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# How the Development of Handedness Could Contribute to the Development of Language

***ABSTRACT:*** *We propose a developmental process which may link the development of handedness with the development of hemispheric specialization for speech processing. Using Arbib's proposed sequence of sensorimotor development of manual skills and gestures (that he considers to be the basis of speech gestures and proto-language), we show how the development of hand-use preferences in proto-reaching skills concatenate into object acquisition skills and eventually into role-differentiated bimanual manipulation skills (that reflect interhemispheric communication and coordination). These latter sensorimotor skills might facilitate the development of speech processing via their influence on the development of tool-using and object management abilities. © 2013 Wiley Periodicals, Inc.* Dev Psychobiol

***Keywords:*** *infants; handedness development; language; hemispheric specialization; embodied cognition*

## INTRODUCTION

Bipedal locomotion, language, tool-construction and use, and an overwhelming predominance of right-handedness in the population are among the characteristics that seem to distinguish humans as a species. Right-handedness and language share another characteristic that is more subtle: hemispheric specialization of function. For most people, the left hemisphere of the brain is involved in speech production and perception and also, it controls the right hand. Handedness and control of the production and perception of speech sometimes have been considered to be relatively independent instances of hemispheric specialization (e.g., Kinsbourne, 1997; Witelson, 1990); whereas others (e.g., Annett, 2002) consider the predominance of right-handedness to be a consequence of the predominance of the left hemisphere control of language. Although the left-hemisphere's involvement in speech processing can be different for left-handers, it still seems to predominate.

Early evidence from neurological adult patients indicated that about 15% of left-handers process speech in the right hemisphere and another 15% exhibit bilateral speech processing as compared to more than 95% of right-handers processing speech in their left hemisphere (Rasmussen & Milner, 1977). Unfortunately, this study used a statistically indefensible means of identifying handedness status. Recently, Knecht et al. (2000), using functional transcranial Doppler sonagraphy, found that the apparent incidence of right hemisphere speech processing increased linearly from 4% in strong right-handers to 27% in strong left-handers (assessed by the Oldfield handedness questionnaire) with 15% right hemisphere speech processing in ambilaterals. The 4% of strong right-handers who process speech in the right hemisphere and the 73% of strong left-handers process speech in their left hemisphere support the notion that handedness and speech lateralization are relatively independent.

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Of course, lateralization for speech production and comprehension depends on the meaning of "speech" (Peelle, 2012). For right-handed adults, imaging studies indicate that both the left and right temporal cortices process phonemes and single words similarly (Binder et al., 2000; Binder, Swanson, Hammeke, & Sabsevitz, 2008; Gainotti, Miceli, Silveri, & Villa, 1982; Hickok et al., 2008). In contrast, processing connected speech (involving not only phonemic and lexical information, but also syntactic, semantic, prosodic, and rhythmic cues conveyed over the course of several seconds) relies more heavily on left hemisphere language regions, most obviously in inferior frontal cortex (Obleser, Meyer, & Friederici, 2011; Peelle, Troiani, Wingfield, & Grossman, 2010; Rodd, Johnsrude, & Davis, 2012; Tyler et al., 2010). Unfortunately, in much of this research, the lateralized differences were not statistically assessed but inferred based on the presence or absence of an activation cluster in a particular brain region. Observing a response in one region, but not another, does not mean that these regions differ significantly in their activity or their contribution to the function (Henson, 2005). Also, we need more studies of hemispheric specialization for speech processing in left-handed individuals. Therefore, there is still much to be learned about the lateralization for speech processing.

Also, the meaning of handedness must be considered when assessing the relation of handedness to hemispheric specialization for language processing. There is no consensus about whether hand-use preferences should be identified via statistically evaluated measures of actual performance, self-reports of performance obtained via questionnaire, or self-assignment. Often, responses on handedness questionnaires are poorly related to general manual proficiency, in part, because questionnaires assess culturally dependent tool-use (cf., Michel, Nelson, Babik, Campbell, & Marcinowski, 2013). Handedness is not a categorical trait but rather varies continuously among individuals, especially with measures of the differences between hands in manual proficiency (Annett, 2002). Even questionnaire measures reveal a continuum of individual variability. Therefore, measures of handedness must use reliable and valid procedures but also they must use classification (into right-, left-, and ambilateral-handedness) techniques that are statistically defensible rather than arbitrarily determined. As with the imaging measures of lateralization of speech processing, handedness categories are often defined without statistical estimates of the probability of misclassification.

Despite their extensive use, determining handedness by questionnaire is not sufficient to capture the variability of adult and child handedness. The relatively weak association of handedness with cerebral asymmetry for speech processing may be, in part, an artifact of simplistic definitions of handedness (Bishop, 1990). Of course, for developmental investigations with infants and young children only actual performance measures can be employed. Consequently, the investigation of the relation of handedness to hemispheric specialization for speech processing might be more appropriate for infants and young children. Given the problems in determining both the lateralization in speech processing and handedness, we conclude that handedness may be related in some way to lateralized differences in speech processing, but the character of that relation and the mechanisms supporting it are not yet known. More systematic research with careful definitions of handedness and speech processing skills is required.

