increased quadratically during infant ages (γ_{21}=-0.051, p=0.037) and exhibited a linear increase across the toddler period (γ_{21}=0.067, p<0.000). Infants and toddlers were significantly variable to warrant a variance component for their respective intercepts. Infants were variable enough to warrant a variance component for the linear slope for nesting, but not for the quadratic slope.

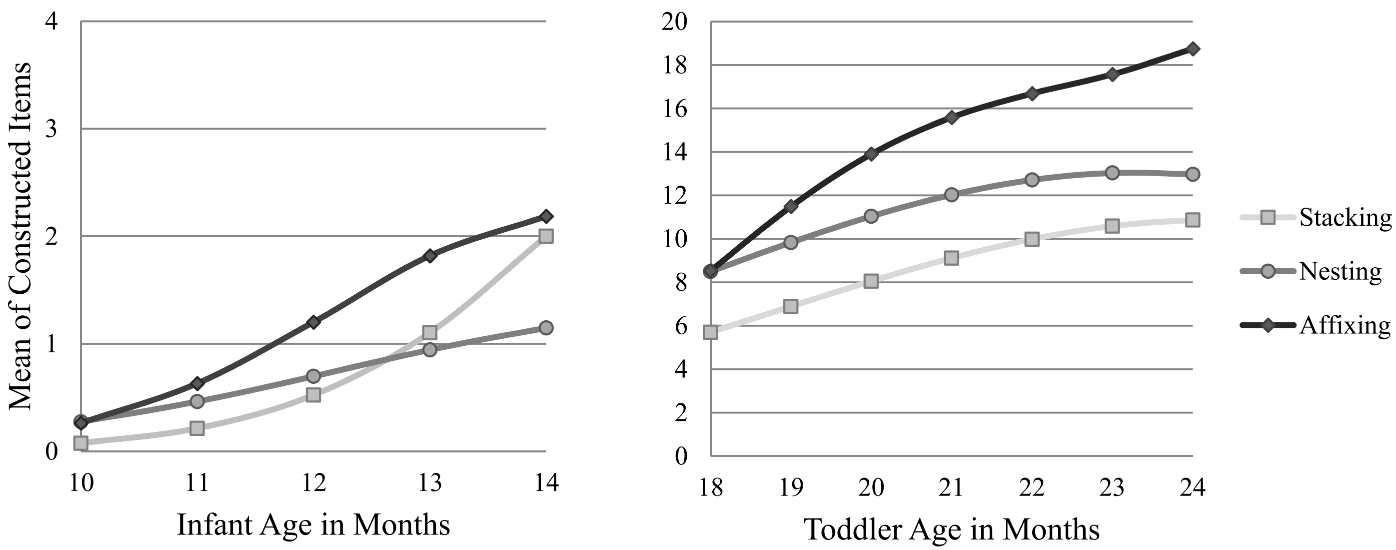
Table 4. Estimated Fixed and Random Effects for Sum of Items Constructed by Action at Infant and Toddler Ages (Unconditional Growth Models)

	Construction		
	Stacking	Nesting	Affixing
Fixed Effects†	*Coefficient*	*Coefficient*	*Coefficient*
Inf Intercept	**-5.334*** **	**-2.886*** **	**-3.049*** **
InfAge	**1.043*** **	**0.361*** **	**0.524*** **
$InfAge^2$	-0.086	**-0.051***	**-0.116*** **
$InfAge^3$	-0.015	**-**	**-**
Todd Intercept	-1.639***	-1.268***	-1.123***
ToddAge	0.108***	**0.067*** **	0.086***
$ToddAge^2$	**-0.016***	-	-0.023***
$ToddAge^3$	**-**	**-**	**0.005***
Random Effects†	*Variance Component*	*Variance Component*	*Variance Component*
Intercept	**9.465*** **	**0.849*** **	**0.859*** **
InfAge	**1.263*** **	**0.045***	**0.033***
$InfAge^2$	**0.240*** **	-	-
$InfAge^3$	**0.084*** **	-	-
Level-1 (σ_ε^2)	0.273	0.657	0.702
Todd Intercept	**0.138*** **	**0.085*** **	**0.060*** **
$ToddAge^2$	**-**	**-**	**0.000***
$ToddAge^3$	**-**	**-**	**0.000****
Level-1 (σ_ε^2)	1.713	1.612	0.897

Figure 9. Construction Skill across Infant and Toddler Ages by Action.

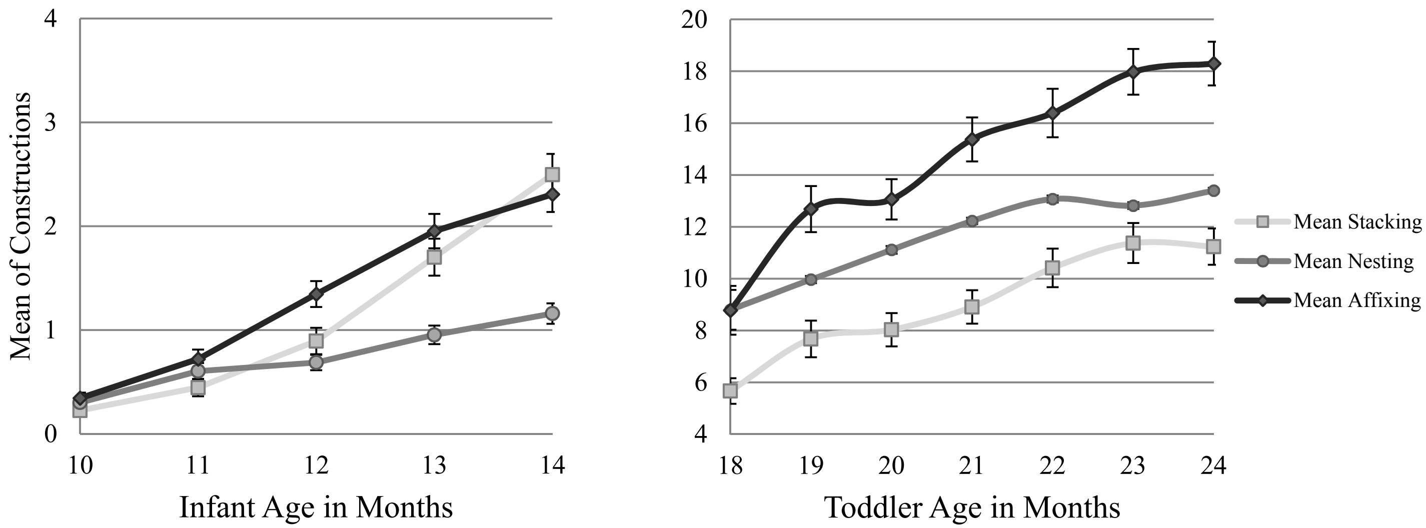
Infant Ages	Toddler Ages

A) Model Estimates of Construction Skill Across Infant and Toddler Ages by Action (Unconditional Growth Model)



Infant Ages	Toddler Ages

B) Mean Construction Skill across Infant and Toddler Ages



Bars are Standard Errors
The nesting lines do have standard errors on them; but they are small.

Additionally, infant construction performance also predicted toddler construction performance for the same action. Performance ability was calculated by creating a proportion of constructed items relative to construction opportunities at 14 months of age. Nesting ability at 14 months predicted 18 month (γ_{01}=0.657, p=0.028) and 24 month (γ_{01}=0.102, p=0.011) nesting ability. Stacking ability at 14 months predicted 18 month (γ_{01}=0.634, p=0.040) and 24 month (γ_{01}=0.635, p=0.040) stacking ability. Affixing ability at 14 months predicted 18 month (γ_{01}=0.096, p=0.005) and 24 month (γ_{01}=0.096, p=0.005) affixing ability.

Construction types also correlated with one another across infancy and some of toddlerhood. Using a Spearman rank-order correlation, stacking correlated with nesting at all infant ages (rs 0.289-0.426, ps 0.001- <0.000). Stacking also correlated with affixing from ages 11-14 months (rs 0.400-0.515, ps <0.000), but not at 10 months (r=0.133, p=0.139). Nesting and affixing correlated at ages 10-13 months (rs 0.247-0.365, ps 0.005-<0.000), but not 14 months (r=0.160, p=0.074). Stacking correlated with affixing at 19 months (r=0.445, p=0.002), 20 months (r=0.404, p=0.004), 22 months (r=0.500, p=0.000), and 23 months (r=0.571, p=0.000). However, stacking did not correlate with nesting, or nesting with affixing during toddlerhood.

How Does Infant Handedness Affect Infant Construction Ability?

GBTM handedness classification was next tested for its effect on the development of construction (Table 5). For stacking, left-handed infants had a significantly lower infant intercept, than stable right- ($\chi 2$=6.620, p=0.035) and trending right-handers

(χ^2=7.075, p=0.028). Infants with a trending right preference had a different infant cubic slope from all other infants for stacking (γ_{32}=-0.110, p=0.027; Table 6). All infant preference groups differed in their quadratic slopes from one another (χ^2s 4.269-13.904 ps 0.036-0.001). At 14 months, stable right-handers (χ^2=14.104, p=0.001) and left-handers (χ^2=17.277, $p < 0.001$) had a higher score, than infants without a preference. Trending right-handers did not differ from any preference group at 14 months (χ^2s 2.166-5.128 ps 0.075-0.339). For affixing, trending right-handers differed in their infant linear slope (γ_{13}=0.164, p=0.018) and intercept (γ_{02}=-0.505, p=0.047). No effects of infant handedness were found for nesting.

Table 5. Full Model for Infant Handedness on Infant Construction†.

$$\log(\lambda_{\text{infant construction}}) = \pi_0 + \pi_1(\text{InfAge}) + \pi_2\,(\text{InfAge}^2) + \pi_3\,(\text{InfAge}^3) + \varepsilon_i$$
$$\pi_0 = \gamma_{00} + \gamma_{01}(\text{InfLeft}) + \gamma_{02}(\text{InfTrend}) + \gamma_{03}(\text{InfStable}) + \delta_{0i}$$
$$\pi_1 = \gamma_{10} + \gamma_{11}(\text{InfLeft}) + \gamma_{12}(\text{InfTrend}) + \gamma_{13}(\text{InfStable}) + \delta_{1i}$$
$$\pi_2 = \gamma_{20} + \gamma_{21}(\text{InfLeft}) + \gamma_{22}(\text{InfTrend}) + \gamma_{23}(\text{InfStable}) + \delta_{2i}$$
$$\pi_3 = \gamma_{30} + \gamma_{31}(\text{InfLeft}) + \gamma_{32}(\text{InfTrend}) + \gamma_{33}(\text{InfStable}) + \delta_{3i}$$

† A model like this was created for each action.

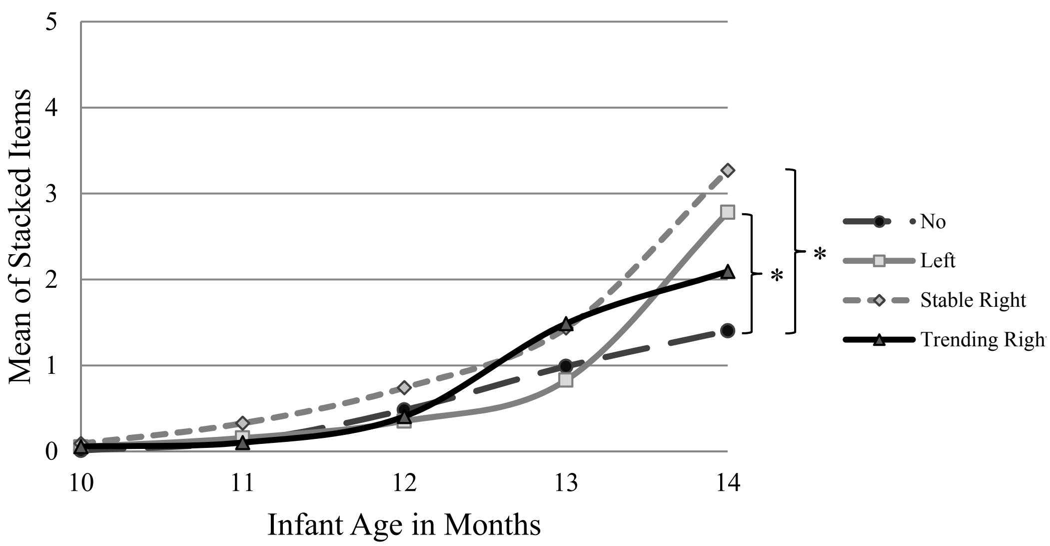
Thus, the ability to stack seems to be affected by an infant hand preference, however not the ability for affixing or nesting objects. Stable right-, left- and trending right-handers all developed the ability to stack differently from infants without a preference and from each other. By 14 months, stable right-handed infants stacked more items than infants without a preference (Figure 10-A). Although stable right-handers did have a different change of rate (quadratic slope) for affixing than trending right-handers, they did not differ on ability at any month (Figure 10-B). Handedness differences for affixing may be significant, but perhaps not meaningful.

Table 6. Estimated Fixed and Random Effects for Sum of Constructed Items by Action and Infant Handedness during Infancy (Final Conditional Growth Model)

	Infant Construction		
Infant Handedness	Stacking	Nesting	Affixing
Fixed Effects†	*Coefficient*	*Coefficient*	*Coefficient*
Inf Intercept	**-4.688*** **	**-2.866*** **	**-2.925*** **
InfAge	**0.976*** **	**0.357*** **	**0.482*** **
$InfAge^2$	**-0.331** **	**-0.054***	**-0.116*** **
$InfAge^3$	0.018	-	-
Left	0.374	-	-
Left*InfAge	-0.313	-	-
Left*$InfAge^2$	**0.305** **	-	-
Stable	0.731	-	-
Stable*InfAge	-0.243	-	-
Stable* $InfAge^2$	**0.208** **	-	-
Trend	-0.382	-	**-0.505***
Trend*InfAge	0.106	-	**0.164***
Trend*$InfAge^2$	**0.364*** **	-	-
Trend*$InfAge^3$	**-0.110***	-	-
Random Effects†	*Variance Component*	*Variance Component*	*Variance Component*
Inf Intercept	**0.690*** **	**0.298*** **	**0.645*** **
Infant Age	**0.013*** **	0.001*	**0.008*** **
Infant Age^2	-	-	**0.007*** **
Inf Level-1 (σ_ε^2)	1.187	1.072	0.857

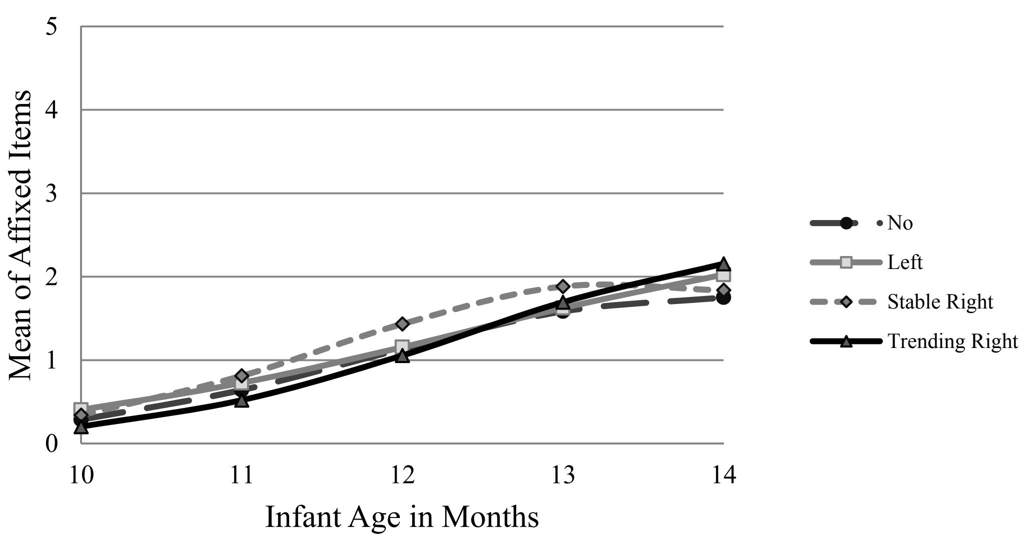
Figure 10. Infant Construction by Infant Handedness Groups (Full Conditional Models)

A) Stacking



* $p<0.05$

B) Affixing



(Nesting was not shown, because there were no effects of handedness.)

Hand Use during Stacking

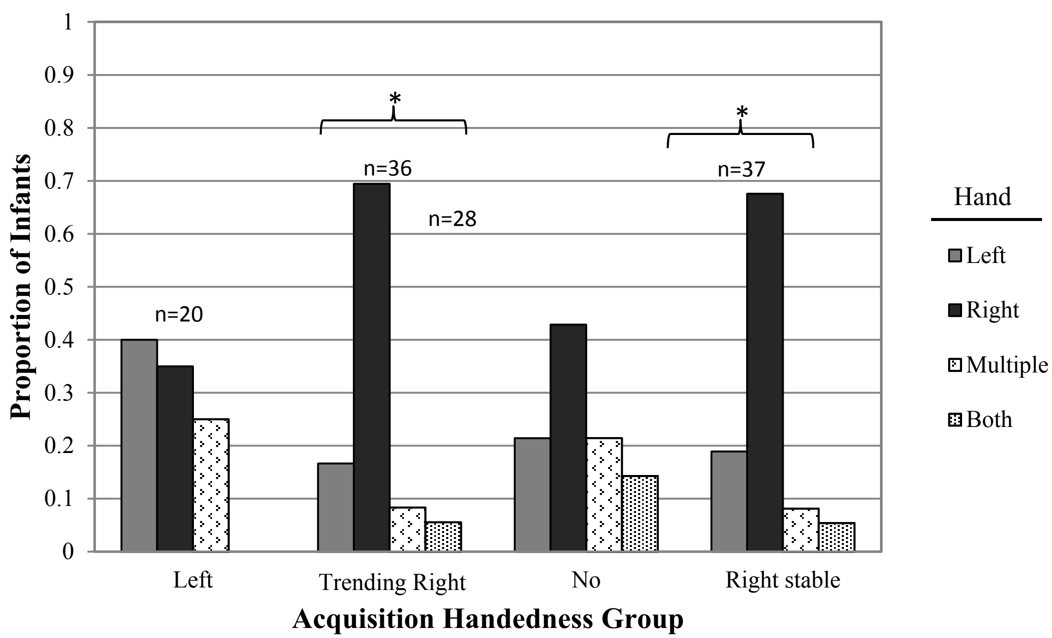
My hypothesis specifically predicts that infants with a preference would perform better only if they used their preferred hand. To test this, I analyzed whether infants with a preference were actually using their preferred hand to stack using binomial tests (Figures 11 A-D). In order to capture the onset of stacking ability, the first visit during which infants could stack was examined. Stable and trending right-handers used their right hands more than their left or both hands (stable: $p<0.000$, trending: $p<0.000$); although no hand effect was found for left-handers or infants without a preference.

