Do hand preferences predict stacking skill during infancy?

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Abstract:

The cascade theory of handedness suggests that hand preferences develop from a history of cascading and sequentially developing manual asymmetries for a variety of actions. Infants who consistently use their preferred hand for a variety of actions likely would gain proficiency using that preferred hand and, consequently, perform more proficiently on other challenging manual tasks. One such task is object stacking, which has been linked with a number of cognitive abilities. If infant hand preference facilitates the development of stacking skill, then this could provide a link by which early hand preference might affect the development of cognition. From a sample of 380 infants assessed for an acquisition hand preference across 6–14 months, 131 infants were assessed for stacking skill from 10 to 14 months at monthly visits. Four unique handedness sub-groups were identified from the 380-infant sample: left, trending right, stable right, or no hand preference. Each of the four hand preference groups exhibited different trajectories in the development of their stacking skills. Left- and stable right-handers stacked more items than infants with no preference by 14 months, whereas infants with a trending right preference did not. The proportion of preferred hand use (right and left) from 6 to 9 months also predicted an earlier initial onset of stacking skill, whereas the proportion of only right hand use did not. Thus, the development of a hand preference predicts an earlier emergence of stacking skill and may have implications for other domains of infant cognitive development.

Keywords: handedness | motor | play

Article:

1 Introduction

Motor development has been shown to affect a number of cognitive skills, including how objects are explored (Soska & Adolph, 2014), how social partners interact with infants (Walle & Campos, 2014), and how infants represent objects symbolically (Kotwica, Ferre, & Michel, 2008). Infants use their hands to acquire a great deal of information about object properties and relations through manual exploration. Manipulating objects enables infants to internally represent the presence of stored objects (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, abstract representations of the physical environment (Brunyé, Gardony, Mahoney, & Taylor, 2012; Casasanto, 2009; Michel, Nelson, Babik, Campbell, Marcinowski, 2013). In essence, manual exploration both enables and facilitates the infant's acquisition of environmental information, particularly about objects.

As with other domains of motor development, would manual asymmetries, like hand preferences, influence cognitive development? Prior research has found that right hand use or right handedness predicts increased skill for motor actions (Larsen, Helder, & Behen, 2012), greater language ability (Esseily, Jacquet, & Fagard, 2011; Nelson, Campbell & Michel, 2014; Vauclair & Cochet, 2013) and greater cognitive abilities (Larsen, Helder, & Behen, 2012), while non-right-handedness was associated with language impairment (Hill & Bishop, 1998), and physical and mental health problems (e.g., prematurity: Domellöf, Johansson, & Rönnqvist, 2011; schizophrenia and schizotypy: Chen & Su, 2006; Hirnstein & Hugdahl, 2014). Greater frequency of right hand use has been connected to greater lateralization of language functions (Gonzalez & Goodale, 2009), especially language production (Esseily, Jacquet, & Fagard, 2011; Jacquet, Esseily, & Fagard, 2012). One proposed reason for the right hand/cognition relation is that increased right hand use during early infancy demonstrates a greater influence of left-lateralized brain organization, particularly for language (i.e., the invariant lateralization theory; Caplan & Kinsbourne, 1976; Kinsbourne, 1975a, 1975b, 1975c, 1976). Right hand use is purported to be an indication of the left hemisphere's control of language and related cognitive functions in humans; thus, a right hand preference emerges from an asymmetry in the functioning of the cerebral hemispheres, according to the invariant lateralization theory.

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 concatenate throughout infancy and early childhood. Initially, a fetus' position in utero affects the neonate's supine head orientation preference (Michel, 1981; Michel & Goodwin, 1979). A head orientation preference leads to increased sensory regard of and proprioceptive feedback from the preferred-side limb and, thus, greater control of the preferred-side limb. This early asymmetry develops into an early hand preference for object contact, reaching and acquisition (Michel & Harkins, 1986). Subsequently, this hand preference for acquisition affects preferences for later object manipulations (unimanual manipulation: Campbell, Marcinowski, Babik, & Michel, 2015; role-differentiated bimanual manipulation: Babik & Michel, 2016; Nelson, Campbell, & Michel, 2013). Because a hand preference emerges from a cascade of earlier developing motor asymmetries affecting the development of later asymmetries, an infant with a hand preference may acquire more information through manual exploration of objects using a preferred hand. In this way, infants are active participants in the development of their own handedness (Michel & Harkins, 1986).

Interestingly, the cascade theory would also predict that hand preferences would affect infant cognition via the affordances associated with having a stable hand preference. That is, a stable hand preference likely affects the development of proficiency for manipulating objects. Since an infant with a hand preference will use their preferred hand more often, an infant may achieve greater manual proficiency with 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. Consequently, an infant with a hand preference may have an advantage over infants without a preference in developing manual skills, particularly those associated with cognition. In this way, infants with a hand preference may develop cognitive abilities sooner or more rapidly than those without a preference.