Embodiment theory may be one way of conceptualizing how handedness can relate to lateralization of speech processing (cf., Michel et al., 2013). Embodied cognition proposes that the processes of language, concept formation and use, and abstract reasoning comprise mental simulations of bodily experiences of actions on objects and interactions of the self with others (e.g., Barsalou, 2008; Lakoff & Johnson, 1999; Oppenheimer, 2008). Accordingly, our comprehension of events, situations, or words involves an implicit mental simulation of our previous sensorimotor engagement with similar events, situations, or physical referents and likely this comprehension would use regions of the brain involved in such perception and action (e.g., Longcamp, Anton, Roth, & Velay, 2005; Willems & Hagoort, 2007; Willems, Hagoort, & Casasanto, 2010; Willems, Toni, Hagoort, & Casasanto, 2009). However, what about concepts that have no sensorimotor equivalent?

Beginning in infancy, people physically approach things typically identified as positive and withdraw from things typically identified as negative (e.g., Hane, Fox, Henderson, & Marshall, 2008). This association connects actions with positive and negative emotions and, according to Casasanto and Dijkstra (2010), since abstract concepts carry either positive or negative *emotional valence*, this mediates their relation to action. In this way, abstract concepts which cannot directly engage our senses or be acted upon (e.g., intelligence, kindness, honesty, poverty, politeness, ethics, etc.) can be embodied. For those who prefer to use their right hand, approach-related behavior is associated with positively valenced experience and that is lateralized to processes in the left frontal lobe, which controls the right side of the body. In contrast, avoidance related behavior is associated with negatively valenced experiences and that is lateralized to the right frontal lobe which controls the left side of the body (e.g., Davidson, 1992; Schiff & Bassel, 1996). A similar (but reversed) contralateral pattern of experience/behavior—brain lateralization organization can be predicted for left-handers and was observed for adults (Brookshire & Casasanto, 2012).

Embodiment theory predicts that there should be differences between right- and left-handers in the left-right lateralization of positive/approach and negative/avoidance characteristics because the more proficient (preferred) hand acts more effectively on the environment and can acquire "desired" objects more effectively. This greater sensorimotor proficiency has been shown to correlate with more positive evaluations of the objects of those interactions (e.g., Beilock & Holt, 2007; Oppenheimer, 2008). Expertise in using our preferred hand implicitly associates positive emotions/good qualities with that side of our bodies and negative emotions/bad qualities with the side of our nonpreferred hand, which we use less proficiently (Casasanto & Chrysikou, 2011). Therefore, if concepts and word meanings are constituted by simulations of our own actions, then right- and left-handers, who consequently interact with their physical environments in systematically different ways, should form correspondingly different mental representations. Casasanto and Hennetz (2012) observed such associations in 5- to 10-year-old children but there has been no such research with infants. Embodiment theory might predict that right-handed infants (defined by their preferred hand acquiring objects) would push away negative stimuli and defend themselves with their left hand. The reverse would be predicted for left-handed infants.

Also, if thinking about actions involves "mental" simulation of the way we execute them, then actions that we perform with our preferred hand (e.g., throwing a ball, turning a key, writing) should have (and do have) different hemispheric representations in right- and left-handed individuals (e.g., Willems & Hagoort, 2007). Imaging techniques have shown that the control of their preferred hand and both the imagery of and reading of manual action verbs depends on their contralateral hemispheres for left- and right-handers (Volkmann, Schnitzler, Witte, & Freund, 1998; Willems et al., 2009). This demonstrates that handedness and language processing may be linked via a co-occurring embodied process. Casasanto (2009) proposed that if language is an embodied process, then it ought to be differently embodied for left- and right-handers. But how?

Language has been characterized as a system of communication for regulating and coordinating social activity (Krauss & Chiu, 1998) or as a formal symbolic system organized by the rules of grammar to express thought (Chomsky, 1966). However, as many have argued (e.g., Arbib, 2006; Corballis, 2003), language also can be characterized as a system of sensorimotor skills enabling the perception and production of speech. If we examine language as a system of sensorimotor skills, its development can be incorporated into what we know about the development of other sensorimotor systems for action and perception. As a system of sensorimotor skills, language automatically becomes part of the developmental and evolutionary transitions that occur in postural control, tool-use, and symbolic gesture that characterize humans (e.g., Arbib, 2011; MacNeilage & Davis, 2005). Consequently, questions can be asked about the relation of the mechanisms involved in the production of speech gestures to those for the motor control of manual gestures. If there is a developmental relationship between these two sensorimotor systems, then the ontogeny of language may involve a progression from actions to gestures to speech (cf., Arbib, 2006, 2011). Interestingly, Jacquet, Esseily, Rider, and Fagard (2012) found no relationship between hand preferences for grasping and declarative pointing. However the method by which handedness was calculated for both conditions permits most scores to have occurred by chance (i.e., $p > .05$). Thus, many infants likely were misclassified. Future studies should examine this relation using more statistically defensible methods for classifying infant handedness.