I also analyzed hand use for multi-item towers. Multi-item towers were rare at most months, except for 14 months of age, so all multi-item tower analyses were conducted on the 14 month visit. Stable and trending right-handers also used their right hands more than left or both hands when placing the first (stable: $p<0.000$, trend: $p<0.000$) and final items (stable: $p=0.016$, trending: $p=0.018$) in a multi-item tower at 14 months. In contrast, left-handers and infants without a preference demonstrated no significant hand preference.

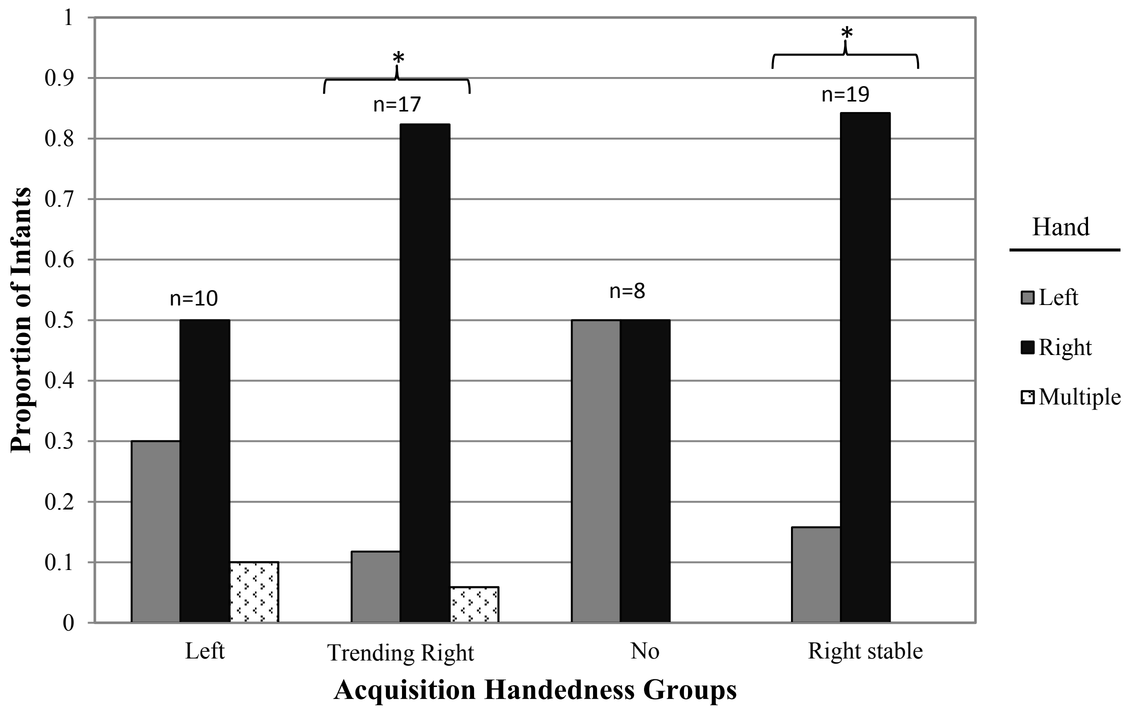
I also assessed how infants used their hands for stacking multi-item towers at 14 months. I categorized an infant's hand-use strategy at each month as a "right" (right hand only), "left" (left hand only), or "mixed" hand strategy (right, left and both hands used or multiple types of strategies were used across toys). No significant differences were found for strategy use for any of the groups; but, regardless of handedness group, infants were more likely to use a mixed strategy ($p<0.000$), than a right or left hand strategy. Within a mixed strategy, stable and trending right-handers used their right hands 70% of the time (n=19). In contrast, left-handers and infants with no hand preference had no identifiable hand bias.

Figure 11. Hand Use for Stacking.

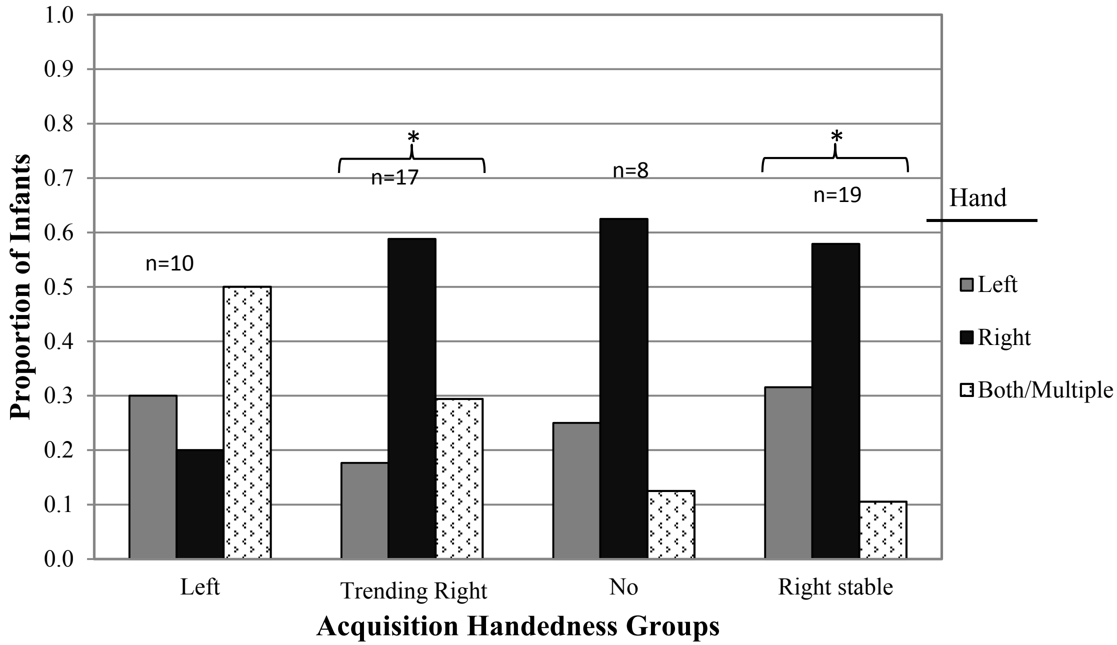
A. Hand used to stack the very first block (At the first visit that an infant could stack).



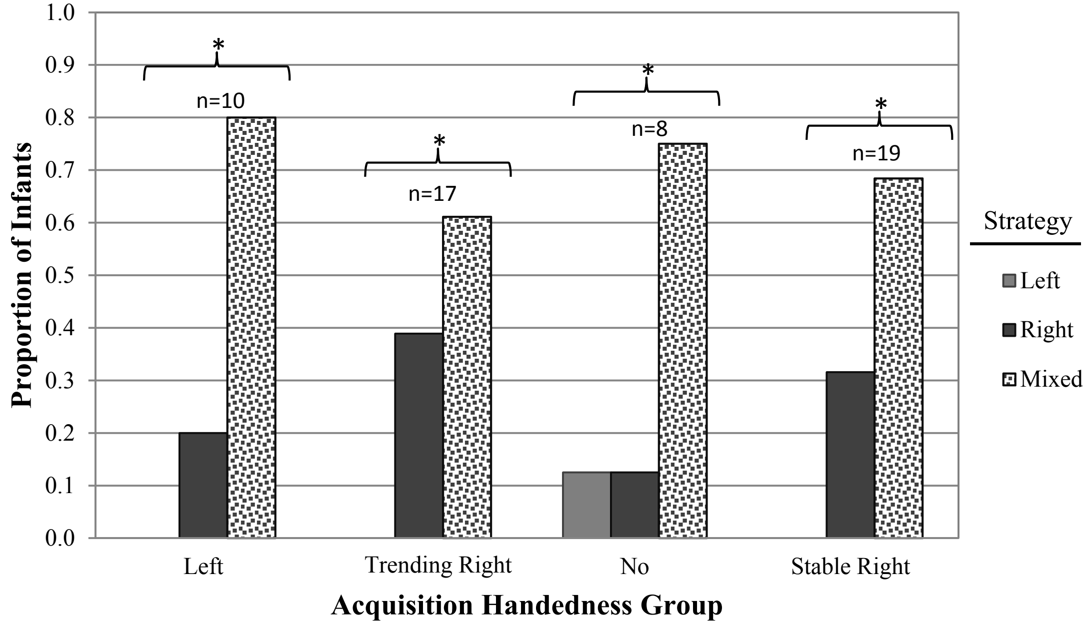
B. Hand used to stack the first item in a multi-item tower (14 months).



C. Hand used to stack the final item in a multi-item tower (14 months).



D. Hand strategies for stacking multi-item towers (14 months).



* Significance at $p<0.05$ using a Binomial test. A-C (Right vs. Not Right) and D (Mixed vs. Not Mixed)

How infants used their hands for stacking 3+ multi-item structures was assessed at 14 months (Figure 11-D). Infant's hand use strategy was categorized as a "right" (right hand only), "left" (left hand only), or "mixed" hand strategy (right, left and both hands used or multiple types of strategies were used across toys). All infant groups were more likely to use a mixed hand strategy (*p*s 0.016-0.001), than a right or left hand strategy. Within a mixed strategy, stable and trending right-handers used their right hands more often than left or both hands (Table 7). In contrast, left-handers and infants with no hand preference used their left hands more often. All groups rarely used both hands to stack (0-5%). This is not unexpected, as the action and size of the toys are more conducive to single hand use.

Table 7. Hand Use during Mixed Hand Strategy for Stacking.

	Left	Right	Both
Left	43%	52%	5%
Trending Right	20%	76%	4%
No	45%	53%	2%
Stable Right	27%	73%	0%

Does Acquisition Hand Use Predict Infant Stacking Ability?

In addition to assessing the effect of hand use during stacking, hand use during acquisition was assessed for its relation to stacking success. The Cascade Theory of Handedness predicts that infants with a hand preference will be more successful at manual skills because the preferred hand will be used more often and become more proficient at performing manual tasks. Other theories of hemispheric specialization of function predict that *right* hand use is actually what will predict success because the left hemisphere is specialized for controlling manual skill. Thus, manual skill should be associated with right hand use rather than *preferred* hand use. An HLM model was conducted to assess whether *right* or *preferred* hand use predicted stacking skill within each handedness group (Table 8). Only stacking was modeled for preferred hand use, since no effects of handedness group were found for nesting or affixing skill.

Hand use during the 6-9 month period was used, since this is period represents an early sub-set of hand use. Using GBTM hand use preference groups means that hand-use for identifying the preference includes those months that occur after the earliest recorded construction ability (e.g., at 10 months). *Right* hand use was calculated in terms of a proportion of right hand use relative to the number of lateralized pick-ups, summed across the 6-9 month visits (Table 8). *Preferred* hand use was calculated in terms of a proportion of preferred hand use relative to the number of lateralized pick-ups, summed across the 6-9 months visits. An infant's GBTM classification (stable right/trending right/left/no) determined which hand was designated as the "preferred" hand (right/right/left/right, respectively).

Infants without a hand preference were kept within the preferred/right hand use models so that model estimates are more ecologically-valid (i.e., not just lateralized infants are tested), because all infants are included in the model. Since infants without a hand preference do not have a "preferred hand", the right hand was designated as their preferred hand for the main analyses. However, the opposite proportion was coded (i.e., preferred hand use = left / (left + right)) for infants without a preference and the right/preferred hand use was analyzed using these proportions instead. This is to ensure that the findings do not differ, on account that the right hand was selected as the preferred hand for infants without a hand preference.

Table 8. Hand Use Proportions.

Proportion of *Right* Hand Use$_{i.}$ = (Σ(Right)$_{i.}$)/(Σ(Right + Left)$_{i.}$)
Proportion of *Preferred* Hand Use$_{i.}$ = (Σ(Preferred)$_{i.}$)/(Σ(Right + Left)$_{i.}$)
Proportion of *Both* Hand Use$_{i.}$ = (Σ(Both)$_{i.}$)/(Σ(Right + Left + Both)$_{i.}$)

Both hand acquisitions were not included in the preferred and right hand proportions, because a hand preference is characterized by lateralized hand use. Both hand acquisitions can be affected by motor milestones which do not affect lateralized hand use (e.g., walking: Babik, Campbell & Michel, 2011) and so, both hand use might not represent that same phenomenon as unimanual hand use. For these reasons, only lateralized hand use was included in the proportions of *preferred* or *right* hand use. *Both* hand use was calculated in terms of a proportion of both hand use relative to the number of pick-ups, summed across the 6-9 month visits. Since both hand acquisitions were not a part of the handedness classifications, all construction actions will be tested for the effect of both hand use.

Prior analyses have shown that handedness groups differ from one another on hand use across all 6-14 month ages; yet no analyses describe whether these groups differ from one another at the 6-9 month age range. Because some groups are changing their level of hand use across these ages (e.g., trending right-handers), whether these handedness groups actually demonstrate preferential hand use during this period is in question. For example, if trending right-handers do not display preferential hand use during 6-9 months, then the right hand is likely not more proficient than the left hand. Thus, having a proficient, preferred hand cannot be argued as the reason for why trending right-handers succeed at stacking, if, in fact, they *do* succeed at stacking. For this reason, hand use from 6-9 months will be described and analyzed relative to the handedness groups.

In an effort to describe hand use across the 6-9 month ages, 3 one-way ANOVAs were conducted to describe differences between handedness groups for right, preferred and both hand use from 6-9 months. Significant group differences were found for preferred ($F(2,96)=54.161$, $p<0.000$) and right ($F(3,127)=61.270$, $p<0.000$) hand use, but not both ($F(3,127)=1.079$, $p=0.361$) hand use. A Tukey post-hoc test revealed that stable right-handers had significantly higher right (ps < 0.000) and preferred (ps < 0.000) hand use from all other groups. Left-handers used their preferred hand use more than trending right-handers ($p=0.008$). Left-handers also used their right hands less than all other groups (ps 0.000-0.002). Only infants without a preference differed from stable right-handers in both hand use from 6-9 months ($p< 0.000$).

Table 9. Acquisition Hand Use from 6-9 months across Handedness Groups.

Group	Preferred Mean (standard deviation)	Right Mean (standard deviation)	Both Mean (standard deviation)
Left	0.589† (0.120)	0.412 (0.120)	0.310† (0.151)
Trending Right	0.512 (0.090)	0.512 (0.090)	0.313† (0.140)
No	-	0.522 (0.111)	0.349† (0.120)
Stable Right	0.737† (0.079)	0.737† (0.079)	0.285† (0.147)
Overall Sample	*0.592 (0.137)*	*0.561 (0.154)*	*0.313 (0.141)*

† *t*-test with a $p<0.05$ against chance (0.5)

In addition, one-sample *t*-tests were performed on all hand use actions to assess whether proportion of hand use was above chance level performance (i.e., 0.5; Table 9). All groups exhibited both hand use lower than chance levels ($t(22\text{-}37)$s -6.035 – -9.016, $p<0.000$). Stable right- ($t(37)=18.493$, $p<0.000$) and left-handers ($t(22)=3.557$, $p=0.002$) exhibited preferred hand use above chance, but trending right-handers did not ($t(37)=0.822$, $p=0.281$). Infants without a hand preference did not use their right hand more than chance ($t(31)=1.121$, $p=0.210$). Thus, only stable right- and left-handers actually demonstrate a preferential use of their preferred hand from 6-9 months, while trending right-handers do not.

Table 10. Full Model for Infant Hand Use from 6-9 months of Age on Infant Construction.

