ABSTRACT

Title of Dissertation: EXAMINING THE ROLE OF THE MOTOR SYSTEM IN EARLY COMMUNICATIVE DEVELOPMENT

Virginia C. Salo, Doctor of Philosophy, 2018

Dissertation directed by: Professor Nathan A. Fox, Department of Human Development and Quantitative Methodology

Action understanding is a proposed foundation for communicative development, such that infants can apply a similar process of interpreting the goal-structure of actions to the understanding of others' gestures as well as spoken language. The mirror neuron system, as indexed by activation of the motor system during both performance and observation of actions, has been implicated as a neural correlate for action understanding, and may be recruited for understanding both gestures and speech. One's experience with actions influences action understanding measured both behaviorally and neurally. This dissertation examines whether experience with gestures is related to recruitment of the mirror neuron system during observation of gestures in infancy, and whether individual differences in this activity might be related to or support communicative development. Mirror neuron system activity was measured in 10- to 12-month-old infants while they observed an experimenter producing gestures. Their experience with gestures was manipulated through a parent-directed intervention aimed at increasing parents' use of pointing gestures with their child. Infant-parent dyads visited the lab twice. At the first visit, parent and infant pointing gesture production, infant vocabulary, and infant mirror neuron system activity were measured. Next, parents were randomly assigned to either receive the gesture intervention, or to a passive control group. One month after training, parent pointing, infant pointing and vocabulary, and infant mirror neuron system activity were reassessed. Infant vocabulary was measured a final time one month after the post-training follow-up. The findings suggest that the mirror neuron system plays a role in infants' communicative development, and that experience with gestures can impact the mirror neuron system response when observing others' gesture. Infants in the training group showed stronger mirror neuron system activity at follow-up compared to those in the control group. Increases in parents' pointing production predicted increases in infants' mirror neuron system activity, which in turn was related to increases in infants' receptive vocabulary over the same time period. The implications of these findings are discussed.

EXAMINING THE ROLE OF THE MOTOR SYSTEM IN EARLY COMMUNICATIVE DEVELOPMENT

by

Virginia C. Salo

Dissertation submitted to the Faculty of the Graduate School of the University of Maryland, College Park, in partial fulfillment of the requirements for the degree of Doctor of Philosophy
2018

Advisory Committee:
Professor Nathan A. Fox, Chair
Professor Lucas P. Butler
Professor Gregory R. Hancock
Professor Tracy Riggins
Professor Meredith L. Rowe

Acknowledgements

I am tremendously grateful for all of the support I have received throughout my life, and over the past six years in particular. I consider myself immensely lucky to have had not one but two advisors to help me find my way, and I thank you both for your guidance, patience, and mentorship. Meredith, thank you for seeing my potential, for sticking with me, and for introducing me to the wild world of preverbal infants. Nathan, thank you for adopting me as one of your own and for helping me to grow as a scientist in ways I could not have imagined.

I thank my committee members – Dr. Lucas Butler, Dr. Gregory Hancock, and Dr. Tracy Riggins – for your guidance, insight, and flexibility throughout this process. I also thank my undergraduate research assistants, the unsung heroes of this work, without whose help this study would not be what it is.

I have had the great pleasure of being surrounded by so many talented and inspiring individuals throughout my time at Maryland. To Dr. Kathryn Leech – thank you for showing me the ropes. To Drs. Doireann Renzi and Courtney Hattan – thank you for encouraging me to relish in the moment. To Drs. Sonya Troller-Renfree, Kathryn Yoo, and Fabrizia Festante – I could not have chosen better office mates, and am so grateful for the friendships that grew from those tight quarters. To Julie Staples-Watson – for drawing me out of my bubble when I needed it most. I feel so lucky for the fact that some of my most esteemed colleagues are also some of my best friends.

I thank all of the members of the Child Development Lab, both past and present, for being part of a supportive, collaborative, and generally wonderful place to work. I especially want to thank Drs. Erin Cannon and Lindsay Bowman for their time and patience, and holding my hand as I ventured into the world of electrophysiology, and Drs. George Buzzell, Santiago Morales, and Betsy Smith for helping me grow confident in my knowledge and skills. A special thanks to Dr. Ranjan Debnath for his integral role in this project, for answering my calls on the weekends, and for reminding me not to panic.

I am so grateful to have more than my fair share of warm, loving, crazy individuals that I get to call my friends and family. Thank you all for your encouragement and for the rejuvenating experiences when I needed them most. To my mother – thank you for every battle fought and opportunity seized for me to learn more and to be intellectually challenged, and for being my best advocate and cheerleader since day one. You and Daddy instilled and fostered in me the curiosity and drive for answers that has supported me throughout this journey, and I am forever grateful. And finally, to Zeke – my partner in life – thank you for all that you are. Thank you for encouraging me, challenging me, loving me, believing in me, and feeding me. I am so lucky to have found you.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

CSD – Current source density

EEG – Electroencephalogram

ERSP – Event related spectral power

FDR – False discovery rate

FIML – Full information maximum likelihood

fMRI – Functional magnetic resonance imaging

IJA – Initiating joint attention

MCDI – MacArthur-Bates Communicative Development Inventory

MNS – Mirror neuron system

RJA – Responding to joint attention

RM-ANOVA – Repeated measures analysis of variance

RMSEA – Root mean square error of approximation

SRMR – Standardized root mean residual

TMS – Transcranial magnetic stimulation

Chapter 1: Introduction

"Society not only continues to exist by transmission, by communication, but it may fairly be said to exist in transmission, in communication. There is more than a verbal tie between the words common, community, and communication." – John Dewey

The latter half of the first year of life has long been of interest in developmental research, due in large part to the profusion of development that occurs in such a relatively short period of time. The ability to understand and intentionally communicate with one's social partners is arguably one of the most important of these developmental achievements, starting a snowballing effect of language development which can have a far reaching impact on social, cognitive, and academic achievements throughout childhood. In this way, the ability to communicate is seen as a launching point in development. However, it has been suggested that the ability to communicate itself derives from an earlier ability to understand and interpret others' actions (e.g., Woodward, 2004). Action understanding is linked to important social cognitive advances, such as imitation and Theory of Mind, and, important for the current study, to the development of communicative skills (e.g., Brooks & Meltzoff, 2008). Critically, gestures have been cited as an important intermediary in this process (Capirci, Contaldo, Caselli, & Volterra, 2005), such that infants are able to extend their understanding of actions to communicative gestures, which in turn supports their understanding of spoken language. Specifically, gestures support a transition from an earlier ability for interpreting concrete actions with visible consequences, to the more difficult process of interpreting spoken words which are completely abstract, often arbitrary, and have no visible consequence in the physical world. The theoretical basis for this link between action and language through gesture is that they are all supported by the same processes of understanding reference, goals, and intentions (Woodward, 2004).

The mirror neuron system (MNS), characterized by resonant activation of the motor system during observation of actions, has been implicated as a neural correlate for action understanding (Rizzolatti & Fabbri-Destro, 2008), and there is a growing body of evidence in support of this interpretation (e.g., Caspers, Zilles, Laird, & Eickhoff, 2010; Cattaneo, Sandrini, & Schwarzbach, 2010; Stadler et al., 2012). Further, there is a small but growing body of research linking MNS activity and the understanding of communicative acts, including both gestures and speech (Moreno et al., 2015; Moreno, de Vega, & León, 2013; Schippers, Gazzola, Goebel, & Keysers, 2009). However, it remains an open question as to whether this system also supports the development of communicative skills, either verbal or nonverbal. The purpose of the current study is to ask just that question. Specifically, I examined whether there is a link between activity of the MNS and the development of early communicative skills, such as the use of gestures and growing one's vocabulary, in search of evidence for recruitment of the MNS in both action understanding and communication and for the theorized link between action understanding and communication.

In addition, there is also growing evidence that experience with a variety of actions is related to both action understanding and also to the strength of MNS activity during observation of actions (de Klerk, Johnson, Heyes, & Southgate, 2015; van Elk, van Schie, Hunnius, Vesper, & Bekkering, 2008). Several studies have shown that when a person has greater physical experience with a specific action, their representation of that action, measured behaviorally (Cannon, Woodward, Gredebäck, Hofsten, & Turek, 2012;

Sommerville, Woodward, & Needham, 2005), and neurally (Cannon et al., 2014; van Elk et al., 2008), is stronger. However, this link between experience and MNS activity in infancy is not fully understood, further it is unknown whether experience with communicative gestures might have cascading effects on the developing MNS system and/or on subsequent communicative development.

The goals of the present study were three-fold. First, to examine whether infants show similar MNS activity when observing a communicative gesture as they do when observing a typical object-directed action. Second, to examine the relations between infants' MNS activation and their communicative skill, both in terms of gesture and vocabulary. The third and final goal was to examine the effect of experience on MNS activation and potential subsequent effects on developing communicative skills. Specifically, I sought to address whether experimentally manipulating infants' experience with specific communicative gestures, pointing gestures, would increase the MNS response to those gestures and in turn have a positive influence on infants' further communicative development.

Study Overview

In order to address the above goals, I employed a randomized experimental design with a longitudinal aspect. At the first assessment, MNS activity, pointing gesture production, and vocabulary were assessed in 81 10- to 12-month-old infants. At the same time, parents' natural pointing production was also assessed. These baseline measures were examined to see whether there was a relation between infant's experience with pointing gestures, either first-hand experience or observational experience, and their resonant motor activity when observing pointing gestures, and between their motor activity and vocabulary. Next parents were randomly assigned to either receive a parent-directed training aimed at increasing parents' use of pointing gestures with their child, or to a passive control group. One main reason for focusing on pointing gestures for the current study is because the mechanical properties of points are similar to those of grasping actions, which are typical object-directed actions used in study of the MNS, without being overly similar (such as with a showing gesture which subsumes a grasp). Further points are the most common communicative gesture in parent-child interaction in infancy, and children of this age are shown to be able to follow others' pointing gestures. In addition to points, MNS activity was measured during observation and execution of grasps and used as a comparison in the current study. Infants' MNS activity was measured as desynchronization of the mu rhythm as captured via electroencephalogram (EEG). The EEG mu rhythm captures fluctuation of the sensorimotor cortex during both observation and execution of actions, and has been shown to effectively measure sensorimotor activity across the lifespan (Cuevas, Cannon, Yoo, & Fox, 2014; Fox et al., 2016). One month after the training, parent pointing, infant pointing and vocabulary, and infant MNS activity were reassessed. In addition, infant vocabulary was measured again one month after the first follow-up. See Figure 1 for the full study design.

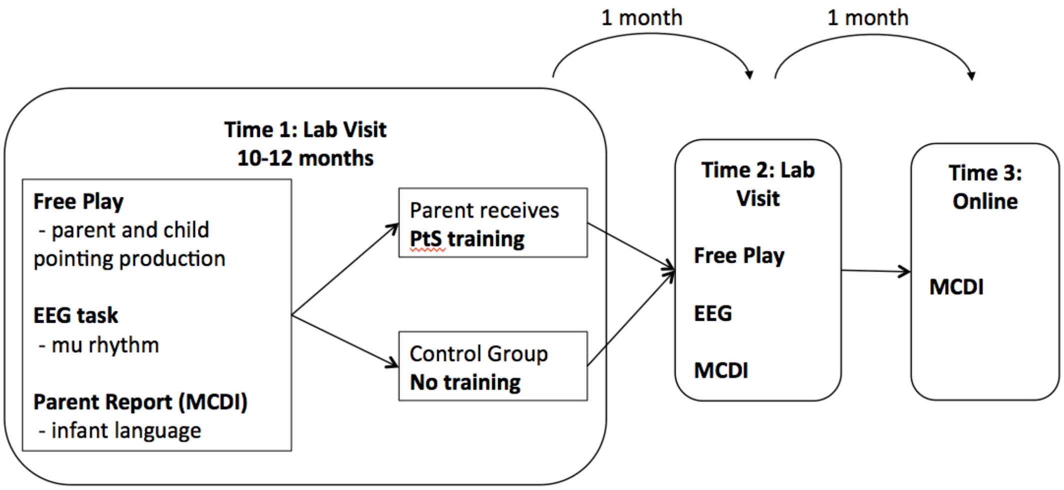


Figure 1. Study design.

Research Questions

The specific research questions and supporting predictions to address the study goals as stated above are as follows:

(1) Do infants exhibit MNS activity, as indexed by mu rhythm desynchronization, during observation of communicative pointing gestures? And, if so, how does that activity compare to their MNS activity during observation and execution of non-communicative grasping actions?

Previous research has found MNS activity in adults during observation of communicative gestures (Quandt, Marshall, Shipley, Beilock, & Goldin-Meadow, 2012; Schippers et al., 2009). Further, the theoretical basis for this study posits similar recognition and interpretation processes during the observation of both actions and gestures (Rizzolatti & Arbib, 1998; Woodward, 2004). Thus, it was predicted that infants would exhibit mu rhythm desynchronization during observation of pointing gestures, and that this activity would be similar to that exhibited during both observation and execution of grasping actions.

(2) What is the relation between infants' MNS activity during observation of pointing gestures and their experience with pointing gestures, at baseline?

This question is two-fold: that is, examining the relation between infants' first-hand experience producing points and their MNS activity, as indexed by mu rhythm desynchronization, and the relation between their observational experience with parental pointing gestures and MNS activity. The majority of the research linking experience with strength of the MNS has focused on first-hand experience, and as such I expected that infants who had greater first-hand experience, those who were producing more pointing gestures, would also exhibit stronger MNS activity during observation of pointing gestures. However, first-hand experience may not be the only important predictor. For instance, de Klerk and colleagues (2016) found that pre-walking infants exhibited mu rhythm desynchronization to videos of other infants walking, suggesting there may be an effect of observational experience on the MNS system as well. While there is little research to draw directly from to inform my hypothesis for the latter question, I expected that infants' observational experience with gestures, as indexed by parents' production of pointing gestures, would also be related to infants' MNS activity during observation of points. Specifically, that infants of parents who produce more points would exhibit stronger mu rhythm desynchronization when observing pointing gestures.

(3) What is the relation between infants' MNS activity during observation of pointing gestures and their language ability, at baseline?

No research has yet examined a relation between MNS activity and language ability in infancy. However, one study (Filippi et al., 2016) found that infants' mu rhythm desynchronization during observation of an experimenter acting on a toy predicted their imitation of the experimenter's goal, a measure of action understanding that has been linked with the development of language (e.g., Charman et al., 2000). Thus, I expected to find a relation between MNS activity and infants' language skill such that infants with stronger mu rhythm desynchronization would also have larger vocabularies.

(4) Does increasing infants' experience with pointing gestures lead to greater MNS activity during observation of points?

Previous research has shown that experience with specific actions leads to greater understanding in infants (e.g., Cannon et al., 2012; Sommerville et al., 2005) and stronger MNS activity, as indexed by mu rhythm desynchronization, during observations of those actions in adults (e.g., Cannon et al., 2014). However, no studies have been done to examine whether experimentally manipulating experience with a gesture, will lead to changes in mu rhythm desynchronization during observation of that same gesture in infancy. While work with both adults and infants suggests that first-hand experience may be the most effective in increasing MNS activity (Cannon et al., 2014; van Elk et al., 2008), recent research suggests that observational experience may also be related to MNS activity (de Klerk et al., 2016). Thus, I predicted that increasing infant's observational, and potentially also their first-hand, experience with pointing gestures through a parent mediated intervention would lead to greater mu rhythm desynchronization during observation of points.

(5) Does increasing infants' experience with pointing gestures lead to increases in their communicative skill?

Building from the theoretical framework outlined thus far, experience promotes understanding and understanding promotes communication. As such, providing infants with more communicative pointing gesture experience should promote both their understanding of those gestures as well as their ability to communicate. Thus, I examined changes in infant pointing production and their developing vocabulary as a function of the parent-mediated intervention. I predicted that children in the training group would produce more points as compared to their peers in the control group, after the training. Further, I expected to see larger vocabularies at follow-up and more growth in vocabularies over the course of the study for those infants' whose parents received the training as compared to those infants' in the control group.

(6) Does infants' MNS activity during observation of pointing gestures mediate the relation between experience with points and their developing vocabulary?

This final question builds upon the previous two questions by directly examining whether the predicted changes in MNS activity, due to increased experience with pointing gestures, would in turn predict changes in infants' own vocabulary growth. I expected that changes in MNS activity, as indexed by mu rhythm desynchronization, would mediate the relation between parent pointing and infant vocabulary growth. See Figure 2 for a conceptualization of the predicted relations. This would be the first explicit evidence for a causal link between experience, MNS activity, and the development of communicative skills.

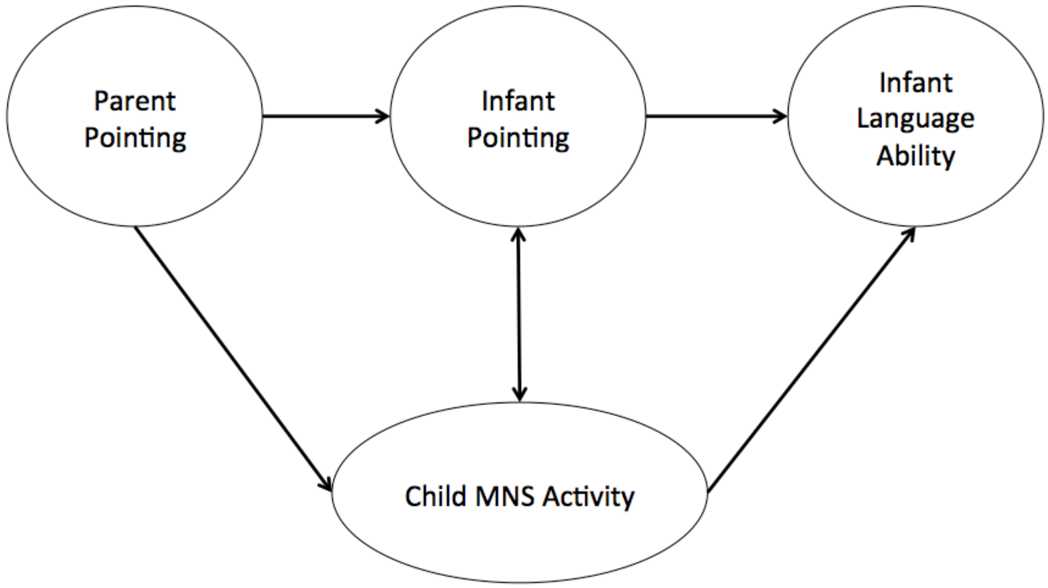


Figure 2. Conceptualization of the predicted relations between pointing experience, MNS activity, and language development.

Chapter 2: Background

In the current chapter, I present the theoretical and empirical work linking action understanding and the development of communication, with a specific focus on the role that gestures play as an intermediary and on MNS activity as an underlying neural correlate. In the first section I consider the theories and empirical evidence for a relation between action understanding and communicative development. This section highlights the notion that action understanding precedes and supports communication, and more specifically, that communicative skills, including both gesture and spoken language, rely at least in part on the same cognitive system utilized in processing and interpreting others' actions. That is, that gestures and words are interpreted as a special case of actions. I further discuss why gestures are an important stepping-stone in the development from action understanding to language understanding. Next, I review the relevant literature linking the neural action-perception system, specifically activation of the sensorimotor regions, with action understanding, followed by a review of the limited research linking MNS activity and communication. I end this section with a review of the research on the link between MNS responses and action understanding in infancy. This section highlights the notion that incorporating the research on recruitment of the MNS as a neural correlate for action understanding can provide unique insight into the relation between action understanding and communication (Rizzolatti & Arbib, 1998). Specifically, that both actions and language are supported by a similar underlying neural system. Lastly, I provide a review of the evidence suggesting experience with specific actions both bolsters one's understanding of those actions and also leads to changes in MNS activity, supporting the notion that experience plays a crucial role in the developmental cascade from actions to communication.

Action Understanding and Communication

Action understanding, what it means and how it develops, has received much attention in developmental research in part because it is viewed as one of the most fundamental abilities in early social-cognitive development. For example, there is a growing body of evidence linking early action understanding with later Theory of Mind (Brooks & Meltzoff, 2015; Charman et al., 2000; Wellman, Phillips, Dunphy-Lelii, & LaLonde, 2004). Likewise, action understanding has been linked to the development of language. In the following sections I will discuss several intersecting theories that propose or support a link between these two constructs, followed by a review of the empirical evidence.

Many theories attempt to explain what supports infants in learning to communicate. One such theory suggests that when infants are faced with the task of learning language they make use of the same mechanisms or processes that they use to understand others' actions. As described by Woodward (2004, p. 150), "In the infant's world, words are actions, and infants most likely draw on their understanding of action in making sense of words from the very beginning." In fact, action and language are proposed to be overlapping systems, and the ability to communicate through language builds, both ontogenetically and phylogenetically, from the ability to understand the intentions and goal driving one's own and others' actions (Corballis, 2012).

An evolutionary argument has been put forth by several researchers (Corballis, 2012; Hewes, 1973; Rizzolatti & Arbib, 1998; Tomasello, 2008). A significantly condensed version of the evolutionary argument unfolds as follows: Prehistoric (and prelingual) man learned that he could direct others' attention through his physical movements (e.g., motioning toward a perceived object of threat), and in turn that others could direct his attention similarly. These physical movements gradually became more refined and specific and became used not only for directing attention but also to convey specific information. These actions, or what we would now refer to as communicative gestures, became the first medium for a human proto-language. According to this evolutionary theory of language development, as the use of gestures to communicate expanded and became somewhat ritualized, these gestures also became paired with vocalizations which exponentiated the number and specificity of ideas one could convey. Just as with gestures, vocalizations became increasingly fine-tuned and eventually became representations and means for communication all on their own. A similar timeline is proposed to unfold ontogenetically, such that infants first learn that actions (both their own and others') can be used to direct attention, then that actions can be used to communicate information (e.g., gestures), and then that vocalizations, and more specifically words, can be used in the same way.

If a similar process is applied to both the understanding of actions and the understanding of words, what then is this process? What is the fundamental shared basis for both action understanding and the development of language? According to Tomasello (1995), it is the ability to understand the psychological relation between a person and an object. Specifically, perceiving others as agents whose actions are intentional and goal-driven. In order to appropriately respond to an observed action, the infant must have an understanding of the actor's intentions underlying that action. As such, understanding actions and responding accordingly relies on the infant's ability to represent her own as well as her partner's goal-related intentional behavior (Tomasello, Carpenter, Call, Behne, & Moll, 2005). When an infant is presented with an action, correct interpretation is based on an understanding of that action in terms of the outcomes it is designed to achieve (Tomasello, Kruger, & Ratner, 1993). An important aspect of this theory is that the infant first comes to understand herself as an intentional agent, and then recognizes that others are intentional agents as well. Several researchers have noted the coinciding development of infants' action understanding and the cognitive skills acquired in accordance with Piaget's sensorimotor stages (Piaget, 1952). The theory being that these cognitive achievements change the way the infant perceives her own and others' behavior, as well as her understanding of the physical world. With an understanding of one's agency and the effect that one can have on the environment, actions are perceived as being not necessarily performed in and of themselves, but as a means toward a particular end. Tying back to the idea of intention understanding, this supports the interpretation of actions in terms of the intended goals or 'ends'.

The theory of embodied cognition (Shapiro, 2011) fits well with this idea in its emphasis on the importance of sensorimotor experiences in development (Overton, 2006). According to the theory of embodied cognition, learning and development are supported by, and in some cases impossible without, direct sensorimotor interaction with the environment (Engel, Maye, Kurthen, & König, 2013; Foglia & Wilson, 2013). Acting on and interacting with the environment, for example through grasping, provides the sensorimotor information necessary to learn not only about the affordances of an object but also the affordances of one's own actions. Further, the sensorimotor experience of observing others act also becomes linked to the sensorimotor experience of an infants' own actions and in this way others' actions become interpretable.

Meltzoff has developed a similar theory in the developmental realm, the "Like Me" theory of social cognition (Meltzoff, 2007; Meltzoff & Gopnik, 1993). According to this theory, "the recognition of self–other equivalences is the foundation … of social cognition. The acts of the self and other are represented within a supramodal code, transcending and integrating sensory modalities. This provides infants with an interpretive framework for understanding the behavior they see" (Meltzoff, 2007, p. 126). Infants are able to recognize others' behavior as 'commensurate' with their own actions, and this you-to-me matching allows the infant to use their own behavior and experiences as a basis for interpreting the behavior of others.

Combining these separate but related theories we are left with an ontogenetic developmental picture in which, through a process of sensorimotor exploration the infants' intentional actions on the environment first become meaningful to her as she uncovers a sense of her own agency. Soon after, the actions produced around her become meaningful. Once an infant understands that the people around her are acting with intention, just as she can and does, every action becomes instilled with meaning and discovering that meaning becomes her task. This is crucial in learning language because to learn the meaning of a communicative symbol (i.e., a gesture or a word) one must understand the purpose for which it was used. To be clear, this does not necessitate that an understanding of intentions is innate, but that this ability, once online supports language learning in the same way that it does the understanding of actions.

There currently exists only a limited body of research that has looked directly at a link between action understanding and later language skills. Researchers have used a range of behaviors to operationalize action understanding in infancy, including, but not limited to, gaze-following, point-following, predictive eye movements, and imitation. In 2008, Brooks and Meltzoff found that gaze following measured in 10- to 11-month-olds predicted the rate of growth in vocabulary over the first two years of life. There is also evidence that gaze following measured at 12 months predicts vocabulary size measured at 18 and 24 months (Tenenbaum, Sobel, Sheinkopf, Malle, & Morgan, 2015). Studies with older infants have provided evidence that imitation is predictive of later language skill (Charman et al., 2000) and can even predict whether or not an infant exhibits later language delays (Zambrana, Ystrom, Schjølberg, & Pons, 2013).

Despite the limited research drawing a direct link between action understanding and language, findings from other areas of developmental research help to elucidate this relationship. For example, research in the realm of joint attention has found consistent relations, both concurrent and predictive, between a set of skills known as initiating and responding to joint attention and later language. Engaging in joint attention involves sharing attention with a partner to a third entity, such as when an infant is attending simultaneously to both a parent and a toy (Seibert, Hogan, & Mundy, 1982; Tomasello & Farrar, 1986). Following into bids for joint attention is referred to as responding to joint attention (RJA) and typically includes gaze and point following, while directing attention is known as Initiating Joint Attention (IJA) and typically includes pointing, showing, and giving gestures (Mundy et al., 2003). Thus, RJA and IJA capture much of the behaviors used to measure infants' action understanding, and research has found links between both RJA and IJA and developing language skills. A study with 14- to 17-month-olds (Mundy & Gomes, 1998) found that, above and beyond the effects of initial receptive language and general cognitive ability, RJA was a significant predictor of receptive language skill measured 16 months later. IJA on the other hand was a significant predictor of later expressive language. Markus, Mundy, Morales, Delgado, and Yale (2000) found evidence for RJA at 12-months predicting expressive vocabulary at both 18- and 21-months, again above and beyond the effect of concurrent language skills and general cognitive development. Mundy and colleagues have even found evidence for RJA measured at 6-months predicting both receptive and expressive language skills as far out as 30 months (Morales et al., 2000; Morales, Mundy, & Rojas, 1998). Desrochers, Morissette, and Ricard (1995) measured the age of onset of pointing production and found that those infants who were pointing to initiate joint attention at 12-months had higher expressive (replicating Camaioni, Caselli, Longobardi, & Volterra, 1991) and receptive (replicating Bates, Benigni, Bretherton, Camaioni, & Volterra, 1979) language skills at 24 months than their peers who were not yet pointers at 12-months.