Arbib and coworkers (Arbib, 2006; Oztop, Arbib, & Bradley, 2006) proposed a sequence of developmental sensorimotor events that might connect the development of the manual skills of grasping, manipulating, and using objects with the development of manual communication skills (proto-sign, involving imitation of manual actions) and speech gestural skills (proto-speech, involving imitation of speech sounds). Although Arbib's hypotheses rest heavily on the presumed developmental functions of mirror neurons, much of the developmental sequence can be described without reference to the hypothetical contributions of mirror neurons. Moreover, much of the developmental sequence occurs during the age period when infants are developing hand-use preferences; hence, the theme for our presentation.

For Arbib, the infant begins by establishing a visuomotor system capable of generating reaching trajectories to ensure successful contact with (proto-reaching), and acquisition of, objects. In a Hebbian manner, this creates a neural repertoire of object-hand trajectories. Acquisition of objects permits grasping skills to develop in relation to both the visual and haptic characteristics of objects. This develops an object-grasp repertoire of the visual affordances of objects that indicate potential successful grasping. Again in a Hebbian association manner, the object-grasp neural repertoire merges with that of the object-hand trajectories to ensure successful acquisition and manipulation of objects. Eventually, these actions can occur without the object (pantomime—e.g., brushing teeth, combing hair); however, these pantomimes often involve substituting a body part for the object (e.g., a finger is the toothbrush, the hand is the comb). Finally, the development of complex imitation permits the acquisition of actions that combine primitive aspects of the child's action repertoire to form new actions, many of which will have symbolic character (proto-signs such as waving bye-bye or saluting). For Arbib (2006), the development of these manual skills is matched by the development of speech gestural skills and the development of complex imitation results in the imitation of speech gestures characteristic of language (proto-speech). Now, what role (if any) might handedness play in this developmental sequence?

We argue that during their first postnatal year, infants transform "proto-reaching movements" into sensorimotor skills that exhibit a hand-use preference for goal-directed actions (acquiring and manipulating objects, using tools, etc.). Infants, as a result of the development of their hand-use skills, acquire sufficient "sensorimotor knowledge" of objects to exhibit arm and wrist adjustments during prehension that "anticipate" grasping according to the character of the object and sometimes they exhibit an "end-state comfort effect" similar to that exhibited by adults (Rosenbaum, van Heugten, & Caldwell, 1996). By the end of their first postnatal year, infants have acquired several manual sensorimotor skills that exhibit handedness and this has consequences on the development of their tool-using skills, object manipulation skills (constructing complex objects from simpler components), and other sensorimotor cognitive abilities, including language. We propose, also, that these manual sensorimotor skills provide the foundation for the perception and production of speech gestures and the representational abilities for symbolic communication and language (Greenfield, 2006) and that handedness contributes to the lateralization of such language skills. Broadly, we propose that the development of handedness during infancy helps teach the brain to speak!

## DEVELOPMENT OF INFANT HANDEDNESS FROM PROTO-REACHING TO SOPHISTICATED OBJECT MANIPULATION

Infant handedness can only be assessed effectively by observing which hand the infant prefers to use. However, we can assume that hand-use preferences derive from lateralized differences in the infant nervous system's ability to coordinate, control, and execute those actions that contribute to a manifest preference in use. Thus, the preferred hand-use must reflect a lateralized difference in neural control of manual actions. It is the presumed sharing of the lateralized control of hand actions (gestures) and speech actions (gestures) that link the development of handedness to the development of language. However, the neural control of these hand-use actions involves mechanisms situated in the spinal cord, the medulla, brain stem, cerebellum, thalamus, basal ganglia, and various parts of the cortex (Bizzi & Mussa-Ivaldi, 1998). Therefore, we would expect that some of these neural control systems may operate earlier than others and, through sensory feedback systems, their operation can influence the development of the later emerging control systems.

Some have proposed that the foundation for proto-reaching may begin as early as 10–15 weeks of fetal development (De Vries et al., 2001; Hepper, Shahidullah, & White, 1991) when fetuses make hand contact with the face and may exhibit preferential arm movement. Hepper, Wells, and Lynch (2005) reported that fetus's apparent differences in the movement patterns of the arms are predictive of later handedness with 100% of fetuses with a prenatal preference to suck the thumb of the right hand exhibiting right-handedness (parental report) at 10–12 years of age and 67% of fetuses who preferred to suck their left-thumb exhibiting left-handedness. Such early asymmetry of arm movements likely reflects spinal reflexes rather than brain-stem or cortical circuits (cf., Hopkins & Rönnqvist, 1998). Therefore, the mechanism by which such lateralized actions would be produced at 15 weeks cannot involve the same cortical neural processes that are involved in handedness of children and adults. Nevertheless, it would not be surprising that, if such lateralized processes controlling limb actions existed at the level of the spinal cord, they would contribute to the developmental sculpting of the neural processes associated with further cerebral lateralization (brain stem, basal ganglia, limbic system, cortex). Therefore, if fetal asymmetrical hand actions predict preteen handedness, then they must do so by contributing to the biasing of the development of the midbrain and forebrain mechanisms controlling handedness in adults.