A. Main Effects of Preferred/Right Hand Use

$$\log(\lambda_{\text{infant construction}}) = \pi_0 + \pi_1(\text{InfAge}) + \pi_2(\text{InfAge}^2) + \pi_3(\text{InfAge}^3) + \varepsilon_i$$
$$\pi_0 = \gamma_{00} + \gamma_{01}(\text{RightHU}) + \gamma_{02}(\text{PrefHU}) + \delta_{0i}$$
$$\pi_1 = \gamma_{10} + \gamma_{11}(\text{RightHU}) + \gamma_{12}(\text{PrefHU}) + \delta_{1i}$$
$$\pi_2 = \gamma_{20} + \gamma_{21}(\text{RightHU}) + \gamma_{22}(\text{PrefHU}) + \delta_{2i}$$
$$\pi_3 = \gamma_{30} + \gamma_{31}(\text{RightHU}) + \gamma_{32}(\text{PrefHU}) + \delta_{3i}$$

B. Both Hand Use

$$\log(\lambda_{\text{infant construction}}) = \pi_0 + \pi_1(\text{InfAge}) + \pi_2(\text{InfAge}^2) + \pi_3(\text{InfAge}^3) + \varepsilon_i$$
$$\pi_0 = \gamma_{00} + \gamma_{01}(\text{BothHU}) + \delta_{0i}$$
$$\pi_1 = \gamma_{10} + \gamma_{11}(\text{BothHU}) + \delta_{1i}$$
$$\pi_2 = \gamma_{20} + \gamma_{21}(\text{BothHU}) + \delta_{2i}$$
$$\pi_3 = \gamma_{30} + \gamma_{31}(\text{BothHU}) + \delta_{3i}$$

HU – stands for hand use

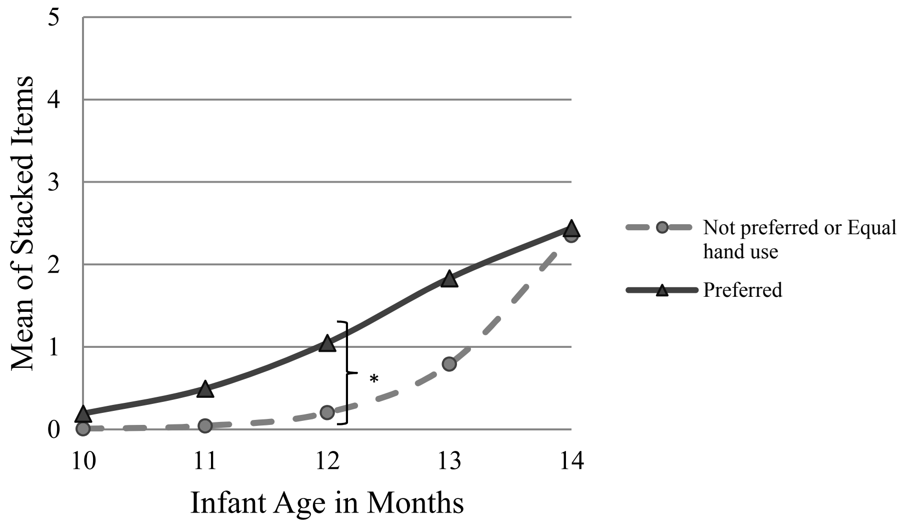
In order to model the effect of hand use on the development of stacking, the proportion of right/preferred/both hand use was included in the HLM model as a continuous variable (Table 10). Based on this model inclusion, the model estimates of proportion of hand use should be interpreted as the mean effect of hand use on stacking skill. The mean effect of *right* hand use did not predict success at infant stacking at the intercept (γ_{01}=1.921, p=0.408), linear slope (γ_{11}=-0.320, p=0.720), quadratic slope (γ_{21}=0.053, p=0.900) or cubic slope (γ_{31}=-0.058, p=0.821; Figure 12-A). The mean effect of *preferred* hand use predicted stacking success at the intercept (γ_{01}=3.242, p=0.031) and linear slope (γ_{11}=-0.801, p=0.049), but not at the quadratic (γ_{21}=0.258, p=0.568) or cubic slope (γ_{31}=0.0.135, p=0.623). The effect of preferred hand use demonstrated higher ability than nonpreferred hand use at 12 months (γ_{01}=1.640, p=0.047). If infants without a preference were removed from the preferred hand analyses, a similar effect for preferred hand use remains (γ_{11}=-0.768, p=0.045). If only infants without a preference were analyzed, no effect for right hand use was found for the intercept (γ_{01}=2.254, p=0.692), linear (γ_{11}=-0.659, p=0.750), and quadratic slope (γ_{21}=-0.419, p=0.837), although this model is estimated on a much smaller sample of infants (n=32) than the full analyses. Infants who used their preferred hand from 6-9 months more often increased their stacking skill more rapidly than infants who used the preferred hand less from 6-9 months; although, infants who used the preferred hand less from 6-9 months caught up by 14 months (Figure 12-A).

Table 11. Estimated Fixed and Random Effects for Sum of Stacked Items and 6-9 month Lateralized Hand Use (Final Conditional Growth Model)

	Infant Construction	
	Stacking	Affixing
Fixed Effects†	*Coefficient*	*Coefficient*
Intercept	**-7.251*****	**-2.769*****
InfAge	**1.513*****	**0.354*****
$InfAge^2$	-0.089	-0.051
$InfAge^3$	-0.012	-
PrefHU	**3.242***	-
PrefHU*InfAge	**-0.801***	**-**
BothHU	**-**	-0.904
BothHU*InfAge	**-**	**0.554***
BothHU*$InfAge^2$	**-**	-0.217
Random Effects†	*Variance Component*	*Variance Component*
Intercept (δ_{0i})	**9.137*****	**0.831*****
InfAge (δ_{1i})	**1.231*****	**0.028****
$InfAge^2$ (δ_{2i})	**0.252*****	-
$InfAge^3$ (δ_{3i})	**0.086*****	-
Level-1 (σ_ε^2)	0.270	0.722

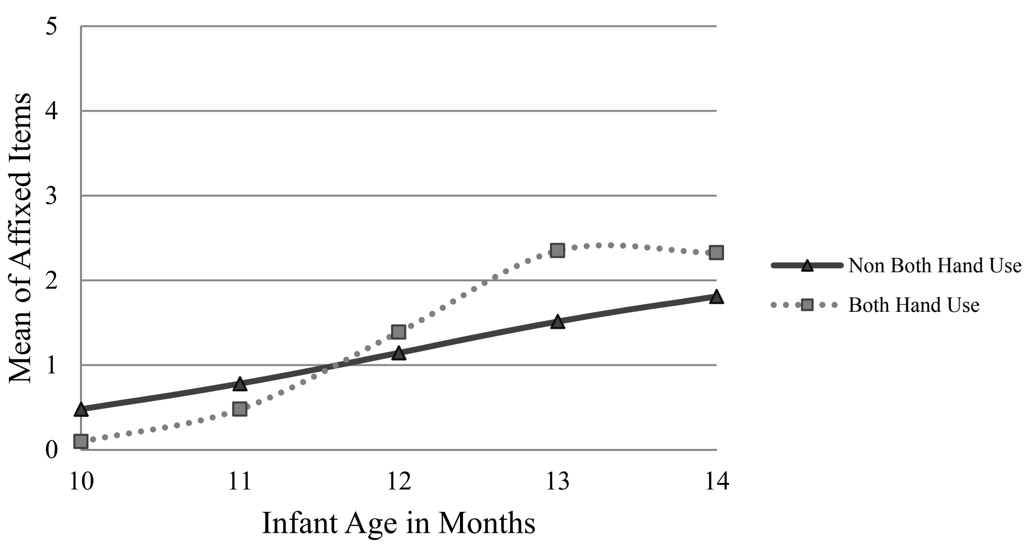
Figure 12. Mean Effects of Acquisition Hand Use on Construction.

A) Mean Effect of Preferred Hand Use on Stacking



* $p < 0.05$

B) Mean Effect of Both Hand Use on Affixing



No significant differences at any one month for affixing.

Both hand use told a different story from lateralized hand use (Figure 12-B. No main effect for both hand use was found for nesting or stacking. Both hand use affected the linear slope for affixing (γ_{11}=0.554, *p*=0.037). It should be noted, however, that there were no significant differences at any one age relative to both hand use (*p*s 0.106-0.384).

Thus, preferred hand use, as opposed to simply right hand use, predicted stacking ability for all groups. Both hand use also predicted a different rate of change for affixing. It is important to note that if a model only tested right hand use, then right hand use *would* predict initial stacking success (γ_{11}=3.100, *p*=0.021) and a higher rate of stacking success (γ_{11}=-0.735, *p*=0.043), similar to the effect found for preferred hand use. Since the majority of infants with a preference are right-handed (i.e., n=76), right hand use might appear to predict stacking ability because any benefits associated with left-handers (n=23) using their left hands are hidden. When a model including both right *and* preferred hand use was tested, right hand use reduced out of the model and preferred hand use remained. Preferred hand use, and not simply right hand use, predicted stacking success.

Handedness and Toddler Construction Ability

Next, the effect of infant and toddler handedness on toddler construction ability was tested (see Table 12). The Level-1 variables were sum of stacking, nesting, and affixing, toddler linear age, toddler quadratic age and toddler cubic age. The Level-2 variables were all infant handedness and toddler handedness groups.

Table 12. Full Model for Infant and Toddler Handedness for Toddler Construction.

$$\log(\lambda_{\text{toddler construction}}) = \pi_0 + \pi_1(\text{TodAge}) + \pi_2(\text{TodAge}^2) + \pi_3(\text{TodAge}^3) + \varepsilon_i$$

$$\begin{aligned}
\pi_0 &= \gamma_{00} + \gamma_{01}(\text{InfLeft}) + \gamma_{02}(\text{InfTrend}) + \gamma_{03}(\text{InfStable}) + \delta_{0i}\\
\pi_1 &= \gamma_{10} + \gamma_{11}(\text{InfLeft}) + \gamma_{12}(\text{InfTrend}) + \gamma_{13}(\text{InfStable}) + \delta_{1i}\\
\pi_2 &= \gamma_{20} + \gamma_{21}(\text{InfLeft}) + \gamma_{22}(\text{InfTrend}) + \gamma_{23}(\text{InfStable}) + \delta_{2i}\\
\pi_3 &= \gamma_{30} + \gamma_{31}(\text{InfLeft}) + \gamma_{32}(\text{InfTrend}) + \gamma_{33}(\text{InfStable}) + \delta_{3i}
\end{aligned}$$

$$\log(\lambda_{\text{toddler construction}}) = \pi_0 + \pi_1(\text{TodAge}) + \pi_2(\text{TodAge}^2) + \pi_3(\text{TodAge}^3) + \varepsilon_i$$

$$\begin{aligned}
\pi_0 &= \gamma_{00} + \gamma_{01}(\text{TodLeft}) + \gamma_{02}(\text{TodHighRight}) + \gamma_{03}(\text{TodModRight}) + \delta_{0i}\\
\pi_1 &= \gamma_{10} + \gamma_{11}(\text{TodLeft}) + \gamma_{12}(\text{TodHighRight}) + \gamma_{13}(\text{TodModRight}) + \delta_{1i}\\
\pi_2 &= \gamma_{20} + \gamma_{21}(\text{TodLeft}) + \gamma_{22}(\text{TodHighRight}) + \gamma_{23}(\text{TodModRight}) + \delta_{2i}\\
\pi_3 &= \gamma_{30} + \gamma_{31}(\text{TodLeft}) + \gamma_{32}(\text{TodHighRight}) + \gamma_{33}(\text{TodModRight}) + \delta_{3i}
\end{aligned}$$

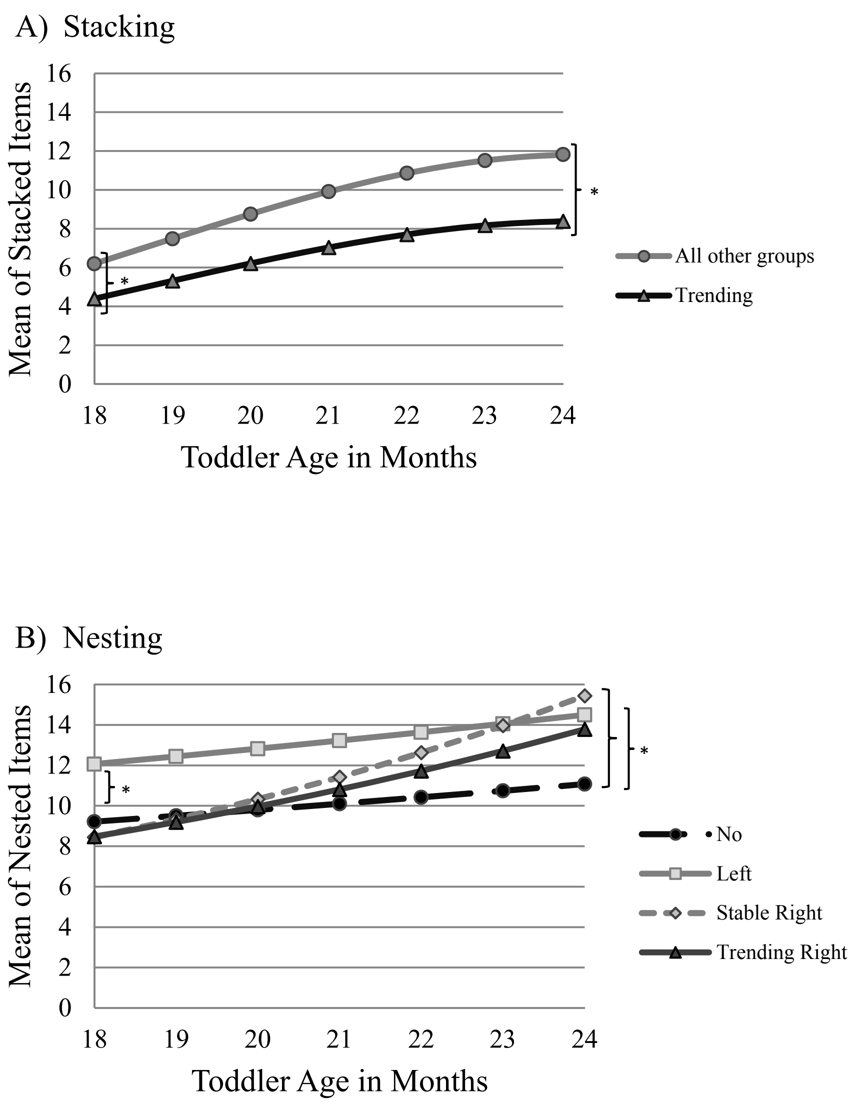
Infant hand preference did appear to affect the development of toddler construction (Table 13 and Figures 13 A-C). Toddlers with a trending right infant preference scored lower on stacking at 18 (γ_{01}=-0.340, p=0.006) and 24 months (γ_{01}=-0.341, p=0.006), than all other groups. Toddlers with a trending right infant preference approached the criterion for being significantly lower at 18 months (γ_{01}=-0.232, p=0.051) on affixing, than left-handers and infants without a hand preference; however they did not differ from stable right- (χ^2=3.360, p=0.184). By 24 months, toddlers with a trending right infant preference equaled all other infants (γ_{01}=-0.062, p=0.307). Toddlers with an infant left hand preference had a higher nesting intercept, than toddlers with a stable right (χ^2=7.792, p=0.020), trending right (χ^2=7.268, p=0.026), or no infant preference (χ^2=4.124, p=0.040). Toddlers with a stable right infant preference had a higher linear slope, than trending right-handers (χ^2=9.014, p=0.011) for nesting. Toddlers with a stable right (γ_{02}=0.331, p=0.021) or left infant preference (γ_{01}=0.269, p=0.045) also have significantly higher nesting scores at 24 months, than toddlers without a hand preference as infants. Toddlers with an infant trending right-hand preference do not differ from toddlers without an infant preference at 24 months (γ_{03}=0.214, p=0.150).

Toddler hand preference had less of an effect on toddler construction, than infant hand preference (Figure 14). High right-handers did exhibit higher stacking at 18 (γ_{01}=0.333, p=0.004) and 24 months (γ_{01}=0.317, p=0.008), than all other groups. No effect for toddler handedness was found for nesting or affixing ability across the 18-24 month period.

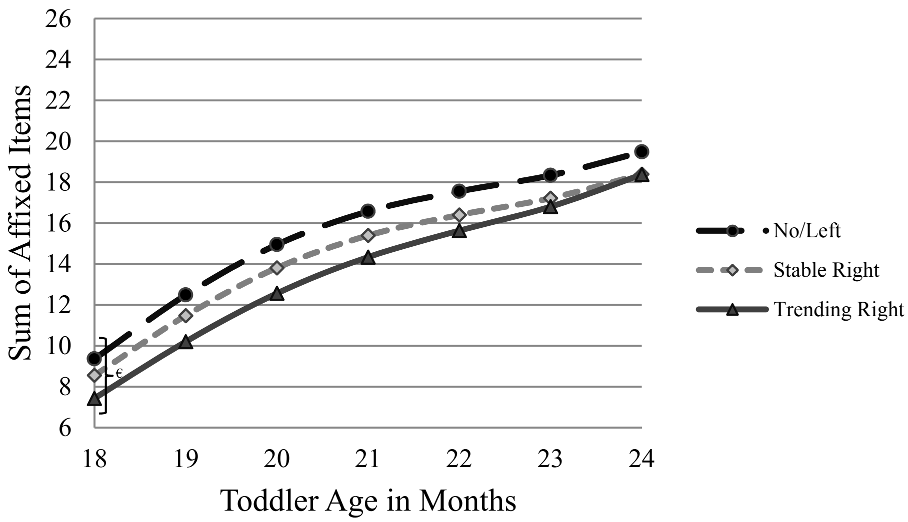
Table 13. Estimated Fixed and Random Effects for Sum of Constructed Items by Action and Handedness (Infancy, Toddlerhood) (Final Conditional Growth Models)

	Toddler Construction		
Infant Preference	Stacking	Nesting	Affixing
Fixed Effects†	*Coefficient*	*Coefficient*	*Coefficient*
Tod Intercept	-1.741***	**-1.275*** **	**-1.029*** **
TodAge	0.155***	0.031	**0.075*** **
$TodAge^2$	0.013	**-**	**-0.023*** **
$TodAge^3$	**-0.014** **	-	0.005
Left	-	**0.269***	-
Left*TodAge	-	-	-
Stable	**-**	-0.087	-0.090
Stable*TodAge	-	**0.070** **	0.005
Trend	**-0.340** **	-0.084	**-0.023**
Trend*TodAge	-	**0.051***	0.029
Toddler Preference	Stacking	Nesting	Affixing
Todd Intercept	-1.725***	**-**	**-**
ToddAge	0.108***	**-**	**-**
$ToddAge^2$	**0.016***	**-**	**-**
Tod High Right	**0.333** **	**-**	**-**
Random Effects†	*Variance Component*	*Variance Component*	*Variance Component*
Tod (InfPref) Intercept	**0.117*** **	**0.078*** **	**0.089** **
Tod (InfPref) Age	**-**	**-**	0.004
Tod (InfPref) Age^2	**-**	**-**	**0.001** **
Tod (InfPref) Age^3	-	-	**0.013***
Inf Level-1 (σ_ε^2)	1.725	1.572	0.820
Tod (TodPref) Intercept	**0.115*** **	**-**	**-**
Tod Level-1 (σ_ε^2)	1.715	**-**	**-**

Figure 13. Model Estimates of Toddler Construction by Infant Handedness Groups (Final Conditional Models)

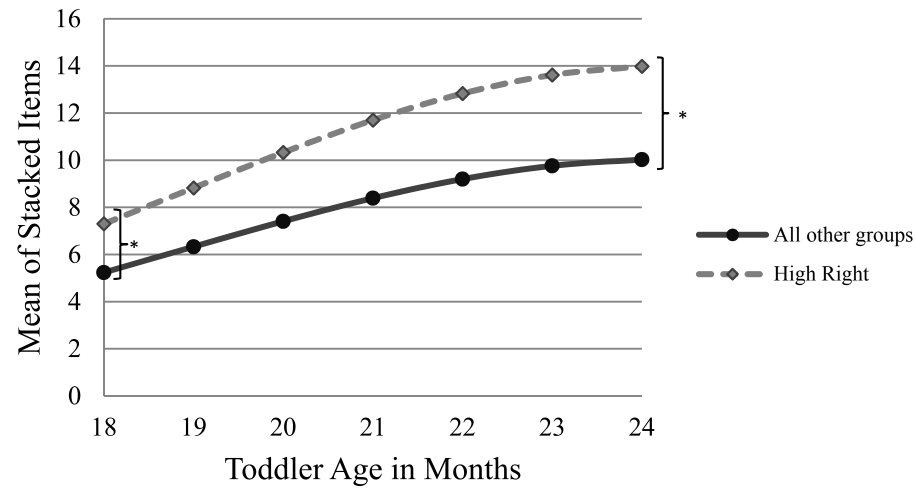


C) Affixing



ϵ p=0.051

Figure 14. Model Estimates of Toddler Stacking by Toddler Handedness Groups (Final Conditional Model)



** p<0.05*

Nesting and Affixing are not shown, because there was no effect of toddler handedness on these actions.