The importance of gestures as an intermediary

As alluded to above, gestures are thought to serve as an important intermediary between actions and language for infants (Capirci et al., 2005). According to this 'gesture as intermediary' hypothesis, infants extend their understanding of actions to communicative gestures, which in turn supports their understanding of spoken language. That is, the same process for understanding the referential and intentional nature of actions is applied to understanding gestures and eventually to word learning (Woodward, 2004). Gestures, a form of nonverbal communication through physical movements of the body (Cartmill, Demir, & Goldin-Meadow, 2012)[1], are pivotal in this developmental trajectory because they support a transition from the earlier ability for interpreting concrete object-directed actions, who's consequences are often visible making inferences about the underlying intentions more accessible, to the more difficult process of interpreting spoken words which are completely abstract, often arbitrary, and have no visible consequence in the physical world. One study in which researchers observed the action, gesture, and language production of three infants starting at 10 months revealed interesting evidence for the link between actions, gestures, and language (Capirci et al., 2005). Specifically, infants produced specific actions with objects (e.g., bringing an empty spoon to their mouth or pushing a toy car) prior to their use of gestures (e.g., bringing an empty hand to their mouth or making a pushing motion) or words (e.g., "eat" or "vroom vroom") to indicate those same objects or actions.

Gestures share important aspects with both actions and words. Gestures are actions in that they involve movement of the body, and there is evidence that production of both actions and gestures can be beneficial. Producing both actions and gestures have been shown to support learning (Kontra, Goldin-Meadow, & Beilock, 2012; Wakefield, Novack, Congdon, Franconeri, & Goldin-Meadow, 2018). Further, as outlined earlier, experience producing actions is linked with one's understanding of those same actions as

[1] It should be noted that the current discussion of gestures does not include baby signs (i.e., arbitrary or iconic signs taught deliberately by parents; Goodwyn, Acredolo, & Brown, 2000). However, the same theory would hold in learning to understand and produce baby signs, and in fact one could argue that baby signs are more akin to words than gestures in their arbitrary link to meaning.

goal-directed (Sommerville et al., 2005), and similarly experience producing gestures is linked with infants' understanding of gestures. As an example, by 12 months, infants exhibit an understanding of the relational aspect of pointing gestures (Woodward & Guajardo, 2002). That is, they understand that a point is associated with a specific referent. It is during this time that infants also begin to produce their own points (Carpenter, Nagell, & Tomasello, 1998), and critically, the ability to make the association between point and referent depends on the infants' own experience producing points. That is, infants are more likely to understand pointing as relational if they already produce object-directed points (Brune & Woodward, 2007). Lastly, experience with both actions and gestures are linked with language development (Iverson, 2010; Iverson & Goldin-Meadow, 2005; LeBarton, Goldin-Meadow, & Raudenbush, 2015; Rowe, Ozçalişkan, & Goldin-Meadow, 2008).

The critical aspect that gestures share with spoken words is that they are also representational. This concept is nicely defined by Novack & Goldin-Meadow:

> When we say that gestures are representational actions, we mean that they are meaningful substitutions and analogical stand-ins for ideas, objects, actions, relations, etc. (2017, p. 1).

It should be noted that there are several categories of gesture, including deictic gestures that reference something in the immediate environment (such as pointing or showing), conventional gestures who's meaning is derived from cultural agreement and has only an arbitrary relationship to their meaning (such as a thumbs up or head nods and shakes), and representational gestures that generally look like the meaning they are meant to convey (such as flapping one's arms to indicate a bird or flying, or spreading one's arms out wide to indicate ‘big’). The category of representational gestures should not be confused with the idea presented here, and by Novack & Goldin-Meadow (2017) that all gestures, across all categories of gesture, are representational. Just as with actions, we interpret gestures in terms of the goal or intention driving one to produce them. However, the intended consequence of a gesture is to represent something that both the producer and observer of the gesture will understand, that is the intention is communicative. This quality is what gestures share with words, and language more broadly, the communicative function that they serve. Through the use of gestures the infant has attained a manner in which to communicate about her world in a modality that is available to her, actions of the hand, before she is able to express herself via speech (Capirci, Iverson, Pizzuto, & Volterra, 1996; Goldin-Meadow & Butcher, 2003; Mcneill, Duncan, Cole, Gallagher, & Bertenthal, 2008; Volterra, Caselli, Capirci, & Pizzuto, 2005). Once an infant understands the goal-directedness of actions, she can extend that property to more abstract gestures, and in turn to words. Indeed, Woodward and Guajardo (2002) found that infant’s understand the object-directedness of concrete actions (i.e., reaching and grasping) a few months earlier than gestures (i.e., pointing).

For the purpose of the current study, the focus is on infant’s experience with pointing gestures specifically. Just as gestures are a middle step between actions and spoken language, deictic gestures, such as pointing, showing, or giving, may be seen as an intermediary between actions and other kinds of gestures. As mentioned above, there is evidence that infants’ are able to understand the action-object link for grasping earlier than that for pointing (Woodward, 1998; Woodward & Guajardo, 2002). Deictic gestures also support word learning in that they narrow the problem space for what the referent of a spoken word might be. Amongst the deictic gestures, pointing has been singled out as having a special role in this process (Kita, 2003). Whereas showing (e.g., holding an object out for a partner to look at) and giving (holding an object out for a partner to take) both involve physical contact with the object, pointing is a more abstract gesture in that it is physically removed from its referent. As such, pointing may act as a stepping-stone in the transition from more concrete actions and gestures to words. Infants production of showing and giving gestures at 10- and 11-months is correlated with their later production of pointing gestures at 12 months (Cameron-Faulkner, Theakston, Lieven, & Tomasello, 2015), and understanding of shows and gives is thought to precede understanding of pointing gestures as well (Rodríguez, Moreno-Núñez, Basilio, & Sosa, 2015). A few researchers have examined whether infants' production of pointing gestures might be predicted by action understanding. For example, intention understanding (measured as completing a failed action) was concurrently related to production of pointing in a sample of 8- to 14-month-olds (Camaioni, Perucchini, Bellagamba, & Colonnesi, 2004). Additionally, infants' gaze-following ability predicts the age at which they begin using pointing gestures (Matthews, Behne, Lieven, & Tomasello, 2012). These findings add further support to there being a predictive and supportive relation between action understanding and communicative development, and further highlight the importance of gestures at large and pointing in particular as a pivotal intermediary in this developmental trajectory.

The Role of the Motor System

The theories described above, including that of embodied cognition (Overton, 2006) and the "Like Me" theory (Meltzoff, 2007), have provided cognitive examples of a system supporting action understanding. Concurrent research in the realm of neuroscience has produced a growing body of evidence for such a mechanism at the neural level, recruitment of the motor system while observing others' actions.

In the 1990s, a group of specialized neurons were discovered in the brain of macaques that were active both when the monkeys performed simple object-directed actions and when they observed conspecifics or humans performing those same actions (di Pellegrino, Fadiga, Fogassi, Gallese, & Rizzolatti, 1992). These neurons, which came to be known as mirror neurons, were found via single-cell recording in the ventral premotor cortex and inferior parietal lobe, providing evidence for a shared neural circuitry in the sensorimotor brain regions for both execution and observation of actions (Rizzolatti, Fadiga, Gallese, & Fogassi, 1996; Rizzolatti, Fogassi, & Gallese, 2001). This resonant activation of the motor system during action observation has been hypothesized as a neural correlate not only for action recognition, but also for the understanding of the goals and intentions that drive actions (Cattaneo et al., 2007; Rizzolatti & Sinigaglia, 2010; Southgate, 2013; although see Steinhorst & Funke, 2014). Using a variety of neuroimaging techniques, including functional neuroimaging (fMRI: see Caspers et al., 2010 for a review), transcranial magnetic stimulation (TMS: e.g., Cattaneo et al., 2010; Stadler et al., 2012), EEG (see Fox et al., 2016 for a review) and even single-cell recording under the rare occasions that is possible (e.g., Mukamel, Ekstrom, Kaplan, Iacoboni, & Fried, 2010), researchers have found evidence that similar sensorimotor activity during action observation also takes place in humans, broadly referred to as the MNS.

While the following review contains studies that have utilized these other methods, the method of measuring MNS activity that is of particular interest for the research proposed herein, is the EEG mu rhythm. The mu rhythm, first documented by Berger in 1929 (Berger, 1929), reflects oscillatory activity within the alpha band (~8-13 Hz in adults, ~6-9 Hz in infants) and exhibits changes in amplitude reflecting activation of the sensorimotor system (Neuper & Pfurtscheller, 2001; Pineda, 2005). Specifically, the amplitude of the signal decreases as compared to baseline activity, with peak suppression over sensorimotor areas (Kuhlman, 1978). This suppression of activity is likely due to an increase in desynchronized neuronal activity associated with the processing of motoric information (Pfurtscheller & Lopes da Silva, 1999), thus from here on I will refer to this phenomenon as mu rhythm desynchronization. Mu rhythm desynchronization has been reported during both execution and observation of actions (see Fox et al., 2016 for a review), and source localization analyses have suggested that the source of the mu rhythm signal is indeed from within the inferior parietal lobe, dorsal premotor cortex, and primary somatosensory cortex (Arnstein, Cui, Keysers, Maurits, & Gazzola, 2011; Thorpe, Cannon, & Fox, 2016).

Importantly for the purposes of the current study, the mu rhythm has proven to be a useful tool for measuring MNS activity across a wide range of ages. Methodologically, EEG is an easier neuroimaging technique with infants as compared to other more invasive and taxing methods, such as fMRI, because it allows more movement of the participant and for the child and parent to remain together during testing, among other reasons. Further, having a consistent measure of MNS activity from infancy through adulthood is key to understanding the functional significance throughout development.

The mu rhythm in infants oscillates at a lower frequency than in adults (~6 to 9 Hz), which is a typical trend in infant compared to adult EEG (Marshall, Bar-Haim, & Fox, 2002). However, the regional specificity of the mu rhythm in infants overlaps with that of adults (Marshall, Young, & Meltzoff, 2011; Thorpe et al., 2016). The greatest desynchronization of the mu rhythm during execution of actions is seen over central regions, while during action observation the activity is a bit more dispersed over frontal, central, and parietal regions. Over the past decade or so there has been an uptick in developmental research utilizing mu rhythm desynchronization (see Cuevas et al., 2014; and Marshall & Meltzoff, 2011 for reviews). In the following sections, I will review the extant literature on the MNS as a neural correlate for action understanding, beginning broadly with a theoretical overview for such a relation and then describing the empirical research, followed by a review of the literature linking the MNS and communication, and finally a review of research within infants utilizing mu rhythm desynchronization as the key measure of MNS activity.

Mirroring and action understanding

Interest in this pattern of resonant activity of the motor system during action observation is in the functional significance of such activity. In particular, and important for the purpose of the proposed study, is the question of what such a mechanism might indicate in terms of our understanding of those actions (Rizzolatti & Fabbri-Destro, 2008). There are a few different hypotheses for how such a mechanism might work.

Rizzolatti and colleagues have proposed that internal representation of perceived actions is supported through activation of a one-to-one overlapping system with one's own actions (Rizzolatti & Craighero, 2004; Rizzolatti et al., 2001). More specifically, according to this direct-matching hypothesis it is through a simulation process with resonant activation of the motor system in which the visual description of an action is mapped on to the corresponding motor representation. Such motor activation indicates that an observed action is described into a motor format, which belongs to the observer's motor repertoire. However, according to some researchers, goal ascription is too complex for a simple mapping system such as motor resonance (e.g., Hickok, 2009). Paulus (2012) has proposed applying the ideomotor theory to explain how motor system activation can lead to action understanding. Based on this account, repeated co-occurrence of an action and its effect creates a bidirectional link between the activation of one's motor system and a representation of the effect. When subsequently observing another person perform the same or a similar action, one's motor program for that action is engaged which in turn activates the effect representation. The effect representation then facilitates anticipatory behaviors relevant to that effect, for example directing visual attention toward the target object of an action (Paulus, 2012). Thus, according to this theory, resonant motor activity during observation of actions (i.e., MNS activity) supports goal interpretation through facilitating an expectation of the outcome. In an even more conservative interpretation, Heyes (2010, 2013) has contended that such a matching system is simply the result of associative learning. Specifically, that contingency and contiguity of action-perception experiences create and shape the function of the motor system during action observation. Alternative accounts (Ferrari, Tramacere, Simpson, & Iriki, 2013; Murray et al., 2016) have emphasized the role of associative learning while also expanding on it, showing, for example, that during development infants can build visuomotor connections through contingencies. However, these cannot be done without strong predispositions and neural prewiring, which prepare the infant brain to capitalize on relatively few opportunities to create new associations in the course of everyday life. In addition to this, Iacoboni and Wilson (2006) propose that several systems are likely interacting to support action understanding, a theory for which there is growing evidence that will be discussed briefly later on. A key difference between these various theories seems to be how encompassing one's definition of action understanding may be, and many researchers have specifically argued for the need to empirically tease apart 'action understanding' from other coincidental processes such as perception and mentalizing (Gallese, Gernsbacher, Heyes, Hickok, & Iacoboni, 2011). What these different theories share is the notion that activity of the motor system is in some way, either directly or more indirectly, related to our understanding of others' actions. And there is a growing body of empirical evidence supporting that conclusion. For example, Cattaneo and colleagues (2010) had adult participants perform either pushing or pulling actions repeatedly while visual access to their actions was blocked. The researchers then used TMS to block activation of the premotor cortex and asked participants to identify whether pictures they were shown were of hands either pushing or pulling. Across groups participants could not reliably discriminate, whereas in an earlier study without TMS the two groups made reliable categorizations. Stadler and colleagues (2012) used TMS to disrupt function of the premotor cortex during observation of actions in which part (1000 ms) of the action was occluded. They then asked participants to predict what occurred during occlusion. TMS was either delivered at the onset of the occlusion or 300s into the occlusion period. The researchers found no effect on prediction for the later TMS delivery; however early TMS was associated with greater prediction errors (as well as compared to TMS over the vertex which was administered as a control). Systematic reviews of studies that have compared object-directed versus non-object-directed actions using fMRI, have found a more consistent pattern of activation during observation of actions that are object-directed (Caspers et al., 2010; Morin & Grèzes, 2008; Van Overwalle & Baetens, 2009). These findings suggest that an individual's motor system is recruited both in predicting the outcomes of others' actions and in interpreting the goals and intentions driving actions.

Mirroring and communication

Through its connection with action understanding, there is growing interest the role of the MNS in the development of more 'higher-order' social cognitive achievements which are thought to build off of basic action understanding skills, including empathy (Carr, Iacoboni, Dubeau, Mazziotta, & Lenzi, 2003; Gallese, 2001, 2005; Iacoboni, 2009) and Theory of Mind (Pineda & Hecht, 2009). Building off of the theorized developmental trajectory outlined earlier in this review, one primary aim of this dissertation is to examine whether activity of the MNS might also be correlated with communicative development. The applied logic for this link very much echoes that for the cognitive link between action understanding and language, such that the ability to represent and interpret others actions is applied to the understanding of communicative gestures and later extended to spoken communication (Corballis, 2010; Rizzolatti & Arbib, 1998). The broader idea underlying the theories that link the MNS, action understanding, and language is that language is a much bigger phenomenon than just speech, which is just one part of a larger class of communicative behaviors (e.g., Redcay, Velnoskey, & Rowe, 2016). The ability to effectively communicate with others, be it on the side of the sender or the receiver of a message, builds on the ability to represent and interpret the acts of others, be they motions of the arms, hands, eyes, mouth, or larynx. The MNS may serve as one means for that representation – a direct link between actor and observer or communicator and receiver.

Although the research is limited, there is evidence in adults for MNS activity during observation of communicative gestures. In a behavioral study, Ping, Goldin-Meadow & Beilock (2014) showed that busying one's own motor system can impede understanding of gestures. Using fMRI, Montgomery, Isenberg, & Haxby (2007) examined the potential overlap between observation and execution of what they termed non-object directed communicative gestures (e.g., fingers curled into the palm and thumb pointing up for "thumbs up" or pointer finger meeting the thumb to create circle and other fingers extended for "ok"), as compared to mimed non-communicative object-directed actions (e.g., striking a match or flipping on a light switch; mimed because the objects were not actually present). They found similar activation in the primary and premotor cortices, inferior parietal lobe, and the superior temporal sulcus during both observation and execution across the two types of actions/gestures. Schippers and colleagues (Schippers et al., 2009) had participants take part in a modified game of charades while monitoring their MNS activity using fMRI. They found activation of the motor cortex during both production and "decoding" of the charades actions. In a follow up analysis, the researchers found that the activation in the observer's brain even followed a similar temporal trajectory as that of the charade producer (Schippers, Roebroeck, Renken, Nanetti, & Keysers, 2010).

A few studies utilizing the EEG mu rhythm desynchronization have also found evidence for MNS activity during observation of gestures (Avanzini et al., 2012; Quandt et al., 2012; Streltsova, Berchio, Gallese, & Umiltà, 2010). For example, Streltsova and colleagues (2010) observed significant desynchronization when participants were watching meaningless hand movements (e.g., moving the thumb in and out of an open palm), communicative gestures (e.g., thumbs up), and grasping that was either social (grasping a ball in someone's hand) or non-social (grasping a ball on a table).

The body of research examining a link between the MNS and processing of spoken language is also limited and has mostly focused on processing of action related words or phrases (see Fischer & Zwaan, 2008 for a review). Using behavioral measures of motor activity (e.g., grip force and posture changes), studies have shown that listening to action-related verbs in sentences induces motor activity (da Silva, Labrecque, Caromano, Higgins, & Frak, 2018; Shiller et al., 2013), however this may be modulated by semantic context (Aravena et al., 2012). Studies using fMRI, TMS, MEG, and the EEG mu rhythm have found activation of the motor system when adults process (hear or read) verbs or phrases about actions (Di Cesare, Errante, Marchi, & Cuccio, 2017; Egorova, Shtyrov, & Pulvermüller, 2016; Hauk, Johnsrude, & Pulvermüller, 2004; Moreno et al., 2015, 2013) or while decoding degraded speech sounds (D 'ausilio, Bufalari, Salmas, & Fadiga, 2012). Indeed, there is evidence that the MNS is functionally linked to representing action related language (Vukovic, Feurra, Shpektor, Myachykov, & Shtyrov, 2017), and some studies have also found left-hemisphere specifiticy for the action-language link (Pulvermüller, Hauk, Nikulin, & Ilmoniemi, 2005). Other TMS studies show motor areas are involved during the hearing of speech sounds or phonemes with no clear meaning, thus suggesting a phonological resonance within the motor cortex (D'Ausilio et al., 2009; Fadiga, Craighero, Buccino, & Rizzolatti, 2002; Roy, Craighero, Fabbri-Destro, & Fadiga, 2008).

Taken as a whole, these findings are promising in terms of identifying a link between MNS activity and language, but more research is clearly needed, and furthermore what is severely lacking is a developmental perspective. One study conducted with 14-month-olds reported mu rhythm desynchronization in the infants during dyadic interactions as compared to non-dyadic interactions (Reid, Striano, & Iacoboni, 2011). Antogini and Daum (2017) have found evidence for sensorimotor activity in toddlers while listening to verbs and action phrases. However, the question remains unanswered whether the MNS might actually play a formative or foundational role in the development of communicative skills.

There is a body of work that has examined the connection between development of children's motor abilities such as sitting, crawling, and walking and communicative development (see Iverson, 2010 for a review). While a comprehensive look at this topic is beyond the scope of the current paper and study, the connection I would make is this: in light of the proposed link between the motor areas of the brain and the development of communication and language, it seems logical that behavioral advances in motor skill, also reflecting activation of the neural motor system would in turn be supportive of or at least related to the development of language. A common driving theory for the link between motor and language development is that certain motoric achievements such as reaching/grasping, sitting, crawling, and walking open up new opportunities for interacting with the environment and increase language learning opportunities. While this is likely the case, I would argue that the connection between these developmental processes is a deeper one in which they are systematically and, as we see evidence for here, neurally linked. The greater range of experiences afforded by developing motor skills may also bolster the process of MNS activity during observation of actions and in turn one's ability to understand and learn from those observed behaviors.

Evidence in infancy

As mentioned above, the use of the mu rhythm as measured via EEG has fostered an increase of attention and research on the development of the MNS in relation to social cognitive development. The youngest infants included in a published observation of mu rhythm desynchronization were 4-month-olds (Virji-Babul, Rose, Moiseeva, & Makan, 2012), and the findings from this study suggest that the infant MNS is initially sensitive to all coherent motion, not necessarily human actions or actions with which they have experience. The infants in that study ranged from 4- to 11-months old and included only 14 total infants, thus results should be interpreted cautiously. However, such a finding fits with behavioral data suggesting that younger infants will attribute goals to both human and nonhuman agents (Luo & Baillargeon, 2007), while older infants only do so for human and human-like agents (Johnson, 2003; Meltzoff, 1995), but not inanimate objects. Thus, interpreted in light of the behavioral findings, this early pattern of non-discriminant mu rhythm desynchronization might suggest that young infants are recruiting their MNS in trying to decipher the meaning or purpose behind all motion as they learn to discriminate that which is similar to their own developing motor repertoire and that which is not. A similar developmental trajectory has been observed in studies of mu rhythm desynchronization in response to goal-directed versus non-goal directed actions. Eight- to nine-month-olds exhibit greater mu desynchronization during observation of a goal-directed action as compared to during observation of a non-goal directed action (Nyström, Ljunghammar, Rosander, & von Hofsten, 2011; Southgate, Johnson, Karoui, & Csibra, 2010), as do older children (Lepage & Théoret, 2006) and adults (Muthukumaraswamy, Johnson, & McNair, 2004; Nyström, 2008). However, six-month-olds do not exhibit such a difference (Nyström, 2008). Thus, MNS activity seems to be correlated with infants' developing understanding of the actions they observe.

In a series of studies with 9-month-olds, Southgate and colleagues found evidence that mu rhythm desynchronization is a reflection of action and goal prediction (Southgate et al., 2010; Southgate, Johnson, Osborne, & Csibra, 2009). Infants' mu rhythm desynchronization was measured during both execution and observation of grasping actions (Southgate et al., 2009). As expected, the researchers found overlap between the two conditions. What was of most interest was the time-course of activation during the observation trials. Specifically, they observed two periods of desynchronization: one that occurred during observation of the reaching/grasping action, and one that occurred just prior to the start of the action. This first period of suppression indicates that the MNS was active even prior to an observed action, suggesting that it is involved not only in prediction of goals, but of the actions performed to reach those goals. This predictive desynchronization was compared across trials and the researchers found that it was only significant after the first three trials, suggesting that once the infants learned that they could expect an action, the MNS came on board to facilitate prediction of that action. In a second study, also with 9-month-olds, infants were shown grasping actions either without an object or with the end of the action being hidden behind an occluder (Southgate et al., 2010). The purpose of these conditions was to compare MNS activity when a goal could (occluder condition) or could not (no object condition) be inferred. Indeed, they found significant mu rhythm desynchronization during action observation in the occluder condition, but not in the no object condition, suggesting that MNS activity is involved in the inference of goals.

More recently, researchers have begun examining how individual differences in activiton of the MNS in infants during observation of actions might predict evidence of action understanding outside of the observation of a specific action. For example, Filippi and colleagues (2016) found that the strength of mu rhythm desynchronization during observation of grasping actions in 7-month-olds was related to the infants' propensity to imitate the observed actor by subsequently selecting the same toy that the actor had grasped. A very recent, unpublished infant study provides further evidence. Yoo, Thorpe, and Fox (2016) found that mu rhythm desynchronization during observation of grasping actions predicted infants' ability to learn a novel means-end motor task (retrieving a toy with a cane) whereas it did not predict their learning in a visual pattern task, further suggesting MNS activity is indeed related to action processing and goal interpretation.

While interest in the link between the MNS and action understanding in infancy is growing, the lack of studies examining the proposed developmental link between the MNS and higher-order social cognitive functions, in particular communication, is becoming more and more apparent. More work is needed to examine the recruitment of the MNS during communicative interactions, how that might compare to non-communicative action processing, and more importantly the relation to communicative development over time. Thus, the main purpose of the current study is to examine what, if any, role the MNS plays in early communicative development.

The Role of Experience

Experience with actions has been shown to have an influence both on one's understanding of the action and on the strength of the MNS response. Thus, a further goal of the current research is to explore the role of experience with gestures on the MNS and subsequently the development of communicative skills. In the following section, I will review the literature linking experience with action understanding and the MNS.

Experience with actions

Experience with actions appears to influence infants' understanding of actions, such that greater or earlier experience leads to greater or earlier understanding. For example, 10-month-olds' ability to perform planful means-end actions is related to their understanding of others' means-end actions (e.g., Sommerville & Woodward, 2005). Sommerville, Woodward, and Needham (2005) provided 3-month-old infants experience with object apprehension through the use of "sticky mittens". These mittens, which had Velcro attached to them, allowed the infants to obtain objects (small stuffed animals) before they were accomplished graspers, by sticking their hands to the toys. These infants were then tested in a habituation paradigm, wherein they repeatedly observed an object being grasped and then during test either the object or the location of the grasp was changed. Performance on the test trials for infants in the "sticky mittens" group was then compared to a group of age matched infants who did not have the "sticky mittens" experience. The "sticky mitten" infants looked longer at the new object test trials than the new location test trials whereas the un-experienced infants showed no such discrimination, suggesting that infants' experience with a specific action may influence their ability to understand the actor-object link.

Cannon and colleagues (2012) conducted a study in which half of their 12-month-old participants were given experience placing toys into a container. Their containment skill during this activity was measured in terms of latency (amount of time before a toy was first placed in the container) and activity (the number of toys placed in the container). The infants were then shown a video of someone placing toys into a container. The infants who had prior experience were more likely to look toward the container before the toy arrived, predicting the outcome of the action, as compared to a group of 12-month-olds who had not yet taken part in the containment practice activity. Further, within the group of infants who had the prior containment experience, the researchers found a significant correlation between infants' containment skill and action prediction, such that infants with stronger containment skill (shorter latency and more activity) produced more anticipatory gazes to the containment location.

Experience with gestures

Interestingly, a study that was aimed at examining the developmental origins of pointing in infancy provides some evidence that observational experience with gestures might similarly influence infants' understanding of that gesture. Matthews, Behne, Lieven, & Tomasello (2012) compared infants pointing behavior before and after a parent-focused training on pointing. Parents in the training group were instructed to practice demonstrating pointing for their infants over a month-long period. There was also a control group in which parents were given instructions to practice nursery rhymes and play with musical instruments with their child. Both exposure to training and frequency of maternal pointing were found to predict infants' ability to monitor their partner's gaze while pointing. Gaze-checking while pointing is considered an indicator that infants' are indeed pointing with communicative intent and thus demonstrating an understanding of their partner's attentional state (e.g., Bates, Camaioni, & Volterra, 1975). These findings suggest that observational experience of points (via the parent) can potentially influence an infants' understanding of how pointing can be used to manipulate the attention state of others. In a similar study, utilizing the same training paradigm as that in the current study, Rowe and Leech (under review) trained parents of 10-month-olds on the importance of pointing with their children, the role pointing plays in language development, and how they can make a difference in their children's development by pointing with them often. Parents in the training group were provided with toys and told to play and point for 15 minutes a day with their children. Parents in the control group were not given the information about pointing, and were also given the toys and told to play for 15 minutes a day. At a follow-up home visit 2 months later, parents in the treatment group pointed more and to a greater number of different objects during play with their 12-month-olds than parents in the control group. Further, the infants of parents in the treatment group pointed more and to a greater number of different objects during play than the infants of parents in the control group.