Some evidence has found a connection between infant hand preference and success at infant cognition. Kotwica, Ferre, and Michel (2008) previously reported that infants with a 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. 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. Interestingly, Bruner (1973) suggested that object storage skill demonstrates an early incidence of abstract representation of objects. 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. Such storage implies the symbolic representation of the object, because it is not present but the object's “remembered” location is readily available to the infant for future manipulation. “Storing” an object implies symbolic representation of the object (Bruner, 1973). Thus, a hand preference during infancy may permit additional self-directed exploration of objects and may promote an earlier use of symbolic representations.

Stacking objects is a kind of construction skill that involves merging multiple objects into a single, unified structure (Marcinowski, 2013). When an infant stacks, multiple objects (“blocks”) become a new, single object (“a tower”) which provides multimodal information about object organizations. The properties of objects may differ dramatically than a structure composed of the same objects (e.g., a block tower is delicate, whereas individual blocks are not). An infant may discover a variety of object characteristics and object-object relations through such construction activities; hence stacking skills can be related to cognitive development. Children who engage in greater levels of object construction (including stacking) display greater levels of cognitive skill, such as visuospatial skills (e.g., block play, and geometric shape and pattern recognition; Caldera et al., 1999), mathematic achievement (e.g., object structures and standardized math scores; Nath & Szucs, 2014; Verdine et al., 2014; Wolfgang, Stannard, & Jones, 2003), and language (e.g., infant construction and spatial relations words; Marcinowski & Campbell, in press). The development of infant construction skill could affect other domains of cognitive development.

However, stacking is a skill closely tied to manual proficiency. For example, 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 early ages, motor precision of the stacking action seems to be important to stacking blocks successfully. Therefore, we propose that infants with a hand preference may succeed at stacking earlier than infants without a hand preference, if a hand preference does afford manual proficiency. If infants with a preference do indeed have an advantage for stacking, then any manual or cognitive skills that are related to stacking could be affected also by the development of infant handedness. The prediction that infants with a preference will develop cognitive abilities earlier differs from the prediction that infants with a right preference will develop cognitive abilities earlier. The latter connects right handedness with the developing left-hemisphere's control of motor skills whereas the former connects preferred hand skill with sensorimotor cognitive ability irrespective of hemisphere control.

The current study examines the relation of infant hand preferences to the development of stacking skill. First, this study will describe the development of stacking skill from 10 to 14 months. Very few studies of stacking skill have examined infants (e.g., Chen et al., 2010; Hanline, Milton & Phelps, 2001; Marcinowski, 2013), therefore a description of stacking at these ages (10–14 months) is important to understanding how this skill emerges.

Second, this study will assess how infant hand preferences affect the development of stacking from 10 to 14 months. We sought to compare two contrasting predictions: 1) the cascade theory of handedness (Michel, 1983, 2002) and 2) the invariant lateralization theory (Caplan & Kinsbourne, 1976; Kinsbourne, 1975a, 1975b, 1975c, 1976). Since a preferred hand is more practiced and proficient, we predict that infants with a hand preference (regardless of direction) will exhibit more rapid development and better stacking skills, than infants without a consistent hand preference (i.e., the cascade theory of handedness). Additionally, early preferred hand use (a consequence of developmental processes/cascade theory) will predict earlier stacking skill, rather than early right hand use (a consequence of a presumed cerebral asymmetry for control of manual actions/invariant lateralization theory).

2 Method

2.1 Participants

A sub-sample of 131 infants was selected from 380 infants who were recruited from Guilford County, NC birth records to come to the Infant Development Center for 9 monthly visits across their 6–14 month period. All 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.

The 131 infants (61 females) selected to have their stacking skills assessed 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., 2014) and Guilford County's ethnic demographics (US Census Bureau, 2010). Families' median yearly household incomes were $60,000–$69,999 (range: $10,000–$150,000+). The mothers' and fathers' education levels ranged from high school graduate to professional degree. The median education level for both was a bachelor's degree. The primary language spoken in the home was English for all participants, except five cases: three Spanish, one Arabic, and one French. No differences were found between the infant handedness sample and the infant construction sub-sample for sex ($\chi 2 = .440$, $p \leq .214$) or infant handedness ($\chi 2 = 4.043$, $p \leq .117$).

2.2 Procedure

During each of the infant's visits, a reliable procedure for assessing hand preference for acquiring objects was administered (Michel, Ovrut, & Harkins, 1985). Analyses of infant hand preference for acquisition were conducted with the 380 infants using the statistical techniques described in Michel, Babik, Sheu, and Campbell (2014).

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 the parent 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. Each visit was recorded in its entirety for later data coding. If the infant became fussy 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).