We, also, consider the development of handedness to be based on events occurring in utero. Asymmetries of the fetal position and actions in utero have been proposed to concatenate into the neonate's supine head orientation preference (HOP) (Michel & Goodwin, 1979). For the first 2 months postpartum, an overwhelming majority of infants prefer to lie with their heads turned to their right and about 15% prefer to turn their heads to the left (Michel, 1981). These proportions are very similar to the proportions of adult right-and left-handedness in those societies without prescriptions against left-handedness. It is likely that the direction of this HOP is a consequence of asymmetrical activation of neuromotor mechanisms (involving vestibular stimulation and reflexes) at the level of brain stem nuclei, cerebellum, thalamus, and perhaps basal ganglia. We expect that such asymmetrical activation had been established in utero and influenced by the fetus' position rather than being simply a reflection of a more generalized hemispheric specialization (Michel, 1983, 1988). Although the mechanism controlling lateralized asymmetry in HOP is different from that controlling handedness in children and adults, they appear to be developmentally tied. The HOP influences early lateralized asymmetries of hand and arm actions and the HOP subsequently predicts development of right and left hand-use preferences for reaching for, and acquiring, objects (Michel, 1981; Michel & Harkins, 1986).

How can the direction of HOP affect the development of the infant's hand-use preference for reaching? Kupperstein (1988) proposed a mechanism that could account for such visuomotor associations. "Foveation" (visual fixation) of the hand as a consequence of the HOP activates neural systems monitoring the tensions of the extraocular eye muscles, whereas nonfoveated "looking" does not produce tensions in the eye muscles. This foveation occurs because the biased activation of the face-side arm-hand movements by the vestibular and neck stretch reflexes. These reflexes, in turn, are prompted by the turned head and place the face side hand precisely within the fixed focal length of the neonate's vision (van der Meer, van der Weel, & Lee, 1995).

An association is built between the activity of the extraocular muscles and that of the activity of muscles of the arm in their postural positions. Since the face side hand is more active (Michel, 1981), it will attract foveation. This builds a proprioceptive "map" that combines head-eye position with hand-arm position and the hand's location in a "map" of visual space. Later, when an object is foveated, the correct arm muscle tensions are "recalled" so as to position the arm to move toward and contact the object. Such movement can operate based on the formation of internal models of antagonistic muscle force levels like those proposed for visually elicited reaching (Bizzi, Hogan, Mussa-Ivaldi, & Giszter, 1992; Mussa-Ivaldi & Bizzi, 2000).

These map-muscle positions are stored in association-like memory built through experience. Since only the terminal postural position of the arm is stored, the trajectory generation and arm dynamics derive from the tension model of muscle dynamics. Hence, the degrees of freedom for organizing the trajectory of reaching toward a visually presented object are greatly reduced and early reaching will be ballistic in character, involving no sensory feedback during its execution.

Some research has reported that the distribution of handedness in blind individuals is similar to those in sighted. Such evidence has been considered as refuting the hypothesis that an infant hand preference develops from the consequences of a HOP influence on hand actions, specifically via visual regard of one hand more than the other (c.f., Hopkins & Rönnqvist, 1998). However "blind" refers to a variety of sight problems from total lack of sensitivity to any light to difficulties resolving images. Blind infants who are still sensitive to light and shadows might exhibit a similar pattern as sighted infants. Ittyerah (1993) compared handedness in sighted and blind children, those with complete congenital blindness and those with some light perception capabilities (46% of the sample). There seemed to be little difference between blind and sighted (but blindfolded) in the proportion of children with right hand use, although the 6- and 7-year-old blind children exhibited less right-hand use than the sighted.

There are three problems with this study. First, all of the blind children received extensive training for using tools and reading Braille that was strongly biased for their right hand. Also, this sample was from India, which has strong cultural rules against left hand use. Finally, their classification for handedness was not statistically defensible. Thus, one cannot separate the influence of specific training on the handedness exhibited by these blind children.