Through a more intensive training study with 17-month-olds, LeBarton, Goldin-Meadow, and Raudenbush (2015) found evidence that infant's production of gestures can be experimentally increased. In this study, the researchers assigned children to receive one of three six-week in-home training conditions: one in which an experimenter modeled pointing and labeling with the child and also encouraged the child to point, one in which the experimenter pointed but did not encourage the child to point, and one in which the experimenter did not point nor did she encourage the child to point. Across the training period, children in the experimenter and child pointing condition produced more gestures (measured as a composite of pointing gestures during training sessions and all gestures produced during interactions with a parent). This increase in child gesture was associated with an increase in parents' gesture use (although parent gesture was not a focus of the study), and, importantly, with group differences in children's productive language at the end of the six-week period. As do the studies by Matthews and colleagues (2012) and by Rowe and Leech (under review), this study suggests that parents' gesture production with their children can be manipulated (increased) relatively easily, that children's own gesture production can also be experimentally increased, and further suggests that such an increase can lead to growth in children's language skills. These experimental studies provide interesting extensions of previous correlational research showing that parents who gesture more have children who gesture more, and that children who gesture more tend to have stronger language skills (Colonnesi, Stams, Koster, & Noom, 2010; Kuhn, Willoughby, Wilbourn, Vernon-Feagans, & Blair, 2014; Rowe, 2000; Rowe & Goldin-Meadow, 2009a, 2009b; Rowe et al., 2008). Thus, we see here evidence that infants' experience with gestures can have an impact on their understanding of those gestures and on their developing language ability.

Experience and changes in MNS recruitment

Similar to the relation seen behaviorally between action experience and action understanding, there is also evidence for a relation between action experience and MNS activity. For the purpose of this review, I will focus on those studies utilizing mu rhythm desynchronization.

Examining this relation within adults, several studies have compared mu rhythm desynchronization during observation of actions in “experts” versus “novices” for a variety of tasks or activities. In a study with dancers, Orgs, Dombrowski, Heil, and Jansen-Osmann (2008) found that professional dancers exhibited greater mu rhythm desynchronization than non-dancers while observing dance movements. Importantly, there was no difference between the groups when observing everyday actions familiar to both groups. Cannon and colleagues (2014) experimentally manipulated experience by randomly assigning adult participants into three groups who either received physical experience using a novel claw tool to grasp objects, visual experience watching an experimenter use the tool, or no experience. They found that participants who had physical experience with the tool exhibited greater mu desynchronization during observation of tool use when compared to both participants in the visual experience group and to the novices. Qualitatively, observers (those with visual experience) did seem to exhibit slightly greater mu desynchronization than the novices, however there was not a significant difference. More research is needed to examine whether observational experience with actions can lead to greater activation of the MNS, particularly in infancy.

Findings from studies with infants mimic those with adults. Crawling experience (how long they had been crawling) in 14- to 16-month-old infants is related to the strength of mu rhythm desynchronization while observing videos of other infants crawling (van Elk et al., 2008). In a 2015 study, Cannon and colleagues found that infants’ reaching and grasping skill, measured as a composite of latency to reach, reaching errors (misjudgments of distance or position), preshaping of the hand, and whether the grasp was made with one hand or two, was related to the strength of mu desynchronization while observing reach/grasp actions. Yoo, Cannon, Thorpe, and Fox (2015) found a relation between grasping skill and mu rhythm desynchronization during observation of grasping within 12-month-olds, but not within 9-month-olds, suggesting that the strength of the coupling of action and perception also increases with experience. One study interestingly contrasts the finding in adults that first-hand experience is necessary to alter one's understanding or neural representation of an action. de Klerk, Southgate, and Csibra (2016) observed predictive eye movements and mu rhythm activity in pre-walking 8-month-olds while they watched videos of infants walking. This finding suggests that first-hand experience is not necessary, but that observational experience may also be related to the strength of MNS activity during observation of actions.

General Summary and Gaps in the Literature

Action understanding has been proposed as a foundation for the development of language (e.g., Woodward, 2004), such that infants apply an understanding of their own agency and intentionality to understand and represent others' actions in terms of their goal-structure, and that this process of interpretation can then be applied to the understanding of others' gestures as well as spoken language (i.e., words). The understanding and use of gestures is proposed as a critical intermediary for this developmental process between action and spoken language (e.g., Capirci et al., 2005). In line with this theory, there appears to be an observable developmental relation between infants' early ability to understand others' actions and their emerging capacity for communication, both through gesture (e.g., Heimann et al., 2006) and spoken language (e.g., Brooks & Meltzoff, 2008). Such a link between action, gesture, and language implies a system that supports the perception and interpretation of others' actions that would also support the understanding of gestures and words. The MNS has been implicated as a neural correlate for action understanding (Rizzolatti & Fabbri-Destro, 2008), and there is a growing body of evidence in support of this interpretation (e.g., Caspers et al., 2010; Cattaneo et al., 2010; Stadler et al., 2012). Further, there is a small but growing body of research linking MNS activity and the understanding of communicative acts, including both gestures and speech (Moreno et al., 2015, 2013; Schippers et al., 2009). Out of the various methods for measuring activation of the MNS, the mu rhythm as measured via EEG seems to be the most promising in terms of exploring the development of this system and has been utilized in several studies with infants (e.g., Cannon et al., 2016; Nyström et al., 2011; Southgate et al., 2010; Yoo et al., 2015). However, as far as I am aware, only one study has examined individual differences in activation of the motor system in infants during observation of actions in relation to a separate measure of infants' action understanding (Filippi et al., 2016), and there are no developmental studies examining the relation between this activity and communication. Thus, more research is needed to gain a more full understanding of the role of the MNS in the development of both action understanding and communication.

There is a growing body of evidence that experience with actions is related to action understanding, such that experience predicts the ability to link actor to object, to infer goal-related outcomes for actions, and potentially to understand the attentional state of one's partner (Cannon et al., 2012; Matthews et al., 2012; Sommerville et al., 2005). Similarly, experience seems to play an important role in the strength of MNS activity.

Several studies have shown that when a person has more first-hand experience with a specific action, their representation of that action, as indexed by the activation of the MNS, is stronger (e.g., Cannon et al., 2014; Orgs et al., 2008; van Elk et al., 2008). However, a few things remain unclear regarding the influence of experience on one's internal neural representation and in understanding others' actions. First, it remains unclear whether observational experience with actions can lead to greater activation of the MNS during observation of actions. Adult studies have shown evidence that first-person experience has the strongest impact on the MNS (e.g., Cannon et al., 2014), however more recent work with infants suggests that first-hand experience may not be necessary (de Klerk et al., 2016). Second, it has not yet been explored whether the impact of experience on one's MNS will have cascading effects on one's action understanding and communicative development.

Specific to the goals of the proposed study, it is yet unknown whether we can expect to see activation of the MNS when infants observe communicative actions, as has been shown during their observation of non-communicative but goal-directed actions. Further, it is unknown whether experience in infancy with communicative gestures, might increase infants' MNS activity during observation of those gestures and in turn have a positive impact on developing communicative skills.

Conclusions

The ability to communicate with others is arguably the most important social-cognitive development in the first few years of life. Action understanding has been proposed as an important foundation for this development, and activity the MNS has emerged as a likely neural correlate for action understanding. More research is needed to fully understand whether MNS activity also subserves or supports communicative development. Gestures have been indicated as a critical stepping-stone between actions and language in early development, however there is very limited empirical research examining this developmental process. Further, experience with actions seems to influence action understanding measured both behaviorally and neurally, however the extent of this influence is not yet fully understood, nor whether there are cascading effects on the development of communicative skills. The current study aims to address these gaps in the literature, to examine the developmental relations between action understanding and communicative development, and to elucidate the processes underlying these early social cognitive milestones in infancy.

Chapter 3: Method

The goals of the current study were three-fold. First, to examine infants' MNS activity in response to observing a communicative gesture and to compare that with their neural activity during a typical object-directed action task. Second to examine the relations between infants' MNS activity and their concurrent communicative skill, both in terms of gesture and vocabulary. The third and final goal was two-fold: to examine whether, experimentally manipulating infants' experience with communicative gestures, specifically pointing, would increase MNS activity while observing those gestures, and to examine whether such changes in turn have a positive influence on the further development of infants' communicative skills. In order to address these goals I employed a randomized experimental design with a longitudinal aspect, in which I examined infants' MNS activity, as indexed by EEG mu rhythm desynchronization, and communicative skills before and after a parent-directed training aimed at increasing infants' exposure to and use of pointing gestures. As stated earlier, I focused on pointing gestures for the current study because of the mechanical properties of the gesture, the fact that points are physically removed from their referent, and that points are the most common gesture produced in infancy. In this chapter, I describe my sample, procedure, and measures.

Participants

81 full-term infants aged 10 to 12 months (M = 11.28, SD = 0.61; 39 females, 42 males) participated in this study. Of that, 72 returned for the Time 2 visit and 69

completed the Time 3 online survey (one of which did not complete the Time 2 visit or surveys).

Participants were recruited through the Infant and Child Studies Database, a database housed at the University of Maryland, College Park consisting of families who have expressed interest in participating in research studies. The database recruits from the counties surrounding the University, including Prince George's, Howard, and Montgomery in Maryland. Participants were also recruited through mailings distributed by the State of Maryland Department of Health and Mental Hygiene, targeting families with infants in the specified age range and living in Prince George's or Montgomery County. Inclusion criteria for participation in the study was based on parent report and as follows: (a) the target child was between 10 and 12 months of age at the time of their first visit, (b) the child was not born pre-term, and (c) the child did not have hearing loss or a known condition that might affect cognitive development. The age range of 10-12 months was chosen because this is when pointing gestures begin to emerge, on average (Bates et al., 1975). Prior to infants' participation in the study, informed consent was obtained from parents. Mothers and fathers were eligible to participate as long as the same parent participated over the course of the entire study; however most parents were mothers (74 mothers, 7 fathers). Mean age of parents was 33.41 years (SD=5.52).

Procedure

Parent-child dyads took part in two visits to the lab, approximately one month apart, and in an online follow-up approximately one month following the second lab visit. At the first visit, dyads were randomly assigned to either the training group or the control group. The procedure for both groups was the same except where specifically noted. All procedures and measures were approved by the University of Maryland Institutional Review Board.

Time 1: Initial Lab Visit

The initial lab visit lasted approximately 90 minutes, and began with the experimenter describing the activities for the visit and obtaining parental consent. This initial consent process did not include any information specific to either the training or control conditions. Parents were then asked to fill out several questionnaires including the MacArthur-Bates Communicative Development Inventory, Short Forms (MCDI: Fenson et al., 2000) reporting on the target child's receptive and expressive vocabulary, as well as surveys on their family's demographics information and the target child's developmental milestones (see Appendix A for all questionnaires). Parent-child dyads then took part in a 10-minute video-taped free play interaction, videotapes of which were transcribed, coded, and used as a baseline measure of parent and infant language and pointing gesture use. Next, infants participated in an EEG task designed to measure MNS activity, as indexed by mu rhythm desynchronization, during observation of grasping actions and pointing gestures, as well as during execution of grasping. Finally, dyads that were assigned to the training group received the *Pointing to Success* training. Dyads in the control group did not receive any training. In the following sections I will describe the free-play interaction, EEG task, and training procedures in greater detail.

Free-play interaction. Dyads took part in a 10-minute videotaped, free play interaction. During these interactions, dyads were provided with an assortment of age appropriate toys including a toy barnyard with animals, an elephant shaped block sorter, and a board book, "Good Dog, Carl" by Alexandra Day (see Appendix B for images of toys). Dyads were instructed to play with the toys as they normally would at home. These interactions were then transcribed and coded for spoken language and pointing gesture production.

EEG task. The purpose of this task was to assess infants' mu rhythm desynchronization during observation of a communicative gesture (pointing), observation of a non-communicative action (grasping), and execution of a non-communicative action (grasping). During the task, the infant, fitted with an EEG cap (for more information, see below for EEG recording and processing procedures), sat on his/her parent's lap in front of a wooden stage (see Figure 3 for room set up). Across the stage, the presenter was positioned to set up and present the various stimuli. Experimenter 1 would raise and lower a curtain on the stage in between trials, and Experimenter 2 was in an adjacent

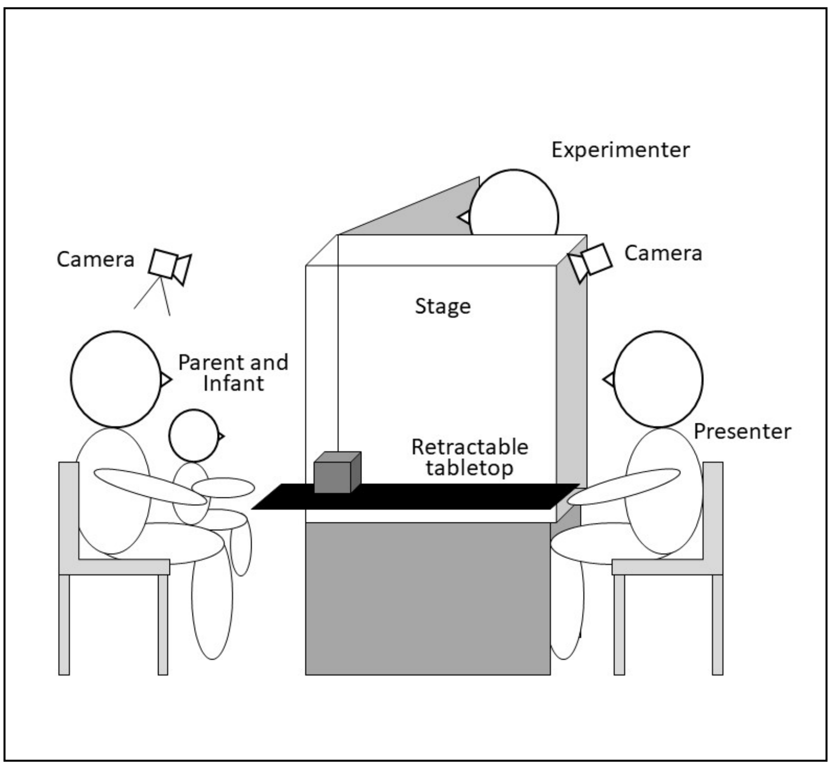


Figure 1. Set-up of participant testing room for EEG task.

room monitoring the recording of the EEG. Parents were asked to avoid interacting with or talking to their infant during the session. The EEG task consisted of three trial types (see Figure 4): observe point, observe grasp, and execute grasp, each of which was preceded by a 3-second baseline period. For the baseline period, the curtain was raised to reveal a multi-colored swinging pendulum. During observe point trials the curtain was raised to reveal the presenter sitting across from the infant with a toy centered on the stage. The presenter first got the infant's attention by saying "Hi, Baby!", and then looked to and simultaneously pointed to the toy. The trial ended when the curtain was lowered. The procedure for the observe grasp trials was identical to observe point trials except the presenter grasped, rather than pointed to, the toy. During execute grasp trials, the curtain was raised to reveal a toy placed at the edge of the stage on a retractable tabletop. The presenter was seated across from the infant, but did not look at or engage the infant. As the curtain was raised, the presenter pushed the tabletop (and toy) toward the infant. The trial ended either when the infant grasped the toy or after approximately

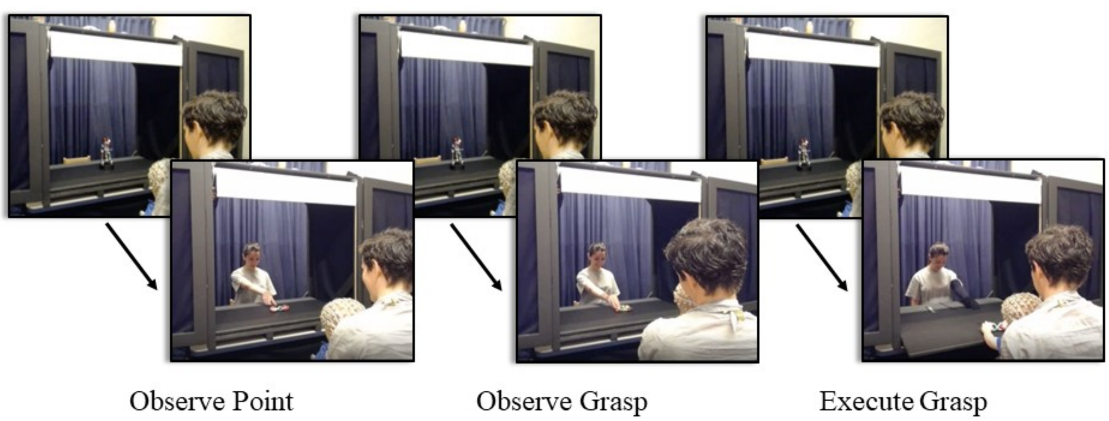


Figure 4. EEG task timeline for one trial set.

20 seconds passed. Trials were presented in a quasi-randomized order, such that infants were presented with a maximum of 15 *trial sets,* each set comprising one of each trial type in a random order, or up to 45 trials total. Infants completed a mean of 25.83 trials (SD=1.15, Range: 4-45) at Time 1, and a mean of 17.89 trials (SD=0.67, Range: 1-30). Within a single trial set, the same toy was used across all three trial types, however five different toys were rotated throughout the task. The random order within trial sets was fixed across participants, however the order in which toys were presented was randomized across infants. EEG was recorded continuously during this task. All trials were recorded using two video cameras for coding and analysis of eye, head, arm and hand movements, one camera focused on the infant and another focused on the presenter.

Training. The following two sections describe procedures for parents assigned to the training and control condition.

Training condition. After completing the EEG task, parents who were assigned to the training condition received the *Pointing to Success* training (Rowe & Leech, under review). This session lasted approximately 10 minutes. The training began with a 4-minute video that describes, in conversational terms, the research findings regarding infants' early pointing production and later language skills, as well as the relations between parent pointing and child pointing production and language ability. The video also describes different ways to point with your child and the importance of doing so for the child's development. After the video, the experimenter asked a short series of set questions including, (1) If you were to describe this video and what it was about to a friend who hadn't seen it, what would you say it was about? and (2) Was any of this new information for you? If so, what was new? Based on the parents' responses to these questions, the experimenter engaged in a brief (~5 minute) conversation about the video and what the parent learned. During this discussion, the experimenter emphasized the important role the parent plays in modeling pointing behavior and eliciting or encouraging points from the child. Parents in the training group were provided will a copy of the training video in DVD form as well as an educational pamphlet summarizing the same material as the video. The parent was then asked to practice pointing with his/her child for 15 minutes each day over the following month, or until their next laboratory visit. Dyads were given a set of toys to aid in this practice (including a block shape sorter, a board book about counting, and a bottle of bubbles: see Appendix C for all training materials given to parents), and the experimenter modeled several ways to point with the toys. However, parents were told that their pointing practice did not have to be limited to playing with these specific toys. Finally, after parents had a chance to ask any questions they had about the pointing practice, they were given a daily log and asked to record (1) whether they played with their infant for 15 minutes that day, (2) whether they pointed during that interaction, and (3) whether their child pointed. This log was used as a measure of fidelity to the training and a way to keep parents engaged in the training between the periods of experimenter contact. Over the next four weeks or until the follow-up lab visit families were contacted via email (or phone if they preferred) once weekly to remind them to continue with the pointing practice and to give parents an opportunity to ask any questions that might come up. Most parents responded with acknowledgement of the reminder, many also responded with anecdotes of their experiences pointing with their child.

Control condition. Parents in the control condition were given the same set of toys to bring home, but were not given any information regarding pointing. During the period of time between the initial and follow-up lab visits, parents in the control condition were only contacted once to remind them about their upcoming visit.

Time 2: Follow-up Lab Visit

Approximately four weeks following the initial lab visit, all dyads from both the training and control groups were asked to return to the lab for a follow-up visit. Average time between the Time 1 and Time 2 lab visits was 34.54 days (range: 27-67).

The protocol for this visit was almost identical to that of the initial visit. At the start of the visit parents completed only the MCDI questionnaire (Fenson et al., 2000). Dyads then participated in a ten-minute videotaped free-play interaction, for which they were provided with a new set of toys including a doll house, a wooden disc stacker, and the board book “Goodnight, Gorilla” by Peggy Rathmann (see Appendix B for images of the toys). Infants then engaged in the same EEG task as in the initial visit.

Time 3: Online

One month after the follow-up visit parents were asked to complete the MCDI (Fenson et al., 2000). This phase of data collection took place entirely online. Average time between the Time 2 lab visit and Time 3 online survey completion was 33.56 days (range: 27-51).

Transcription and Coding of Free-Play Interactions

All speech and pointing gestures during the mother-infant videotaped interactions during the Time 1 and Time 2 lab visits were transcribed by research assistants trained to transcribe reliably using the CHAT conventions of the Child Language Data Exchange System (CHILDES; MacWhinney, 2000). The unit of transcription was the utterance, bounded by grammatical closure, a pause of more than two seconds, or transition in speaker. In addition to spoken language produced, all actions and gestures produced were also transcribed. All transcripts went through a two-step verification process wherein one transcriber produced an initial transcript and then a second transcriber verified each transcript. Any disagreements were resolved through discussion.

Parent and infant pointing production was coded from the transcripts of the videotaped free-play interactions. Coders identified when a point occurred, defined as an extension of the arm, hand, and index finger that is primarily communicative. In addition, for each point coders identified the referent associated with the gesture, which was the object or event pointed to.

Two research assistants were trained to code the transcripts using the above coding scheme. Coding reliability was calculated on a subset of 10% of the transcripts. To check for reliability between coders for the frequency of points produced, correlations were run and a high level of agreement was found (parent pointing frequency $r = .99$; child pointing frequency $r = .96$). Out of 329 total points identified by either coder, there was agreement on the occurrence of 282 points (85%). Agreement for identifying the referent of points was also high (93%, kappa=.88).

Coding and Processing EEG Data

Behavioral coding of EEG task

Videos of the EEG task were coded to identify and synchronize live events with the continuous EEG recording. Two independent coders viewed each video (100% of the videos) off-line, frame-by-frame, to identify the following events of interest. For observe grasp events, coders identified the frame in which the presenter completed the grasp, defined as the frame in which the presenter's fingers were fully closed around the toy. For observe point events, coders identified the frame in which the presenter completed the point, defined as the frame in which the index finger was fully extended and the arm stopped its downward trajectory. For execute grasp trials, coders identified the frame in which the infant completed the grasp (if a grasp was executed). This was defined as either a) the frame prior to that in which the object began be lifted from the table, if the infant picked the toy up, or b) the frame in which the infant's fingers were fully closed around the toy, if there was no pick up.

Video was recorded at a frame rate of 30Hz, allowing for coding accuracy within approximately 33ms for identifying the events of interest outlined above. Inter-rater agreement, within 100ms (approximately 3 frames), was achieved on 99% of the observe grasp trials, 98% of the observe point trials, and 96% of the execute grasp trials. Averaged event times, across the two coders, were used in EEG segmenting. Coders also identified trials (including both baseline and observe/execute periods) in which the infant made any reaching or grasping actions, gestures, or gross motor movements, or in which the caregiver interfered through movement, gesture, or speaking. These trials were subsequently removed from analysis.

EEG data acquisition and processing

EEG was recorded from scalp electrodes using a 128-channel HydroCel Geodesic Sensor Net and sampled at 500 Hz using EGI software (Net Station v4.5.4; Electrical Geodesics, Inc., Eugene, OR). Impedance values for all EEG channels were kept below

100 kΩ (e.g., Marshall et al., 2011). Several infants' data were excluded prior to processing due to technical issues (Time 1 N=11; Time 2 N=3), or due to not having enough trials/data to process, usually because the infant fussed out prior to the task starting (Time 1 N=5; Time 2 N=2), leaving data from 65 infants to be processed at Time 1, and 67 at Time 2.

All processing of the data was completed offline in MATLAB (R2015a; The MathWorks, Natick, MA) with EEGLAB (v13.4.4b) toolbox (Delorme & Makeig, 2004). A predefined set of channels (17, 38, 43, 44, 48, 49, 56, 63, 68, 73, 81, 88, 94, 99, 107, 113, 114, 119, 120, 121, 125, 126, 127, 128) were excluded from analysis because they lie on the outer-most ring of the sensor array on the sides of the face and at the nape of the neck, and as such are heavily prone to artifact. Continuous data from the entire recording session were high pass filtered (0.3Hz) and then low pass filtered (49Hz) with the FIRfilt plugin for EEGLAB (developed by A. Widmann: www.unileipzig.de/~biocog/content/widmann/eeglab-plugins/) using windowed sinc FIR filters with a Hamming window. Automatic rejection of artifacted channels was performed using the EEGLAB plugin FASTER (Nolan, Whelan, & Reilly, 2010) which classifies artifactual channels based on having a Z-score of ±3 on any of three calculated parameters: variance, mean correlation, and Hurst exponent. On average 3.01 channels were rejected at Time 1 (Range: 1-5) and 3.12 channels were rejected, on average, at Time 2 (Range: 0-7).

Following automated artifact rejection, remaining artifact due to blinks, saccades, and generic noise were identified and rejected via extended infomax independent component analysis (ICA). First, a copy of the dataset was created and then high pass filtered at 1Hz and segmented into 1s epochs. This copied dataset was then rigorously cleaned of artifact to achieve improved ICA decomposition. Noisy data segments were rejected using a combined voltage threshold of ±1000µV and spectral threshold (range -30dB to +100dB) within the 24-40Hz frequency band to remove EMG-like activity. After ICA decomposition, artifactual ICs were identified through a combination of automated and manual processes including the EEGLAB ADJUST plugin (Mognon, Jovicich, Bruzzone, & Buiatti, 2011) and visual inspection. Weights for the independent components (ICs) were then transferred from the ICA copied dataset to the original dataset. After removal of the artifactual ICs, the data were segmented into windows surrounding the events of interest. The segmentation window for all observe and execute trials was -1500ms *prior* to the completion of the grasp or point, as identified through the behavioral coding described above, through 500ms *after* the completion of the grasp or point. For the baseline event (pendulum presentation), the middle 2-second window was segmented (i.e., 5000 ms to 2500 ms from the *start* of the baseline event). Trials that were marked as bad during the behavioral coding (due to child or parent interference) were removed. Any trials that contained discontinuity in the EEG signal due to the earlier artifact rejection procedure will be excluded from analysis, and then a final artifact rejection process was completed. Specifically, a voltage threshold rejection (±250µV) was applied in the six frontal channels (1, 8, 14, 21, 25, 34 ; see figure 2). Any epoch in which the frontal channels exceeded the voltage threshold of ±250µV was rejected. The same voltage threshold was applied to all other channels, and any rejected channels in each epoch were interpolated by artifact free data of the surrounding channels within that epoch using spherical interpolation as implemented by EEGLAB. If more than 10% of channels within an epoch were interpolated, that epoch was rejected. If more than 50% of epochs within a channel were interpolated, that channel was rejected.

After preprocessing, participants were excluded, within each condition, if they had fewer than 3 artifact free trials. This minimum requirement is based on previous infant mu rhythm studies (e.g., Debnath, Salo, Buzzell, Yoo, & Fox, under review; Marshall et al., 2011; Monroy, Meyer, Schröer, Gerson, & Hunnius, 2017). At Time 1, 24 participants were excluded in the observe grasp condition, 23 were excluded in the observe point condition, and 26 were excluded in the execute grasp condition. At Time 2, 25 participants were excluded in the observe grasp condition, 27 were excluded in the observe point condition, and 30 were excluded in the execute grasp condition. All epoched data were then converted into current source density (CSD) using the CSD toolbox (Kayser & Tenke, 2006). The application of a spatial filter and transforming the EEG signal into a CSD waveform minimizes volume conduction by attenuating activity that is disperse across most electrodes and highlighting activity that is evident at smaller clusters of electrodes (Cohen, 2014; Tenke & Kayser, 2012). All analyses were performed on the CSD transformed data.

Measures

In the following sections, I describe the method for gleaning measures of spoken language and pointing gesture production from the free-play interaction transcripts, measures of infant language and pointing production from the parent questionnaires, and the measure of MNS activity, mu rhythm desynchronization, from the EEG task.

Infant language

Spontaneous language production during free play. Automated analyses of the transcripts using the CLAN program were conducted to yield descriptive measures of infant and parent speech. The total number of words produced (word tokens) serves as a measure of quantity of speech. The total number of unique words spoken (word types) serves as a measure of vocabulary diversity.