2.3 Handedness (6-14 months)

The monthly hand preference assessment involved 32 presentations of objects of varying shapes and sizes. The objects were presented either singly (26 objects) or in pairs (6 objects). Single objects were presented either on the table (23 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 (picked-up) or for 20 seconds, whichever occurred first. The entire handedness assessment lasted approximately 15 min. 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, over all inter-rater agreement was 93.22% (Cohen's $\kappa = .898$) and the overall intra-rater agreement was 97.9% (Cohen's $\kappa = .969$). Different videos were randomly selected for inter- and intra-rater reliability coding and both sets of video samples were stratified by infant age (i.e., equal numbers of videos from each age). For intra-rater reliability, the same rater scored the same video twice on occasions and the codes from the two videos were compared.

Infant hand preference for acquisition was ascertained using group-based trajectory modeling (GBTM), also called latent class growth analysis (Michel et al., 2014) and BIC for identifying numbers of classes. GBTM is a statistical technique which clusters similar patterns of trajectories together, and identifies sub-groups whose members follow similar developmental trends (Haviland, Nagin, Rosenbaum, & Tremblay, 2008). This method assumes that the observations are drawn from a population characterized by distinct subgroups. These subgroups are assumed to be qualitatively different from one another, but members are considered homogeneous within sub-groups (Michel, Sheu, & Brumley, 2002). To achieve optimal determination of subgroup membership, GBTM analysis was performed on the full dataset ($n = 380$) prior to the analysis sub-sample ($n = 131$) used in this study.

2.4 Stacking task (10-14 months)

The stacking task was created originally for this project and was composed of four sets of objects which afforded stacking: 1) four cylinder blocks (one red, three purple) and 2) five cubic blocks with alphabet letters painted with multiple colors on all sides; and 3) four stacking cups painted to look like cakes (two brown, two white). The maximum number of stacks for each toy was three for the cylinder blocks, four for the cubic blocks, and three for each of the cups presentations (totaling 13). Before presenting the task to the infant, the presenter demonstrated how the task could be stacked and then disassembled it. Then, the objects were presented to the infant using both hands in a completely deconstructed state. 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 s. The entire stacking assessment took approximately 6 min.

Only successful stacks were counted for the statistical analyses. Successful stacks were defined as when the object in the infant's hand was placed upon a “base” object and the infant removes his/her hand without the object immediately losing its placement. If the object fell out of place once the infant let go of the object, then this is not counted as a successful stack. As with the acquisition handedness assessments, videotapes of the stacking tasks were coded using Noldus © Observer XT 10.1. On a 20% of age-stratified, randomly selected sample of stacking videos, inter-rater reliability showed an overall agreement rate of 96.6% (Cohen's $\kappa = .953$); while a separate 20% age-stratified random sample of videos showed intra-rater reliability had an overall agreement rate of 97.9% ($\kappa = .975$).

3 Results

3.1 Description of infant stacking skill

Originally, infants were coded for stacking at 9 months; however, very little stacking occurred at this age. Out of 37 pilot-coded infants, 9-month-olds had a mean of .07 stacks, a median of 0 stacks, and a range of 0–1 stacks. Since the amount of stacking observed during these visits was negligible, they were not coded further for stacking or included in longitudinal models.

Figure 1 shows the percentages of infants whose most complex structure involved 0, 1, 2, or 3 stacks at each month from 10 to 14 months. Infants are stacking at a very low level at the 10 months of age (mean = .17 stacks, median = 0). Note that for the 10-month-old infants, only 15% were able to stack one piece on another and .8% could stack two or more pieces on another piece. By 14 months, 35% of infants could build at least one structure by stacking two or more pieces.

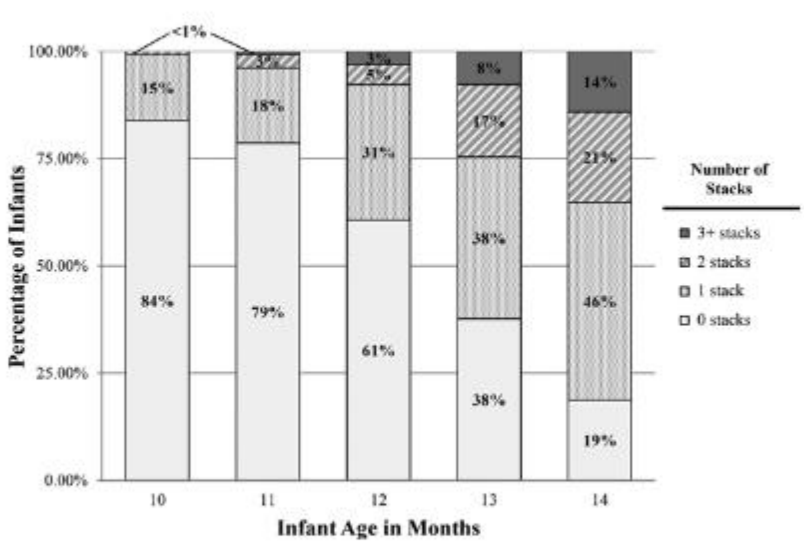

Figure 1. Cumulative percentages of infants performing at each level of stacking by age