In a recent large sample of blind children in Turkey, Caliskan and Dane (2009) reported that left-handedness was significantly greater for congenitally blind children (16% left-handed), those with very poor visual acuity (22% left-handed), and those with poor visual acuity (24% left-handed) when compared to sighted children (10% left-handed). These distributions of left-handedness in blind children match the distribution of leftward HOP observed in newborn infants (Michel, 1981). Moreover, Michel (1983, 1988, 2002) discussed other contributions (i.e., proprioceptive/kinesthetic) to the development of differential neural control of the hand that need not depend on sight. Thus, an early HOP, even without some sight dependent perception, would be expected to contribute to feedback processes for shaping neural control of the hands.

Note that before 4–5 months of age, turning the lights off during a reach does not disrupt reaching (Clifton, Muir, Ashmead, & Clarkson, 1993), indicating that the reach trajectory is ballistic. In contrast, by 6–7 months, blocking the sight of the hand during the reach disrupts or impairs its performance (Lasky, 1977; Wishart, Bower, & Dunkeld, 1978). Also, veering angles (changes in arm trajectories as a result of correction during a reach) during prehension suggest the emergence of on-line monitoring of sensory feedback and adjustment of the trajectory ("'continuous' correction of movement errors") by 6 months (Mathew & Cook, 1990, p. 1238). By 7 months, this adjustment can occur even when the reach is at 75% of its distance (McCarty, Clifton, Ashmead, Lee, & Goubet, 2001). Thus, after the first half year postpartum, the infant is using vision in coordinating the prehension act rather than vision simply eliciting a reach trajectory. In addition, once contact is made, haptic feedback is used to make corrective movements for grasping and acquiring the object, (Lasky, 1977; Wimmers, Savelsbergh, Beek, & Hopkins, 1998; Wishart et al., 1978). But how does object acquisition develop?

Within days after birth, a visual stimulus elicits eye-head orienting. von Hofsten (1982) reported that 3-day-old infants, supported in a reclined infant seat, exhibited more forward-extending arm movements (swiping) which were closer to a moving target during fixation as compared to when they were not fixated on the target. Ruff and Halton (1978) provided evidence indicating that this early "reaching" may be more apparent than real because arm movements are elicited by the infant's head orientation which creates the impression of swiping to a target. Coryell and Michel (1978; see also Michel & Harkins, 1986) were unable to find such differential "swiping" during "fixation" for the ages from 2 to 10 weeks of age. However, by 10–12 weeks there are more arm movements when the head/eyes are directed toward the object than when they are not (Coryell & Michel, 1978; Michel & Harkins, 1986). These visually elicited swiping movements were similar to the swiping at visually presented objects by 2–3 months as reported by von Hofsten (1991). Moreover, by 12 weeks, the hand that had been on the face side of the infant's supine HOP during the first 8 weeks was the more active hand when looking at objects (Michel, 1981). Thus, the two months of hand regard and differential activity prompted by the infant's supine HOP is sufficient to establish a hand-use preference for visually elicited swiping at objects (proto-reaching).

By 16 weeks of age, infants are frequently contacting objects with their swipes (Michel & Harkins, 1986; von Hofsten & Ronnqvist, 1988). However, there is little evidence for the acquisition of those objects that were contacted as well as little evidence of any preshaping of the hand for acquisition. Newell, Scully, McDonald, and Baillargeon (1989) observed some hand-shaping after contact with the object during the 4- to 6-month age period. But hand shaping during reaching only begins to appear by 9–10 months (von Hofsten & Ronnqvist, 1988). Interestingly, Newell et al. (1989) reported that the haptically adjusted grasps that occur after contact at 4–6 months are similar to the visually adjusted grasps that appear later at 9 months. This similarity suggests that the early post contact haptic grasp configurations become target configurations for preshaping prehension some 3–5 months later. Therefore, many months of grasping objects permits the establishment of an object-grasp repertoire and its association with the hand-trajectory repertoire so that the formation of visual affordances will permit hand preshaping for successful grasping during prehension. But how does the infant acquire information about the "grasp-ability" of objects?

Again, the neonatal HOP plays a role. During their first 2 months postpartum, neonates exhibit a hand difference in duration of "reflexive" grasping of objects (Caplan & Kinsbourne, 1976). This early grasping of objects permits the infant to sense the effects of their actions. The hand difference is primarily a consequence of the influence of the infant's HOP on manual actions (Schwartz & Michel, 1992). The direction of the head turn results in greater probability of "dropping" by the hand away from the direction of head turn and hence a shorter duration of left-hand grasping by the majority of infants with a rightward HOP preference (and vice versa for the minority of infants with a leftward HOP). In this way, the HOP can contribute to lateralized differences in the extraction of object properties affording grasping.