Parent reported infant receptive vocabulary. Scores from the short form of the MacArthur-Bates Communicative Development Inventory (MCDI: Fenson et al., 2000) was used as a measure of children's language at all three time points. Parents completed the infant short form which is suitable for infants aged 8- to 18-months and provides a checklist of 89 words for parents to indicate whether their child understands, or understands and uses each word. The total number of words a parent indicated their child understands served as a measure of infants' receptive vocabulary. The measure of productive vocabulary typically extracted from the MCDI, the total number of words a parent indicated their child understands and says, did not show sufficient variability in this sample and was thus not included.

Parent and infant pointing production

Spontaneous pointing production during free play. The CLAN program from CHILDES (MacWhinney, 2000) was used to extract instances of parent and child pointing from each transcript. Point tokens, or the total number of pointing gestures produced, serves as a measure of pointing quantity. Point types, or the total number of different meanings conveyed through point, serves as a measure of pointing diversity (e.g., Goldin-Meadow, Mylander, de Villiers, Bates, & Volterra, 1984; Rowe & Goldin-

Meadow, 2009a). These measures were calculated separately for both parent and child and at both Time 1 and Time 2.

Parent reported infant pointing production. At the start of the initial visit at Time 1, parents filled out a short survey asking if and when their infant reached certain motor and communicative milestones (see Appendix A for individual items). Among these items is one question that asks whether their child had started pointing. It is possible that infants who had begun pointing would not actually point during the free play. Therefore, this parent report of child pointing was used as a supplementary means of measuring infants' pointing ability.

Infant MNS activity

Mu rhythm desynchronization. The cleaned, epoched, and CSD transformed EEG data were then decomposed into the time-frequency domain using the EEGLAB newtimef function. Time-frequency analysis provides a two-dimensional perspective of the data, across time and frequency band. Event related spectral perturbation (ERSP) were then calculated on the time-frequency data, providing an estimate of average changes in spectral power (in dB) relative to baseline (Delorme & Makeig, 2004; Makeig, Debener, Onton, & Delorme, 2004). Specifically, spectral power in the frequency range of 5-40Hz was estimated within each epoch with complex Morlet wavelets. Wavelet cycles ranged from 3 cycles at the lowest frequency up to 12 cycles at the highest frequency. ERSPs were computed for all channels and separately for the three events of interests (observe grasp, observe point, and execute grasp) and for each epoch relative to the preceding 2-second epoched baseline period. Negative ERSPs indicate desynchronization during the test event relative to baseline, and positive scores indicate synchronization. Average ERSPs were than calculated for pre-defined electrode clusters over frontal, central, parietal, and occipital sites defined as follows (see Figure 4): frontal (F3: 19, 20, 23, 24, 27, 28; F4: 3, 4, 117, 118, 123, 124), central (C3: 29, 30, 36, 41, 42; C4: 93, 103, 104, 105, 111), parietal (P3: 47, 51, 52, 53, 59, 60; P4: 85, 86, 91, 92, 97, 98), and occipital (O3: 66, 69, 70, 71, 74; O4: 76, 82, 83, 84, 89). The primary ERSP of interest was mu (6-9Hz) rhythm activity on electrodes overlying the motor cortex (C3, C4). However, ERSPs in the same frequency band as mu rhythm were analyzed for all electrode clusters. ESRPs were further averaged into four time windows across the two-second epochs. These were: 1500ms to 1000ms prior to the action completion, 1000ms to 500 ms prior to the action completion, 500ms to 0ms prior to the action completion, and 0ms to 500ms after the action completion. From henceforth, to avoid confusion with the term Time referring to study design measurement times (i.e., Time 1, Time 2, and Time 3) these time windows are referred to as epochs. For the observe conditions, the first two epochs capture the period when the action starts (when the experimenter's arm starts moving) and the experimenter's arm is moving toward the toy. The third epoch captures the final goal-state of the action (that being either grasping the toy or pointing to it), and is of particular interest. During the final epoch, the experimenter remains still, either with her hand on the toy or pointing at it. There is a documented rebound of the mu rhythm after an observed action has ended (Southgate et al., 2010), and inclusion of this post-action epoch is intended to capture that. Due to the erratic nature of infants' movements, what occurs during each epoch is not as consistent. However, whenever a grasp occurred this two-second period captured the infants' arm(s) moving toward the toy and either holding it, picking it up, or releasing it.

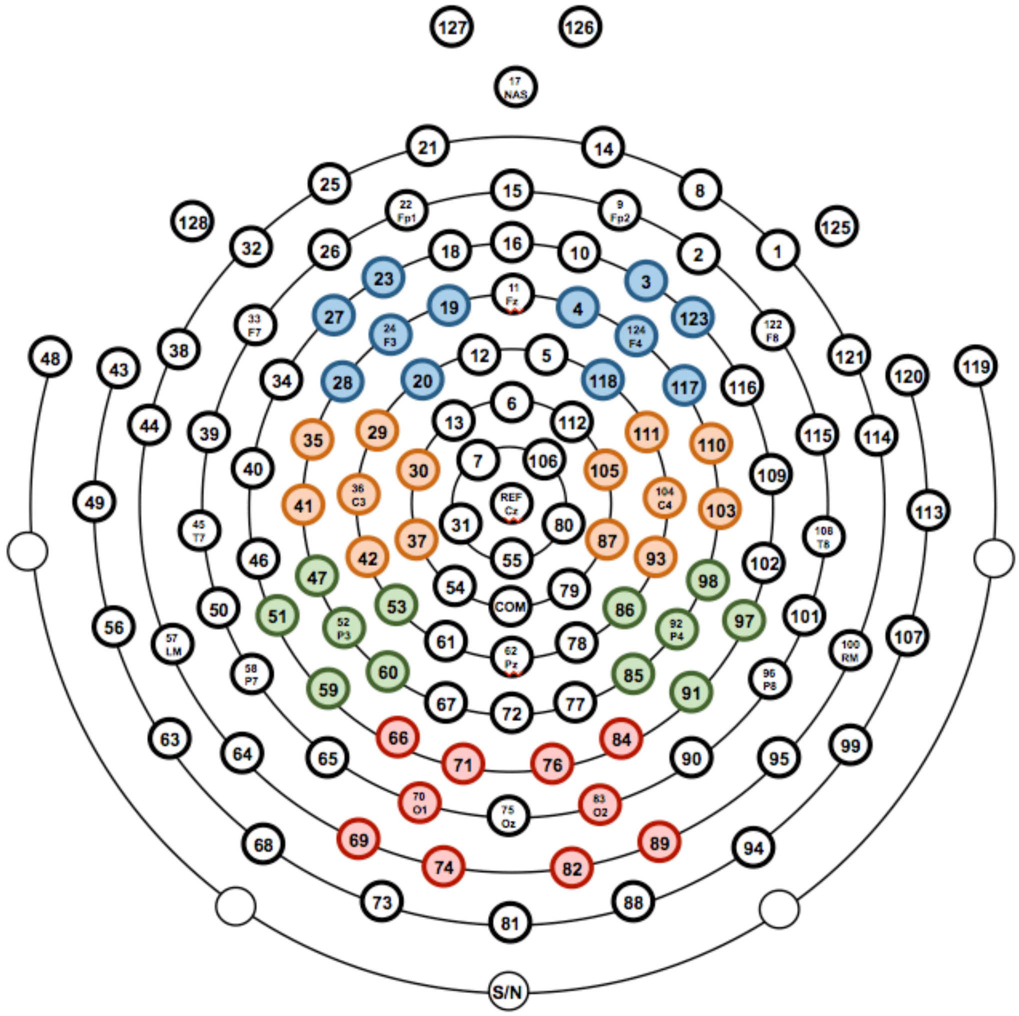


Figure 5. Electrode clusters for Frontal (blue), Central (orange), Parietal (green), and Occipital (red) scalp locations.

Data Analysis Plan

Prior to addressing my primary research questions, preliminary analyses were done aimed at ensuring comparability across the training and control group at Time 1. A series of independent sample t-tests were conducted to ensure that the two groups did not differ in terms of age or gender, on behavioral measures prior to randomization (parent or child pointing, child language), nor in terms of infant mu rhythm desynchronization measured during the first lab visit.

RQ 1. Do infants exhibit MNS activity, as indexed by mu rhythm desynchronization, during observation of communicative pointing gestures? And if so, how does that activity compare to their MNS activity during observation and execution of non-communicative grasping actions?

To identify significant mu rhythm desynchronization at Time 1, a point-wise analysis of spectral power modulation in all channels for each event of interest was conducted. This analysis compares EEG activity modulation (the difference from baseline) against a null hypothesis of zero, and allows visualization of the statistically significant time-frequency intervals. One-sample non-parametric permutation tests against zero were computed for each time point using the “std_stat” function of the EEGLAB toolbox. False discover rate (FDR) correction was applied to the 2000 permutations that were conducted. To statistically compare mu rhythm desynchronization across the three conditions, a repeated measures analysis of variance (ANOVA) was conducted with Condition (Observe Point, Observe Grasp, and Execute Grasp), Region (Frontal, Central, Parietal, and Occipital), Hemisphere (Left and Right), and Epoch (-1500 to -1000ms, -1000 to -500ms, -500 to 0ms, 0 to 500ms windows) as within-subjects factors. Greenhouse-Geisser correction was applied for any violations of sphericity, and FDR correction was applied for multiple comparisons.

Based on previous research with adults finding mu rhythm desynchronization during observation of communicative gestures (e.g., Quandt et al., 2012; Streltsova et al., 2010), I expected to find significant desynchronization of the mu rhythm during observation of pointing gestures that would be similar to that seen during observation of grasping. Further, I expected to see the greatest mu rhythm desynchronization during execution of grasping as compared to the two observation conditions, but I also expected to see topographic similarity across the three conditions.

RQ 2. What is the relation between infants' MNS activity during observation of pointing gestures and their experience with pointing gestures, at baseline?

Two sets of analyses were conducted to address the second research question, regarding the relations between mu rhythm desynchronization during observation of pointing gestures and experience with pointing, at baseline. As described earlier, the useable measure of infant pointing was the parent report question as to whether their child had started pointing yet, asked at the Time 1 visit. Thus, to first address the relation between infant mu rhythm desynchronization and first-hand production of pointing gestures, I compared infants' mu rhythm desynchronization during observation of the pointing gestures between those infants who were designated as 'pointers' by their parents and those who had not yet started pointing. A RM-ANOVA with Condition (Observe Point, Observe Grasp, and Execute Grasp), Region (Frontal, Central, Parietal, and Occipital), Hemisphere (Left and Right), and Epoch (-1500 to -1000ms, -1000 to -500ms, -500 to 0ms, 0 to 500ms windows) as within-subjects factors and with pointing status (Pointers, Non-Pointers) as a between-subjects factor was conducted. Drawing on my theoretical approach to this study, I expected that infants' who were categorized as pointers by their parents would exhibit stronger mirroring activity to pointing (and thus have more negative mu rhythm desynchronization) than their peers who were not yet pointing.

Second, to address the relation between infant MNS activity and their observational experience with pointing gestures, Pearson correlations were calculated between parents' pointing production during the free play and their infants' mu rhythm desynchronization during observation of pointing gestures. Previous research has shown, in adults, that first-hand experience leads to stronger MNS activity as compared to observational experience (Cannon et al., 2014), however more recent research suggests that first-hand experience may not be necessary (de Klerk et al., 2016). Thus, I expected to find a significant negative relation between parents' pointing production and their infant's mu rhythm desynchronization during observation of pointing, such that infants of parents who produced more points would exhibit stronger MNS activity when observing pointing gestures.

RQ 3. What is the relation between infants' MNS activity during observation of pointing gestures and their language ability, at baseline?

To examine relations between infants' MNS activity while observing points and their language ability, at baseline, Pearson correlations were calculated between infants' mu rhythm desynchronization during observation of the pointing gestures and infants' MCDI receptive vocabulary scores at Time 1.

RQ 4. Does increasing infants' experience with pointing gestures lead to greater MNS activity during observation of points?

Addressing the question of whether increasing infants' experience with pointing gestures lead to greater MNS activity during observation of points occurred in several steps. First, I assessed the effectiveness of the training at increasing infants' experience with pointing gestures, that is, on parent or infant pointing production. As can be seen below, in the descriptive statistics, most of the infants did not point at Time 2. This indicates either, the training either had no effect on infant pointing or that the current measures were too crude to accurately capture infants' pointing ability. Thus, these analyses regarding the effect of training focused specifically on parents' pointing, that is, infants' observational experience with points. A series of independent samples t-tests, with FDR correction for multiple comparisons, were conducted to compare the training and control groups on raw measures of parent pointing at Time 2. Additionally, change scores were calculated for measures of parent pointing, calculated as Time 2 measure – Time 1 measure. Comparisons of these change scores control for any potential differences at Time 1.

Next, I examined the effect of experience on infants' mu rhythm desynchronization in two ways: in terms of overall training group differences, and the incremental effect that experience might have had. First, a RM-ANOVA was conducted with Region (Frontal, Central, Parietal, Occipital), Hemisphere (Left, Right), and Epoch (-1500ms to -1000ms, -1000ms to -500ms, -500ms to 0ms, 0ms to 500ms) as within-subjects factors, and Training Group (Training, Control) as a between-subjects factor, with interest specifically in whether there was a main effect of training or any interactions with training group. In anticipation of low power due to the small sample size and likely small effect sizes, a series of independent t-tests, comparing infants' mu rhythm desynchronization scores measured at Time 2, across the two groups will be conducted to examine group differences within each region, hemisphere and epoch. Both the RM-ANOVA and t-tests were conducted twice, first using Time 2 ERSPs and then using change in neural activity from Time 1 to Time 2 (calculated as desynchronization at Time 2 – desynchronization at T1). I expected to see infants in the pointing training group exhibit greater change in their mirroring activity as a result of their increased experience with pointing gestures. Specifically, I expected that infants in the training group would exhibit significantly stronger mu rhythm desynchronization at Time 2 and greater change such that their change scores would be more negative than those in the control group.

To further explore the relation between experience and mu rhythm desynchronization at the level of individual differences, I also examined the relation between change in parent pointing and change in infant mirroring activity. To capture the continuous relations between change in parent pointing and change in infant mirroring activity and to maximize power by using information from all participants, including those with missing data, a change score model was conducted in Mplus (Muthen & Muthen, 2012). A change score model allows for missing data using Full Information Maximum Likelihood (FIML) estimation, which provides robust parameter estimates and standard errors for data that is missing at random or completely at random. Thus, I was able to include data from all 81 participants. In addition, Satorra-Bentler correction was applied to account for assumed nonnormality of the data to ensure robust standard errors and avoid potential for inflated significance and Type 1 errors (Satorra & Bentler, 1994). This type of model also provides estimates of fixed effects, i.e., population parameters as estimated by the average model of the entire sample, and random effects, i.e., individual variation in model parameters, and is further ideal for the current study because it can provide estimates of both direct and indirect effects, and allows the testing of explicit directionality in relations between variables, for example that change in parent pointing would predict change in infants' mu rhythm activity. A single full model was fit, simultaneously testing all direct and mediating effects, controlling for all other effects in the model.

Figure 6 shows the full model that was estimated. Infants' starting mu rhythm activity and change score were modeled as a function of baseline (Time 1) and change in parent pointing, infants' parent-reported pointing status at Time 1, and training group. Change score variables were estimated to capture change in both parent pointing and infant mu rhythm. Pointing status was dummy coded with pointers as 1 and non-pointers as 0, and training group was dummy coded with the training group as 1 and control group as 0. Both pointing status and training were treated as dichotomous measured variables. The measure(s) of mu rhythm activity included in this model was informed by the results of the previous analyses examining group level differences. That is, the combination(s) of hemisphere and epoch that showed significant group differences based on the above t-tests were included as the measure(s) of infant mu rhythm activity. This model was repeated twice using point tokens and then point types as the measure of parent pointing.

This analysis allowed me to determine whether differences in the efficacy of the training, that is, how much each dyad increased in their pointing production from Time 1 to Time 2, had an incremental effect on infants' mu rhythm desynchronization. In their study looking at the relation between crawling experience and mirroring activity, van Elk and colleagues (2008) found a significant relation. Thus, I predicted that the amount of change in pointing experience would be related to change in infant's mu rhythm desynchronization, and that this would mediate the effect of training group on change in infant mu rhythm.

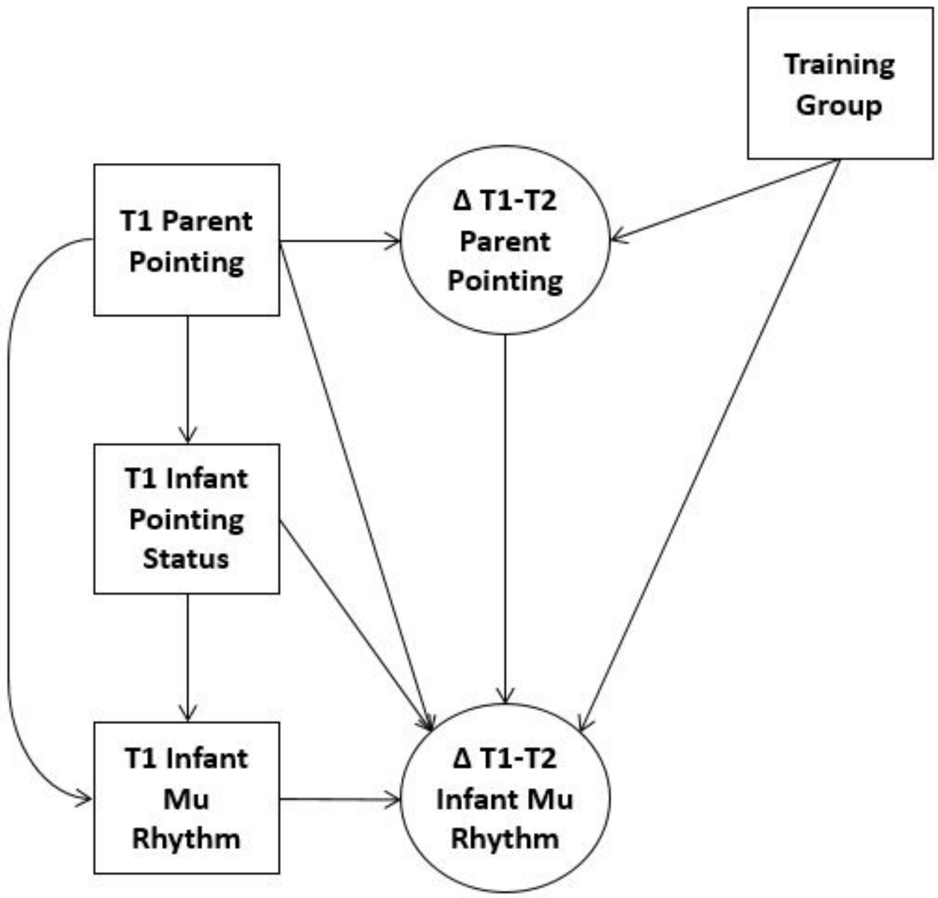


Figure 6. Planned change score model for examining change in infant mirroring activity as a function of change in parent pointing.

RQ 5. Does increasing infants' experience with pointing gestures lead to increases in their communicative skill?

Prior to examining change in infants' language, I looked at relations between infants' and parents' pointing and infants' language skills at Time 1, using either t-tests to look at differences based on infants' parent reported pointing status or Pearson correlations to examine relations with parents point tokens and types.

Due to the lack of infant points during the free play, the effect of the training on infants' pointing could not be assessed. Therefore, these analyses focus on the effect of the training on infants' vocabulary as opposed to both pointing and vocabulary. Change scores were calculated for infants' receptive vocabulary, similarly to the ERSP change scores described above. Two sets of change scores were calculated to capture change from Time 1 to Time 2 (Time 2 vocab – Time 1 vocab) and from Time 2 to Time 3 (Time 3 vocab – Time 2 vocab). In order to examine change in infants' language skills, specifically their vocabulary as measured via parent report, I utilized a similar change score model to that described above swapping in change in infants' receptive vocabulary as the outcome variable of interest (Figure 7). Specifically, change in infants' receptive vocabulary scores across all three time points were modeled as a function of baseline and change in parent pointing. As such, two change variables were estimated to capture change from Time 1 to Time 2 and then from Time 2 to Time 3. I predicted that the effect of the training on child language would be mediated by parent pointing.

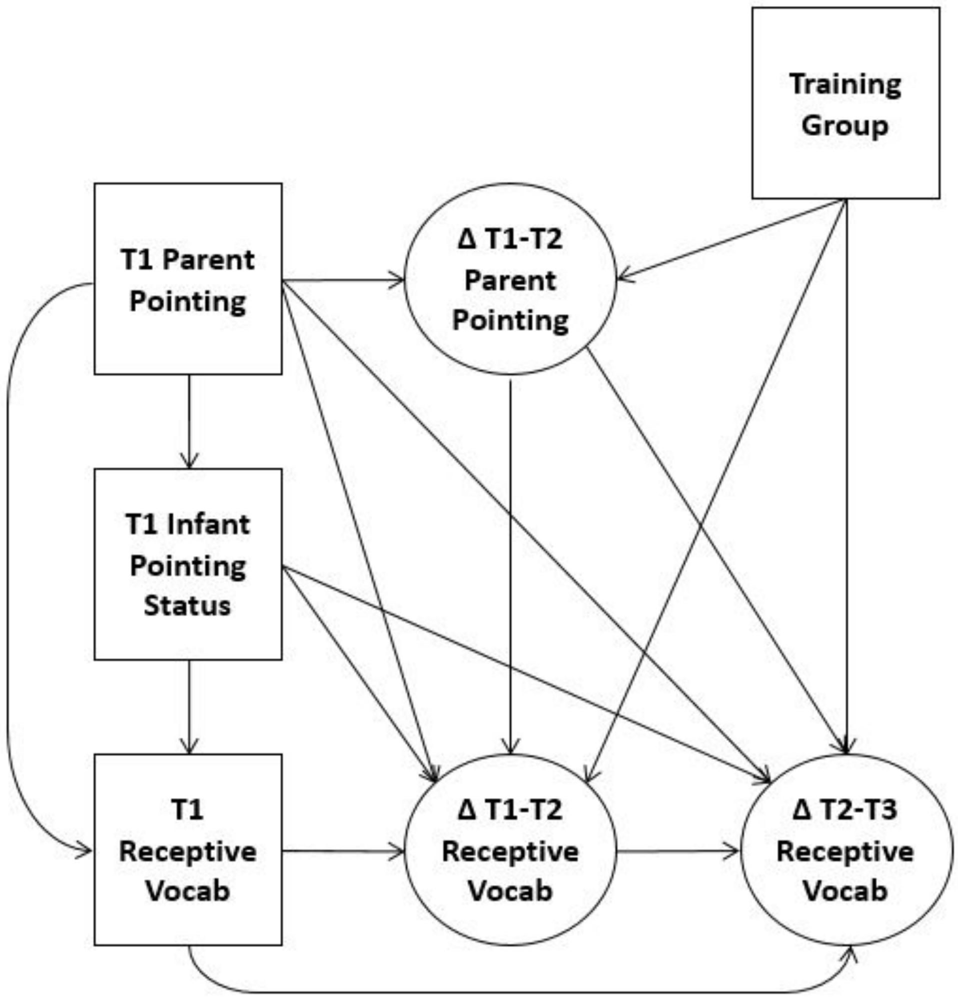


Figure 7. Planned change score model for examining change in infant receptive vocabulary as a function of change in parent pointing.

RQ 6. Does infants' MNS activity during observation of pointing gestures mediate the relation between experience with points and their developing vocabulary?

This final question builds upon the previous two questions by directly examining whether the changes in MNS activity, predicted by increased experience with pointing gestures, in turn predicts changes in infants' own vocabulary growth. To address this question the previous two sets of change score models were combined (Figure 8). Time 1 mu rhythm activity and change in mu rhythm activity from Time 1 to Time 2 were inserted as mediators between infant/parent pointing and infant vocabulary. Of particular interest was the indirect effect from change in parent pointing to infant vocabulary through change in infant's mu rhythm activity. Support for such a model would be the first explicit evidence for a causal link between experience, MNS activity, and the development of communicative skills.

Due to the binary nature of the infant pointing measure at Time 1, traditional fit statistics for the models could not be derived. Thus, to assess fit, all of the above models were regenerated ignoring the categorical status of this measure to determine a rough estimate of model fit. All of these alternate models fit the data well: all RMSEA values < .08 and all SRMR values < .08.

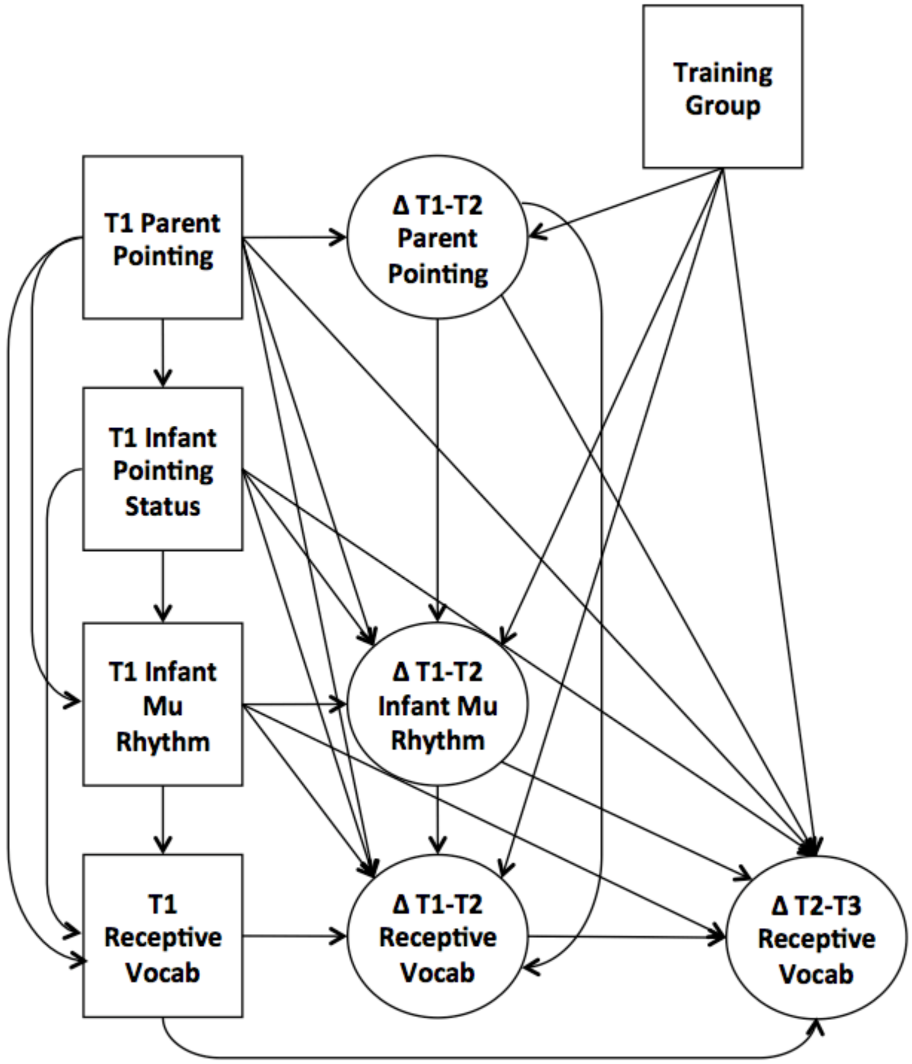


Figure 8. Planned change score model for examining change in infant mirroring activity as a mediator for the relation between change in parent pointing and change in infant receptive vocabulary.