3.2 Handedness classification

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 right hand use = (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 (Babik, Campbell, & Michel, 2013; Jones, Nagin, & Roeder, 2001) on the entire sample (n = 380), and the sub-sample's handedness classification from the larger analysis was used for the current study. GBTM is a statistical technique which clusters similar patterns of trajectories together, and identifies sub-groups whose members follow similar developmental trends (Haviland et al., 2008). Each infant's probability of membership for all groups is calculated (i.e., the posterior probability) and the infant is identified as a member of the group that is most likely (i.e., with the highest posterior probability). Four groups were found from these analyses within the larger sample (n = 380): stable right (32.2%), trending right (25.4%), left (12.2%), and no stable handedness (30.2%).

The GBTM identified all four groups as statistically distinct from one another (Figure 2). Stable right-handers initially started at a high proportion of right hand use and remained high right across the entire period (mean range: .70–.74). In contrast, the trending right-handed group initially exhibited a low proportion of right hand use (actually, significantly left-handed at 6 months: $M = .38$; $t(1,87) = -2.84$, $p < .01$), rapidly increased their right hand use from 7 to 9 months (mean range: .47–.60), and then exhibited a high proportion of right hand use from 10 to 14 months (mean range: .68–.71). The trending right group also had a significant quadratic slope ($\beta22 = -.08$, $t(3,91) = -4.24$, $p < .01$), whereas the stable right-handers did not have a significant linear ($\beta14 = .01$, $t(3,126) = .013$, $p = .27$) or quadratic slope ($\beta24 = -.002$, $t(3,126) = -.002$, $p = .20$). Left-handers initially began at equal hand use ($M = .46$, $t(1,44) = -1.22$, $p = .19$), but then steadily increased their left hand use across the period (8–14 months, mean range: .34–.41). Finally, infants without a hand preference exhibited no hand preference from 8–11 months (mean range: .48–.53), but increased in their right hand use from 12 to 14 months (mean range: .56–.59). It should be noted that none of the handedness group exhibited similar trajectories to one another and left-handers were not the “mirror images” of either of the right handedness groups.

From these data, the subsample was drawn (n = 131), 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. The average posterior probability of group assignment was .800 (left = .849, trending = .753, no = .798, stable right = .821).

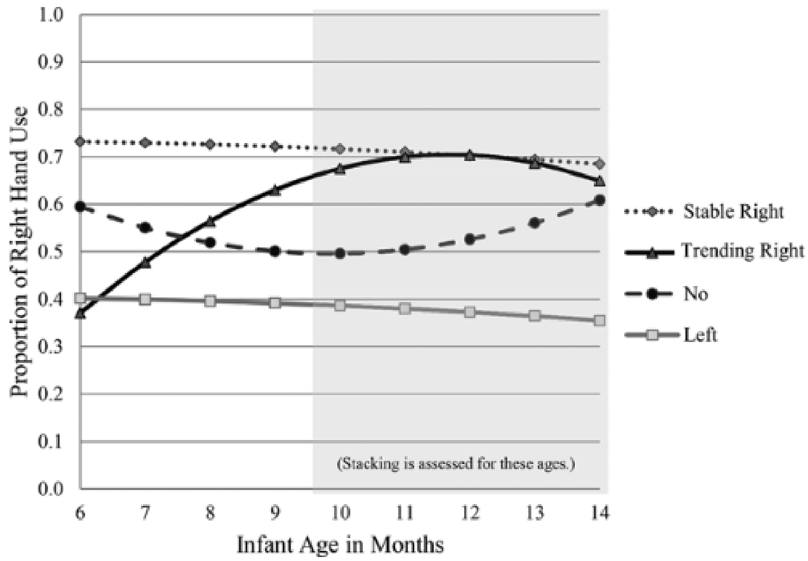

Figure 2. Infant acquisition hand preference trajectories determined by GBTM method (n = 380)

3.3 Models of stacking skill

The dependent variable ("Stacking") was calculated as a sum of all successful stacks relative to the number of opportunities across all stacking toys. For example, an infant that stacked two cakes, three cylinder blocks, and zero of the other toys, would have a score of "5" for stacking. This data was analyzed under a multilevel Poisson longitudinal model (MPLM), using the software program, Hierarchical Linear Modeling (HLM v.7). This analysis describes change over time, how these changes vary across individuals and groups, and appropriately accounts for Poisson-distributed data (Cameron & Triveldi, 1998; Singer & Willett, 2003). This model can accommodate changing (Level 1, i.e., age changes in individual stacking scores), as well as stable (Level 2, i.e., hand preference group) variables over time.