By 2 months, infants actively engage their hands in mutual fingering and manipulate their feet, clothing, and other objects that come into their hands. Most of these manual actions occur within the infant's visual field. This "exploration" is important for establishing a basic array of biomechanically feasible reach and grasp configurations in the sensorimotor circuits of the brain (most likely in the supplementary motor area of the cortex). These investigatory actions facilitate development of attention to the manipulanda and permit the discovery of affordances. Thus, such manipulation contributes to the development of a repertoire of grasps but also the recognition that different affordances relate to the visual characteristics of objects. These contribute to the visuomotor coordination that permits the selection and control of the effective movement and hand preshaping. Thus, via spontaneous behavior, the infant's activity provides experience on the possibilities for action in the environment and the "discovery" of the affordances of objects (e.g., a set of grasps that can be applied to secure objects of particular shapes and sizes). The neonatal HOP insures that there will be a hand-use difference in these experiences extending through 4 months of age.

By 5 months, infants can reliably contact objects, show a hand-use preference for such contact (as predicted by the direction of their neonatal HOP), and often acquire them (Michel & Harkins, 1986). By 6 months, infants are very reliably acquiring objects with a hand-use preference for acquisition that continues for the next nine months (Ferre, Babik, & Michel, 2010). By 7–9 months, this experience of acquiring objects has enabled visually informed feed-forward control of the acquisition movement to permit hand preshaping to the character of the goal object (Newell et al., 1989; von Hofsten & Ronnqvist, 1988). By 9 months, infants can use visual information to correct errors in their reach trajectory to ensure object contact (von Hofsten, 1979) and they can orient the hand to match the objects orientation (Lockman, Ashmead, & Bushnell, 1984).

Of course, some of the development of these skills is affected by the development of corticospinal pathways (Forrsberg, 1998; Olivier, Edgley, Armand, & Lemon, 1997) which begin to form prenatally (e.g., Eyre, Miller, Clowry, Conway, & Watts, 2000). There is evidence that the ipsilateral/contralateral pattern of corticospinal and corticomotoneural control of the hands is influenced by their activity (Eyre, Taylor, Villagra, Smith, & Miller, 2001). Thus, differential activation of the hands as a consequence of the HOP can help shape their contralateral control. Slight differences in their reinforcement can change the pattern of neural representation and control of the use of the forepaws in rats (Spinelli & Jensen, 1982). However, all sensorimotor skills depend upon the dynamic interaction among many neural circuits, biomechanical characteristics, environmental and social contexts. Perhaps, the initial primary use of the "power grasp" (object held in the palm and encased by all of the fingers) during the first postnatal year likely constrains manipulative configurations for tactile exploration of object affordances (albeit affording greater probability of successful acquisition). Therefore, bimanual grasping, followed by intermanual transfer, in the last third of the infant's first postnatal year encourages manual exploration which weakens the dominance of the power grasp. Bimanual transfers likely direct attention to select attributes of the object and increase affordance recognition.

During development, the infant must acquire greater control of arm, trunk, and postural movements so as to generate the consistent feedback needed to form stable links between perceptual and motor schemas (Michel, 1991). By 12 months, these experiences provide a set of grasps, including some precision grips, with preshaping to visual affordances. It is likely that sensory feedback from successful grasps nurtures further exploratory reaches to grasp. The infant's HOP provides an early lateralized asymmetry of experience for the neural mechanisms as they develop control over the grasping actions. These types of experiences eventually permit infants to use feedback to adjust movement planning parameters based on visual information during prehension and feed-forward adjustments of the movements based on visual information obtained before the initiation of prehension.

Although infants can exhibit a hand-use preference (right or left) for acquiring objects from 6 to 14 months of age (Ferre et al., 2010), unimanual manipulation of objects exhibits a different developmental progression. Manipulating objects with one hand occurs early in development and its relative frequency in the infant's manual repertoire remains stable from 6 to 12 months. However, there is no manifested hand-use preference for unimanual manipulation until 11 months (Hinojosa, Sheu, & Michel, 2003). The infant's hand-use preference for acquiring objects predicts his/her hand use preference for unimanual manipulation at 11 months, but not before. Since sensorimotor skills are continuously refined by proprioceptive, somatosensory, and other sensory experience and feedback, it is likely that a hand-use preference for unimanual manipulation arises as a consequence of the infant's hand use preference for acquiring objects. As a consequence of acquiring an object, that acquiring hand will have more opportunity to engage in manipulation. It seems to take some 4–5 months of such "practice" for the infant to transfer his/her hand-use preference for acquiring objects to a preference for unimanually manipulating them. In this way, a hand-use preference for the actions of acquiring objects can expand into a hand-use preference for unimanual manipulation. Consequently, the controlling hemisphere's processing abilities expand.

Preferences for acquiring objects and manipulating them can cascade in to hand-use preferences for later-developing role-differentiated bimanual manipulation (RDBM). RDBM requires that each hand performs different but complementary movements on one or many objects (Michel, 1998; Michel, Ovrut, & Harkins, 1985). Typically, one hand (the nonpreferred) supports the fine motor manipulation actions of the other (preferred) hand (e.g., holding a cup to remove an object from it). Complex RDBM actions not only require sophisticated bimanual coordination but also considerable interhemispheric transfer of information (Fagard & Corroyer, 2003). Vauclair (1984) proposed that manual preferences for RDBM form the foundation of the handedness manifested in tool-use and construction skills. These latter manual skills likely involve higher-level cognitive skills such as imitation of complex actions, planning, decision making, and the ability to account for spatial and temporal characteristics of objects and situations.