Handedness Consistency and Toddler Construction

Since the Cascade theory specifically predicts that children with a history of preferential hand use will develop greater manual control of the preferred and subsequent proficiency at related manual tasks, toddlers who had a consistent infant and toddler hand preference classification were also tested for greater construction ability. Since there were multiple right hand groups for infant (stable and trending) and toddler (moderate and high), three consistent preference variables were tested. A toddler was considered to be “consistent” if they exhibited a consistent hand preference in the same direction (e.g., right-right). The first was a “consistent right” group (CR; n=24), which comprised right-handed infants (trending or stable) becoming right-handed toddlers (moderate or high).

The second was a “consistent stable right” group (CStR; n=16), which comprised infants with an infant stable right preference becoming right-handed toddlers (moderate or high). The final was a “consistent lateralized” group (n=24), which comprised stable right- and left-handed infants becoming right-handed (moderate or high) or left-handed as toddlers, respectively. Concerns for sample size precluded the possibility of testing a “consistent left” group, separately from right-handers.

No effect was found for the “consistent right” grouping for any action. No consistency effect was found for sum of affixing across the toddler ages. Consistent stable right-handers showed a higher linear growth rate for nesting (γ_{11}=0.056, p=0.023), than other infants (Figure 15 and Table 14). Consistent stable right-handers also approached the significance criterion for greater stacking ability at 18 (γ_{01}=0.213, p=0.051) and 24 months (γ_{01}=0.216, p=0.050), than other infants. Consistently lateralized infants did not differ in their linear growth (γ_{11}=0.041, p=0.059) for nesting; but consistently-lateralized infants had greater nesting ability at 24 months (γ_{01}=0.212, p=0.015).

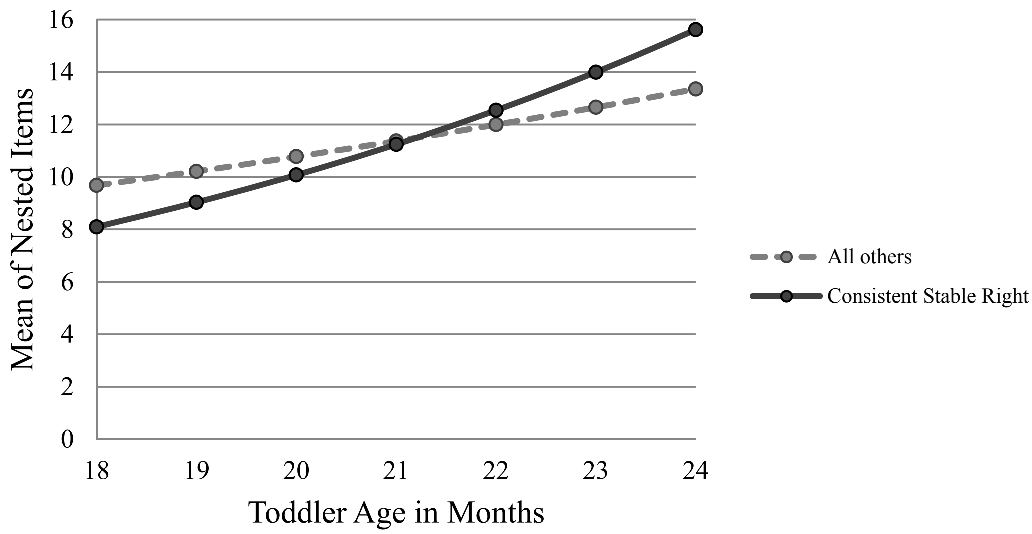
Table 14. Estimated Fixed and Random Effects for Sum of Items Constructed by Action (Toddlerhood) and Handedness Consistency (Infant-Toddler) (Final Conditional Growth Model)

	Toddler Construction	
Consistency	Stacking	Nesting
Fixed Effects†	*Coefficient*	*Coefficient*
Tod Intercept	-1.741***	**-1.257*** **
TodAge	**0.113*** **	**0.053*** **
TodAge^2	-0.011	**-**
CLat	**-**	**0.342***
CStR	**0.214$^{€}$**	**-0.490***
CStR*TodAge	-	**0.056***
CStR*TodAge^2	-	-
CStR*TodAge^3	**-**	-
Random Effects†	*Variance Component*	*Variance Component*
Tod Intercept	**0.130*** **	**0.086*** **
Level-1 (σ_{ε}^2)	1.744	1.262

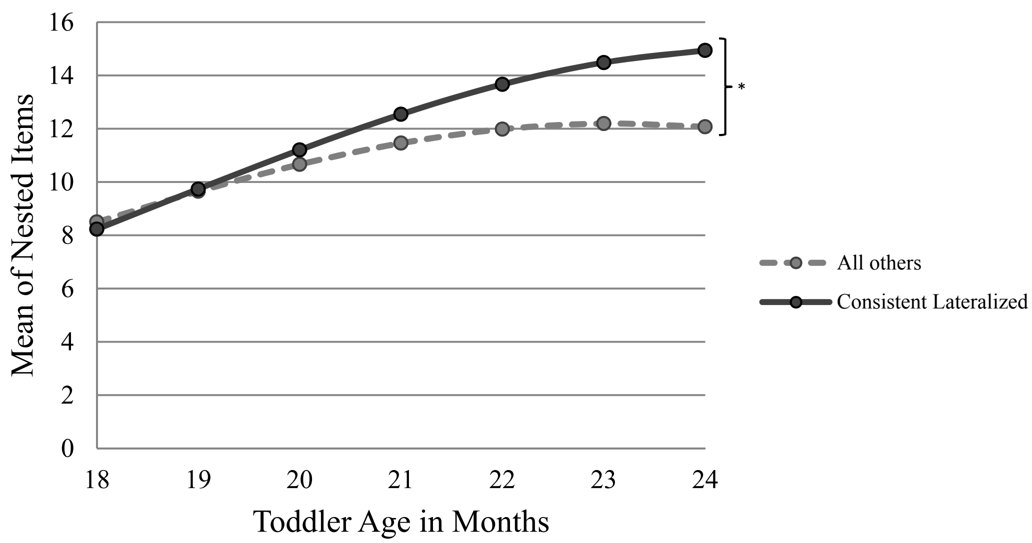
CStR – "consistent stable right" CLat – "consistent lateralized"
$^{€}$ p=0.051

Figure 15. Hand Preference Consistency on Toddler Nesting and Stacking Ability.

A) Nesting

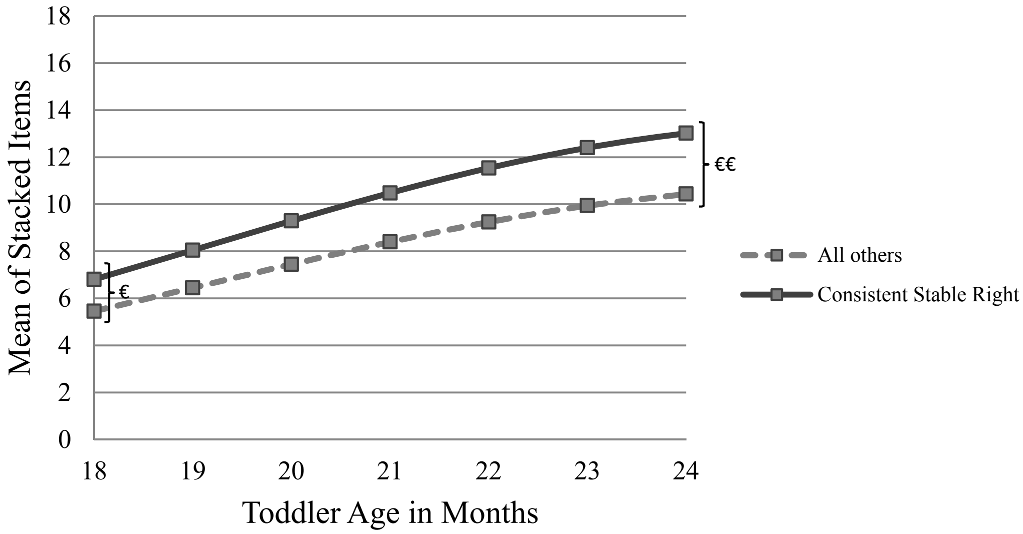


No significant differences between consistent stable right-handers and all other groups at any one month for nesting.



* *p*<0.05

B) Stacking



€ p=0.051 €€ p=0.050

Does Hand Use Also Affect Toddler Construction?

As with the infant sample, hand use was assessed for its effect on construction success. An HLM model was conducted to assess whether *right* or *preferred* hand use predicted stacking skill within each handedness group. Unlike the infant sample, both hand use cannot be modeled, because toddler handedness is based on RDBM, which by its definition does not allow for coding both hand use.

Since there was no point at which toddlers were given only the handedness task, hand use at the 18 month visit was used to calculate the proportions of lateralized hand use. Also, to compare hand use at the end of the period with construction ability at the end of the period, the proportion of lateralized hand use at the 24 month visit was also calculated for analysis. In the same way that infant hand use proportions were calculated, toddler proportions of right and preferred hand use were created. *Right* hand use was calculated in terms of a proportion of right hand use relative to the total number of RDBMs at the 18 or 24 month visits. *Preferred* hand use was calculated in terms of a proportion of preferred hand use relative to the number of RDBMs at the 18 or 24 month visits. The preferred hand for each toddler was again designated based on their GBTM classification (i.e., the left hand was the preferred hand of the left-handed toddlers). Since toddlers without a hand preference exhibited a slight right hand preference, the right hand was designated as the preferred hand for these toddlers. As with the infant analyses, the reverse proportion was also tested (i.e., a left proportion for toddlers without a preference was also modeled).

Although prior analyses have shown that toddler handedness groups differ from one another on hand use for RDBM across the 18-24 month ages, these analyses do not describe how the groups differ from one another at the 18 and 24 month ages. As with the infant hand use variables, 2 one-ways ANOVAs were conducted to describe group differences for right and preferred hand use at 18 and 24 months (Table 15). Significant group differences were found for preferred ($F(2,51)=5.27$, $p<0.008$) and right ($F(2,51)=127.569$, $p<0.000$) hand use at 18 months. A Tukey post-hoc test revealed that high right-handers had significantly higher right ($p<0.000$) and preferred ($p=0.009$) hand use, than left-handers. High right-handers did not have right hand use that was higher than moderate right-handers, although the t value was near criterion cut-off ($p=0.052$). Left-handers used their preferred hand more than trending right-handers (p=0.008). Left-handers also used their right hands less than either right hand group (ps <0.000).

At 24 months, significant group differences were found for preferred ($F(2,47)=22.809$, $p<0.000$) and right ($F(3,63)=259.954$, $p<0.000$) hand use at 24 months. High right-handers had a higher proportion of right hand use than all groups (ps <0.000), while left-handers had the lowest proportion of right hand use (ps <0.000). Moderate right-handers had a higher proportion of right hand use, than toddlers without a preference ($p<0.000$). Left-handers had a lower proportion of preferred hand use, than moderate ($p=0.006$) and high ($p<0.000$) right-handers at 24 months.

Table 15. RDBM Hand Use at 18 months across Handedness Groups

Groups	Preferred Mean (standard deviation)	Right Mean (standard deviation)
	18 months	
Left	0.762† (0.132)	0.238† (0.132)
Moderate Right	0.795† (0.172)	0.795† (0.172)
No	-	0.597 (0.271)
High Right	0.900† (0.056)	0.900† (0.056)
Overall Sample	*0.818† (0.141)*	*0.647† (0.318)*
	24 months	
Left	0.646† (0.197)	0.354† (0.0.132)
Moderate Right	0.774† (0.044)	0.774† (0.044)
No	-	0.573† (0.063)
High Right	0.914† (0.042)	0.914† (0.042)
Overall Sample	*0.787† (0.149)*	*0.647† (0.318)*

† t-test with a $p<0.05$ against chance (0.5)

In addition, one-sample t-tests were performed on all hand use actions to assess whether proportion of hand use was above chance level performance at 18 and 24 months (i.e., 0.5; Table 15). All groups exhibited preferred hand use higher than chance levels at 18 ($t(16\text{-}17)$s 7.265-29.493, ps <0.000) and 24 months ($t(13\text{-}18)$s 2.676-40.998, ps 0.019-0.000). High right, moderate right and toddlers without a preference all use their hands right hands more than chance at 18 and 24 months, while left-handers use their left hands more than chance at both ages.

Table 16. Full Model for Toddler Hand Use at 18 months of Age on Toddler Construction.

$$\log(\lambda_{\text{toddler construction}}) = \pi_0 + \pi_1(\text{TodAge}) + \pi_2\,(\text{TodAge}^2) + \pi_3\,(\text{TodAge}^3) + \varepsilon_i$$
$$\pi_0 = \gamma_{00} + \gamma_{01}(\text{RightHU}) + \gamma_{02}(\text{PrefHU}) + \delta_{0i}$$
$$\pi_1 = \gamma_{10} + \gamma_{11}(\text{RightHU}) + \gamma_{12}(\text{PrefHU}) + \delta_{1i}$$
$$\pi_2 = \gamma_{20} + \gamma_{21}(\text{RightHU}) + \gamma_{22}(\text{PrefHU}) + \delta_{2i}$$
$$\pi_3 = \gamma_{30} + \gamma_{31}(\text{RightHU}) + \gamma_{32}(\text{PrefHU}) + \delta_{3i}$$

HU – stands for hand use

Next, right and preferred hand use were modeled on toddler construction ability (Tables 16 and 17). *Right* hand use did not predict success at toddler stacking at the intercept (γ_{02}=0.595, p=0.229), linear slope (γ_{12}=-0.113, p=0.428), quadratic slope (γ_{22}=0.005, p=0.884), or cubic slope (γ_{32}=0.008, p=0.688). The main effect of *preferred* hand use predicted stacking success at the linear slope (γ_{11}=0.121, p=0.030) but not at the quadratic (γ_{21}=0.005, p=0.916) or cubic (γ_{31}=-0.047, p=0.076) slopes. Toddlers that used their preferred hand more often at 18 months had higher stacking skill at 24 months (γ_{01}=0.521, p=0.023), than toddlers who used the preferred hand less (Figure 16-A). Again, when the proportion of preferred hand use at 18 months was reversed for toddlers without a preference (i.e., a left proportion was modeled, rather than a right), a preferred hand use at 18 months predicted higher stacking for 18 (γ_{01}=0.435, p=0.032) and 24 months (γ_{01}=0.434, p=0.032).

Table 17. Estimated Fixed and Random Effects for Sum of Constructed Items and 18 month Lateralized Hand Use (Final Conditional Growth Model)

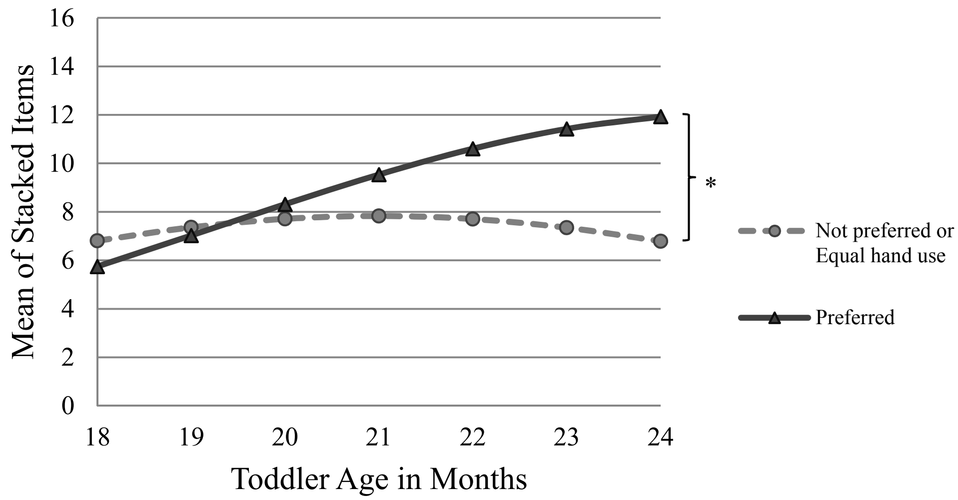
	Toddler Construction	
	Stacking	Nesting
Fixed Effects†	*Coefficient*	*Coefficient*
Intercept	**-1.491*** **	**-1.152*** **
TodAge	0.008	-0.005
TodAge^2	**-0.017***	**-**
TodAge^3	0.001	**-**
PrefHU	-0.169	-0.156
PrefHU*TodAge	**0.122***	**0.096***
Random Effects†	*Variance Component*	*Variance Component*
Intercept (δ_{0i})	**0.137*** **	**0.084*** **
Level-1 (σ_ε^2)	1.688	1.600

For nesting, again *right* hand use did not predict success at the intercept (γ_{02}=-0.416, p=0.138), linear slope (γ_{12}=0.002, p=0.963), or quadratic slope (γ_{22}=0.038, p=0.106; Figure 17-B). On the other hand, *preferred* hand use predicted a higher rate of nesting development (γ_{11}=0.096, p=0.036). Preferred or right hand use had no effect on the development of affixing during toddlerhood.