Chapter 4: Results

Descriptive Statistics and Preliminary Analyses

Table 1 provides sample sizes and descriptive statistics for the infant and parent pointing and infant language measures at each time point. All parent measures were within an acceptable range (±2) of skewness to be considered univariate normally distributed, however several infant measures were not. This was mostly due to a large proportion of infants not producing any words or points. Specifically, at Time 1, 67 infants (82.7%) did not produce any words during the free play and 67 infants (82.7%) did not produce any points during the free play. It should be noted that these are not the exact same infants across the two measures; 57 infants produced neither words nor points at Time 1. At Time 2, 54 infants (66.7%) did not speak during the free play and 49 (68.1%) did not point. Due to these uneven distributions, these measures were excluded from further analyses. Infant EEG measures were also examined to identify any outliers or issues with non-normality. No issues were identified.

Within the subsample of participants who returned for Visit 2 (N=72; $N_{\text{Training Group}}$=35; $N_{\text{Control Group}}$=37), there were no group differences on any measures of pointing or language, nor age (all *t*'s < 1.26, all *p*'s > 0.21). Infant gender was also relatively matched across the groups (Control: females=19, males=18; Training: females=15, males=20). There were also no group differences at Time 1in terms of infant mu rhythm desynchronization. Due to data loss in the EEG processing steps, sample sizes vary depending on the condition(s) and time point(s) being considered. Table 2 summarizes this information. Due to the small sample sizes, primary analyses are conducted within condition where applicable, with a focus on the observe point condition (see

Supplemental Analyses for similar analyses within the observe grasp and execute grasp conditions).

Table 1. Descriptive Statistics for pointing and language measures at each time point.

	Time 1 N=81	**Time 2** N=72	**Time 3** N=69
Infant Measures			
Free play pointing			
Point tokens	M=0.41, SD=1.16 Range: 0-7	M=1.21, SD=2.48 Range: 0-11	
Point types	M=0.31, SD=0.77 Range: 0-3	M=0.90, SD=1.83 Range: 0-8	
Pointing Status	Pointed n=14 Did not n=67	Pointed n=23 Did not n=49	
Parent report pointing			
Pointing Status	Pointing n=55 Not yet n=26		
Free play language			
Word Tokens	M=0.69, SD=2.08 Range: 0-13	M=0.69, SD=1.78 Range: 0-11	
Word Types	M=0.37, SD=1.11 Range: 0-7	M=0.36, SD=0.79 Range: 0-5	
MCDI language			
Receptive Vocab	M=17.81, SD=18.61 Range: 0-87	M=27.49, SD=22.06 Range: 1-89	M=40.61, SD=24.46 Range: 5-89
Parent Measures			
Free play pointing			
Point tokens	M=11.70, SD=9.29 Range: 0-42	M=22.57, SD=19.12 Range: 0-69	
Point types	M=5.93, SD=3.79 Range: 0-15	M=10.74, SD=7.07 Range: 0-30	

Table 2. Number of infants with useable EEG data after processing

	Observe Point			Observe Grasp			Execute Grasp			All Conditions		
	All	Tx	Cx	All	Tx	Cx	All	Tx	Cx	All	Tx	Cx
Time 1	42	20	22	41	19	22	39	19	20	27	15	12
Time 2	40	21	19	42	21	21	37	19	18	27	12	15
Time 1 + Time 2	29	16	13	28	16	12	24	12	12	12	7	5

Note. All – whole sample; Tx – Training group; Cx – Control group

Primary Analyses

Mirroring activity during observation of pointing gestures

RQ 1. Do infants exhibit MNS activity, as indexed by mu rhythm desynchronization, during observation of communicative pointing gestures? And, if so, how does that activity compare to their MNS activity during observation and execution of non-communicative grasping actions?

Figure 9 shows results of the time-frequency analysis on EEG activity at Time 1, and Figure 10 shows the statistically significant time-frequency intervals as revealed by point-wise analysis. Topographic plots of the baseline corrected activity within the 6-9Hz frequency band over the scalp were also generated to allow for visual, qualitative comparison of the topography of activity across the three conditions (Figure 11).

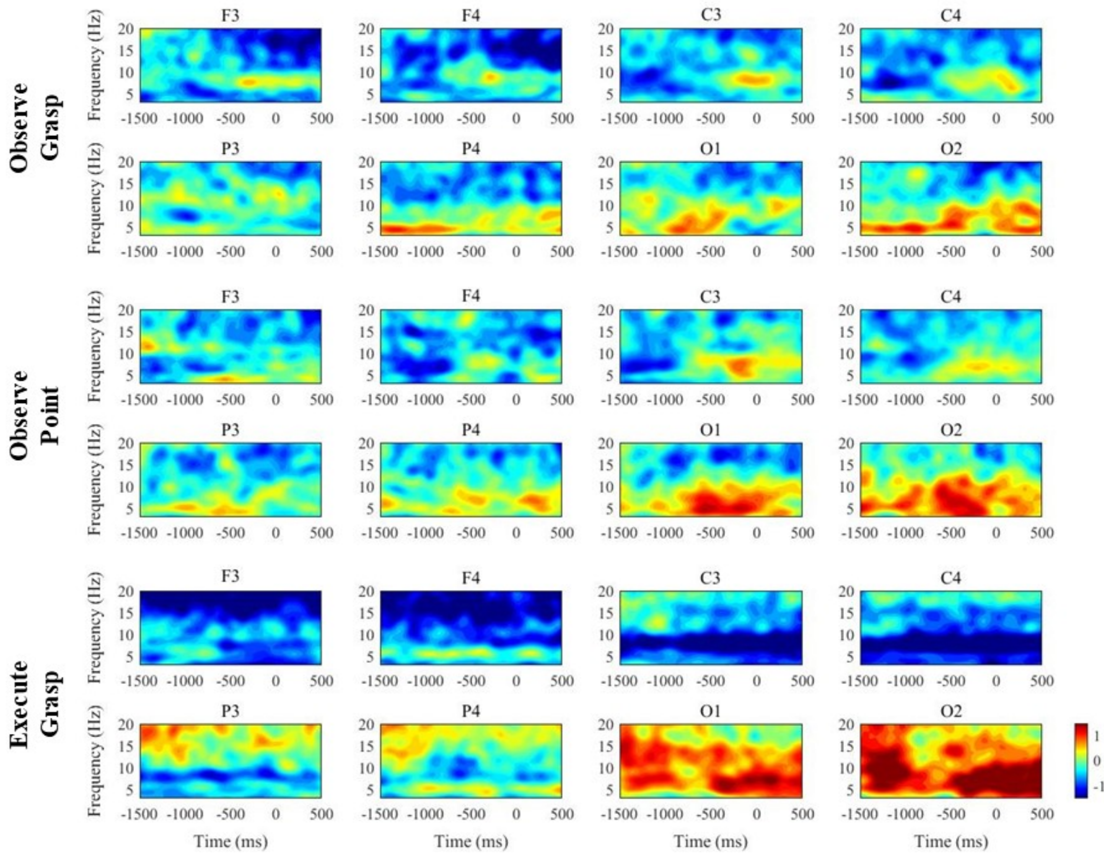


Figure 9. Time frequency plots of average infant baseline corrected activity at Time 1 during the observe grasp condition (top rows), observe point condition (middle rows), and execute grasp condition (bottom rows) within each electrode cluster, divided by region and hemisphere. Time 0 in all conditions indicates completion of the action/gesture.

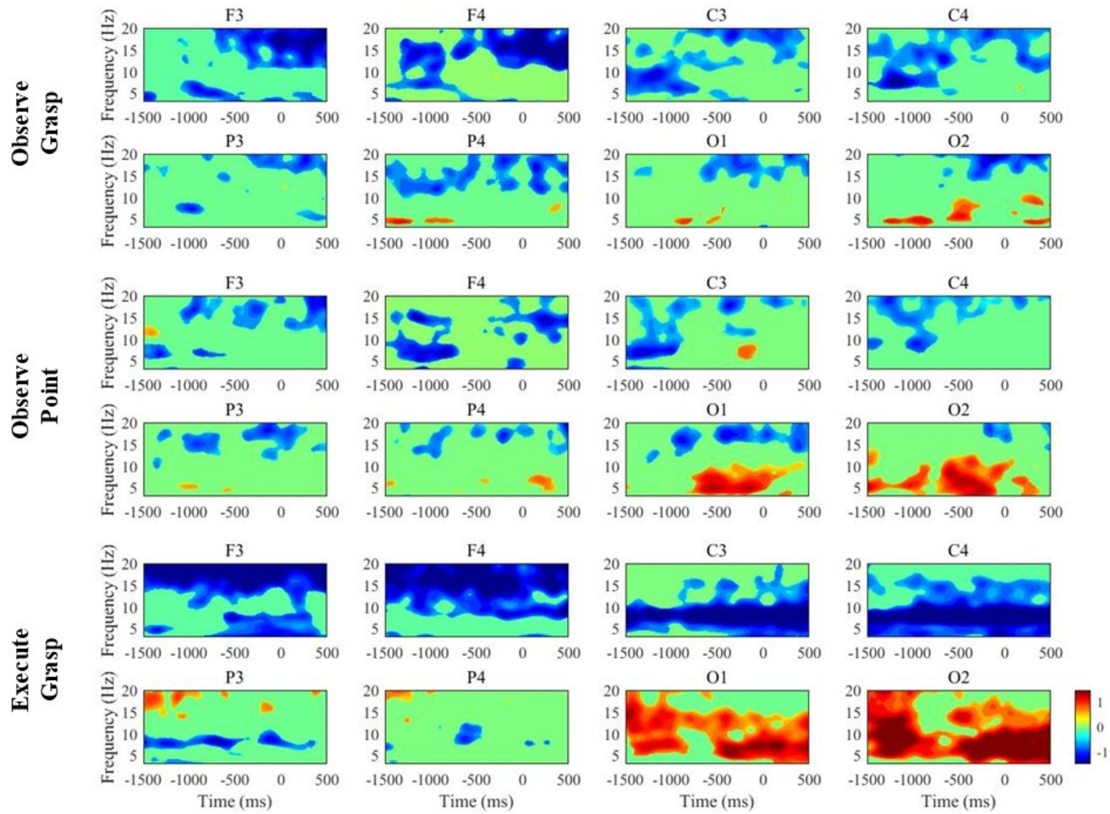


Figure 10. Time frequency plots of average infant baseline corrected activity at Time 1, with non-significant activity masked, during the observe grasp condition (top rows), observe point condition (middle rows), and execute grasp condition (bottom rows) within each electrode cluster, divided by region and hemisphere. Time 0 in all conditions indicates completion of the action/gesture. Green indicates non-significant (p>.05) activity.

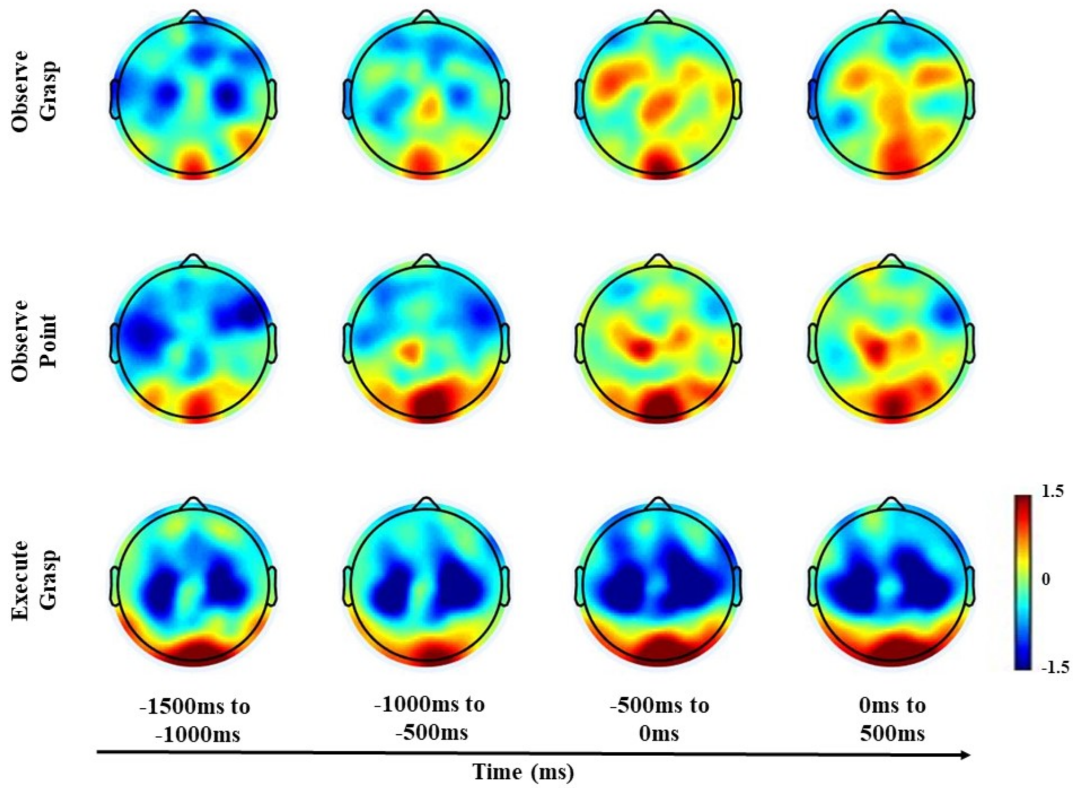


Figure 11. Topographic plots of infant baseline corrected activity averaged over the 6-9 Hz frequency band in the observe grasp condition (top row), observe point condition (middle row), and execute grasp condition (bottom row). Plots are divided according to the four 500ms epochs (-1500ms to -1000ms, -1000ms to -500ms, -500ms to 0 ms, oms to 500ms) surrounding the completion of the action (0ms).

As can be seen from the above figures, all three conditions evoked mu desynchronization over the central region/electrode cluster, however there were temporal differences across the conditions. In the execute grasp condition, there was significant mu rhythm desynchronization overlying the motor cortex (C3, C4) throughout the time period of interest, spanning both the period prior to grasp completion (during the action) and after the grasp was completed (Figure 9/10 – bottom two rows; Figure 11 - bottom row). There was also significant mu rhythm desynchronization during the observation of both grasping (Figure 9/10 – top two rows, Figure 11 – top row) and pointing (Figure

9/10- middle two rows. Figure 11 – middle row) around the start of the action in the earliest time window which tapered off as the action was completed.

Results of the RM-ANOVA revealed a significant main effect of Region ($F(2.16, 56.11)=27.91$, $p<.001$, $\eta_p^2=0.52$). Follow-up analyses indicated that infants showed an increase in power relative to baseline (or synchronization) over the occipital region ($M=0.89$, $SE=0.18$), whereas there was desynchronization over all other regions (Frontal: $M=-0.36$, $SE=0.12$; Central: $M=-0.71$, $SE=0.22$; Parietal: $M=-0.14$, $SE=0.13$). Occipital power was significantly greater than that over all other regions (Frontal: $t(26)=6.52$, $p<.001$; Central: $t(26)=6.40$, $p<.001$; Parietal: $t(26)=6.53$, $p<.001$), and there was significantly more desynchronization over the central than parietal region ($t(26)=3.49$, $p=.002$).

The ANOVA also revealed a significant main effect of Epoch ($F(3, 78)=11.11$, $p<.001$, $\eta_p^2=.30$). Follow-up analyses indicated that desynchronization was greatest in the earliest epoch ($M_{-1500to-1000ms}=-0.28$, $SE=0.14$) and this was significantly greater than that in the last two epochs ($M_{-500to-0ms}=0.11$, $SE=0.13$, $t(26)=4.44$, $p<.001$; $M_{0to500ms}=0.08$, $SE=0.14$, $t(26)=3.72$, $p=.001$). Desynchronization in the second epoch ($M_{-1000to-500ms}=-0.22$, $SE=0.14$) was also significantly greater than that in the last two epochs (-500to0ms: $t(26)=5.23$, $p<.001$; 0to500ms: $t(26)=3.46$, $p=.002$). However, there was no difference between the first and second nor between the third and fourth epochs.

Additionally, there was a significant Condition x Region interaction ($F(3.59, 93.29)=9.95$, $p<.001$, $\eta_p^2=.28$), such that desynchronization in the central region was significantly greater in the execute grasp condition as compared to the observe grasp ($t(30)=4.88$, $p<.001$) and the observe point ($t(31)=5.65$, $p<.001$) conditions. There were no significant differences between the two observe conditions. Further, *synchronization* in the occipital region was significantly greater in the execute grasp condition than the observe grasp condition ($t(30)=2.89$, $p=.007$). Lastly, there was also a significant Condition x Region x Epoch interaction ($F(8.50, 221.02)=4.55$, $p<.001$, $\eta_p^2=.15$). Within the execute grasp condition, there was consistent desynchronization across all epochs in the frontal, central, and parietal regions, however in both of the observe conditions, there was desynchronization in the first epochs which tapered off in the later time windows.

- - -

In sum, at Time 1 infants' do show mirroring activity during observation of pointing gestures. This activity shares topographic similarities with that during observation and execution of grasping actions, and is also similar in timing and strength of activity to that during observation of grasping.

Relations between mirroring activity and experience with gestures

RQ 2. What is the relation between infants' MNS activity during observation of pointing gestures and their experience with pointing gestures, at baseline?

Results of the RM-ANOVA comparing neural activity between those infants who were designated as 'pointers' by their parents and those who were not showed no main effect of or interactions with pointing status. However, the distribution of pointers v. non-pointers was quite uneven. Of the 27 infants who had useable EEG in all three conditions, 20 were pointers and 7 were non-pointers. Therefore, this analyses was repeated within the observe point condition. Of the 42 infants with useable EEG data in the observe point condition at Time 1, 28 were pointers, 13 were non-pointers, and one parent did not respond to this question. Again, results of this second RM-ANOVA did not reveal any main effect or interactions with pointing status.

Similarly, there were no significant relations between parents' pointing production during the free play and their infants' mu rhythm desynchronization during observation of pointing gestures (Table 3). Neither parents' point tokens nor point types were significantly related to infants' ERSPs in the observe point condition (see Supplemental Analyses for results of similar analysis with ERSPs in other conditions).

- - -

Thus, at Time 1, I did not find evidence for a relation between infant's own or observational experience with pointing and their mirroring activity to pointing.

Table 3. Correlations between parent pointing and infant ERSPs during the observe point condition at Time 1 (N=42).

	Parent Point Tokens	Parent Point Types		Parent Point Tokens	Parent Point Types
F3			**C3**		
-1500 to -1000	-.15	-.21	-1500 to -1000	-.01	-.05
-1000 to -500	.10	.12	-1000 to -500	-.16	-.11
-500 to 0	-.18	-.05	-500 to 0	-.14	-.05
0 to 500	-.06	-.01	0 to 500	-.21	-.20
F4			**C4**		
-1500 to -1000	.09	.26	-1500 to -1000	.07	.24
-1000 to -500	.09	.27	-1000 to -500	.10	.27
-500 to 0	.13	.19	-500 to 0	-.09	.12
0 to 500	.16	.23	0 to 500	-.01	.09
P3			**O1**		
-1500 to -1000	.06	.05	-1500 to -1000	.12	.08
-1000 to -500	.04	.05	-1000 to -500	-.03	-.02
-500 to 0	.10	.19	-500 to 0	.03	.00
0 to 500	.28	.20	0 to 500	.21	.16
P4			**O2**		
-1500 to -1000	.28	.30	-1500 to -1000	.11	.04
-1000 to -500	.11	.14	-1000 to -500	.15	.09
-500 to 0	.10	.04	-500 to 0	.06	.01
0 to 500	.15	.11	0 to 500	.16	.03

Relations between mirroring activity and language ability

RQ 3. What is the relation between infants' MNS activity during observation of pointing gestures and their language ability, at baseline?

As can be seen in Table 4, relations between infants' mu rhythm desynchronization during observation of the pointing gestures and infants' MCDI receptive vocabulary scores at Time 1 approached significance only between infants' receptive vocabulary and their ERSPs over the Central region, that is, specifically with their mu rhythm activity. Only one relation, that with the ERSP over C3 in the -1000ms to -500ms epoch was significant. This does not hold up after correction for multiple comparisons, however there was a similar pattern of relations across epochs in the C3 cluster. The relation is moderately significant when collapsed across epochs ($r=-.28$, $p=.07$).

- - -

Thus, there is a trend but not conclusive evidence for a relation between infants' mirroring activity during observation of pointing gestures and their receptive vocabulary ability, at Time 1.

Table 4. Correlations between infants' receptive vocabulary and ERSPs during the observe point condition at Time 1.

	T1 MCDI Receptive		T1 MCDI Receptive
F3		**C3**	
-1500 to -1000	-.17	-1500 to -1000	-.19
-1000 to -500	-.08	-1000 to -500	-.33*
-500 to 0	-.14	-500 to 0	-.24
0 to 500	-.11	0 to 500	-.24
F4		**C4**	
-1500 to -1000	-.05	-1500 to -1000	-.08
-1000 to -500	.05	-1000 to -500	-.02
-500 to 0	.03	-500 to 0	-.05
0 to 500	.01	0 to 500	-.06
P3		**O1**	
-1500 to -1000	-.07	-1500 to -1000	-.03
-1000 to -500	-.10	-1000 to -500	-.18
-500 to 0	-.18	-500 to 0	-.23
0 to 500	-.02	0 to 500	.13
P4		**O2**	
-1500 to -1000	.08	-1500 to -1000	.21
-1000 to -500	.01	-1000 to -500	.11
-500 to 0	-.06	-500 to 0	.02
0 to 500	.11	0 to 500	.16

Note. * p <.05

Effect of training on infants' mirroring response and communicative skill

Results of the independent samples t-tests comparing the training and control group on parent pointing measures at Time 2 showed that parents in the training group produced significantly more point tokens ($t(70)=5.12$, $p<.001$) and point types ($t(70)=4.20$, $p<.001$) at Time 2 than those in the control group (Figure 12). Additionally, parents in the training group also showed a greater positive change in the amount of point tokens ($t(70)=5.44$, $p<.001$) and point types ($t(70)=4.67$, $p<.001$) that they produced as compared to parents in the control group.

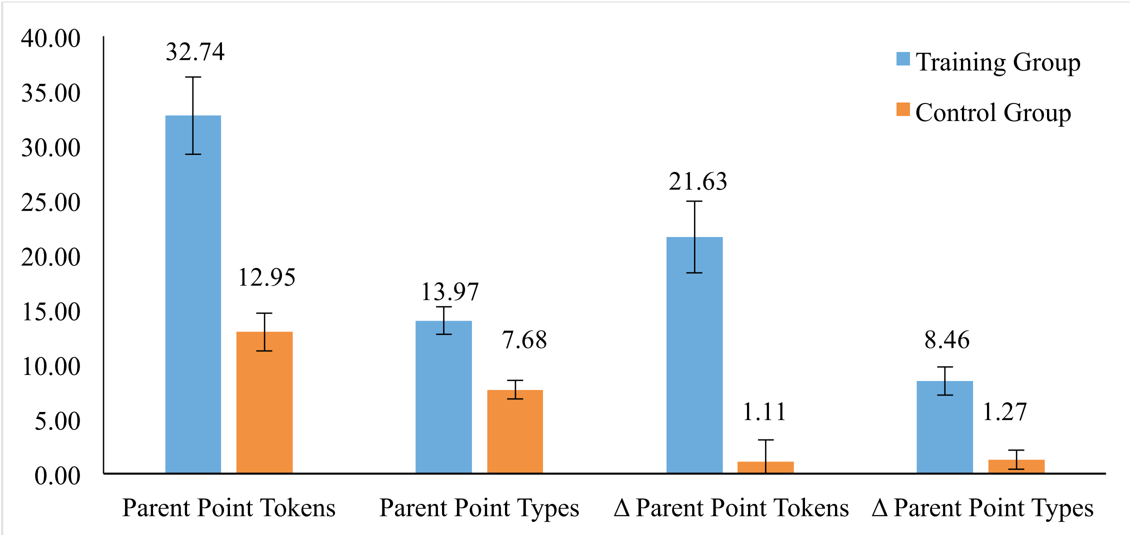


Figure 12. Comparison of parent pointing post-training across the training and control groups.

Effect of training on mirroring response.

RQ 4. Does increasing infants' experience with pointing gestures lead to greater MNS activity during observation of points?

Overall group differences. Results of the RM-ANOVA comparing activity at Time 2 across the training and control group showed that the main effect of training group was not significant ($F(1,38)=1.83$, $p=.18$, $\eta_p^2=.05$), and the four-way interaction between Region x Hemisphere x Epoch x Training Group was the only interaction with training group that even approached significance ($F(9,342)=1.60$, $p=.11$, $\eta_p^2=.04$). Despite these null to marginal results, the series of planned independent t-tests were conducted, comparing infants' mu rhythm desynchronization measured at Time 2, across the two groups (Figures 13-16). My hypotheses focused on seeing differences in the Central region, but for comparison these analyses were repeated across all four regions. There was a significant group difference in the right Central electrode cluster (C4) in the epoch capturing the final goal-state, just prior to the completion of the point (-500ms to

0ms: $t(38)=-2.18$, p=.036) and a moderately significant group difference also in C4 in the epoch capturing the start of the movement ($t(38)=-1.73$, p=.09). While no other comparisons were significant, there is an overall pattern across the Frontal, Central, and Parietal regions with the training group showing stronger desynchronization as compared to the control group. Thus, infants in the training group tended to show a stronger and longer sustained mirroring response at Time 2 than those in the control group.

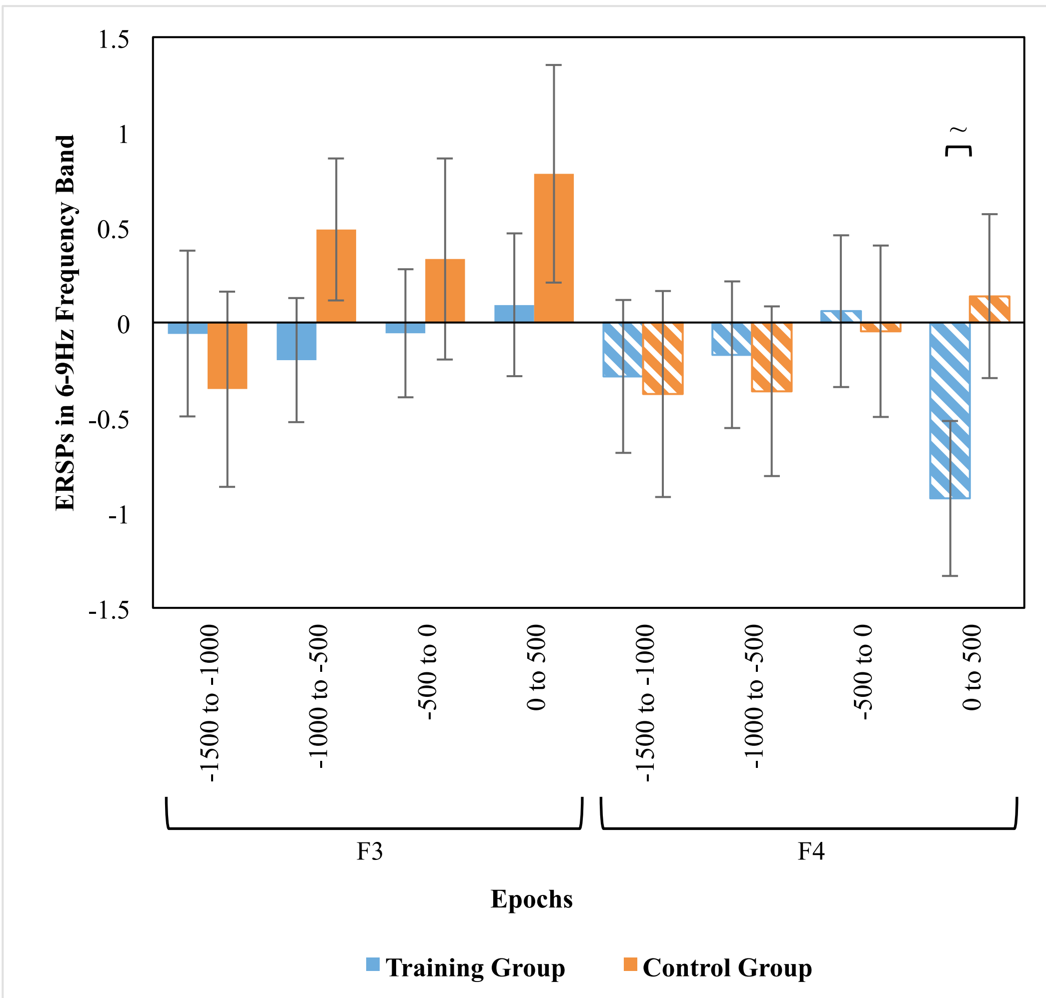


Figure 13. Comparison of EEG activity, as compared to baseline, at Time 2 during the observe point condition over the Frontal region.