Two additional features of the current study's data were accounted for in the model: underdispersion and variable exposure. First, underdispersion in Poisson models occurs when data exhibit less variability than expected under a standard Poisson model, in which the conditional variance should equal the conditional mean. It can occur in datasets with an abundance of zeroes and other small count values, as might be expected with a burgeoning infant skill like stacking. Second, 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 median of 12 available items (out of 13 possible) and ranged from as few as 9 to as many as 12 stackable items ($M = 11.39$, $s = 1.40$ items). Therefore, a variable exposure parameter was included into the model in an effort to accommodate for differing opportunities to stack. Thus, the dependent variable can be conceptualized as the rate by which stacking increased, relative to the total number of stacking opportunities, at each visit.

The level-1 (time-varying) variables were Age, Age2, and Age3, 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 (Age2 = (Age–Mean Age)2) and Cubic age (Age3 = (Age–Mean Age)3) were both coded orthogonally to Age to decrease multicollinearity (Bock, 1975). The posterior probabilities of each preference group (stable right, trending right, left) were modeled and no preference served as the reference group.

Posterior probabilities were used to represent handedness preferences, instead of absolute handedness category, in order to account for the uncertainties of handedness group assignment by the GBTM model better.

3.4 Longitudinal change in stacking skill

The model-building strategies recommended by Raudenbush, Bryk, Cheong, Congdon, and du Toit (2004) and Singer and Willett (2003) were employed in developing the models. This means that the analyses started with the unconditional (Age, Age2, and Age3) and then the conditional growth models (Age, Age2, Age3, Handedness, and interactions). In the unconditional growth model, fixed effects for Age and Age2 were significant predictors of stacking skill (Table 1); thus infants developed stacking skill quadratically, on average. The variance components for the intercept, linear slope, and quadratic slope were all significant − meaning that infants exhibited substantial degrees of individual variability at the beginning of the period (intercept) and in their individual trajectories (linear, quadratic, and cubic components of trend) across the 10–14 month period. Although the fixed effect for the cubic slope was not significant, the random effect was (i.e., $\tau 33$); thus, both the fixed and random effects for the cubic slope were retained in the final unconditional growth model. This indicates that infants exhibit substantial variability in their degrees of change, but on average, infants with positive cubic change offset the infants with negative degrees of change.

	Stacking	
	Unconditional growth	**Conditional growth**
Fixed effects	*Coefficient*	*Coefficient*
Intercept (γ_{00})	−5.334***	−5.790***
Age (γ_{10})	1.043***	1.262***
Age^2 (γ_{20})	−.086	−.420**
Age^3 (γ_{30})	−.015	.062
Left (γ_{01})	–	.636
Left*age (γ_{11})	–	−.564
Left*age^2 (γ_{21})	–	.448*
Stable right (γ_{02})	–	1.759*
Stable right*age (γ_{12})	–	−.651*
Stable right*age^2 (γ_{22})	–	.333*
Trending right (γ_{03})	–	−.773
Trending right*age (γ_{13})	–	.291
Trending right*age^2 (γ_{23})	–	.523*
Trending right*age^3 (γ_{33})	–	−.245*
Random effects	*Variance component*	*Variance component*
Intercept (τ_{0i})	9.465***	9.759***
Linear (τ_{1i})	1.263***	1.289***
Quadratic (τ_{2i})	.240***	.246***
Cubic (τ_{3i})	.084***	.089***
Level-1 (σ_ε^2)	.273	.262

*$p < .05$; **$p < .01$; ***$p < .001$.
[a]Handedness refers to the mean effect of posterior probabilities for each handedness group from the GBTM.

Table 1. Final growth models of handedness a and stacking from 10–14 months

Next, the full conditional growth model was tested, which incorporates Age, Handedness and their interactions (Figure 3). Trending right-handers were the only group to demonstrate unique cubic change compared to infants without a preference ($\gamma33 = -.245$, $p \leq .026$). Left- ($\gamma21 = .448$, $p \leq .015$) and stable right-handers ($\gamma22 = .333$, $p \leq .033$) both developed stacking significantly differently, from infants without a hand preference (Table 1). In addition, all groups changed differently from one another in their quadratic slopes ($\chi2$s 4.068–8.968, ps ≤ .041–.018). Left-handers ($\chi2 = 13.342$ $p < .002$) and stable right-handers ($\chi2 = 9.899$, $p < .007$) differed significantly from infants without a hand preference at 14 months. Trending right-handers did not differ from any handedness group at 14 months ($\chi2$s 1.492–3.969, ps ≥ .135–.500).