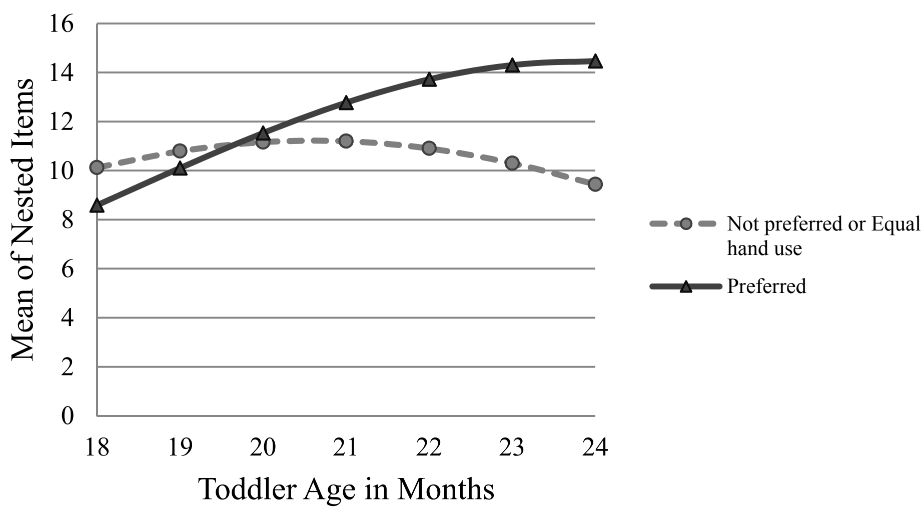
Preferred hand use for RDBM and not simply right hand use was shown to predict success at stacking and nesting (Figures 16 A-B). Again, it should be noted that right hand use at 24 months predicted stacking ability at 24 months (γ_{02}=0.498, p=0.049), when preferred hand use was not included in the model. Right hand use at 18 months does not predict the linear slope for stacking (γ_{11}=0.021, p=0.593), while preferred hand use does. Also, preferred hand use at 24 months predicts higher stacking ability at 24 months (γ_{01}=0.978, *p*=0.004). Interestingly, *only* preferred hand use predicts an increased rate of nesting development, while right hand use does not predict nesting at the intercept (γ_{02}=-0.094, *p*=0.640), linear slope (γ_{12}=0.027, *p*=0.484) or quadratic slope (γ_{22}=0.029, *p*=0.186). As with the infant data, *preferred* hand use, rather than *right* hand use, appears to predict construction ability.

Figure 16. Model Estimates of Toddler Construction and RDBM Hand Use (Final Conditional Models)

A) Mean Effect of Preferred Hand Use for Stacking



B) Mean Effect of Preferred Hand Use for Nesting



* $p<0.05$

Affixing was not included, because there were no effects of hand use.

One interesting feature of these data is the role of preferred hand use and the increase in skill. All lines have a slope different from 0; but not all lines appear to increase across 18-24 months. Using a repeated measures *t*-test, the model estimate for the 24 month visit on the preferred hand use line was higher than the 18 month visit ($t(63)=2.579$, $p=0.016$), indicating a significant increase from 18-24 months. However, the model estimate for the 24 month visit on the non-preferred hand use line was found to be equal to the 18 month visit $t(63)=0.255$, $p=0.397$), indicating no significant increase in ability across toddlerhood.

Analyses of the Infant and Toddler Ages within a Single Model

Finally, the role of infant and toddler handedness was explored across the entire period (i.e., within a single model) using a piecewise multilevel Poisson longitudinal model. A piecewise model does not assume that the rate of growth has a constant change. It is often used when there are distinct periods of change or where there is a "natural" breaking point (e.g., onset of walking, entry into kindergarten, halves in a soccer game). The current study's dataset comprises two unique periods of change (infant and toddler) and so, a piecewise model was used to marry the longitudinal information from both periods and more accurately fit the non-constant change.

The current study used an incremental age coding scheme to model age across infant and toddler ages. An incremental age coding scheme allows for change occurring from infant through toddler ages, as well as account for any unique change during the toddler ages (see Appendix C for age coding). Within a piecewise model, multiple age codes (and any higher order multiples) are created in order to separate the two periods of change within the model. Regarding the current study's coding scheme, there are two age periods: the infant/toddler ages and the toddler-only ages. The infant/toddler ages encompass all 12 timepoints across 10-24 months. The toddler-only ages separate the 18-24 months for separate analysis from the infant/toddler ages. For this overall picture of infant and toddler construction development, the effect of infant handedness on infant and toddler construction ability was modeled (see Table 18).

The incremental coding scheme was specifically chosen, because earlier infant construction skill was found to predict toddler construction skill. Another coding scheme (i.e., a two-rate model) can separate change within the infant and toddler ages from one another. Within a two-rate model, an "infant-only" variable denotes change within the infant period (e.g., 0, 1, 2, 3, 4), but then the toddler ages are constant (e.g., 4, 4, 4, etc.). Then "toddler-only" variables exhibit no change during the infant period (e.g., 0, 0, 0, etc.) and then change occurs during toddler visits (e.g., 1, 2, 3, etc.). However, infant construction skill was found to predict toddler construction skill for all actions. Any change that occurs during infancy must have some effect on the development of toddler construction skill. For this reason, an incremental model was selected, rather than a two-rate model.

Table 18. Model Estimates for Sum of Constructed Items by Action Using a Piecewise Model (Unconditional Growth Models)

	Infant-Toddler Construction		
	Stacking	Nesting	Affixing
Fixed Effects†	*Coefficient*	*Coefficient*	*Coefficient*
Intercept	-0.802***	-1.731***	-0.815***
InfTodAge	-0.156***	0.033	-0.105***
InfTodAge^2	**-0.130*****	**-0.040*****	**-0.091*****
TodAge	0.391***	0.219*	0.440***
ToddAge^2	**0.118*****	**0.024****	**0.070*****
Random Effects†	*Variance Component*	*Variance Component*	*Variance Component*
Intercept (δ_{0i})	**0.947****	**0.934****	**0.922*****
InfTodAge (δ_{1i})	**0.026****	**0.028****	**0.018*****
InfTodAge^2 (δ_{2i})	**0.001*****	**0.000***	-
TodAge (δ_{3i})	**0.195****	**0.145****	**0.083*****
Tod Age^2 (δ_{4i})	-	-	**0.001*****
Level-1 (σ_ε^2)	1.148	0.996	0.823

The infant and toddler ages were marked by quadratic change (Figure 18). Stacking (γ_{20}=-0.130, p<0.000), nesting (γ_{20}=0.040, p<0.000), and affixing (γ_{20}=-0.091, p<0.000) all had significant quadratic slopes. Also, all parameters had significant variance components for the infant-toddler age variable. The toddler-only age slope provided a unique contribution to the model, above and beyond the infant-toddler age slope in all three types of construction. Stacking (γ_{40}=0.118, p<0.000), nesting (γ_{40}=0.024, p=0.009), and affixing (γ_{40}=0.070, p<0.000) all had a toddler-only quadratic term. Because the toddler-only slopes were significant, toddlerhood does not develop as one continuous trajectory from infancy through toddlerhood. Instead the 18-24 ages represent a meaningful change in the way construction develops between infancy and toddlerhood.

Handedness also affected the development of all three construction actions across toddlerhood (Table 19). Trending right-handedness affected the development of stacking at the toddler age quadratic slope (γ_{51}=0.051, p=0.036); however no other preference group affected stacking at the toddler-only slope (see Figures 18 A and B). Stable right-handers (γ_{11}=-0.036, p=0.046) had a lower linear slope than infants without a preference (χ^2=11.654, p=0.003) and had a higher linear slope than trending right-handers (χ^2=6.512, p=0.037). Trending right-handers also differed from other handedness groups for affixing at the infant-toddler quadratic slope (γ_{21}=-0.038, p=0.020) and the toddler quadratic slope (γ_{41}=0.041, p=0.017; Figure 19). For nesting, left-handers had a higher infant-toddler linear slope (γ_{21}=0.069, p=0.012), but then slowed significantly more than all other groups (γ_{31}=-0.012, p=0.002; Figure 20).

Figure 17. Model Estimates of Construction Skill across Infant and Toddler Ages (Unconditional Growth Model)

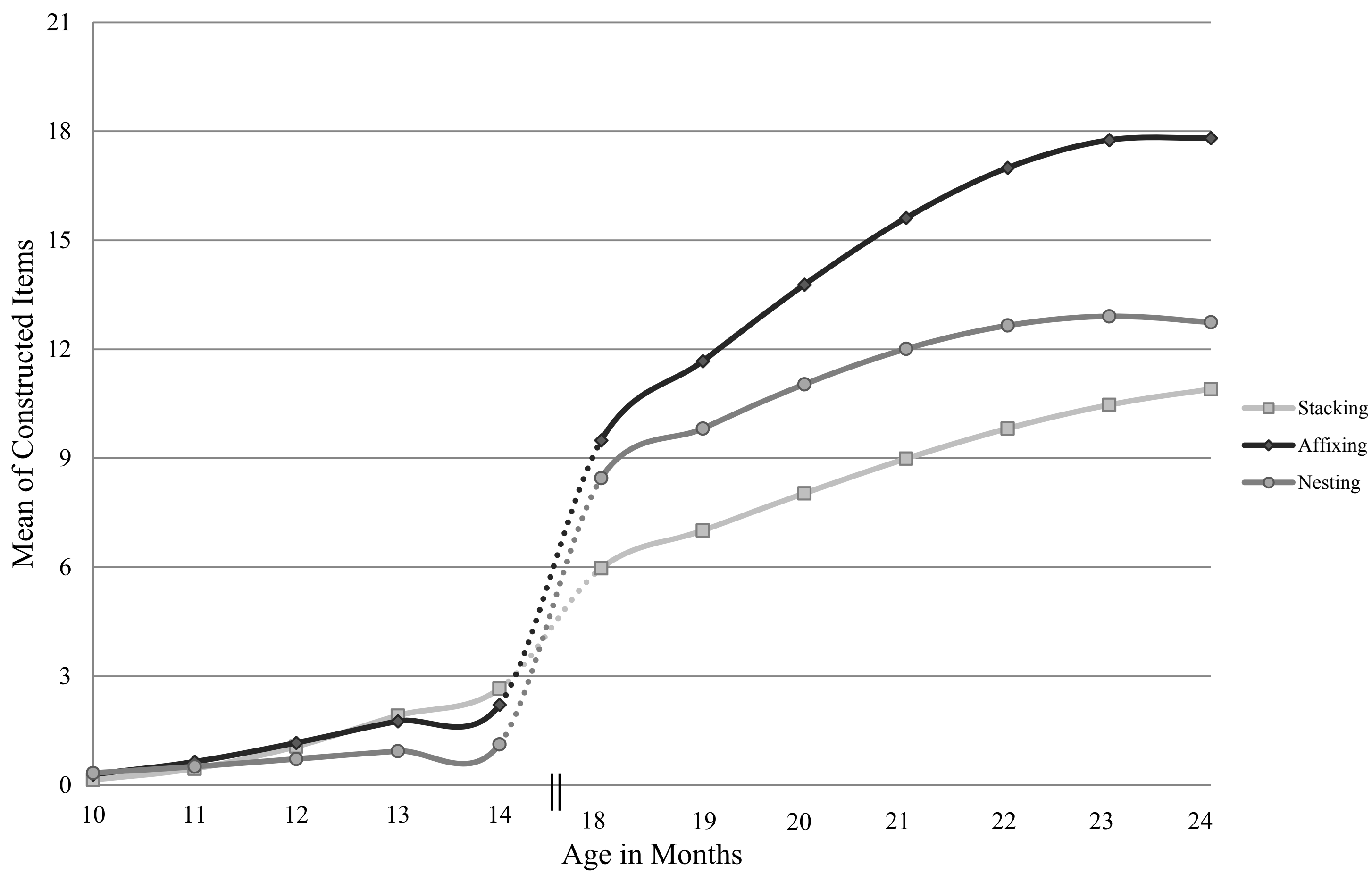
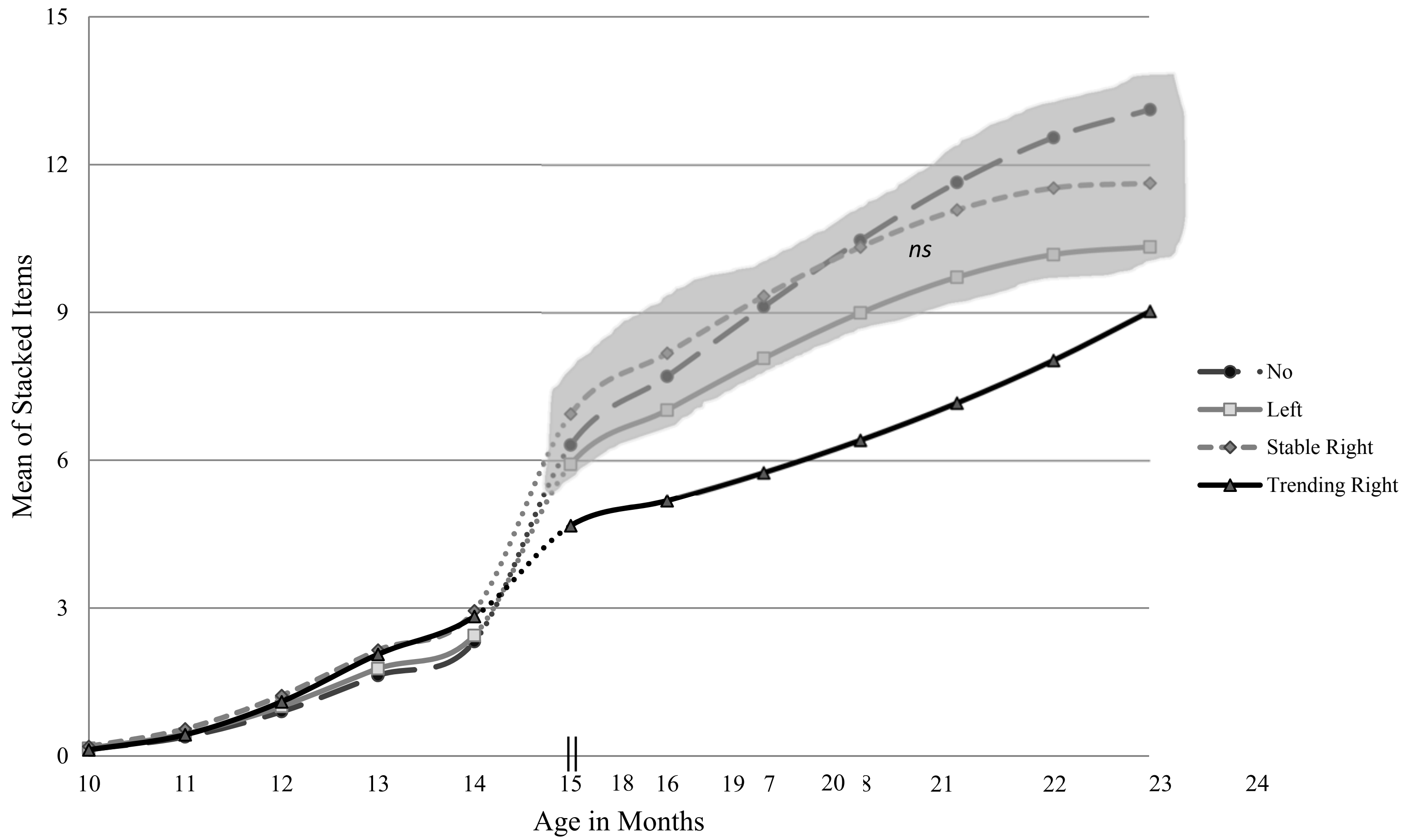


Table 19. Estimated Fixed and Random Effects for Sum of Constructed Items by Action and Infant Handedness Using a Piecewise Model (Final Conditional Growth Models)