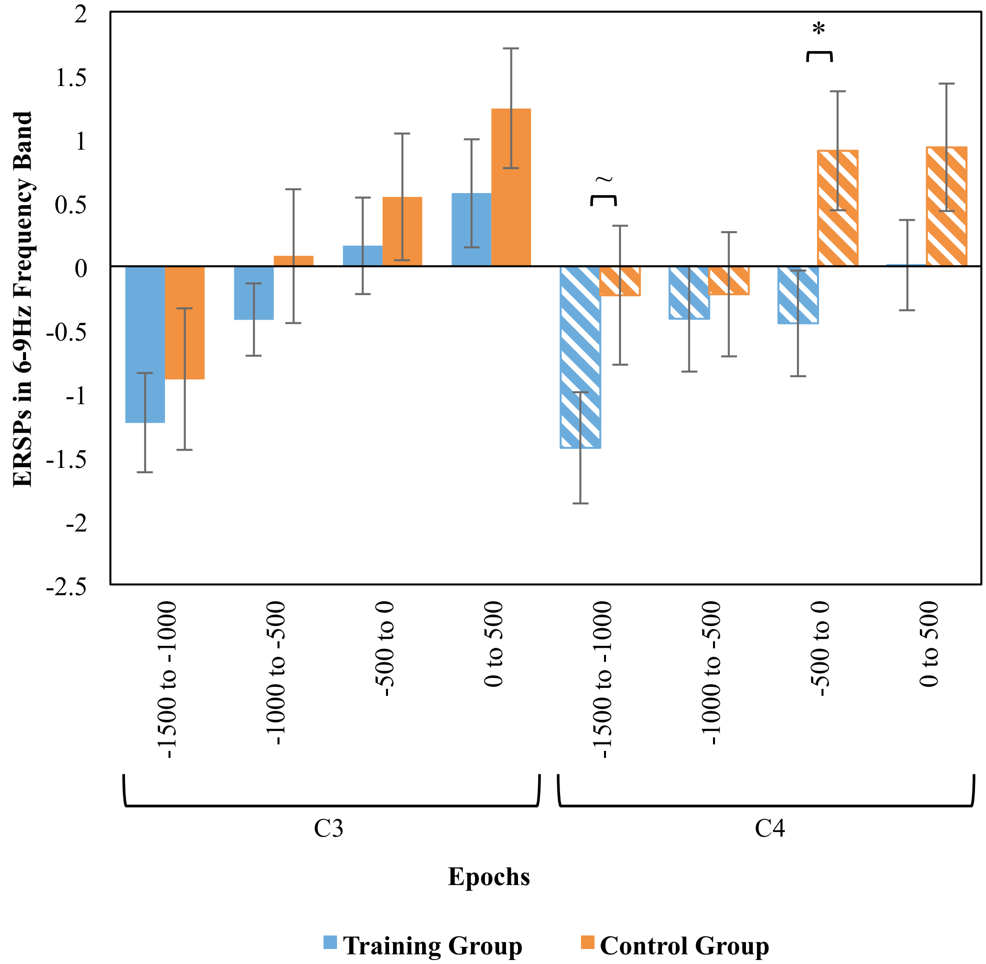


Figure 14. Comparison of EEG activity, as compared to baseline, at Time 2 during the observe point condition over the Central region.

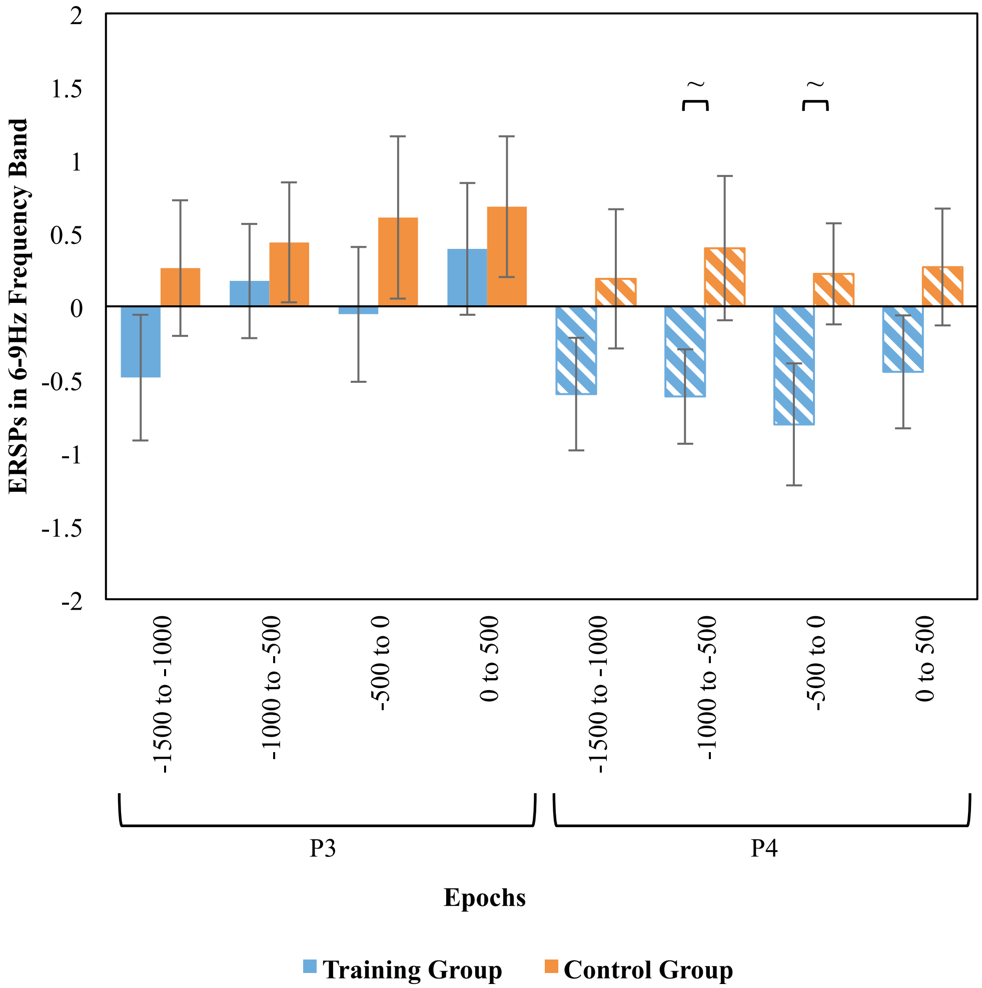


Figure 15. Comparison of EEG activity, as compared to baseline, at Time 2 during the observe point condition over the Parietal region.

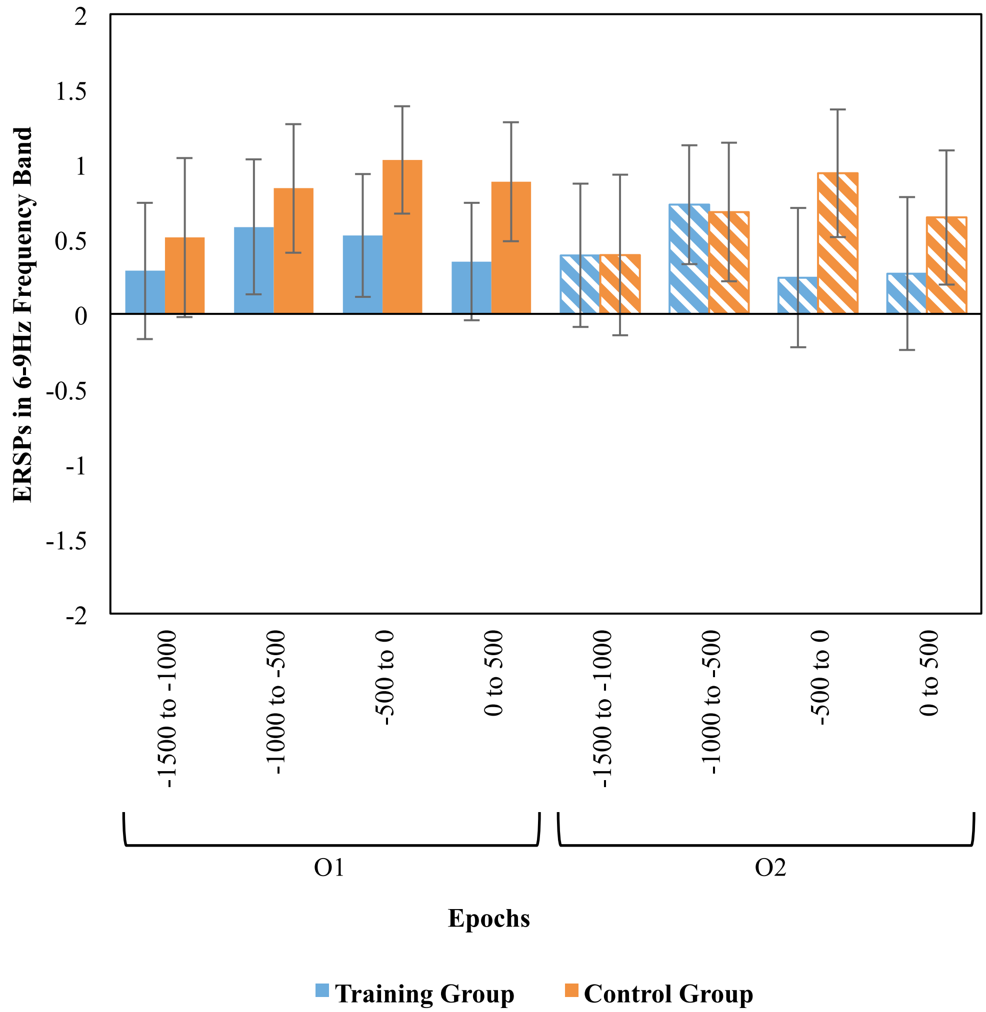


Figure 16. Comparison of EEG activity, as compared to baseline, at Time 2 during the observe point condition over the Occipital region.

Results of the second RM-ANOVA using change scores showed, again, that the main effect of training group was not significant ($F(1,27)=.001$, $p=.97$, $\eta_p^2=.00$), however there was a significant Epoch x Training Group interaction ($F(2.35, 63.47)=4.06$, $p=.02$, $\eta_p^2=.13$), such that the control group saw a greater decrease in activity from Time 1 to Time 2 over the first ($M_{Central}$=-.30, SE=.38; $M_{Training}$=.07, SE=.34t) and second ($M_{Control}$=-.40, SE=.33; $M_{Training}$=.16 SE=.30) epochs, whereas the training group saw a greater decrease in activity from Time 1 to Time 2 over the third ($M_{Control}$=-.15, SE=.35;

$M_{Training}$=-.39, SE=..31) and fourth ($M_{Control}$=.25, SE=.39; $M_{Training}$=-.50 SE=.35) epochs. There was also a moderate Hemisphere x Training Group interaction (F(1, 27)=3.03, p=.09, η_p^2=.10), such that the control group saw a greater decrease in activity from Time 1 to Time 2 over the left hemisphere ($M_{Control}$=-.24, SE=.36; $M_{Training}$=.19, SE=.33), whereas the training group saw a greater decrease in activity from Time 1 to Time 2 over the right hemisphere ($M_{Control}$=-.06, SE=.36; $M_{Training}$=-.52, SE=.32).

Again, the series of planned independent t-tests were conducted, comparing change in infants' mu rhythm desynchronization ERSPs, across the two groups (Figures 17-20). As in the comparison of Time 2 activity, the comparison of change in activity from Time 1 to Time 2 showed that the greatest group difference in the Central electrode cluster is in the right hemisphere (C4) in the later epochs. Specifically, there was a marginally significant group difference in the epoch where the experimenter held still in the final goal-state, just after completion of the point (0ms to 500ms: $t(27)$=-1.84, p=.08). This same epoch showed group differences in the right frontal (F4: $t(27)$=-2.19, p=.04) and right occipital (O2: $t(27)$=-1.77, p=.09) electrode clusters as well.

- - -

Thus, summarizing the results from comparing activity at Time 2 and comparing change in activity from Time 1 to Time 2, infants in the training group not only showed more mirroring activity after the training period, but also showed greater change in their mirroring response from Time 1 to Time 2. Both of these comparisons are greatest toward the end of the window of interest, that is, during the final goal-state of the pointing gesture.

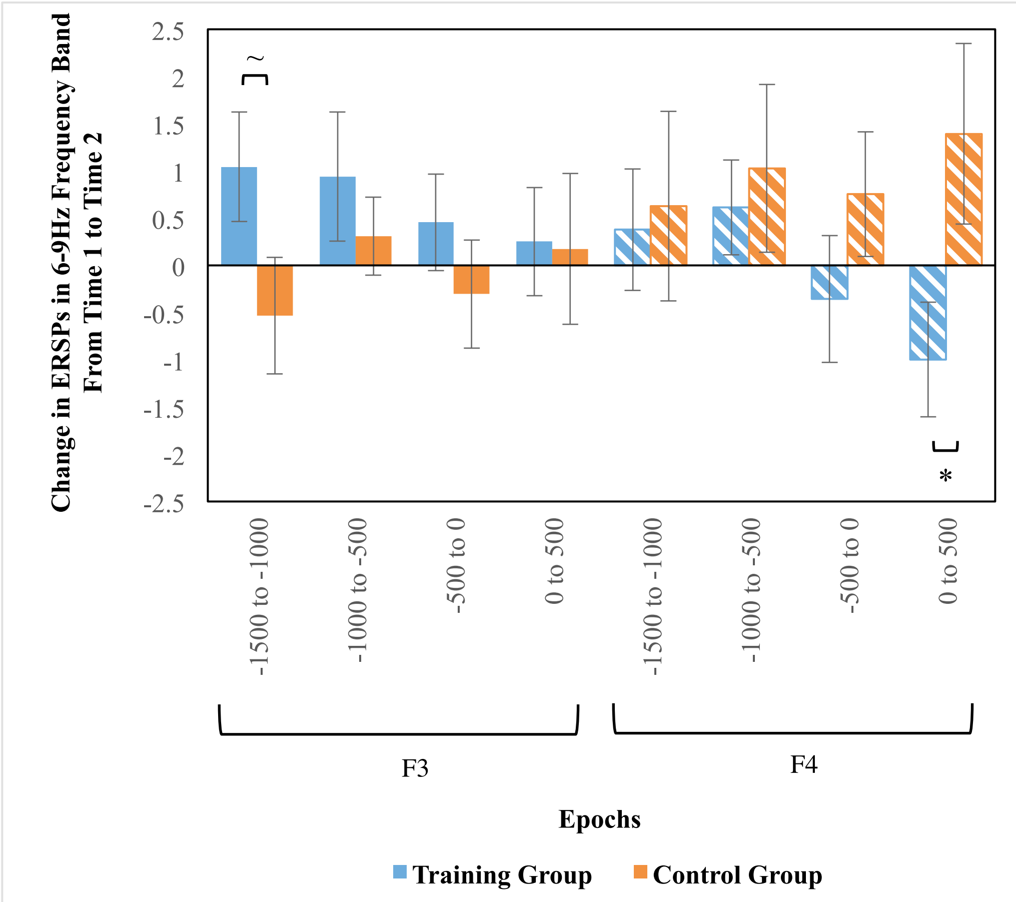


Figure 17. Comparison of change in EEG activity from Time 1 to Time 2 during the observe point condition over the Frontal region.

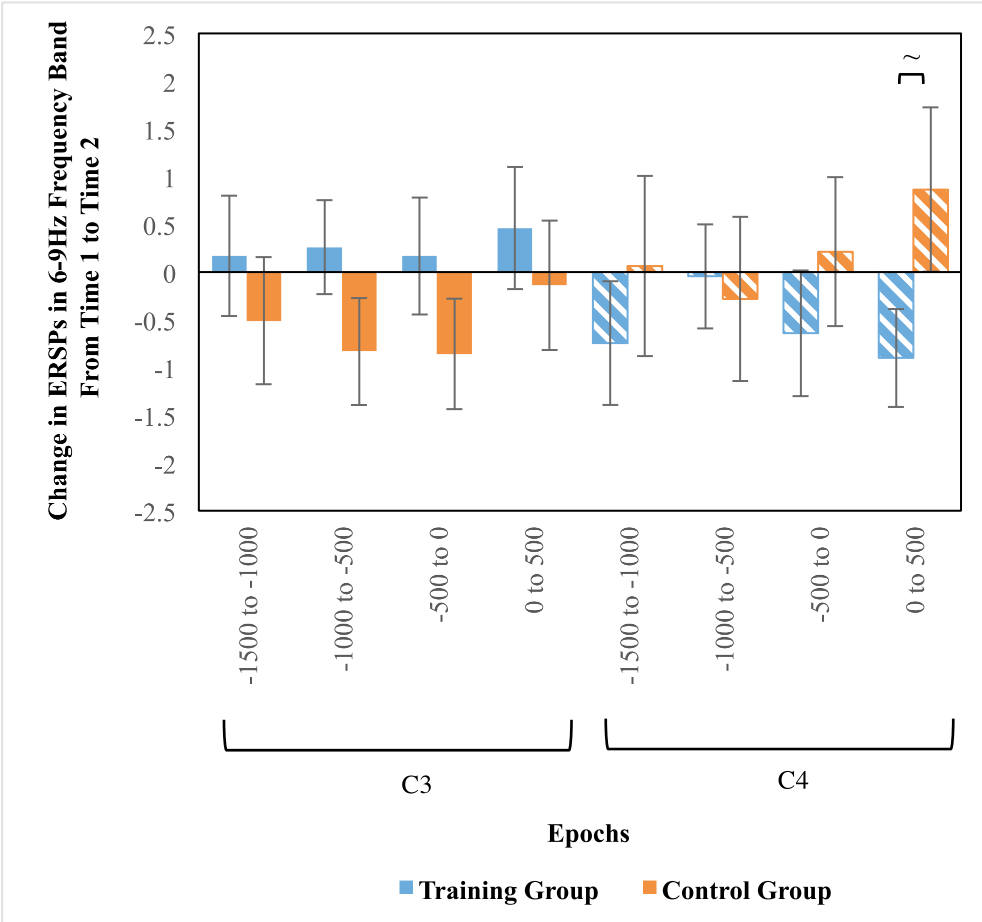


Figure 18. Comparison of change in EEG activity from Time 1 to Time 2 during the observe point condition over the Central region.

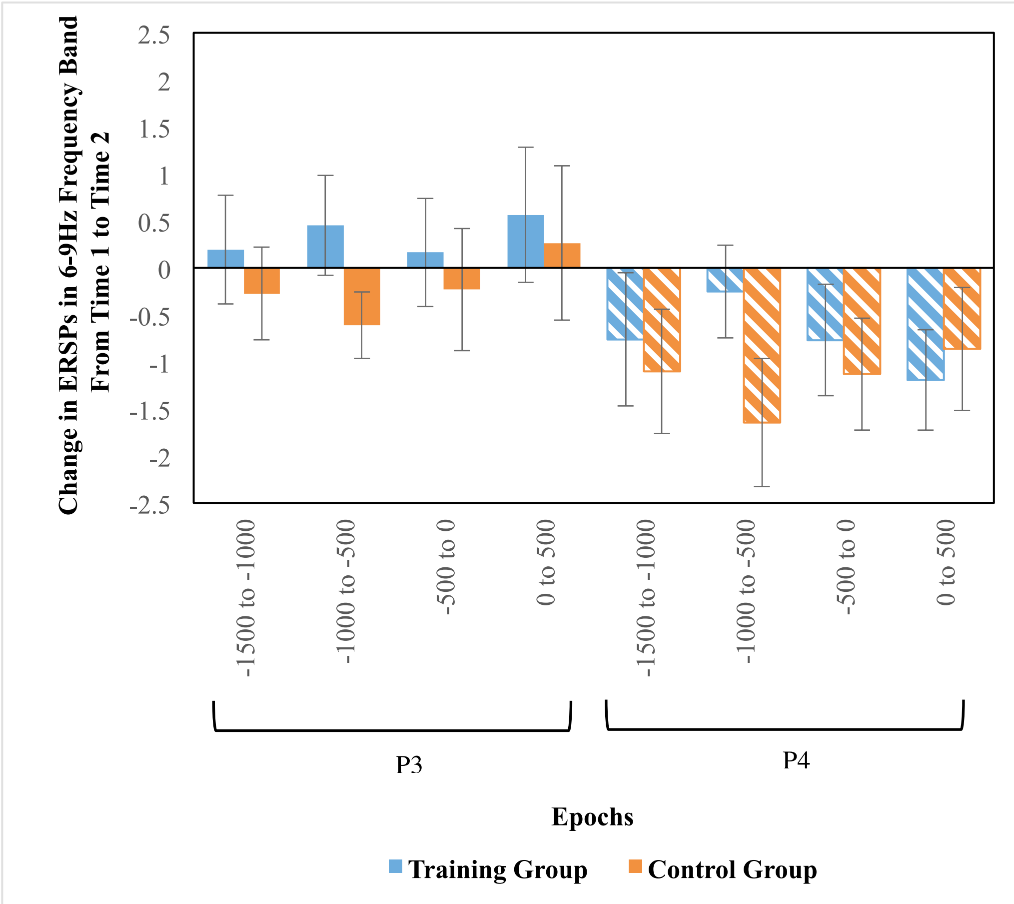


Figure 19. Comparison of change in EEG activity from Time 1 to Time 2 during the observe point condition over the Parietal region.

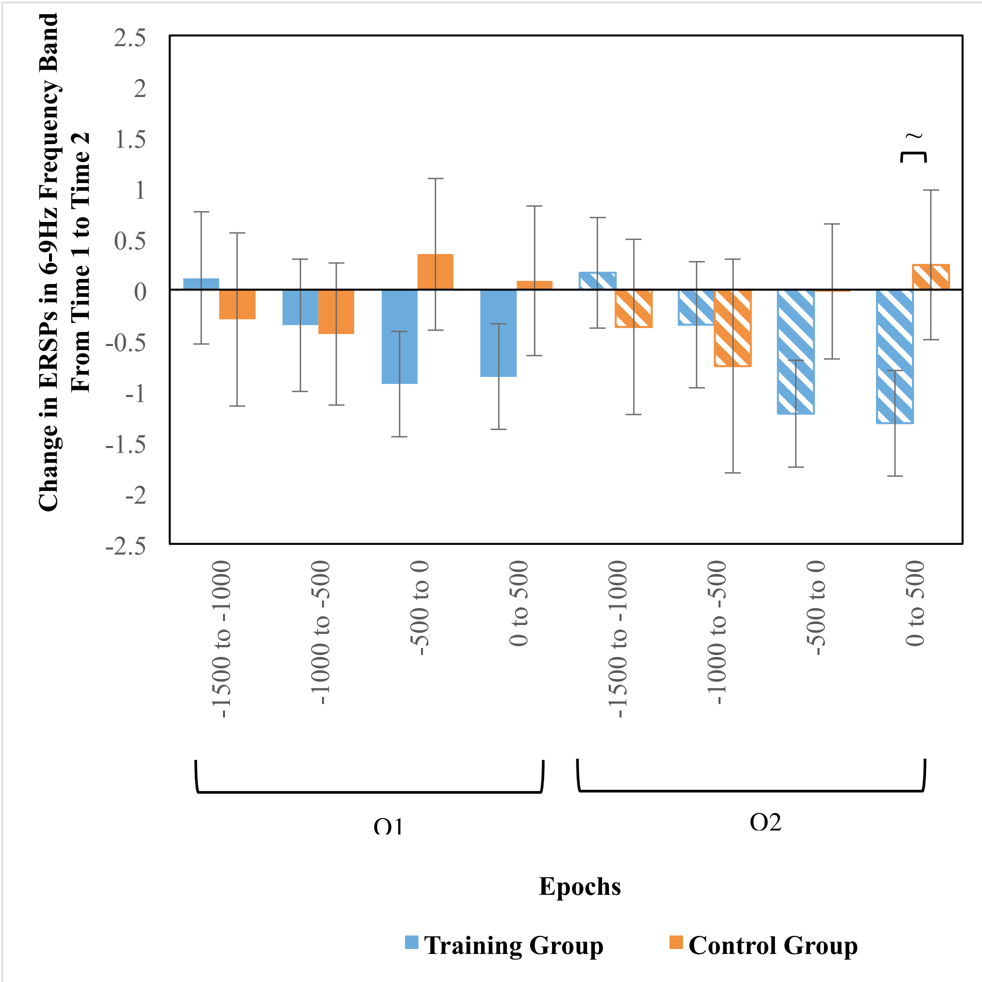


Figure 20. Comparison of change in EEG activity from Time 1 to Time 2 during the observe point condition over the Occipital region.

Relations between individual differences in change. Results of the change score models examining relations between change in parent pointing and change in infant mu rhythm activity follow. For these, and the following, analyses I focused specifically on the hemisphere and epochs in the Central electrode cluster (i.e., measuring sensorimotor activity) that showed the overall greatest group differences in activity measured at Time 2 and in change in activity from Time 1 to Time 2. Specifically, an average was created capturing change in activity from Time 1 to Time 2 in the 1-second period surrounding the completion of the point (average of the -500ms to 0ms epoch and the 0ms to 500ms epoch) in the C4 electrode cluster.

Figure 21 shows results for the model explaining change in infants' mu rhythm activity using point tokens as the measure of parent pointing. There was no direct effect of training group on change in infants' mu rhythm, however positive change in parent point tokens significantly predicted negative change in infants' mu rhythm activity from Time 1 to Time 2. The indirect effect of training group on Time1-Time2 change in mu rhythm activity was also significant ($B=-.81$, $p=.01$). Neither infant pointing status nor parents' point tokens at Time 1 were related to infant mu rhythm activity at Time 1 or change in mu rhythm activity. Parents who produced more point tokens at Time 1 saw less change in their own point tokens, and, as we saw before in the analysis examining the effect of training on parent pointing, training group significantly positively predicted change in parents' point tokens. Results for the model explaining change in infants' mu rhythm activity using point types as the measure of parent pointing can be seen in Figure 22. As before, there was no direct effect of training group on change in infants' mu rhythm, but there was a significant negative relation between change in parent point types and change in infants' mu rhythm activity from Time 1 to Time 2. Again, the indirect effect of training group on Time1-Time2 change in mu rhythm activity was also significant ($B=-1.06$, $p=.001$).

- - -

In sum, these findings indicate that the training was effective not only in increasing parents' pointing production, but also had a significant indirect effect on infants' mirroring activity. Parents in the training group saw greater positive

change in the number of point tokens and types produced, and greater positive change in parent point tokens and point types was related to greater negative change in infants' mu rhythm desynchronization.