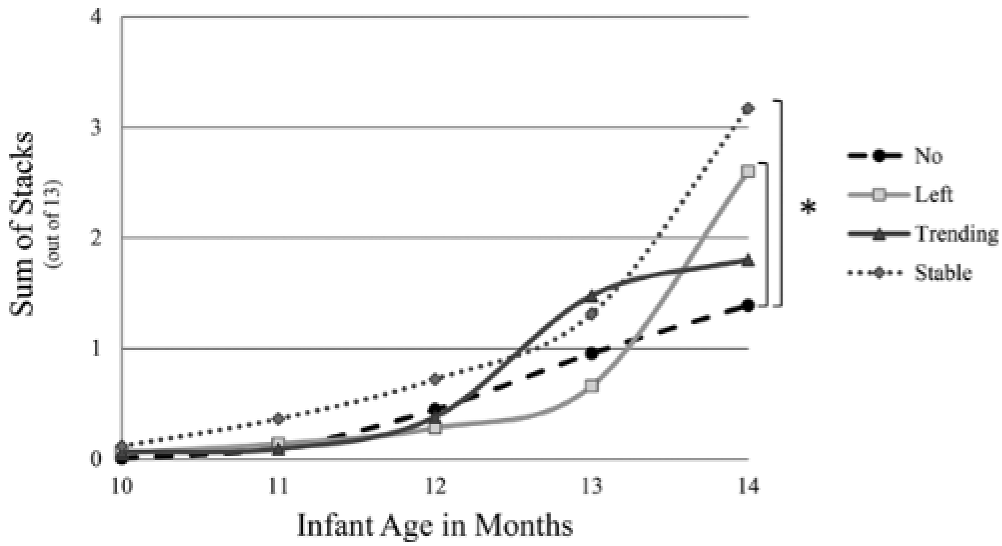

Figure 3. The mean effect of handedness on stacking across age. (n = 131) (Final Conditional Model). *p ≤ 0.05. “Handedness” refers to the mean effect of posterior probabilities for each handedness group from the GBTM

In sum, stacking skill increased across the 10–14 month ages; although it was at an inconsistent rate of change across handedness groups. Stable right- and left-handers rapidly increased their rate of stacking skill following the first incidence of stacking (i.e., quadratic trends). Trending right-handers had less acute rates of increase in stacking skill, although they experience a rapid rise in skill between 12 and 13 months that subsequently leveled off (i.e., cubic trend). Thus, trending right-, stable right- and left-handers rapidly developed stacking after 12 months, while only trending right-handers' development slowed after 13 months.

3.5 Does acquisition hand use predict infant stacking?

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 for manual skill propose that right hand use (left hemisphere control) will predict early success at cognitive activities. According to these theories, stacking success should be associated with greater right hand use rather than preferred hand use. Thus, an HLM analysis was conducted to assess whether right or preferred hand use predicted stacking skill for each handedness group.

Hand use during the 6–9 month period was used, since this is period represents an early sub-set of hand use prior to the onset of stacking. In contrast, the GBTM uses all ages from 6 to 14 months to assign infants into hand preference groups. When these groups are used to predict stacking, hand use assessments at later ages may be used to predict preceding stacking assessments (i.e, hand use from 6 to 14 months is used to predict 10–14 month stacking). To address this limitation, only hand use proportions from 6 to 9 months were used to predict stacking. Right hand use was calculated as the proportion of right hand use relative to the number of lateralized pick-ups, summed across the 6–9 month visits. Preferred hand use was calculated as the 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,1 respectively).

To evaluate hand use across the 6–9 month ages, three one-way ANOVAs were conducted to describe differences between handedness groups for right and preferred hand use from 6–9 months. Group differences were found for preferred ($F(2,96) = 54.161$, $p \leq .001$) and right ($F(3,127) = 61.270$, $p \leq .001$) hand use. A Tukey post-hoc test revealed that stable right-handers had significantly higher right/preferred ($ps \leq .001$) hand use from all other groups. Left-handers used their preferred hand more than trending right-handers ($p \leq .008$) and left-handers also used their right hands less than all other groups ($ps \leq .000$–$.002$).

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., .5; Table 2). Stable right- ($t(1,37) = 18.493$, $p \leq .001$) and left-handers ($t(1,22) = 3.557$, $p \leq .002$) exhibited preferred hand use above chance, but trending right-handers did not ($t(1,37) = .822$, $p \geq .281$). Infants without a hand preference did not use their right hand more than chance ($t(1,31) = 1.121$, $p > .210$). Thus, only stable right- and left-handers actually demonstrate a preferential use of their preferred hand from 6 to 9 months, while trending right-handers do not.

Group	Preferred	Right
	Mean (standard deviation)	Mean (standard deviation)
Left	.589[a] (.120)	.412 (.120)
Trending right	.512 (.090)	.512 (.090)
No	–	.522 (.111)
Stable right	.737[a] (.079)	.737[a] (.079)

[a]t-test with a $p \leq .05$ against chance (.5).