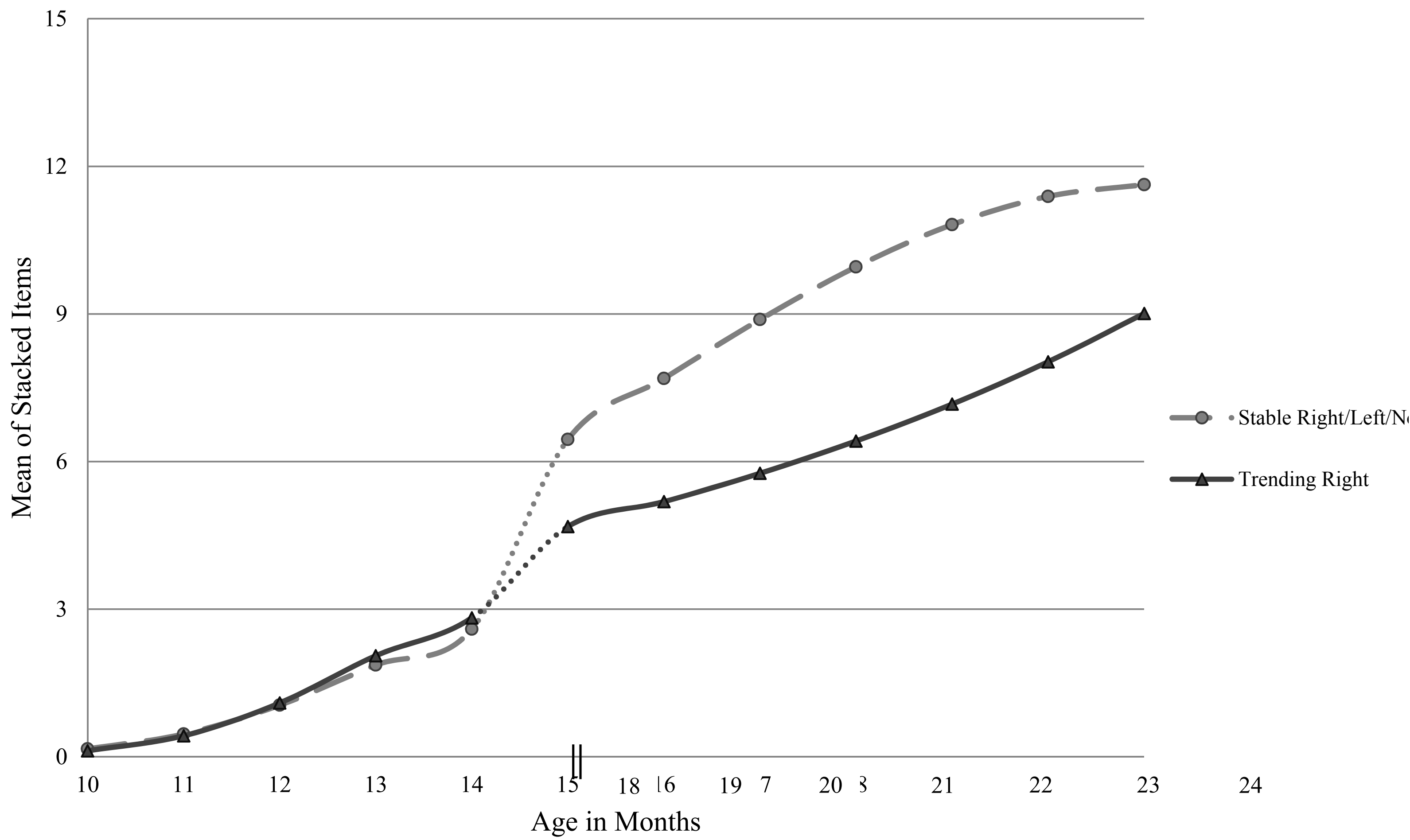
	Construction		
	Stacking	Nesting	Affixing
Fixed Effects†	*Coefficient*	*Coefficient*	*Coefficient*
Intercept	-1.182***	-1.687***	-0.928***
InfTodAge	-0.098*	0.0168	-0.083*
$InfTodAge^2$	**-0.122*****	**-0.039*****	**-0.082*****
$InfTodAge^3$	-	-	-
TodAge	0.395**	0.222*	0.422***
$ToddAge^2$	**0.106*****	**0.025****	**0.060*****
Left	0.169	-0.145	-
Left*InfTodAge	-0.029	0.069*	-
Left*$InfTodAge^2$	-	**-0.012****	-
Stable	0.382	-	-
Stable*InfTodAge	**-0.036***	-	-
Stable* $InfTodAge^2$	-	-	-
Stable*TodAge	-	-	-
Trend	0.896	-	0.489
Trend*InfTodAge	-0.159	-	-0.094
Trend*$InfTodAge^2$	-0.034	-	**-0.038***
Trend*$InfTodAge^3$	-	-	-
Trend*TodAge	-0.044	-	0.084
Trend*$TodAge^2$	**0.051***	-	**0.041***
Random Effects†	*Variance Component*	*Variance Component*	*Variance Component*
Intercept (δ_{0i})	**0.942*****	**0.920****	**0.927*****
InfTodAge (δ_{1i})	**0.157****	**0.027****	**0.018*****
$InfTodAge^2$ (δ_{2i})	**0.031*****	**0.000***	-
TodAge (δ_{3i})	**0.437****	**0.141****	**0.084****
Tod Age^2 (δ_{4i})	-	-	**0.001****
Level-1 (σ_ε^2)	1.151	0.999	0.821

Figure 18. Model Estimates of Infant Handedness Groups across Infant and Toddler Ages for Stacking.

A) Full Piecewise Conditional Growth Model



B) Reduced Piecewise Conditional Growth Model



No differences between stable right, left and no preference groups.

Figure 19. Model Estimates of Infant Handedness Groups across Infant and Toddler Ages for Affixing (Final Piecewise Conditional Growth Model)

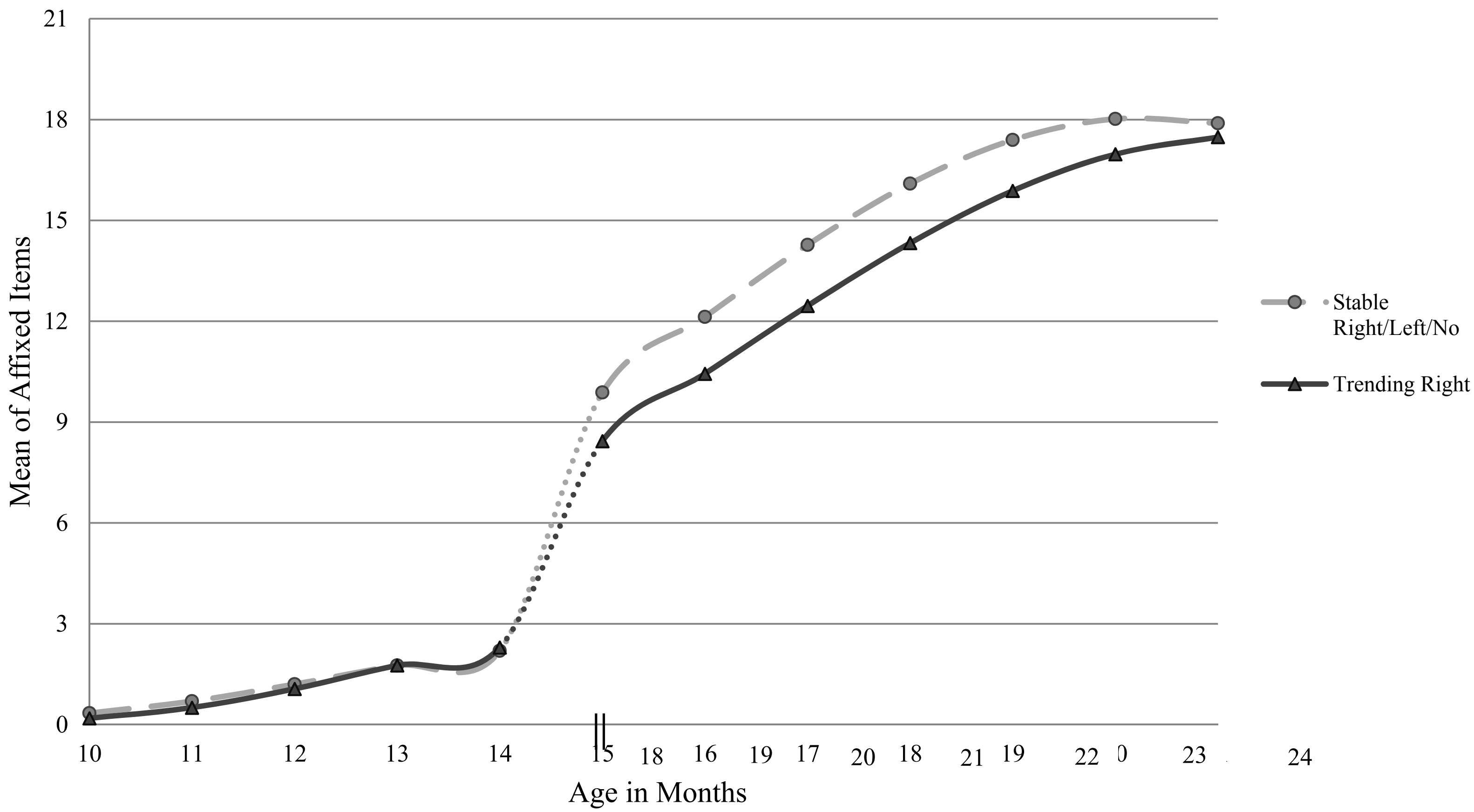
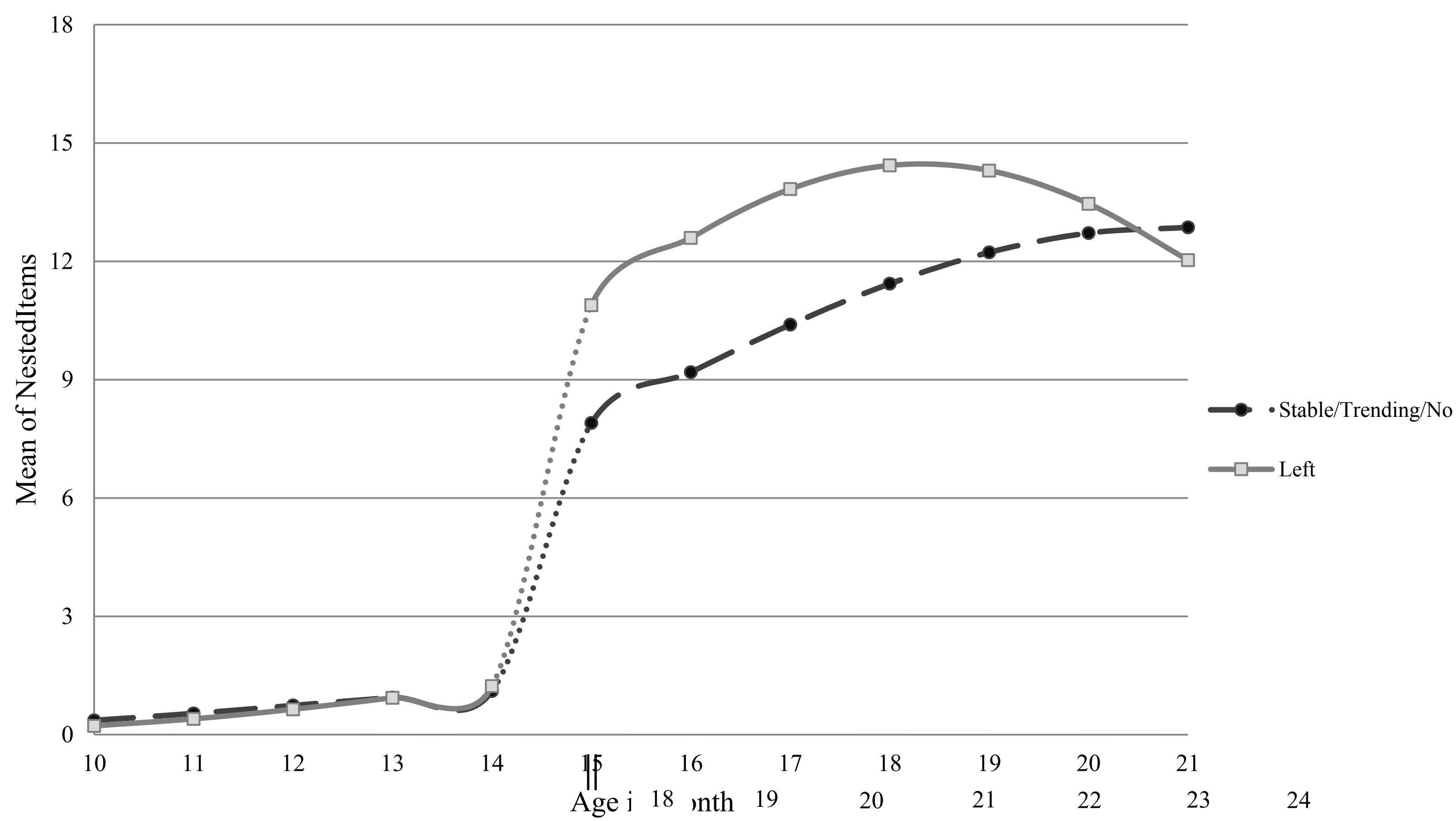


Figure 20. Model Estimates of Infant Handedness Groups across Infant and Toddler Ages for Nesting (Final Piecewise Conditional Growth Model)



Interestingly, trending right-handers developed differently from all other handedness groups for both stacking and affixing. Trending right-handers developed these toddler construction abilities more slowly, than other groups. Also, left-handers started out nesting more than all other groups at toddler ages; although the other groups caught up by 24 months.

The piecewise models revealed that trending right-handers developed stacking and affixing skill more slowly during toddler ages, than all other preference groups. All infants exhibited quadratic change for stacking across the toddler ages, yet trending right-handers and all other groups changed in "opposite" ways. Trending right-handers began the period with a slow rate of change, followed by a rapid increase in stacking development. All other infants rapidly developed stacking initially and then slowed their rate of development. Functionally, the "burst" of stacking development occurs later in the toddler period for trending right-handers, while all other groups have an earlier appearance of their stacking burst. Trending right-handers also had a slowed initial rate of affixing development and started out the toddler ages at a lower level of affixing. By the end of the toddlerhood, trending right-handers had caught up to all other groups (i.e., they did not differ from other groups at 24 months).

Unexpectedly, left-handers had a different rate of nesting development, than all other groups. Left-handers started out the toddler ages at a (much) higher rate of nesting. Nevertheless, left-handers had a quadratic slope which caused a lower increase in development, than all other groups, and all other groups caught up to left-handers.

CHAPTER IV

DISCUSSION

The purpose of this dissertation was twofold, a) describe the development of construction skills during infant and toddler ages, and b) investigate whether handedness and hand use affected the development of construction. Infant construction ability did appear to predict toddler construction ability. Individual construction actions also related to other construction actions during infancy, although this relation diminished greatly during toddlerhood. Despite these relations, these construction actions do appear to develop in very different ways from one another. Actions developed differently depending on the age period (e.g., infant vs. toddler), motor development (e.g., hand use) affected each action differently, and these actions differed in the way they changed (e.g., linear vs. cubic vs. quadratic slopes) during development. In the future, these actions should not be analyzed as a single variable, as has been done in the past (e.g., Marcinowski, 2013). Instead, each action should be modeled as separate manual skills. This finding also raises the question of whether a single, cognitive ability at older ages emerges from these actions. Future research might address the issue of the divergence of these actions throughout these ages and whether the development of object construction does represent a single, cognitive ability and, if it does, when does that occur.

Future research could investigate the onset of nesting skill in terms of the "strategy" employed during early childhood, rather than measuring it as a "frequency of occurrence" in the current study. Nesting strategy, or how cups are combined, has been measured successfully and changes from infancy through toddlerhood (Greenfield, Nelson, & Saltzman, 1972). Initially, infants interact with single objects, then pair objects together, and finally multi-object structures are combined in linear or hierarchically-arranged ways (Greenfield et al., 1972). These early pairings are not a failure to combine 3 or more objects into a single structure; rather, children only ever attempt to combine pairs of objects. Next, children can combine more than 2 objects together; but these strategies require objects to be structured hierarchically. One method of combining, "the pot method," has multiple acting objects, each occurring in succession, and a single acted upon object (i.e., a medium cup is inserted into a large cup, and then a small cup is inserted into the medium cup within the large cup). A more complicated method, "subassembly," refers to an actor and an acted upon object which are combined to form a structure, which then becomes the next actor-object. This new actor-object can then be placed into another object. Instead of placing cups one at a time into the largest cup as in the "pot method", here sub-structures are created *en route* to the final structure. For this reason, subassembly is a hierarchically-arranged strategy, as opposed to prior methods of nesting. These changes in strategy for nesting cups may be more important for understanding the development of nesting skill, and they are missed by measures of number of nested items. Thus, the transition from potting to subassembly denotes a change from linear combinations to hierarchically-structured combinations and the *number* of nested cups might not differ between strategies. If so, the difference between toddlers who sub-assemble and toddlers who pot will be missed by conceptualizing nesting only number of items nested, rather than in terms of strategy.

Whether combination strategy changes other actions besides nesting will require further study. Strategy for affixing objects will likely depend on the action. Some fitted toys might have a fixed pattern of combination, which limits the way objects are combined (e.g., puzzles), while others might not (e.g., magnets). The development of strategy might manifest differently across different affixing activities, but might not necessitate certain strategies. On the other hand, the development of stacking skill may not change depending on strategy, in the same way that it does with nesting. Although some strategies are used for stacking at some point in early development (e.g., pairing, potting), hierarchical strategies are not conducive to successful strategies for stacking (i.e., subassembly). Creating a sub-structure with two cups and then moving the sub-structure is unlikely to disrupt the cohesion of the two-cup structure; however movement would almost certainly perturb a two-block sub-structure *en route* to the next block. Future study should investigate object combination strategies and how they might affect the development of construction across early childhood. Because of the limitations on our knowledge of how strategies might operate for different construction activities, number of items constructed was thought to be the best measure of construction skill for this initial investigation of its development.

Handedness and Infant Construction

The second purpose of this project was to understand how handedness and hand use affected the development of construction ability. Many children showed a hand preference at the infant (70%) and toddler ages (80%), and many of these children demonstrated a consistent, concordant preference across both age periods (89% of toddlers with a preference). As infants, both trending right-handers and infants without a preference had a roughly equal chance of being in each of the four toddler preference categories. Despite being classified as right-biased, many trending right-handers do not appear to continue increasing their right hand use. Stable right-handers were predominantly right-handed as toddlers and left-handers had the highest chance of becoming left-handed toddlers, relative to all other infant groups. Thus, despite a different measure of hand preference between toddlers (RDBM) and infants (acquisition), the infant preference significantly predicted the toddler preference, particularly for left preferring infants.