Note that in the current account, handedness is not emerging independently in any succession of more complex manual skills. Instead, handedness for simple reaching and contact expands into handedness for acquiring objects which, in turn, transfers into hand-use preferences in later-emerging skills such as unimanual manipulation and RDBM. Moreover, as development of manual skills continues, the earlier skills become more automatized and lose some of the striking distinctiveness of the preference (either hand can acquire an object although one hand might be slightly more adept than the other). Thus, it could be hypothesized that hand-use preferences for a manual skill will vary with the development of that skill. That is, when a particular motor skill (e.g., role-differentiated bimanual manipulation) is beginning to be manifested in the infant's manual repertoire, clear hand-use preferences likely will not be observed and only very simple RDBMs will be manifested. As the RDBM action becomes skilled, the distinctive hand-use preference will appear as promoted by the biases created in the earlier hand-use preferences (for RDBM, these would be the acquisition and unimanual hand-use preferences). As the action becomes highly skilled, the hand-use preference lessens. In other words, the trajectory of the degree of lateralized asymmetry observed for any particular manual action is predicted to have an inverted U-shape form with lateralization being low at the emergence of the action, increasing as the skill becomes mastered, and then decreases as the action becomes highly skilled and more automatic. Thus, to assess handedness during infancy, the tasks must be sufficiently difficult to elicit a preference, but not too difficult.

To further illustrate this cascading development of lateralized asymmetry in handedness, let us consider the emergence of handedness for RDBM in more detail. RDBMs may be observed as early as 6–7 months. However, these earlier developing RDBMs do not exhibit much skill (i.e., the precise coordination of intermanual movements and their timing) and seem to emerge incidentally from the particular affordances of the object (Kimmerle, Ferre, Kotwica, & Michel, 2010; Kimmerle, Mick, & Michel, 1995). Indeed, these RDBMs likely occur in the absence of efficient callosal transfer of information for controlling the movements of the hands. Since these early RDBMs may be performed in the absence of interhemispheric communication, they likely would involve minimum hemispheric specialization or preferential hand use. RDBMs manifested by 12–13 months of age are much more complex actions and likely involve interhemispheric communication. It is at this age that RDBMs become a much larger proportion of the infant's manual repertoire, show evidence of "planning" in the execution of the actions, and exhibit a hand-use preference (Kimmerle et al., 2010). Moreover, there is some preliminary evidence that the hand-use preference in RDBM by 13–14 months of age reflects the infant's hand-use preference for acquiring objects (Babik, in press).

By 18–24 months, toddlers exhibit an extensive array of complex RDBMs and their handedness for RDBM is predicted by their handedness for acquiring objects during infancy (Nelson, Campbell, & Michel, 2013). Moreover, infants who exhibited no hand-use preference for acquiring objects do exhibit hand-use preferences for RDBM as toddlers with the majority of them being right-handed for RDBM.

Such cascading transformations in how handedness is manifested during infancy may change the conventional view that handedness for reaching, unimanual manipulation, role-differentiated manipulation, pointing, construction, or tool-use is unstable and subject to fluctuations in the development (Michel, 2002). This means that often observed variability in handedness (Corbetta & Thelen, 1999, 2002; Fagard, 1998; Fagard & Lockman, 2005; McCormick & Maurer, 1988; Piek, 2002; Thelen, 1995; Thelen, Corbetta, & Spencer, 1996) likely derives from variability of succession of different kinds of handedness that are related to each other developmentally. Consequently, the timing of the measurement of the different types of handedness becomes critical.

For example, Hinojosa et al. (2003) found that infants exhibiting right-handedness for reaching and grasping objects are more likely to use right hand during unimanual manipulation at the age of 11 months, but not at 7 months, when unimanual manipulation is initially being expressed. Thus, a researcher may not obtain a valid measure of handedness while using a unimanual procedure to assess handedness in infants younger than 11 months. Furthermore, although some researchers may consider RDBM to provide a more valid measure of handedness than reaching in 1-year-old infants, hand-use preferences in RDBMs are likely to be variable at best until 13 months of age or later (Kimmerle et al., 1995, 2010).