Table 2. Acquisition hand use from 6–9 months across handedness groups

In order to model the effect of hand use on the development of stacking, the proportions of right and preferred hand use were included in a MPLM as continuous variables at Level 2. 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 ($\gamma01 = 1.921$, $p \leq .408$), linear slope ($\gamma11 = -.320$, $p \leq .720$), quadratic slope ($\gamma21 = .053$, $p \leq .900$) or cubic slope ($\gamma31 = -.058$, $p \leq .821$; Figure 3). The mean effect of preferred hand use did predict stacking success at the intercept ($\gamma01 = 3.242$, $p \leq .031$) and linear slope ($\gamma11 = -.801$, $p \leq .049$), but not at the quadratic ($\gamma21 = .258$, $p \leq .568$) or cubic slope ($\gamma31 = ..135$, $p \leq .623$). The effect of preferred hand use demonstrated higher skill than nonpreferred hand use at 12 months ($\gamma01 = 1.640$, $p \leq .047$). When infants without a preference are removed from the preferred hand analyses, a similar effect for preferred hand use remains ($\gamma11 = -.768$, $p \leq .045$). When only infants without a preference are analyzed, no effect for right hand use was found for the intercept ($\gamma01 = 2.254$, $p \leq .692$), linear ($\gamma11 = -.659$, $p \leq .750$), and quadratic slope ($\gamma21 = -.419$, $p \leq .837$), although this model is estimated on a much smaller sample of infants ($n = 32$) than the full analyses. Infants who used their preferred hand more often from 6 to 9 months increased their stacking skill more rapidly than infants who used the preferred hand less from 6 to 9 months; although, infants who used the preferred hand less from 6 to 9 months caught up by 14 months (Figure 4).

Preferred hand use, as opposed to simply right hand use, predicted stacking skill for all groups. It is important to note that if our model had only tested right hand use, then right hand use would have predicted initial stacking success ($\gamma 11 = 3.100$, $p \leq .021$) and a faster rate of development of stacking success ($\gamma 11 = -.735$, $p \leq .043$), 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 skill because any benefits associated with left-handers (n = 23) using their left hands are masked. When a model including both right and preferred hand use was tested, right hand use reduced out of the model and preferred hand use solely predicted stacking.

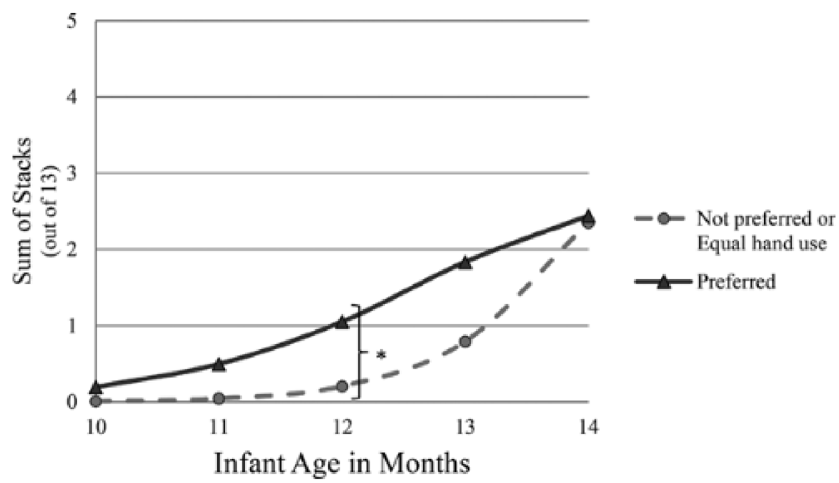

Figure 4. Mean effect of preferred hand use on stacking. (n = 131). *p ≤ 0.05

4 Discussion

The main purpose of this project was to determine whether hand preferences and hand use affected the development of object construction skill during infancy. We compared the cascade theory of handedness (Michel, 1983, 2002) and the invariant lateralization theory (Caplan & Kinsbourne, 1976; Kinsbourne, 1975a, 1975b, 1975c, 1976). The invariant lateralization theory suggests that lateralized hand use is the result of an “innate” lateralization of left hemisphere functioning and, once a manual skill emerges, lateralization is apparent and stable throughout development. Additionally, the lateralization of one behavior does not have an effect on the development on another lateralized behavior since they simply represent the same underlying hemispheric lateralization. So rather than a hand preference developing as a cascade of skills influencing the development of other skills, any apparent changes in hand preference are explained the transfer of that task to the hemisphere designed to perform the task more efficiently (the invariant lateralization theory). In contrast, the cascade theory of handedness suggests that a preference for a manual skill develops via a transfer from the preferences for previously-established skills. Consequently, the unique consequences of having a hand preference or not leads to different developmental trajectories for motor skills and cognition.