In the Cascade Theory of Handedness, Michel (1983) predicted that early handedness would predict a greater ability to perform manual skills, such as construction. Handedness did affect the way infants developed stacking. Each infant group developed stacking in a unique way from one another, as every infant group had a unique slope from one another. Stable right- and left-handers had greater success stacking than infants without a hand preference at 14 months; although trending right-handers did not differ from any group. Also as expected, infants without a hand preference displayed the lowest stacking scores of the handedness groups and had significantly lower stacking scores at 14 months.

Unlike stable right- and left-handers, trending right-handers did not succeed more at stacking, than infants without a preference. They did not have a faster rate of development and did not have a higher stacking score at 14 months than infants without a preference. One reason for this finding may lie with their history of right hand use, particularly from 6-9 months of age. Trending right handers do not have a strong preference for acquiring objects with their right hand during the 6-9 month time period and do not use their right hand more often than chance levels. In contrast, stable right- and left-handers do, which has led to greater motor proficiency for their preferred hand. When stable right- and left-handers are using their preferred hand more often prior to the onset of stacking, they are more successful at stacking. In contrast, trending right-handers did not use their preferred hand as much as stable right- or left-handers do prior to the onset of stacking. An inconsistent history of preferred hand use has likely contributed to less proficiency in their right hand which diminishes manual proficiency for stacking. Thus, when trending right-handers use their right hand to stack, they are not necessarily using a more proficient hand, merely their currently preferred hand. The "trend" in their hand preference trajectory from 6-9 months likely affects how capable infants are of controlling their hands when attempting to stack objects, since greater control of the hand has been shown to affect stacking performance (Chen et al., 2010). Even though infants with a (trending) preference were not more successful than infants without a preference, these findings still fit within the framework of the Cascade theory of handedness.

However, it was hypothesized that handedness would affect all infant construction actions, whereas this was not the case. During infant ages, handedness and lateralized hand use did not predict nesting at all and was only mildly related to the development of affixing. However, only stacking (of the construction actions measured) requires sophisticated acquisition and placements skill. Thus, stacking skill would be more likely to be related to acquisition hand preference. Since most construction skills assessed during later ages (toddlerhood and preschool) require role-differentiated bimanual manipulation of the objects, it would be predicted that advances in these construction skills would be related to hand preference for RDBM. Of course, this is a question to be addressed in future research.

Handedness and Toddler Construction

The relation between handedness and construction skill was less clear during toddlerhood. Both infant and toddler handedness classifications did predict toddler construction. High right-handed toddlers could stack more items, than all other groups at 18 and 24 months of age. Toddlers who had a left infant preference could nest more items 18 months; although the other groups caught up by 24 months. These toddler handedness classifications did not affect the rate of development across toddlerhood, yet left-handed infants and high right-handed toddlers were better at construction during early toddlerhood. The toddler findings are further complicated, in that not only did direction of handedness affect stacking and nesting, but handedness consistency did too. Toddlers whose handedness was consistent from infancy to toddlerhood could stack and nest more at 18 months and they developed the ability to nest more quickly than those whose handedness was inconsistent. Perhaps, infants with a consistent preference throughout infancy and toddlerhood have an advantage for manually-challenging tasks, like stacking. Also supporting the connection between toddler handedness and stacking is that preferred hand use at the beginning of toddlerhood predicted a faster rate of change and greater stacking ability at 24 months. Thus, infants with a preference do seem to develop stacking earlier and more quickly across toddlerhood.

Unlike their counterparts with a preference, toddlers who had a trending infant right preference performed *more poorly* on construction across toddlerhood. For stacking and affixing, toddlers with a trending infant right preference constructed fewer items at the beginning of toddlerhood and, for stacking, trending right-handers remained lower than all other toddlers. When considering all infant and toddler ages simultaneously, trending right-handers developed stacking and affixing more slowly across the entire period. Interestingly, trending right-handers were again shown to be delayed in their development of affixing and stacking skill. Trending right-handers consistently show a lower rate of development at the toddler ages.

The reason for why infants with a trending right acquisition preference perform more poorly on construction in early toddlerhood may be related to both consistency and hand use. Within the trending right group, they tend to distribute equally into all four toddler RDBM hand-use preference groups. Although this characteristic might be expected of infants without an established preference, trending right-handers have a clear right preference towards the end of the infant period, but many go on to switch to a left preference or lack a preference as toddlers. Trending right-handers seem to be an inconsistent and variable group. Initially, trending right-handers exhibit equal hand use (6-8 months), and then rapidly acquire a right preference for acquisition preference (9-14 months). Then, their right acquisition preference does not convey into a right preference for a different action (i.e., RDBM). Perhaps as a result, their manual proficiency is not well established for the preferred hand and successful hand strategies for construction cannot be practiced.

Since other researchers have not previously identified a trending preference group during infancy (perhaps because few have recorded handedness with so many infants and time points), there is little information upon which to speculate why this group exhibits poorer construction skill and a slower development of construction skills. Preliminary evidence suggests that neuromotor development, rather than age, may uniquely affect hand use development specifically for this "trending right" group of infants but not for the other preference groups during infancy (Koucheki, Campbell, & Michel, 2015). Future research should investigate whether neuromotor development is relevant to construction skill development for this group. This could elucidate why this group's object acquisition preference does not readily translate to an RDBM preference and why object construction skills increase more slowly for them.

Toddler nesting skill was predicted by infant preferences (i.e., left and stable right), preference consistency and preferred hand use, rather than toddler preferences.

There are several reasons for this set of findings. First, right-handers who were consistently right-handed through infancy (i.e., stable right) and toddlerhood (i.e., moderate or high right) may gain an advantage for nesting. Therefore, consistency rather than right handedness may be driving the right-handed effect. Second, left-handed infants displayed a higher skill for nesting at the beginning of toddlerhood, than all other groups. Left-handed infants nested more items at the beginning of toddlerhood, than all other handedness groups. Although this finding was certainly unexpected, this pattern of nesting could indicate that left-handers develop relevant cognitive skills in a unique way from right-handers and toddlers without a preference.

Additionally, the development of nesting may differ for left-handers, because left-handers may develop spatial skills more quickly, than all other groups, which in turn provides left-handers with a greater ability to nest. Although the literature on the development of handedness and spatial skill is limited, some research has found a connection (e.g., mental rotation strategies: Cook, Früh, Mehr, Regard, & Landis, 1994; Koenig, Reiss, & Kosslyn, 1990). The handedness differences in spatial skills could provide one explanation for why left-handers differ from all other groups for nesting, since successful nesting may rely on the development of spatial skills. Nevertheless, the literature is very unclear on this proposed relation and future study should be conducted to find what connection exists between handedness, nesting and spatial ability during toddlerhood.

Hand Use and Construction

One big difference between the Cascade Theory and other handedness theories (e.g., Invariant Lateralization) is that *preferred* hand use is expected to predict success at manual skill, rather than *right* hand use. Prior research has primarily found that right hand use or right handedness predicted increased skill for motor actions (Larsen, Helder, & Behen, 2012), greater language ability (Esseily, Jacquet, & Fagard, 2011; Nelson, Campbell & Michel, 2014; Vauclair & Cochet, 2012) and greater cognitive abilities (Larsen, Helder, & Behen, 2012), while non-right-handedness was associated with physical health problems (e.g., prematurity: Domellöf, Johansson, & Rönnqvist, 2011; epilepsy and high blood pressure; Bryden, Bruyn, & Fletcher, 2005), language impairment (Hill & Bishop, 1998) and mental health problems (e.g., schizophrenia and schizotypy: Chen & Su, 2006; Hirnstein, & Hugdahl, 2014; pedophilia: Fazio, Lykins, & Cantor, 2014). In particular, higher levels of right hand use have been connected to more lateralized language function (Gonzalez & Goodale. 2009) and language production (Esseily, Jacquet, & Fagard, 2011; Jacquet, Esseily, & Fagard, 2012). Kinsbourne (1975) posited that increased right hand use during early infancy demonstrated a greater influence of left-lateralized brain organization, particularly for language (Kinsbourne, 1975). Often, early right hand use has been shown to be an indicator of innate biases for handedness and language. Most notably, Kinsbourne (1975) claimed, “Cerebral dominance for language does not develop; it is there from the start” (p. 248). If the development of object construction is related to later cognitive development, then increased *right* hand use or handedness may, in fact, be related to an earlier onset or a more rapid rate of object construction development.

Many studies on handedness are somewhat problematic, because left-handers are often underrepresented or absent from study (e.g., n<5: Esseily, Jacquet, & Fagard, 2011; Nelson, Campbell, & Michel, 2013; Ramsay, 1985; Vauclair & Cochet, 2012). Handedness is often conceptualized into "right" and "non-right" handedness (e.g., Esseily, Jacquet & Fagard, 2011; Vauclair & Cochet, 2012). The "non-right-handed" category combines left-handed, ambidextral (no preference with two skilled hands) and ambisinistral (non-preference with two poorly-skilled hands: Flowers, 1975) individuals; so "preferred" hand use cannot be tested in a meaningful way. And since, right-handers predominate over left-handers within infant samples; it is not surprising that a main effect of right hand use could be found and drown out any left hand use from a small number of left-handed infants. Given the marked differences found between left-handers and infants without a preference in this project, any "non-right-handed" group is heterogeneous at best and misleading at worst. Though the literature has found a number of connections between right hand use and skill, there is still a question about whether the distinction between right- and non-right-handedness is even a meaningful connection. This raises the question – is *right* hand use associated with ability or could *preferred* hand use actually be the connection?

This project differed, in that enough left-handers were present to distinguish between *right* or *preferred* hand use. Interestingly, *preferred* hand use predicted success at stacking, rather than simply *right* hand use. Infants who used their preferred hand more prior to the onset of object construction developed stacking ability more quickly, than infants who used their preferred hands less. As during infancy, preferred hand use predicted success at stacking and nesting during toddlerhood, but not affixing. Toddlers that used their preferred hands developed stacking and nesting ability more quickly. Indeed, toddlers who used their preferred hand increased their stacking and nesting ability from 18-24 months, whereas those who used their nonpreferred hand exhibited little increase in ability. At the infant and toddler ages, *preferred* hand use, rather than *right* hand use, predicted the level of construction skill and increased the rate of some object construction developments.

While "lateralized" hand use was shown to predict stacking success, "both" hand use did not. Given that using both hands to stack is rare during 10-14 months, perhaps acquiring skills with using both hands does not benefit a largely unimanual task. However, it is possible that both hand use could predict success at performing other construction actions that require bimanual coordination. Of course, *this does not mean that infants with a preference will perform worse at these bimanual actions.* Infants with a hand preference were more capable of coordinating a both hand reach when one had was confronted with a barrier, than infants without a hand preference (Goldfield & Michel, 1986). When infants with a preference reach bimanually, the path of the nonpreferred hand is controlled by mechanisms controlling the preferred hand's path. When a barrier is present on the preferred side, an infant with a preference can coordinate both hands around the barrier, since the preferred hand can "lead" the nonpreferred hand around it and the bimanual reach is uninterrupted. In contrast, infants without a hand preference appear to control each hand separately. A hand is halted by a barrier no matter which side the barrier is on and the bimanual reach will be disrupted. Since a hand preference benefits bimanually-controlled actions (as with bimanual reaching), it might still benefit bimanually-controlled construction actions at later ages. At the very least, bimanually-controlled actions may develop in qualitatively different ways between infants with or without a hand preference.

One prediction of the Cascade theory was that infants with a hand preference could build more, than infants without a hand preference. This was expected only if the infant used their preferred hand for the action; however this was not found for all successful preference groups. Stable right-hander did use their right hand more often to stack objects, while left-handers did not. Left-handers did use their left hands more than other groups; but they had roughly equal left and right hand use for stacking. Even more puzzling was that early preferred hand use for acquisition *still* predicted stacking success in left-handers, as it did with trending and stable right-handers. Two reasons may explain why left-handers succeed at stacking, despite not stacking with their left hands predominantly. First, the failure to find a preferred hand bias for stacking could be an incidence of Type II error. Three of the 4 indicators of hand use were on multi-item towers at 14 months (first item, last item and hand strategies). Only 10 left-handers completed a multi-item tower at 14 months, as compared to 17 trending right- and 19 stable right-handers. Although the binomial tests employed in the current study *could* have found a significant result for 10 data points, Type II error would have been high. For acquisition, left-handers used their left hands 36%-40% of the time across 6-14 months and the lowest frequency of hand use at the initial ages for acquisition. If left-handers follow a similar pattern of hand use onset for stacking, as for acquisition, then 6 of the 10 infants would exhibit the left bias. This theoretical amount would have been found not significant (*p*=0.205), since the critical value for a binomial test on 10 data points is 8 (*p*=0.044). On the very first block stacked, 20 left-handers stacked at some point during the 10-14 month period, as compared to 36 trending right- or 37 stable right-handers. Of these 20, 8 left-handers used their left hands to place the first block. This is lower than might be expected by the previously-specified theoretical amount (i.e., 12), but this theoretical guideline is met if all left-handers that used a left hand at their first month are included (i.e., adding in the 4 "multiple" hand using infants). Even if left-handers do use both hands equally, then the Cascade theory predicts a lower level of hand use at the initial onset of a manual skill, followed by an increase in the proportion of preferred hand use for the skill. Thus, these "theoretical" estimates could be artificially high for left-handers, since the 10-14 month ages represent a very early point of their development. At this point, more data must be collected on left-handers' stacking development to resolve this issue of power.

Additionally, if left-handers do indeed exhibit equal hand use during this early ability, then this finding might reflect a hand use strategy unique to left-handers. Left-handers may succeed at stacking by using different hand strategies, than other handedness groups. A right-bias exists in the social and physical environment, because human adults are predominantly right-handed. Mothers are more likely to use their right hand to interact with their infant (Michel, 1992; Mundale, 1992), right-handed adults are more likely to cradle infants on the left side (Scola & Vauclair, 2010; van der Meer & Husby, 2006), and the environment is more likely to be structured to fit right-handers (e.g., door knobs, scissors, etc.). As a result, left-handed infants use their non-preferred hand more and consequently may be less biased, than right-handed infants (Michel, Babik, Sheu, & Campbell, 2013). If left-handers do manipulate objects differently from right-handers, then it would suggest that left- and right-handers may exhibit fundamentally different trajectories for manual skills. Another observation left unexplained is that left-handers succeed at stacking using both hands to stack, and yet infants without a preference do not. Clearly, future research should be conducted to characterize left-handed infants' hand use strategies during construction.

Handedness and Object Construction Changing in an Embodied World

Developmental research has begun to demonstrate that the way an infant interacts with the environment shapes the way cognition develops. Spatial exploration predicts spatial memory (Oudgenoeg-Paz, Leseman, & Volman, 2014), place learning ability relates to spatial prepositions (Balcomb, Newcombe, & Ferrara, 2011), and sitting enabled an understanding of object properties (e.g., Soska & Adolph, 2014). Different physical interactions with the environment lead to differences in cognitive ability, which supports the embodied cognition argument that our interactions with the physical environment shape the development of our cognitive abilities (e.g., Dellatolas et al., 2003; Barsalou, 2008; Lakoff & Johnson, 1999; Oppenheimer, 2008). Certainly, infancy is a time during which environmental interactions seem to be especially important for development.

According to the embodied cognition account an infant who is more capable of object exploration gains additional experience with the properties of objects and this affects the development of the infant's cognitive processing. Thus, an infant's posture changes the way an infant is capable of manipulating objects. A sitting infant is more capable of manual exploration and transferring objects from one hand to another, than a prone infant (Soska & Adolph, 2014). A sitting infant's upper limbs are free to manipulate objects, and so, that infant is more likely to discover different properties of objects and successfully perform more actions with that object than is the prone infant. This permits infants to discover the correlation between their actions and the ensuing consequences on the environment (Smith & Gasser, 2005). Thus, one must understand the development of motor skills to understand cognitive development (Lakoff & Johnson, 1980).

Since the development of handedness is a motor skill, it may have an impact on the development of cognition (e.g., Dellatolas et al., 2003; Michel et al., 2013). Right- and left-handed children tend to attribute positive or negative valences to locations within the environment (Casasanto, 2009; Casasanto & Henetz, 2011). Objects located to the child's preferred side were identified as more positive (e.g., "happy"), while objects located to the non-preferred side were identified as more negative (e.g., "sad") and this was true for both left- and right-handed children. Also, left- and right-handers have memory bias for recalling spatial locations, depending on the valence of that location

(Brunyé et al., 2012). Right-handers remembered postitively-valenced locations more when presented to the right side and negatively-valenced locations more when presented to the left side; yet the opposite relation was found for left-handers (Brunyé et al., 2012). The proposed reason why there is this positivity/preferred side bias is that the ease of manipulation associated with objects makes that side more positive. When a child has a preference, objects to the preferred side are more convenient for the child to manipulate manually and are implicitly labeled as more positive. Objects to the nonpreferred side are less convenient to manipulate, because it requires either use of the nonpreferred hand or for the preferred hand to cross the body's midline; so objects on the nonpreferred side are implicitly labeled as negative. In this way, a motor characteristic (i.e., handedness) has affected the way in which abstract concepts of the environment (i.e., positivity/preferred side bias) develop.

But how might handedness *specifically* change the way an infant develops cognitive ability? As infants explore objects manually, they are transducing sensory information about objects. An infant with a preference will be transducing sensory information about their environment asymmetrically, unlike infants without a preference. Infants with a preference will explore objects with one hand (preferred hand) more than the other hand (nonpreferred hand). The preferred hand receives sensory information from active manipulation. Because of this difference in experience and the contralateral control of the hands, one hemisphere of the brain will receive different sensory information or a greater amount of sensory information from manual exploration of objects. Asymmetrical transduction of the environment may then encourage further lateralized brain organization in the infant with a hand preference (Michel et al., 2013).