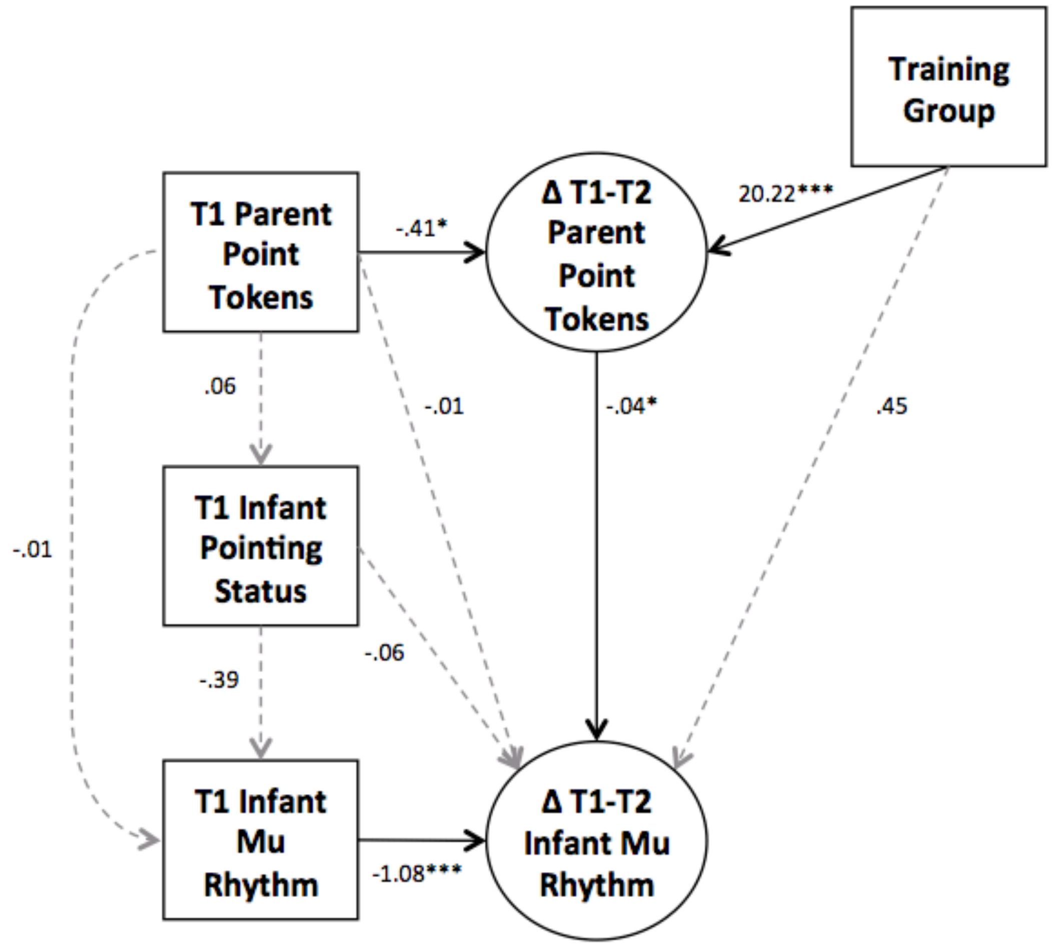


Figure 21. Change score model estimating infants' change in infants' mu rhythm activity using point tokens as the measure of parent pointing. Solid black lines indicate p < .05 and dotted gray lines indicate p > .10. *** p < .001, ** p <.01, * p <.05.

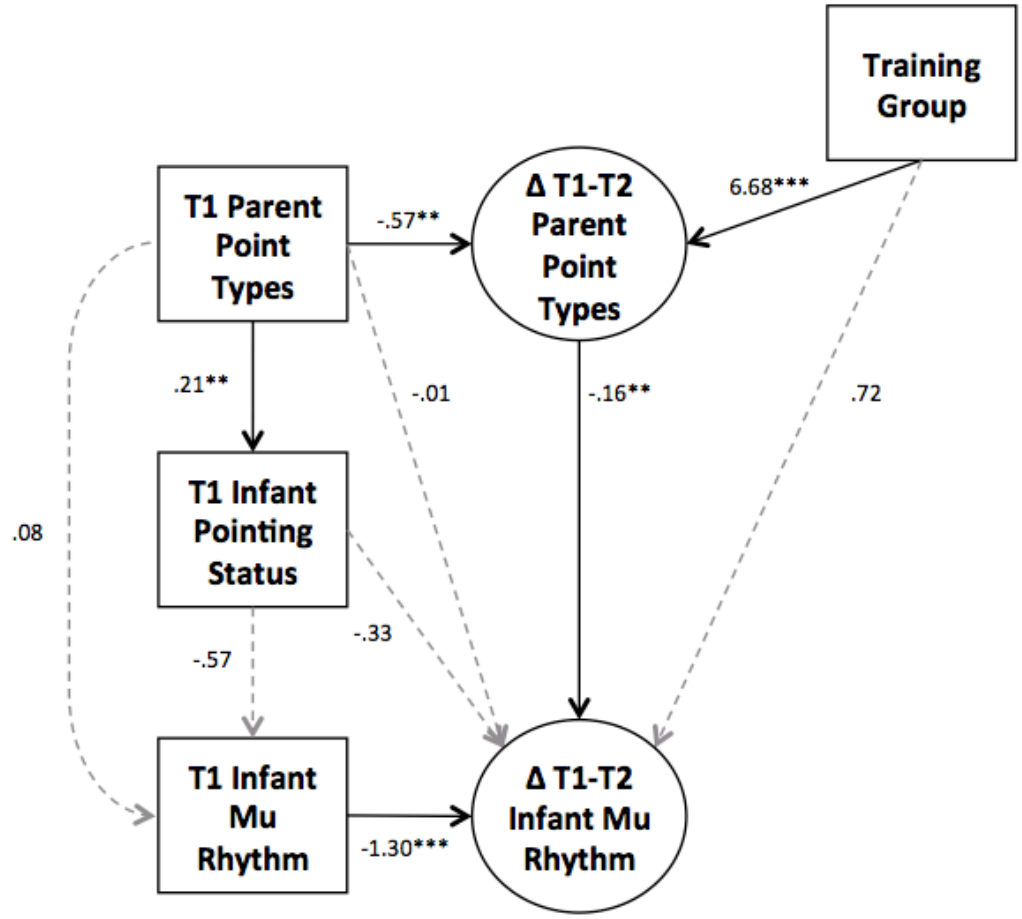


Figure 22. Change score model estimating infants' change in infants' mu rhythm activity using point types as the measure of parent pointing. Solid black lines indicate p < .05 and dotted gray lines indicate p > .10. *** p < .001, ** p <.01, * p <.05.

Effect of training on communicative skill

RQ 5. Does increasing infants' experience with pointing gestures lead to increases in their communicative skill?

Analysis of relations between infants' pointing, parent pointing, and infant language at Time 1 showed that infants' parent reported pointing status was not related to receptive vocabulary (t(78)=-0.57, p=.57). Further, the number of point tokens parents produced was significantly related to their infants' receptive vocabulary (r=.37, p=.001).

Parents' point types were also related to infants' receptive ($r=.30$, $p=.007$) vocabulary. Parents' pointing also differed depending on infants' pointing status. Parents who had designated their infant as a 'pointer' at Time 1 produced more point tokens ($M_{Training}=13.00$, $SD=9.24$; $M_{Control}=8.56$, $SD=8.92$; $t=-2.01$, $p=.05$) and point types ($M_{Training}=6.60$, $SD=3.67$; $M_{Control}=4.12$, $SD=3.23$, $t=-2.90$, $p=.005$) than parents whose infants were not yet pointing, according to their report.

Overall, infants' showed significant positive change in their vocabulary scores during both time periods (ΔTime1 to Time2: N=72, Mean=11.29, SD=12.36, $t(71)=7.75$, $p<.001$; ΔTime2 to Time 3: N=68, Mean=12.25, SD=12.41, $t(67)=8.14$, $p<.001$). Results for the model explaining change in infants' receptive vocabulary and using point tokens as the measure of parent pointing can be seen in Figure 23. There was no direct effect of training group on change in infants' receptive vocabulary. As shown previously, parents' point tokens at T1 predicted infants' vocabulary at T1. Change in parent point tokens moderately predicted change in infants' vocabulary from Time 1 to Time 2 and from Time 2 to Time 3, however this relation was positive with Time 1 to Time 2 change and negative with Time 2 to Time 3 change. The indirect effect of training group on Time1-Time2 change in receptive vocabulary was also moderately significant ($B=2.28$, $p=.07$), as was the indirect effect of training on Time2-Time3 change ($B=-2.57$, $p=.09$). Results for the model explaining change in infants' receptive vocabulary and using point types as the measure of parent pointing can be seen in Figure 24. Results mirror the previous model, however parent point types at Time 1 significantly predicts the likelihood of a child being a pointer at Time 1 and change in infant's receptive vocabulary from Time 1 to Time 2. As before, there is a moderate and positive relation between change in parent point types and infant vocabulary change from Time 1 to Time 2, and a moderate and negative relation between change in parent point types and infant vocabulary change from Time 2 to Time 3. The indirect effect of training group on Time1-Time2 change in receptive vocabulary was also moderately significant (B=2.55, p=.10), as was the indirect effect of the training on Time2-Time3 change in receptive vocabulary (B=-2.63, p=.07). These results suggest a positive indirect effect of the training on infants' receptive vocabulary growth from Time 1 to Time 2, as a function of change in parents' point tokens and point types. This positive effect seems to reverse for change in infant receptive vocabulary from Time 2 to Time 3, such that more of an increase in parent point types from Time 1 to Time 2 is related to less change in infants' receptive vocabulary from Time 2 to Time 3.

- - -

In sum, the training had a moderate indirect effect on growth in receptive vocabulary through its direct effect on increases in parent pointing. The relation between change in parent pointing (both tokens and types) and change in infants' vocabulary was nuanced, such that the concurrent relations of change from Time 1 to Time 2 were positive – greater positive change in parent pointing was related to greater positive change in infant vocabulary – whereas the predictive relations from change in parent pointing from Time 1 to Time 2 to change in infant vocabulary from Time 2 to Time 3 were negative – greater positive change in parent pointing predicted smaller or less growth in infants' vocabulary from Time 2 to Time 3.

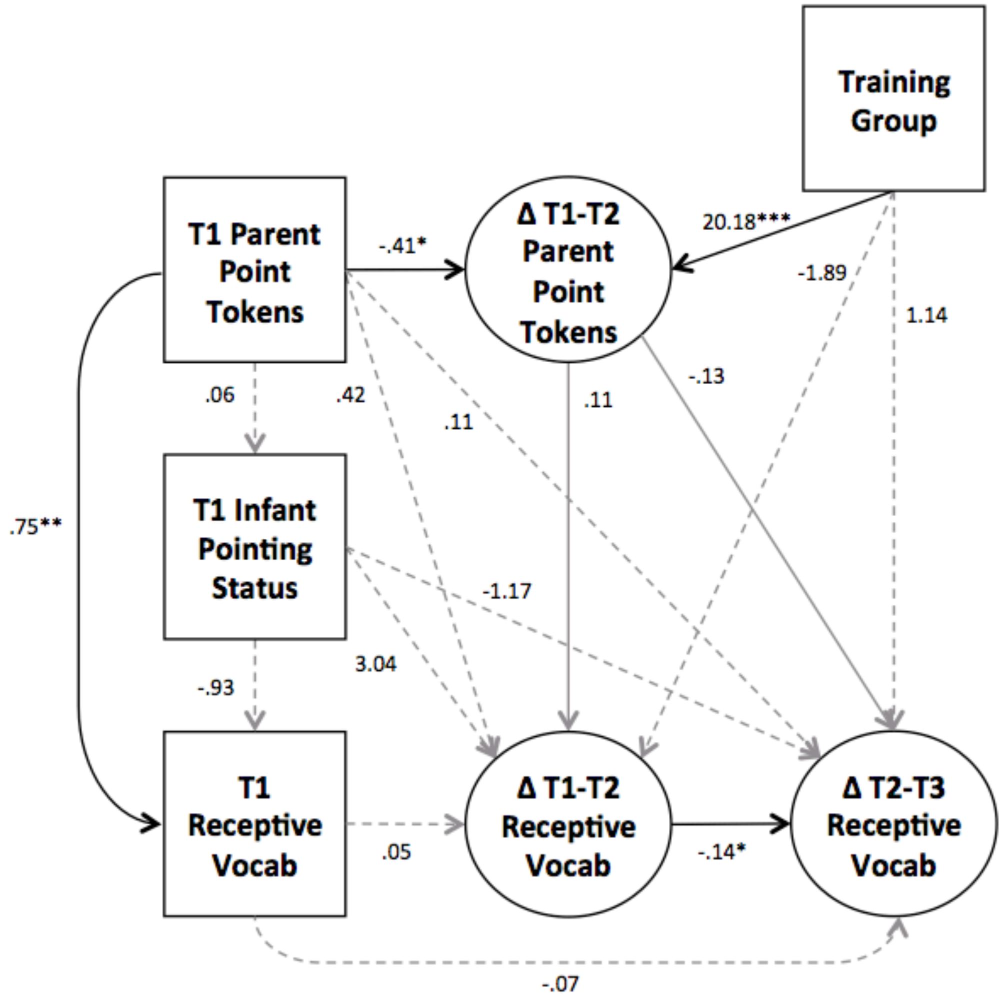


Figure 23. Change score model estimating infants' change in receptive vocabulary and using point tokens as the measure of parent pointing. Solid black lines indicate p < .05, solid gray lines indicate p < .10, and dotted gray lines indicate p > .10. *** p < .001, ** p <.01, * p <.05.

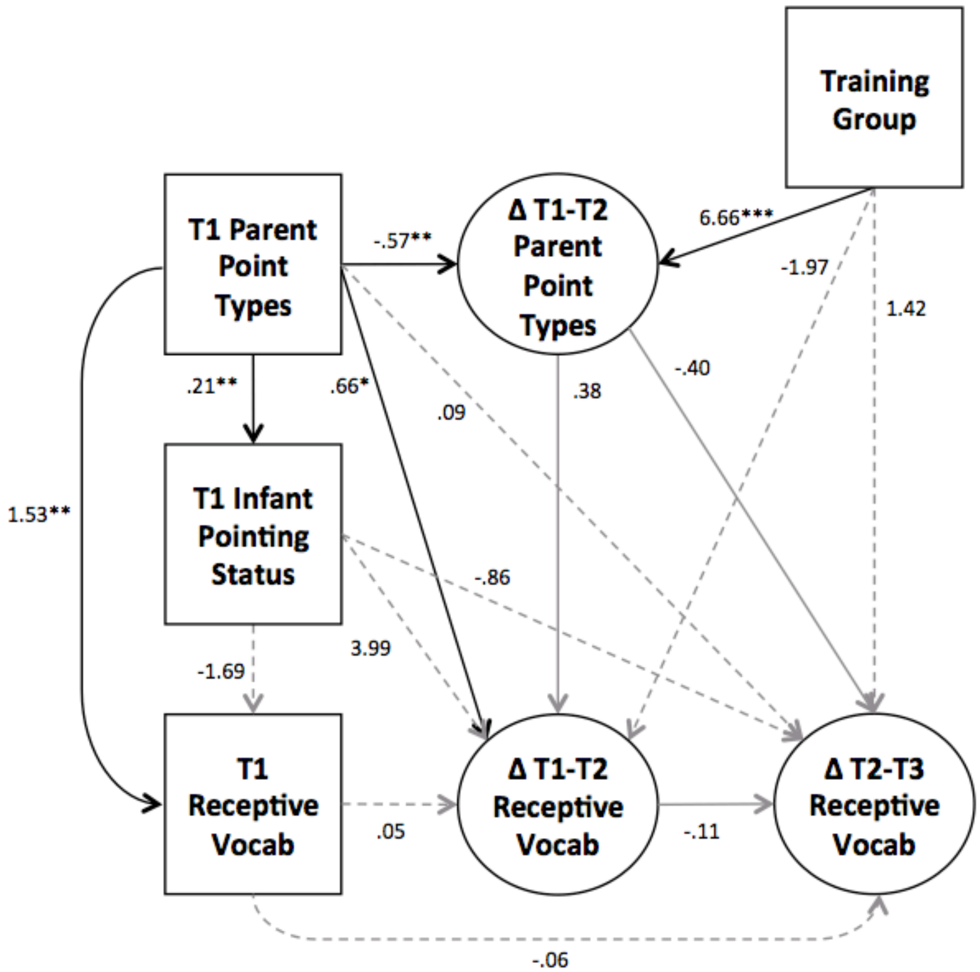


Figure 24. Change score model estimating infants' change in receptive vocabulary and using point types as the measure of parent pointing. Solid black lines indicate p < .05, solid gray lines indicate p < .10, and dotted gray lines indicate p > .10. *** p < .001, ** p <.01, * p <.05.

Mirroring activity as a mediator

RQ 6. Does infants' MNS activity during observation of pointing gestures mediate the relation between experience with points and their developing vocabulary?

Results for the model exploring change in infant mu rhythm as a mediator for the relation between change in parent pointing and change in infant vocabulary, and using parent point tokens as the measure of parent pointing, can be seen in Figure 25. Infant mu rhythm activity at Time 1 significantly predicted change in mu rhythm activity, as well as infants' vocabulary from Time 1 to Time 2 and from Time 2 to Time 3. The direct effect between change in parent point tokens and change in infant mu rhythm activity was significant, as was that between change in infant mu rhythm activity and change in infant receptive vocabulary from Time 1 to Time 2. However, change in infant mu rhythm activity did not predict change in vocabulary from Time 2 to Time 3. The indirect effect from change in parent point tokens to change in infant receptive vocabulary from Time 1 to Time 2, through change in infant mu rhythm activity, was also significant ($B=.09$, $p=.02$). Results for the model exploring change in infant mu rhythm as a mediator, and using parent point types as the measure of parent pointing, can be seen in Figure 26. As we saw in the previous model, mu rhythm activity was a significant predictor of change in mu rhythm activity, as well as both measures of change in infant receptive vocabulary. Change in parent point types predicted change in infant mu rhythm, which in turn predicted change in infants' receptive vocabulary from Time 1 to Time 2. The indirect effect was also significant ($B=.37$, $p=.03$). In this model, change in parent point types was significantly negatively predictive of change in infant receptive vocabulary from Time 2 to time 3.

- - -

In sum, the results from these two models provide evidence that the positive relation between changes in parent pointing and infant receptive vocabulary development is, in part, mediated by changes to infants' resonant motor system activity during observation of pointing gestures.

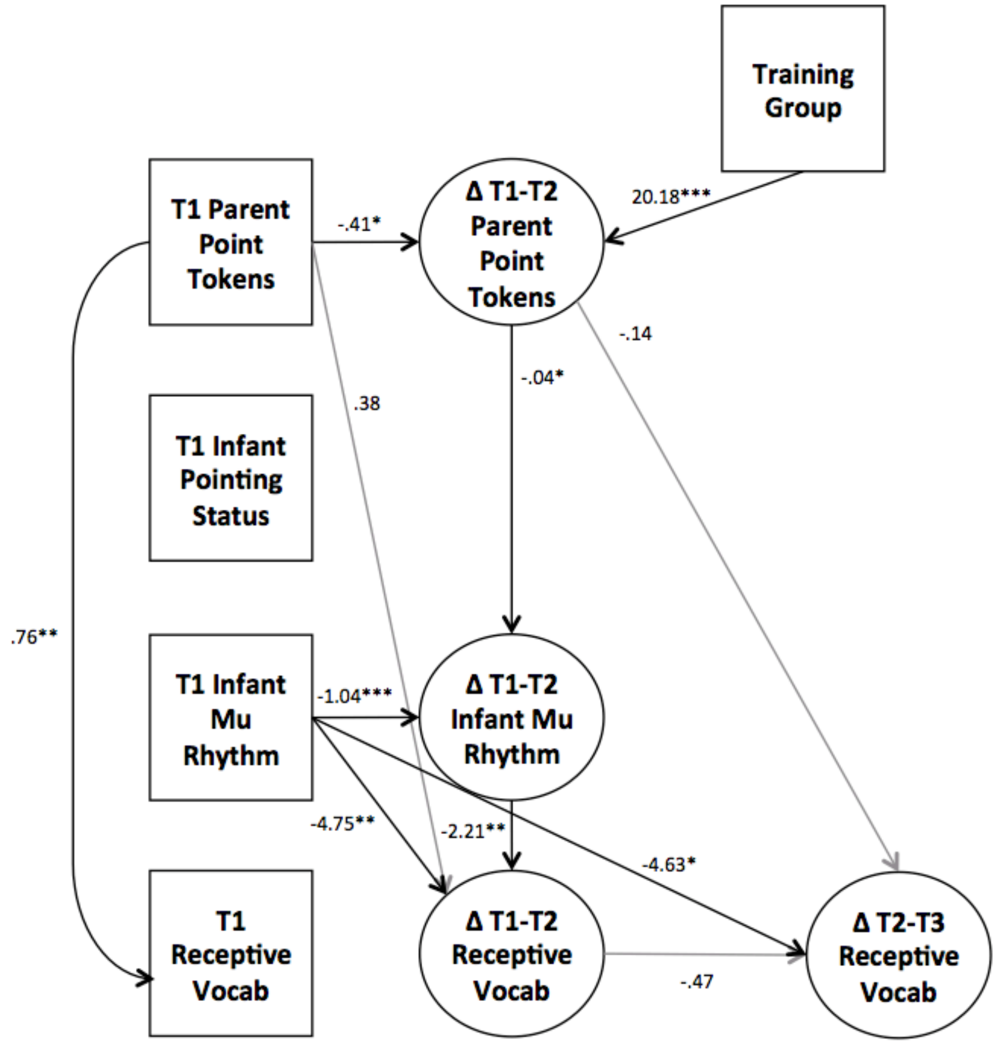


Figure 25. Change score model estimating the mediating effect of change in infant mu rhythm activity on the relation between infants' change in receptive vocabulary, using point tokens as the measure of parent pointing. Solid black lines indicate p < .05, solid gray lines indicate p < .10. *** p < .001, ** p <.01, * p <.05. Paths with p-values > .10 are not shown.

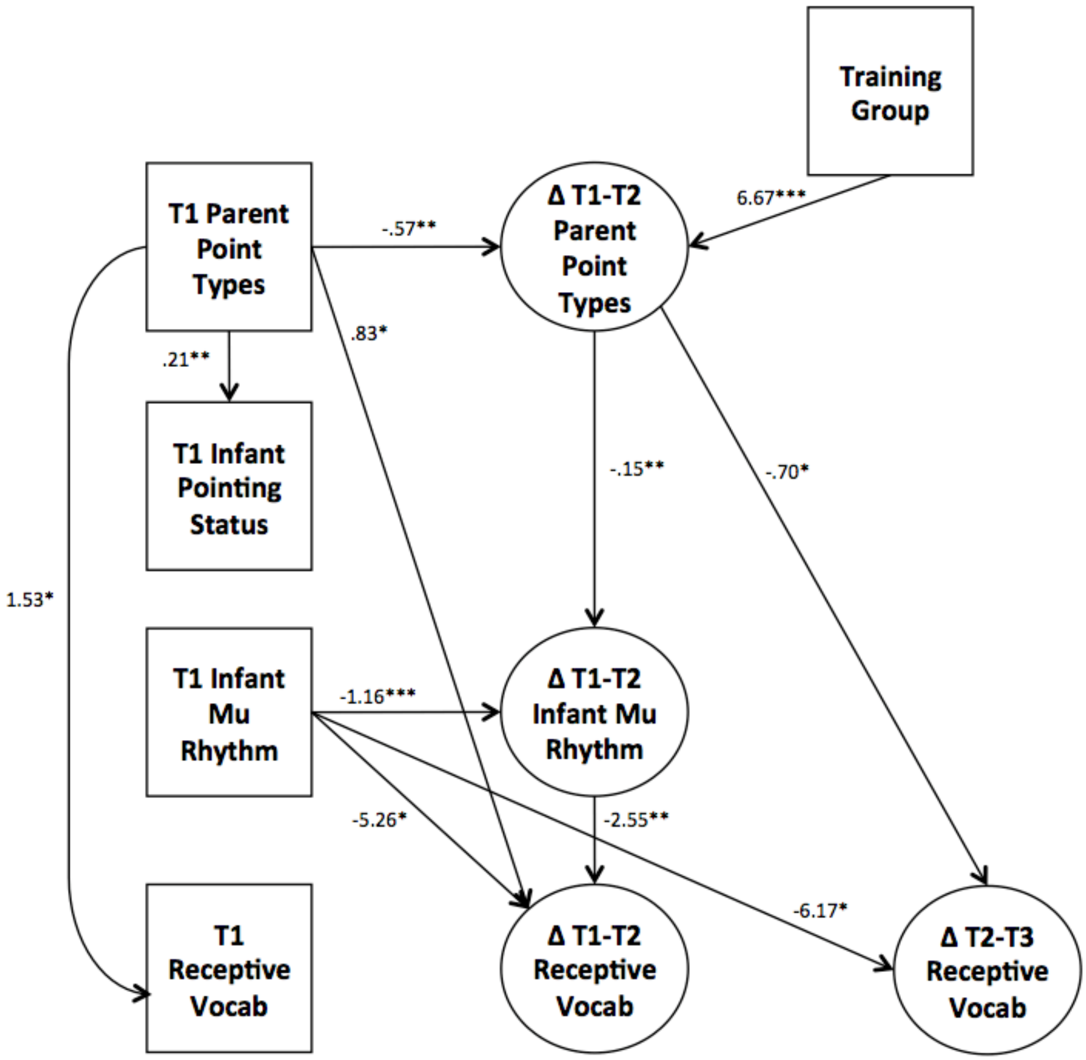


Figure 26. Change score model estimating the mediating effect of change in infant mu rhythm activity on the relation between infants' change in receptive vocabulary, using point types as the measure of parent pointing. Solid black lines indicate p < .05. *** p < .001, ** p <.01, * p <.05. Paths with p-values > .10 are not shown.

Supplemental Analyses

Relations with infant age

The current study recruited infants from a relatively wide age range (10- to 12-months) considering the rapid developmental changes that can occur during this time period. The following supplemental analysis examines whether child age had an influence on any of the key findings reviewed above. Infant age was examined in relation to child pointing status at Time 1, parent pointing at Time 1 and Time 2, change in parent pointing, infant language at all time points, change in infant language, and all infant EEG measures, and there were no significant relations across all of these analyses.

Infant age of pointing

If parents reported, at Time 1, that their child had started pointing (N=50), they were also asked to report the age at which their child had started pointing. On average, parents reported their children to have started pointing at 9.45 months, however this ranged from 3 months up to 11.5 months. The lower end of this range is much lower than would be expected, as research has shown pointing to emerge in the latter half of the first year through the second year of life. Thus, there is likely some error in this measure. Pointing age was not related to the measures of parent pointing or infant EEG. There was a significant relation between pointing age and infants' language ability at all three time points, however when the infant reported to have started pointing at 3 months was excluded, all correlations were no longer significant.

Number of days between visits

Parent-infant dyads varied in the amount of time between visits (T1 to T2 range: 27-67 days; T2 to T3 range: 27-51 days). To examine whether the length of time between visits could account for any variance in the amount of change parents or infants exhibited in their pointing, or mirroring and vocabulary, respectively, the above change score models were conducted again including the number of days between as a predictor of change. However, the number of days between visits did not predict change in any of these variables and thus was not included in the final models.

Training group fidelity measures

Parents in the training group were asked to fill out a daily log every day in the time between their first and second visits. Only three parents did not fill out or return their daily log. Each log entry consisted of two yes/no questions and one multiple-choice question, as follows:

1) Did you play with your child for 15 minutes today? Yes No

2) Did you point during that time? Yes No

3) Today my child pointed: a) Not at all b) Some c) Many times

Data from the logs are summarized in Table 5. If a parent filled out the log they also reported having pointed that day, however this ranged from roughly half the training period to every day between the two visits. Infants were reported to have pointed at all more than half the days of the training, but this also ranged from never pointing to pointing every day. However, a large majority of the infants were reported to have pointed at all more than 80% of the training days. When Question 3 was scored as 0 –

Not at all, 1 – Some, 2 – Many times, infants scored an average of 0.96 (SD=.59, Range: 0 – 1.74).