These findings support the cascade theory of handedness development. Michel (1983, 2002) predicted that infants with a hand preference would develop cognitive skills earlier, and the current study found that a hand preference did relate to earlier development of object stacking skills. Each infant hand preference group developed stacking in a unique way. As predicted, infants without a hand preference displayed the lowest level and slowest development of stacking skill of all handedness groups across 10–14 months. Stable right- and left-handers did develop stacking skill faster and had greater success at stacking at 14 months, than infants without a hand preference.

Unlike stable right- and left-handers, trending right-handers exhibited stacking skills similar to infants without a preference. They exhibited a slower rate of development and had less success at 14 months, than infants with a left or stable right preference. Consistent with our hypothesis, trending right-handers do not exhibit a preference for acquiring objects with their right hand during the 6–9 month time period before stacking was assessed. In contrast, infants with left- and stable right preferences did use their preferred hands more frequently than by chance during these early ages. As expected, stable right- and left-handers are using their preferred hand more often prior to the onset of stacking and that likely contributes to their earlier development of stacking skills. The inconsistent history of preferred hand use for trending right-handers, on the other hand, likely contributed to less proficiency in hand skills, which in turn, diminished the manual proficiency needed for stacking. Thus, when trending right-handers use their right hand to stack, they are not necessarily using a more proficient hand, although stacking success does depend on greater hand control during stacking actions (Chen et al., 2010).

One major difference between the cascade theory and some other handedness theories is that preferred hand use is expected to predict success at manual skill, rather than right hand use. Many studies of early handedness are somewhat limited, because left-handers are often underrepresented or absent from the studies (e.g., $n \leq 5$: Esseily, Jacquet, & Fagard, 2011; Nelson, Campbell, & Michel, 2013; Ramsay, 1985; Vauclair & Cochet, 2013). Since left-handers are difficult to recruit in sufficient numbers to analyze, handedness is often conceptualized into "right" and "non-right" categories according to an arbitrary criterion (e.g., Esseily, Jacquet & Fagard, 2011; Vauclair & Cochet, 2013). This "non-right-handed" category may combine left-handed, ambidextral (no preference with two skilled hands) and ambisinistral (non-preference with two poorly-skilled hands: Flowers, 1975) individuals. Since right-handers predominate over left-handers within infant samples, it is not surprising that a main effect of right hand use on cognition is often found in the literature. Given the marked differences that we found between left-handers and infants without a preference, any "non-right-handed" group is too heterogeneous for comparison with a "right-handed" group.

This project differed, in that enough left-handers were sampled to compare right versus preferred hand use. Preferred hand use was found to predict earlier stacking skill development, rather than simply right hand use. Infants who used their preferred hand more prior to the onset of object construction developed stacking skill more quickly, than infants who used their preferred hands less. Preferred hand use, rather than right hand use, changed how stacking skill developed and predicted earlier success at stacking.

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, Volman, & Leseman, 2012), place learning ability relates to spatial prepositions (Balcomb, Newcombe, & Ferrara, 2011), object construction relates to spatial relational words (Marcinowski & Campbell, in press), and sitting facilitated an understanding of object properties (e.g., Soska & Adolph, 2014). Different physical interactions with the environment lead to differences in cognition, which supports the embodied cognition account of development (e.g., Barsalou, 2008; Dellatolas et al., 2003; Lakoff & Johnson, 1999; Oppenheimer, 2008). According to this theory, 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, one must understand the development of motor skills to understand cognitive development (Lakoff & Johnson, 1980).

Since handedness has been demonstrated to affect a cognitive skill (i.e., stacking), how might handedness specifically change the way an infant develops cognition? 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 and receive sensory information with one hand (preferred hand) more than the other (nonpreferred hand). 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. Asymmetrical transduction of the environment may then encourage further lateralized brain organization in the infant with a hand preference (Michel et al., 2013).

If a connection does exist between preferential hand use, object construction and cognition, then differences in developmental trajectories of hand preference signal potentially unique trajectories for cognitive development relative to hand preference (Michel et al., 2013). Infants with a stable right hand preference show more right hand use across 6–14 months. This contrasts with trending right-handers, who have equal hand use initially and then increase in their right hand use by 14 months age. Even if trending and stable right-handed infants both become right-handed toddlers, these children's handedness trajectories are both distinguished by a unique feature − early stability versus instability. “Stability” could be associated with greater lateralization of cognitive abilities, while “instability” could characterize less lateralization or more interhemispheric control of cognitive abilities. Thus, unique developmental trajectories for manual skills may mean unique trajectories for other types of cognition (Michel et al., 2013). Future study is needed to clarify the role of developing hand preferences and object construction on the development of other cognitive abilities; however, these results reveal one potential means by which infant hand preferences might contribute to the development of cognition in early childhood.

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Endnotes

1. 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 also analyzed using these proportions. 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.

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