## HANDEDNESS AND LANGUAGE DEVELOPMENT

If we return to Arbib's account of how sensorimotor development can scaffold the development of speech processing, then we have demonstrated how handedness for proto-reaching contributes to the development of handedness for effective acquisition and manipulation of objects. But what about the link between the development of handedness and the development of gestures (e.g., pointing)? Since handedness for object acquisition precedes pointing as a gesture, do infants with a hand-use preference exhibit pointing sooner than those without? Also, do infants point with the same hand that they prefer to use for manual actions such as object acquisition and manipulation? Although infants show a right hand preference for pointing (e.g., Esseily, Jacquet, & Fagard, 2011; Franco & Butterworth, 1996), the results of studies linking hand preferences for action to those for communication have been ambiguous, with the strongest connections reported for periods of significant language change (e.g., Bates, O'Connell, Vaid, Sledge, & Oakes, 1986; Jacquet et al., 2012; Ramsay, 1984, 1985; Vauclair & Imbault, 2009). Clearly, more research examining links between these two domains for which infants use their hands and exhibit clear preferences is needed.

By its nature, gesture as a measure of developing language ability is confounded by the fact that it shares the same manner of expression (i.e., hands) as developing sensorimotor skills. To address this issue, we have recently begun to examine language level using standardized scales in children whom we have been extensively following for manual hand use preferences. We have evidence that children who developed handedness for unimanual acquisition of objects as infants were more advanced on their standardized language skills as 2-year-olds when compared to children who had not exhibited handedness as infants, but became left- or right-handed as toddlers (Nelson, Campbell, & Michel, in revision). We are continuing to collect data with two more waves of children over the 6- to 24-month period as well as collecting handedness and language assessment data at 3 and 4 years of age.

Several sets of information support the relation of speech/language development and the development of the sensorimotor skills observed in manual skill. Sensorimotor skills in manual actions depend upon finely timed transitions between appropriately ordered sequences of acts and speech gestures also depend on similarly finely timed transition between appropriately ordered sequences of acts (Abbs & Grecco, 1983). Moreover, the decoding of heard speech seems to depend upon the sensorimotor skills needed to produce it (Liberman & Mattingly, 1985). Speech phonology exhibits a rule system similar to both the rule system in the control of manual gestures and in the organization of the syntax of language (Cooper & Paccia-Cooper, 1980). Therefore, the programming of speech may derive, in part, from the programming of manual actions and the programming of manual actions derive from experience, likely the experiences associated with the control of a preferred hand. Perhaps, by this set of connections the development of handedness can contribute to the development of speech processing.

Currently we are examining the role of infant handedness for acquiring objects in the development of both conventionalized and nonconventionalized tool-using skills, construction of complex objects from component parts, gestural communication (pointing), conventional protosign (e.g., bye-bye), and conventional language abilities. We have collected monthly data from 6 to 14 months of age on hand-use preferences for acquiring objects from 328 infants (Michel, Babik, Sheu, & Campbell, submitted). Using group based trajectory models (Nagin, 2005) with Bayesian information criterion to identify the number of groups (Schwarz, 1978) we found that there are three developmental trajectories for the handedness for acquiring objects: consistently right-handed (38% of infants), consistently left-handed (14% of infants), and those that are trending toward right-handedness (48% of infants). We are comparing these groups on the development of their tool-using and object construction skills. Other comparisons will follow. We have some evidence that 7- to 13-month-old infants who are slow to develop hand-use preferences for acquiring objects are slow to develop the object management skills that Bruner (1973) proposed were the earliest expression of symbolic functioning (Kotwica, Ferre, & Michel, 2008). Thus, we are beginning to map the developmental relation of handedness to language during infancy and this may enable us to connect the development of handedness with the development of hemispheric specialization for language.

## CONCLUSIONS

The examination of the relation of handedness to the development of cognitive and linguistic skills requires study from infancy into the preschool years. If mental metaphors are created differently in right- and left-handers via a developmental history of asymmetrical sensorimotor experience created by their preferred hand actions on the environment as well as via embodiment of the positively and negatively valenced experiences (e.g., Casasanto & Henetz, 2012), then developmental variations in thinking in preschool children should be linked to the pattern of their handedness development. Thus, there may be three "types" of neurocognitive developmental trajectories during early childhood, two representing those who develop strong right- or left-handedness early in infancy and one representing those who do not develop strong hand-use preferences during infancy but do so as toddlers (Michel et al., submitted; Nelson et al., 2013) or later.

Although early infancy represents a significant time during handedness development, handedness continues to develop after 14 months of age, especially for those infants who enter toddlerhood without a hand-use preference. Thus, it is likely that these trajectories continue to shape subsequent cognitive and language development. Research on adults shows that most members of a group of "ambilaterals" manifest poor manual skill with either hand (Doane & Todor, 1978; Flowers, 1975). Hence, we might expect a different development of their conceptual ability, and perhaps less distinct hemispheric specialization of function, for those infants without a hand-use preference by 14 months. In this way, notions about the embodied differences in cognitive processing among right-, left-, and ambiguously handed individuals can be tested beginning with the early development of handedness. By examining the differences in the development of motor abilities and language skills in infants and children who differ in the development of their handedness, Arbib's (2006, 2011) sensorimotor theory of language development as well as the theoretical notions of embodied cognition may be assessed more directly.

## NOTES

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