The affordances of objects affects the type of information obtained through object exploration. Single object interactions provide feedback on only a single object's characteristics, while object-on-object interactions provide feedback on the acting object, the receiving or substrate object, and how they relate to one another. For example, shaking a rattle in the air would only provide information on a single rattle (noise, weight, etc.). In contrast, scraping a rattle on a table provides information about properties of the rattle (noise, weight, etc.) and the table surface (hardness, etc.); but it also indicates that moving a hard object on a hard surface produces a new noise (scraping). Single object, unimanual manipulation also begets different sensory information, than manipulating two objects together bimanually (Bushnell & Boudreau, 1991). Shaking an object provides haptic information only to one hand, while clacking objects together provides haptic information to both hands in a very specific pattern to each other. In addition, the consequences of single-object, object-on-object or multi-object manipulations differ. Two- or multi-object manipulations demonstrate how objects can be related or combined, while single-object manipulations do not. A multi-object structure also relies more heavily on correct spatial placement to achieve success. A block must be placed "on" another block relative to its center of gravity, to create a block tower, rather than "next to" another block. Although blocks that are placed next to one another might create a visually-connected structure (a "wall"), such placement of the objects creates a more loosely-connected structure to one another than a tower, because they are affected differently by gravity. Perturbing a block in a tower is much more likely to disturb the other blocks, than perturbing a block in a block wall. In contrast, an unsuccessful, two-object combination requires less specificity to produce a similar result. An infant can make a clapping sound by clacking a block on the side, top or bottom of another block. Building structures from objects can afford unique sensory information about the properties of objects or structures.

Manipulating objects in new and more complicated ways, such as building with them, changes how a child develops other cognitive abilities. Combining objects into structures provides structural and causal relational information relevant to cognitive development. When an infant manipulates objects into a structure, this manipulation provides the infant with multimodal information about structure. Even if the infant "accidentally" organizes a structure, the infant still gains useful experience through manipulation of objects into an inadvertent structure. Object manipulation also enables infants to internalize the presence of objects (abstract representation; Bruner, 1972), object structures (back of objects: Soska, Adolph, & Johnson, 2010), causal relations (e.g., what happens if I place a cup within another cup?), object categories (a cup can be a container, while a block cannot: Iverson, 2010), and, eventually, abstract representations of the physical environment (Casasanto, 2009; Michel et al., 2013). Hence, the new sensory information gained through object construction during infancy and toddlerhood becomes embodied into the nervous system. If the way an infant interacts with the physical environment influences cognitive development, then differences in patterns of object exploration (like, object construction) might indicate different trajectories of cognitive development.

Throughout infancy and toddler ages, this project has shown an effect of handedness and hand use on the development of object construction skill. If construction does indeed provide unique experiences concerning the properties of objects, then the way in which infants use their hands to build will alter the way environmental information is embodied. Infants with a stable right preference have an early preponderance of right hand use in development and tend to use their right hands to stack. In these infants, sensory stimulation from (primarily) right hand manipulation will reinforce neural pathways in the left hemisphere. Additionally, any information on object properties or structures gained from stacking will be processed in the left hemisphere of the brain more than the right. Any emerging cognitive abilities intimately connected to such sensory information would emerge in the left hemisphere, in part because of asymmetrical experience with object manipulation. In contrast, infants who change their hand preference (i.e., trending right-handers) or are not concordant for hand preferences across manual skills will not reinforce neural pathways to the same hemisphere for manual tasks in the same way. Consistent, preferential hand use across multiple action types (which provide unique sensory information to the infant) may be one mechanism by which object construction skill and handedness specifically affect cognitive development.

If a connection exists between preferential hand use, object construction and cognition, then trajectories of handedness signal potentially unique trajectories for cognitive development (Michel et al., 2013) according to hand preference. Infants with a stable hand preference show a high amount of right hand use that is relatively stable across 6-14 months. This contrasts with trending right-handers, who have equal hand use at 6 months and then increase in their right hand use by 14 months age. Even if a trending and stable right-handed infant becomes a right-handed toddler, these children's handedness trajectories are both marked by a unique feature – stability or instability. "Stability" could be associated with greater lateralization of cognitive abilities, while "instability" could characterize less or more interhemispheric control of cognitive abilities. In essence, unique developmental trajectories for manual skills might eventually translate into unique trajectories for other types of cognition (Michel et al., 2013).

Conclusions and Future Directions

This project has established that the development of infant handedness plays a role in the development of object construction. Infants with a preference have an increased level of success for stacking. Toddlers with a consistent preference initially stacked and nested more than inconsistent toddlers and some hand preferences differentially predicted skill for some object construction types during toddlerhood. Preferred hand use also predicted a more rapid development of stacking and nesting during toddlerhood. These findings do support the Cascade theory's account; nevertheless, the lateralized preference groups were unique from one another which may have led to unique trajectories for object construction. Stable right-handers and infants without a preference exhibited no change across the infant period, although stable right-handers used their right hands preferentially. Trending right-handers and left-handers increased in their preferred hand use across the early infant ages with trending right-handers exhibiting a more rapid rate of change, than left-handers. Consequently, all preference groups developed object construction skills in unique ways during infancy and some differences continued into toddlerhood. Right- and left-handed infants were not mirror images of one another, and so, it might be expected that their trajectories for object construction would differ from one another.

Additional study is needed to elucidate the role of handedness in the development of object construction from infancy through toddlerhood. First, the gap between 14-18 months should be studied in order to get a better picture of construction development from infancy through toddlerhood. Although this project attempted to compensate for this gap using piecewise regression analyses, it is unknown how construction changes across this period. The findings within this project hinted at potential changes unique to these ages and could affect later construction ability. For example, infants without a hand preference had a slow rate of stacking development across the 10-14 month ages, but then showed no differences from stable right- or left-handers by 18 months. This likely indicates that infants without a preference must increase their rate of stacking at some point within the 14-18 month ages, in order to catch up to the stable right- and left-handers. How, when and why this increase occurs from 14-18 months could shed light on any compensatory mechanisms which may emerge for infants without a hand preference from 14-18 months. Future research should aim to fill this gap and determine whether this age period yields particularly relevant changes to the development of construction and cognition.

Second, the way in which handedness affects object construction may depend on which construction actions are examined. A preference for acquisition might not be a relevant skill for the nesting or affixing tasks during infancy but the skill of acquiring objects is important for stacking, because orientation of the object in an infant's hand is vital to a successful stack. For example, a cubic block is more successfully stacked, if the block is acquired so that the flat side on the bottom of the acquired block is parallel to the flat side on the top of the tower. In contrast, the way a ring is acquired is less relevant to placing it on a stand.

Task constraints could also explain why both hand use predicted the development of affixing. The chosen affixing tasks could be performed with two hands (e.g., two held magnets can be adhered by pressing them together), just as easily as with a single hand (e.g., one held magnet can be adhered by touching it to another magnet on the table). Skill at coordinating two hands could in turn affect an infant's ability to affix (particularly, adhering magnets). Tasks chosen to assess stacking would be more challenging to perform with two hands, either by combining two held blocks or holding a single block with two hands. Using two hands is less conducive to stacking, than it is to affixing. Thus, affixing task constraints could explain why handedness and lateralized hand use did not predict affixing success, while both hand use did.

Acquisition could be a relevant skill for nesting, but potentially not at the assessed infant ages. The way a cup is acquired *could* be relevant to how it is nested within a larger cup for more sophisticated strategies of this ability. That is, a medium cup that is oriented open side upwards within a larger will afford additional nesting, as opposed to a medium cup that is oriented open side downwards or on its side. How a cup is acquired could affect whether a medium cup is inserted open side upwards or downwards into a larger cup; however, the majority of infants are only inserting 1 cup into another at best from 10-14 months (75-98%). Since infants are less capable of nesting a larger number of cups, the way a cup is acquired is less relevant to nesting success. Once children are capable of nesting more items, there could be benefits of infant acquisition preference on nesting, as with stable right- and left-handers at early points in toddlerhood. It is also possible that a preference for performing other exploratory actions (e.g., unimanual actions) rather than acquisition could benefit the development of nesting. For example, rotating or re-orienting an object might be a more relevant skill to the development of nesting. If multi-item nesting occurs at a later point in development, then skill at performing another exploratory action could affect nesting skill, instead of object acquisition. Thus, the ability to acquire objects could be unrelated to the development of nesting whereas a preference for unimanual manipulation may be related.

Additionally, the act of nesting or affixing objects requires less manual precision to perform, than stacking. Successful stacking often requires the infant to monitor the rate of placement approach, such that the arm must slow their approach near the tower (Chen et al., 2010). Yet, the demands on proficiency may be less relevant for nesting and affixing. As one magnet nears another, little proficiency is needed to adhere magnets, and the demand for precise placement actually decreases. When an infant places a ring onto a stand, the stand is rarely so delicate that it warrants careful placement. In both cases of affixing, the demand for proficiency is low. The nesting cups used in this project had noticeable size differences between cup gradations. Again, only a small degree of manual precision would be needed to insert one cup into another, especially between the smallest and largest cup. Based on the types of nesting and affixing tasks of which infants are capable from 10-14 months, manual proficiency might be less relevant to success. The types of tasks of which older children are capable might warrant manual proficiency (e.g., assembling Legos or combining nesting dolls), and so, handedness could play a role at older ages.

Since most of the toddler construction tasks chosen for study were dependent upon unimanual manipulation and do not require RDBM skill, this may have affected the weak relation found between RDBM handedness and construction skill. Most construction skills assessed during infancy and toddlerhood do not require RDBM ability (e.g., stacking blocks, nesting cups, adhering magnets, and assembling rings). Instead, unimanual handedness during late infancy might be more relevant for the chosen toddler construction development, rather than a preference for RDBM. Unimanual hand preferences emerge by 14 months (Campbell et al., 2015), thus the timing of this developing preference coincides with the development of construction skills during toddlerhood. For example, when adhering multiple magnets onto a structure, the toddler may inadvertently attempt to adhere a north pole to another north pole. The toddler can easily correct this error by re-orienting the magnet or placing the magnet on the table and picking up the magnet in the correct orientation. A toddler that is more adept at unimanual object manipulation (i.e., rotating, placing or acquiring an object) may be able to create more complicated structures, than toddler who is less-skilled at unimanual manipulation. However, later-emerging construction skills may depend on RDBM skills. Assembling puzzles, models (e.g., building a model airplane) or using tools relies more heavily on bimanual coordination, thus a hand preference for RDBM would then be quite relevant for successful construction. Again, further study is needed to understand how hand preferences for multiple action types might differentially affect the development of object construction. Particularly of interest would be what the timing is between the development of a hand preference, the onset of a construction skill and at what point the preference begins to affect the construction skill.

Although this project did not examine whether infant manual asymmetries and skills *could* affect the development of cognitive abilities, prior literature suggested that right hand use or handedness was related to greater cognitive abilities (particularly language). Based on these prior findings, it could be suggested that right hand use might predict greater success at construction, while the Cascade theory proposed that preferred hand use would predict greater construction skill. Interestingly, preferred hand use was found to be related to success, rather than right hand use. However, preferred hand use often led to differences in the *way* that construction developed, rather than a simple "better" or "worse" outcome. During infancy, preferred hand use led to a faster initial increase and greater skill at 12 months for stacking skill. Yet, during toddlerhood, preferred hand use led to a faster rate of increase and greater skill at later ages for both stacking and nesting. The way in which hand use and therefore handedness affects object construction is nuanced and requires careful, developmental study. These developmental trajectories must be adequately studied before concrete connections between manual skills and asymmetries can be connected to the development of cognition. Future study is needed in order to clarify the role of handedness, object construction on the development of cognitive abilities, before more concrete connections can be suggested.

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APPENDIX A

COMPARISON OF PARAMETERS FOR A LONGITUDINAL MULTILEVEL AND REPEATED MEASURES ANOVA POISSON MODELS (SAMPLE MULTILEVEL POISSON MODEL)

	Multilevel Model	**Repeated Measures ANOVA**
	Model Separated by Level	*Model Separated by Level*
Level-1	$\mathbf{log(\lambda) = \pi_0 + \pi_1(Age) + \pi_2\ (Age^2) + \varepsilon_i}$	$\log(\lambda) = \pi_0 + \pi_1(\text{Age}) + \pi_2\ (\text{Age}^2) + \varepsilon_i$
Level-2	$\pi_0 = \gamma_{00} + \gamma_{01}(\text{Level 2 Variable}) + \boldsymbol{\delta_{0i}}$ $\pi_1 = \gamma_{10} + \gamma_{11}(\text{Level 2 Variable}) + \boldsymbol{\delta_{1i}}$ $\pi_2 = \gamma_{20} + \gamma_{21}(\text{Level 2 Variable}) + \boldsymbol{\delta_{2i}}$	$\pi_0 = \gamma_{00} + \gamma_{01}(\text{Variable})$ $\pi_1 = \gamma_{10} + \gamma_{11}(\text{Variable})$ $\pi_2 = \gamma_{20} + \gamma_{21}(\text{Variable})$
	Mixed Model	*Mixed Model*
	$\log(\lambda) = \gamma_{00} + \gamma_{01}(\text{Level 2 Variable}) + \gamma_{10}\ (\text{Age}) + \gamma_{11}(\text{Age*Level 2 Variable}) + \gamma_{20}(\text{Age}^2) + \gamma_{21}\ (\text{Age}^2\text{*Level 2 Variable}) + (\boldsymbol{\delta_{0i} + \delta_{1i} + \delta_{2i}} + \varepsilon_i)$	$\log(\lambda) = \gamma_{00} + \gamma_{01}(\text{Variable}) + \gamma_{10}\ (\text{Age}) + \gamma_{11}(\text{Age*Variable}) + \gamma_{20}(\text{Age}^2) + \gamma_{21}\ (\text{Variable* Age}^2) + \varepsilon_i$
	Model Separated by Level (Sex Example)	*Model Separated by Level (Sex Example)*
Level-1	$\mathbf{log(\lambda) = \pi_0 + \pi_1(Age) + \pi_2\ (Age^2) + \varepsilon_i}$	$\log(\lambda) = \pi_0 + \pi_1(\text{Age}) + \pi_2\ (\text{Age}^2) + \varepsilon_i$
Level-2	$\pi_0 = \gamma_{00} + \gamma_{01}(\text{Sex}) + \boldsymbol{\delta_{0i}}$ $\pi_1 = \gamma_{10} + \boldsymbol{\delta_{1i}}$ $\pi_2 = \gamma_{20} + \boldsymbol{\delta_{2i}}$	$\pi_0 = \gamma_{00} + \gamma_{01}(\text{Sex})$ $\pi_1 = \gamma_{10}$ $\pi_2 = \gamma_{20}$
	Mixed Model	*Mixed Model*
	$\log(\lambda) = \gamma_{00} + \gamma_{01}(\text{Sex}) + \gamma_{10}\ (\text{Age}) + \gamma_{20}(\text{Age}^2) + (\boldsymbol{\delta_{0i} + \delta_{1i} + \delta_{2i}} + \varepsilon_i)$	$\log(\lambda) = \gamma_{00} + \gamma_{01}(\text{Variable}) + \gamma_{10}\ (\text{Age}) + \gamma_{20}(\text{Age}^2) + \varepsilon_i$

APPENDIX B

DESCRIPTION OF EACH TERM IN A MULTILEVEL POISSON LONGITUDINAL MODEL.

Notation	Definition	Meaning
π_0	**Intercept term**	**Average skill at the age coded as "0" (e.g., first month)**
γ_{00}	Intercept without the Level-2 variables taken into account	Average skill at the age coded as "0" (e.g., first month) for the reference group
γ_{01}	The effect of the Level 2 Variable on the intercept	How much the Level 2 variable affects the intercept
δ_{0i}	**Variance component for intercept**	**Variability associated with skill *at the intercept***
π_1	**Linear slope term (Age)**	**Average initial rate of change of the skill**
γ_{10}	Linear slope without the Level-2 variables taken into account	Average initial rate of change of skill for the reference group
γ_{11}	The effect of the Level 2 Variable on the linear slope	How much the Level 2 variable affects the linear slope
δ_{1i}	**Variance component for the linear slope**	**Variability associated with skill *at the linear slope***
π_2	**Quadratic Slope Term (Age^2)**	**Average change of rate of the skill**
γ_{20}	Intercept without the Level-2 variables taken into account	Average change of rate of skill for the reference group
γ_{21}	The effect of the Level 2 variable on the quadratic slope	How much the Level 2 variable affects the quadratic slope, relative to the Level 2 variable
δ_{2i}	**Variance component for the quadratic slope**	**Variability associated with skill *at the quadratic slope***
ε_i	**Level-1 Variance term**	**Residual or error variance**
λ	Dependent variable ("y"), taking into account variable exposure	The rate by which y increases, relative to the total number of opportunities at time point (like a proportion)

APPENDIX C

INCREMENTAL CODING SCHEMES FOR AGE VARIABLES IN THE PIECEWISE REGRESSION MODEL.

	Linear Age	Quadratic Age	Cubic Age
Infant/Toddler Formula:	Age = (ContinuousAge-10)	Age^2 = (ContinuousAge-Mean $Age)^2$	Age^3 = (ContinuousAge-Mean $Age)^3$
Toddler Formula:	Age = (ContinuousAge-17)	Age^2 = (ContinuousAge-Mean $Age)^2$	Age^3 = (ContinuousAge-Mean $Age)^3$

Mean Age = 15.35 months

Variables	Infant Ages					Toddler Ages						
	10	11	12	13	14	18	19	20	21	22	23	24
Infant/Toddler (linear)	0	1	2	3	4	8	9	10	11	12	13	14
Infant/Toddler (quadratic)	28.62	18.923	11.22	5.52	1.823	7.02	13.32	21.62	31.92	44.22	58.52	74.82
Infant/Toddler (cubic)	-153.13	-82.31	-37.6	-12.98	-2.46	18.61	48.627	100.55	180.36	294.08	447.7	647.22
Toddler (linear)	0	0	0	0	0	1	2	3	4	5	6	7
Toddler (quadratic)	0	0	0	0	0	7.02	13.32	21.62	31.92	44.22	58.52	74.82
Toddler (cubic)	0	0	0	0	0	18.61	48.63	100.55	180.36	294.08	447.7	647.22