Table 5. Summary of training group's daily log data (N=32)

	Mean (SD)	**Range**
# Days from Time 1 to Time 2	33.09 (7.36)	27 - 56
	Mean % days (SD)	**Range**
Q1. Played for 15 minutes	.90 (.11)	.57 – 1
Q2. Parent pointed	.90 (.11)	.57 – 1
Q3. Child pointed	.63 (.35)	0 – 1

The measures gleaned from the training logs were examined as potential measures of infants' experience with pointing gestures over the course of the study, similar to the measures of change in parent pointing. Specifically, Pearson correlations were calculated to examine the relations between the percent of training days that parents pointed and infants' mu rhythm activity at Time 2, as well as with change in their mu rhythm activity from Time 1 to Time 2. These analyses focused on that specific measure which was identified and utilized in the primary analyses, the activity in the C4 electrode clusters in the third (-500ms to 0ms) and fourth (0ms to 500ms) epochs. This was repeated to examine relations with the percent of days that the infant pointed and infants' average daily pointing score. No relations were found.

Parents' speech

There is a large body of work linking parents' speech with their children and children's language development (Hart & Risley, 1992, 1995; Huttenlocher, Haight, Bryk, Seltzer, & Lyons, 1991; Pan, Rowe, Singer, & Snow, 2005; Rowe, 2012). Additionally, parents who talk more tend to use more pointing gestures in interactions with their young children (Rowe, 2000). In the following series of analyses, I examined the role that parents' speech may have played in the observed effects. Measures of parents' speech were extracted from the transcripts of the free-play interactions at both Time 1 and Time 2, including their word tokens and word types (as defined in the Measures section). At Time 1, parent word tokens was significantly related to their own production of point tokens ($r=.34$, $p=.002$) and point types ($r=.36$, $p=.001$). Parent word tokens was not related to infants' receptive vocabulary at Time 1 nor to infants' pointing status. Parent word types was not related to any measure of parent pointing, infant pointing, or infant vocabulary. Further, at Time 1, neither parents' word types nor word tokens were related to infants' mu rhythm activity.

Parents in the training group did increase their production of word tokens significantly more than those in the control group ($t(70)=2.62$, $p=.01$). In fact, parents in the control group saw an average decrease in their word tokens from Time 1 to Time 2 ($M=-9.03$, $SE=21.72$) while parents in the training group saw a large increase on average ($M=80.46$, $SE=26.67$). However, when substituted into the change score models in place of parents' pointing, parent word tokens was not a significant predictor of infant mu rhythm activity, infant receptive vocabulary, or change in either measure. Thus, while the training also impacted parents' speech production, the effects on the infants' mirroring activity and vocabulary development were specific to changes in parents' production of pointing gestures.

Analyses of observe grasp and execute grasp

Relations with pointing experience at baseline. Of the 41 infants with useable observe grasp EEG data at Time 1, 28 were categorized as 'pointers' by parent report, and 13 were ‘non-pointers’. A RM-ANOVA within the observe grasp condition with Region, Hemisphere, and Epoch as within-subjects factors and Pointing Status as a between-subjects factor showed no main effect of or interactions with Pointing Status. Of the 38 infants with useable EEG data from the execute grasp condition at Time 1, 30 were pointers and 8 were non-pointers. A similar RM-ANOVA within the execute grasp condition did show a main effect of Pointing Status ($F(6.24,38.30)=5.86$, $p=.02$, $\eta_p^2=.14$) and an Epoch x Pointing Status interaction ($F(2.79,100.32)=4.84$, $p=.004$, $\eta_p^2=.12$). Follow-up non-parametric Mann-Whitney U-tests within each epoch showed that non-pointers were always showing stronger desynchronization than their pointing peers, and this difference was significant in the first epoch ($U=39$, $p=.004$) and moderately significant in the last epoch ($U=66$, $p=.05$). However, with the drastically uneven sample sizes, these results should be interpreted cautiously. There were no relations between parents’ production of point tokens or point types with infants’ EEG activity during either the observe grasp or execute grasp conditions.

Relations with language ability at baseline. Pearson correlation analyses revealed no significant relations between infants’ neural activity in the Observe Grasp condition and their receptive vocabulary (Table 6). In the Execute Grasp condition, there were significant negative relations with activity in the Frontal, Parietal, and Occipital regions, but not in the Central region (Table 7).

Table 6. Correlations between infants' vocabulary and ERSPs during observation of a grasping action at Time 1.

	T1 MCDI Receptive		**T1 MCDI Receptive**
F3		**C3**	
-1500 to -1000	-.10	-1500 to -1000	-.03
-1000 to -500	-.29~	-1000 to -500	-.13
-500 to 0	-.02	-500 to 0	.05
0 to 500	-.11	0 to 500	-.06
F4		**C4**	
-1500 to -1000	.09	-1500 to -1000	-.02
-1000 to -500	-.14	-1000 to -500	.06
-500 to 0	-.06	-500 to 0	-.06
0 to 500	-.09	0 to 500	-.02
P3		**O1**	
-1500 to -1000	.05	-1500 to -1000	-.14
-1000 to -500	-.11	-1000 to -500	-.22
-500 to 0	-.05	-500 to 0	-.31~
0 to 500	-.06	0 to 500	-.18
P4		**O2**	
-1500 to -1000	-.04	-1500 to -1000	-.05
-1000 to -500	.001	-1000 to -500	-.05
-500 to 0	-.15	-500 to 0	-.14
0 to 500	-.05	0 to 500	-.05

Note. ~ p <.10

Table 7. Correlations between infants' vocabulary and ERSPs during execution of grasping actions at Time 1.

	T1 MCDI Receptive		**T1 MCDI Receptive**
F3		**C3**	
-1500 to -1000	-.32*	-1500 to -1000	-.26
-1000 to -500	-.21	-1000 to -500	-.25
-500 to 0	-.10	-500 to 0	-.26
0 to 500	-.06	0 to 500	-.17
F4		**C4**	
-1500 to -1000	-.26	-1500 to -1000	-.21
-1000 to -500	-.11	-1000 to -500	-.23
-500 to 0	-.12	-500 to 0	-.19
0 to 500	-.24	0 to 500	-.14
P3		**O1**	
-1500 to -1000	-.21	-1500 to -1000	-.38*
-1000 to -500	-.15	-1000 to -500	-.31~
-500 to 0	-.25	-500 to 0	-.32~
0 to 500	-.09	0 to 500	-.32*
P4		**O2**	
-1500 to -1000	-.31~	-1500 to -1000	-.13
-1000 to -500	-.29~	-1000 to -500	-.03
-500 to 0	-.42**	-500 to 0	-.16
0 to 500	-.37*	0 to 500	-.07

Note. ~ p <.10

Effect of training. RM-ANOVAs were conducted within each condition, with Region (Frontal, Central, Parietal, Occipital), Hemisphere (Left, Right), and Epoch (-1500ms to -1000ms, -1000ms to -500ms, -500ms to 0ms, 0ms to 500ms) as within-subjects factors, and Training Group (Training, Control) as a between-subjects factor, with interest specifically in whether there was a main effect of training or any interactions with training group. There were no such effects for the Execute Grasp condition. Results for the Observe Grasp condition, however, revealed a moderate Region x Training Group interaction ($F(2.05, 81.96)=2.41$, $p=.09$, $\eta_p^2=.06$), and a moderate Hemisphere x Epoch x Training Group interaction ($F(2.78, 111.32)=2.28$, $p=.09$, $\eta_p^2=.05$). No comparisons across groups (via t-test) within specific regions, hemispheres, and epochs showed significant differences for either the observe grasp or execute grasp conditions. There were no relations between change in parent pointing and mu rhythm activity in either the Execute Grasp or Observe Grasp condition at Time 2. Lastly, when mu rhythm activity during the execute grasp or observe grasp conditions was substituted into the change score models described above, neither models showed relations with parent pointing or infant vocabulary.

Chapter 5: Discussion

The overarching goal of the current study was to examine activity the MNS during observation of gestures as a neural correlate for understanding gestures and its role in early communicative development. The current study aimed to 1) examine whether infants would show similar MNS activity when observing a communicative gesture, specifically pointing, as they do when observing a typical object-directed action, 2) examine the relation between infants' MNS activity and their communicative skill, both in terms of gesture and vocabulary, and 3) examine the effect of experience on MNS activity and potential subsequent effects on developing communicative skills. To address these aims, infants' MNS activity during observation of pointing and grasping was assessed at age 10- to 12-months, as was their pointing experience (measured as both their own pointing production and their parents'), and language ability. The EEG mu rhythm was utilized as the measure of infants' MNS activity, as previous research has shown it to be a reliable and valid index of sensorimotor activity and that it is modulated both when one performs an action oneself and when watching another perform an action (Fox et al., 2016). Half of the parent-infant dyads then received a parent-directed training aimed at increasing parents' use of pointing gestures with their child, half received no training. One month after the training, parent pointing, infant pointing and vocabulary, and infant MNS activity were reassessed. Infant vocabulary was measured again one month after the first follow-up.

The results indicated that infant's do exhibit MNS activity during observation of communicative gestures. Relations between infants' MNS activity and their pointing experience or language ability did not appear at the first time point. However, post-training analyses revealed both group differences in infants' mirroring, as indexed by the

EEG mu rhythm, and relations with their growing receptive vocabulary. Further, individual differences in the amount of change parents' exhibited in their pointing production predicted increases in infants' MNS activity from pre- to post-training, which in turn predicted concurrent increases in infants' receptive vocabulary. These findings suggest that neural mirroring activity plays a mediating role in the relation between infants' exposure to gestures and their language development. A more detailed discussion of the findings is presented below.

Mirroring Activity during Observation of Pointing Gestures

In line with the initial hypothesis, infants in this study did exhibit mirroring activity during observation of pointing gestures at the baseline – Time 1 – visit. This activity was focused primarily during the period when the experimenter's arm was moving, likely the most motorically salient part of the action. As expected, the mu rhythm desynchronization was strongest and most sustained in the execute grasp condition. There were significant differences in both the strength and timing of the mu rhythm activity between the execute and observe conditions, however, as predicted, there were topographic and temporal similarities in mu rhythm activity between the observe grasp and observe point conditions. This finding suggests that the MNS system is similarly recruited during observation of non-communicative actions and communicative gestures, in infancy.

Previous research has examined and found mu rhythm desynchronization in adults during observation of communicative gestures (e.g., Avanzini et al., 2012; Quandt et al., 2012; Schippers et al., 2009). This is among the first evidence that the same neural processes are recruited when infants, who are just beginning to develop their overtly intentional communicative skills, observe communicative gestures, and provides further support for the theoretical bases of this study, that similar recognition and interpretation processes are recruited during the observation of both actions and gestures (Rizzolatti & Arbib, 1998; Woodward, 2004).

Baseline Relations between Mirroring Activity, Gesture Experience, and Language

Contrary to my prediction, infants' mu rhythm desynchronization during observation of pointing was not related to their experience with pointing gestures, at the baseline – Time 1 – visit, however, it is worth noting the limitations of the measures of infant pointing. Very few infants pointed at all during the free-play so I was not able to use a continuous measure of infants' first-hand pointing experience. In contrast, parents reported over half of the infants (n=55) to have started pointing by the Time 1 visit. The free-play was likely not well suited to elicit points from infants as all of the toys were within reach of the child. Our comparison of those infants who were reported to have started pointing with their non-pointing peers showed no group differences in their mu rhythm activity. Brune and Woodward (2007) found evidence that 9- to 11-month-old infants who were characterized as pointers were more likely to associate a pointing gesture with a specific referent, interpreted as their understanding of the link between the gesture and the referent. Their study also relied on parent report. It is also possible that there is a threshold for experience before which differences in mirroring activity might not be exhibited. In an as of yet unpublished study using a similar EEG paradigm to measure infants' neural activity during observation of gestures, a more nuanced measure of infant pointing was found to relate to infants' motor system activity (Salo et al., in prep). Specifically, in that study parents' reported whether their child pointed never, sometimes, or often. The only group to show significant mu rhythm desynchronization during observation of points was the infants who were reported to point often, that is those with the most first-hand experience pointing. Thus, it is possible that the dichotomous measure used in the current study was not sensitive enough to capture potentially informative differences in infants' pointing experience.

There were also no relations between the continuous measures of parent pointing and their infants' mu rhythm desynchronization to pointing, at Time 1.The majority of the research linking experience with strength of motor system activation has focused on first-hand experience, however, I anticipated that infants' observational experience with points would also be related to their mu rhythm activity. A recent study (de Klerk et al., 2016) indeed found evidence that pre-walking infants exhibited mu rhythm desynchronization to videos of other infants walking, suggesting there may be an effect of observational experience. However, when comparing baseline measurements no such relation was found.

Based on research that has found relations between individual differences in infants' mu rhythm desynchronization and concurrent high-order social cognitive skills, such as imitation (Filippi et al., 2016), I predicted to find a relation between mu rhythm desynchronization and infants' language skill such that infants with stronger mu rhythm desynchronization would also have larger vocabularies, at baseline. In this case, there was a pattern of activity that trended in support of this hypothesis. There was a significant negative relation between infants' mu rhythm activity during observation of a point and their receptive vocabulary at Time 1. This significant relation was specific to the epoch -1000ms to -500ms prior to the point completion over the left hemisphere. Relations with activity in the last two epochs of interest, those immediately surrounding the completion of the point, followed the same pattern but were not significant. While conjectures could be made about the left hemisphere being linked with language processing in the brain, no specific hypotheses as such were set out from the beginning, so it would be just that. Predictive relations with their later vocabulary growth was found with activity over the right hemisphere. This is the first study to link MNS activity with early language development, thus more work is needed to explore and determine whether there is topographic specificity in the relation between mirroring activity and an infants' growing vocabulary.

Effect of Training on Mirroring Activity

The Pointing to Success training was effective at increasing parents' pointing with their infants. Parents in the training group produced significantly more point tokens and point types at follow-up than parents in the control group, and also exhibited greater change from Time 1 to Time 2 in both point tokens and point types. Again, due to the lack of infants' pointing during the free-play at either time point, I was unable to assess the effect of the training on infants' own pointing production. However, as predicted, there was both a group level and incremental effect of the training on infants' MNS activity. Specifically, infants in the training group showed stronger mu rhythm desynchronization during observation of a point after the training period than their peers in the control group. In fact, mean mu rhythm activity was negative for the training group, indicating desynchronization and activation of the sensorimotor cortex, whereas the mean was positive for the control group, indicating synchronization and the opposite of the expected pattern. The comparison of change in infants' MNS activity from Time 1 to Time 2 yielded the same result, such that infants in the training group exhibited greater negative change in mu rhythm desynchronization as compared to the control group. While infants in the training group showed the strongest desynchronization in the earliest epoch of interest, when the action was starting, the difference across groups was greatest in the last two epochs, the period during which the experimenter completed and held the point. This is the part of the action when the final goal-state is reached. Thus, infants in the control group seemed to show a rebound of the mu rhythm activity prior to the action completion, whereas infants in the training group showed a more sustained pattern of activity that lasted beyond the most motorically salient period (when the experimenter's arm was moving) and through the part of the action that would require the most understanding and interpretation of the actors' intention. While this temporal pattern was not originally hypothesized, it provides further support for the theoretical links between mirroring and action/gesture understanding. Further, studies with adults have found a sustained pattern of activity such that the mu rhythm remains desynchronized throughout the entire action and does not rebound until after the action is completed or the goal state is reached (Avanzini et al., 2012). Future work would benefit from further examining the relation between individual differences in experience and temporal patterns in mirroring activity.

Change score modeling was employed in order to look at changes in infants' MNS activity as a function of changes in parents' pointing. Using FIML, these models harness the power of the full sample of 81 infants by using all of the information available to inform the model, rather than that only from those infants who had complete data at all time points. Both changes in parents' point tokens and changes in parents' point types significantly predicted changes in infants' mu rhythm activity from Time 1 to Time 2. These continuous relations explained the group differences found between the training and control group. Thus, increasing infants' observational experience with pointing gestures increased the response of the mirroring system during observation of points. This suggests that through increased experience the infants in the training group were building a more robust internal representation of pointing gestures. The supplemental analysis of the other two conditions from the EEG task, observe grasp and execute grasp, show that these training effects are specific to the observe point condition. Experience with specific actions leads to greater understanding of those actions in infants (Cannon et al., 2012; Sommerville et al., 2005) and stronger mu rhythm desynchronization during observations of those actions in adults (Orgs et al., 2008). Experimental paradigms have been used previously to examine the effect of experience on the mu rhythm, but mostly in adults and only with non-communicative actions (e.g., Cannon et al., 2014; de Klerk et al., 2015). This is the first evidence that the MNS can be bolstered through experimentally increased experience with communicative gestures in infancy. Further, the experience we were able to measure in this study is observational. The continuous relation between changes in parent pointing and infant mirroring activity speak to the effect being driven, at least in part, by an increase in the infants' second-hand, observational experience with pointing gestures. It is possible that the group differences in mu rhythm activity were actually, or in part, caused by an effect of the training on infants' own pointing production. More work, with better measures of infant pointing production, is needed to examine whether the effects seen here are better explained or perhaps moderated by changes in infants' own pointing production.

Effect of Training on Communicative Skill

There was no direct effect of training group on changes in infant's vocabulary, however there was a moderately significant direct effect of change in parent pointing, both tokens and types, on change in infants' receptive vocabulary from Time 1 to Time 2. This relation was positive, such that parents who exhibited a greater increase in their pointing production had infants who exhibited a greater increase in their receptive vocabulary over that same time period. The indirect effect of training through the effect of change in parent point types was also moderately significant. Surprisingly, there was a moderately negative relation between change in parent pointing and change in infants' vocabulary from Time 2 to Time 3, the month following the training period. The advantage infants' experienced due to changes in their parents' pointing does not some seem to sustain and in fact reverses. Infants in the training group may have seen a boom in their vocabulary growth when their parents' started pointing more with them, and that initial period of growth likely dropped off over the next month. In fact, infants in the control group showed slightly greater change in their vocabulary from Time 2 to Time 3, although this difference was not even moderately significant. Parents in the control group were not told about the pointing training until after the third time point and final vocabulary measure, however it is possible that they naturally increased their own pointing production with their children in that final month. It is possible that this study simply shifted a normal developmental pattern slightly earlier for those in the training group. More research with continuous measures of changes in parents' and infants' pointing behavior and infants' developing language skills would be needed to examine this as a possible explanation for the reversal observed herein.

Mirroring Activity as a Mediator

Given the findings for an effect of training on both infant MNS activity and receptive vocabulary, I then sought to examine whether changes in the MNS mediated the relation between parent pointing and infant vocabulary. In line with my hypothesis, over the Time 1 to Time 2 period, change in parent pointing predicted change in MNS activity, which in turn predicted change in infants' receptive vocabulary. The indirect effect of change in parent pointing on change in infant vocabulary through changes in infant MNS activity was significant, indicating a mediating effect of mirroring. Interestingly, change in mirroring activity did not predict later change in infants' vocabulary, only concurrent change. However, infants' mirroring activity at Time 1, baseline, significantly predicted change in infants' vocabulary over the course of the study. That is, the relations between infants' mirroring activity at baseline and their change in receptive vocabulary from Time 1 to Time 2 and from Time 2 to Time 3 were both significant, such that stronger mirroring was related to a larger increase in vocabulary. Therefore, despite the lack of a sustained effect of the training in the current study, these findings provide evidence that the mirroring system, particularly as it is activated during observation of gestures, supports infants' receptive vocabulary development.

Limitations and Future Directions

While the current study and results are promising, there are several limitations to take note of and avenues by which future work can build on these findings to continue to grow our understanding of the role of action understanding, gestures, experience and the mirroring system in infants' communicative development. The greatest limitation of the current study was in the measurement of infants' own pointing production. I believe the lack of infants' pointing was a direct consequence of the physical set-up of the free-play interaction. All of the toys were laid out on the floor and, while they were some distance apart, the infants could easily crawl to whatever toy drew their attention. That is, they did not need to communicate with their parent. Other studies that have had success eliciting a range pointing behavior from infants in this same age range tend to have some toys available to the child and many other interesting toys and objects out of the child's reach so that they must draw their parent's attention to the objects through gesture or language. This was an unfortunate oversight in the current work, but future work with better measures of infant pointing production could help to elucidate how infants' first-hand experience with gestures might influence the trajectory of effects seen here.

Identification of the specific epochs in which the experimental effects were strongest was exploratory in the current study. Group differences were greatest, and thus relations with experience were strongest, in the epochs immediately surrounding the completion of the point. In the case of the pointing gesture, the communicative goal is not clear until the final moment. The arm movement toward an object can look very similar for both a grasping action and a pointing gesture, however the final movement of the hand and its relation to the object is the part of the action that differentiates and requires further understanding. While the timing effect aligns with the theoretical underpinning for the current study, it is important to see if the temporal specificity can be replicated. This does have to be specific to mirroring of gestures, but rather to see whether differences in experience with certain actions is related specifically to individual differences in mirroring activity during the goal state of the action.

The negative relations between change in parent pointing and infants' later vocabulary change (from Time 2 to Time 3) was unexpected and warrants follow-up. I have offered one possible explanation, that the training effectively shifted a typical pattern of vocabulary growth slightly earlier and that the negative relation seen simply reflects a drop-off of the positive training effect not a reversal. However, further investigation is needed to gain a more robust understanding of the short and long term effects of the Pointing to Success training. In that vein, measuring mirroring activity at the third time point might have helped to explain the pattern of changes in receptive vocabulary.

Lastly, the current study only captures change and development over a very brief and specific time period – future work should examine how and whether the role of experience and mirroring change in their relations to communicative development throughout the lifespan. Through both longitudinal and cross-sectional designs, several questions could be examined including, but not limited to, whether there is a maximum threshold for the positive effects of experience on mirroring and understanding, how different types of gestures (deictic, conventional, or representational) elicit mirroring responses, and whether MNS activity in response to different types of communicative acts differs at various stages of communicative development. For example, there is work with adults (Di Cesare et al., 2017; Egorova et al., 2016; Hauk et al., 2004; Moreno et al., 2015, 2013) and toddlers (Antognini & Daum, 2017) showing MNS activity during speech processing, however no studies have yet looked at whether the infant MNS is also responsive to spoken language. It would be interesting to compare activity to gestures and activity to speech in infants and throughout early years of language development. In addition, the studies above all focus on action-related language (verbs and action phrases). Evidence of mirroring during non-action-related speech would indicate an even more complex link between the MNS and language.

Conclusions

The current study aimed to examine the developmental relations between action understanding and communicative development, and to elucidate the processes underlying these early social cognitive milestones in infancy. Understanding what mechanisms play a role in infants' language development is particularly important during this age, that is, around the end of the first year, as this is when infants' ability to intentionally communicate with others through language really begins to emerge. And the rate at which infants' vocabulary grows in the first few years of life is an important predictor of later social and academic success. In this study, I examined the theory that the MNS subserves or supports communicative development, specifically mirroring activity during the observation of gestures. Indeed, the results provide evidence for the theorized developmental trajectory from action understanding to language development through the understanding of gestures, and that the MNS is a neural correlate for this cascade of development. I found evidence that increasing infants' observational experience with gestures strengthens their internal representation thereof, as measured by their mirroring activity, which can in turn have a positive impact on their language development. These findings contribute to our understanding of the mechanisms that support social cognitive and communicative achievements and growth in the first few years of life.

Appendices

Appendix A. Questionnaires

Child developmental background questionnaire

Child Development Lab
Background Survey

Child's birth date ____________ Child's birth weight: _________

Child's sibling order: Child is ___ of ___ (ex. 3rd of 3)

Was your child born within 3 weeks of her/his due date? (Circle one) Yes No

Does your child have any history of diagnosed neurological delays or deficits?

Does your child have any diagnosed motor delays or motor deficits?

How old was your child when he/she began obtaining toys on his/her own? e.g., grasping objects and picking them up? (in months and weeks, if possible)

Is your child sitting up on his/her own? (Circle one) Yes No
If yes, at what age did this begin?

Has your child begun crawling effectively? (Circle one) Yes No
If yes, at what age did this begin? (in months and weeks, if possible)

Does (or did) your child ever cruise? (Circle one) Yes No
Cruising is standing with the support of furniture and shuffling legs side to side.
If yes, at what age did this begin? (in months and weeks, if possible)

Has your child begun walking on his/her own? (Circle one) Yes No
If yes, at what age did this begin?

Has your child begun pointing to objects, people, or places? (Circle one) Yes No
If yes, at what age did this begin?

Handedness of mother: Left Right Unknown

Handedness of father: Left Right Unknown

Is handedness of **primary caregiver** reported above? (circle one)

mother father no*

*If no, handedness of primary caregiver: Left Right Unknown

Demographics questionnaire

Child Development Laboratory
Department of Human Development, University of Maryland, College Park, MD 20742

Parent and Child Demographic Form Study________ ID#_________

CHILD Info:

1. **I would identify my child's sex as:**
   _____ Male
   _____ Female
2. **My child's date of birth is** ______/________/________
3. **I would identify my child's ethnicity as:**
   _____ Hispanic or Latino
   _____ Non-Hispanic or Latino
4. **I would identify my child's race as:**
   _____ American Indian/Alaska Native
   _____ Asian
   _____ Native Hawaiian or Other Pacific Islander
   _____ Black or African American
   _____ White
   _____ More than One Race ________________________
   _____ Other: ____________________________

PARENT 1 Info:

5. **I would identify my sex as:**
   _____ Male
   _____ Female
6. **My date of birth is** ______/________/________
7. **My relationship to my child is (Parent 1):** (circle one)
   Biological Mother
   Biological Father
   Other ______________________
   If other, are you the child's legal guardian? (Circle One) Yes No
8. **A. Occupation:** ___________________________
   B. Hours per week ________________________
9. **I (Parent 1) would identify my ethnicity as:**
   _____ Hispanic or Latino
   _____ Non-Hispanic or Latino
10. **I (Parent 1) would identify my race as:**
    _____ American Indian/Alaska Native
    _____ Asian
    _____ Native Hawaiian or Other Pacific Islander
    _____ Black or African American
    _____ White
    _____ More than One Race ________________________
    _____ Other: ____________________________
11. **My (Parent 1) highest educational level is:**
    _____ Before high school diploma
    _____ GED
    _____ High school diploma
    _____ Some college
    _____ 2 year or professional degree
    _____ 4 year college degree
    _____ Advanced degree

Child Development Laboratory
Department of Human Development, University of Maryland, College Park, MD 20742

PARENT 2 Info:

12. **I (Parent 2) would identify my sex as:**
    _____ Male
    _____ Female

13. **My date of birth is** ______/________/________

14. **My relationship to my child is:**
    (circle one)
    Biological Mother
    Biological Father
    Other _______________________
    If other, are you the child's legal guardian? (Circle One) Yes No

15. **A. Occupation:** ___________________________
    B. Hours per week ________________________

16. **I (Parent 2) would identify my ethnicity as:**
    _____ Hispanic or Latino
    _____ Non-Hispanic or Latino

17. **I (Parent 2) would identify my race as:**
    _____ American Indian/Alaska Native
    _____ Asian
    _____ Native Hawaiian or Other Pacific Islander
    _____ Black or African American
    _____ White
    _____ More than One Race ________________________
    _____ Other: ____________________________

18. **My (Parent 2) highest educational level is:**
    _____ Before high school diploma
    _____ GED
    _____ High school diploma
    _____ Some college
    _____ 2 year or professional degree
    _____ 4 year college degree
    _____ Advanced degree

19. Our average annual household income is: __________________

Child Development Laboratory
Department of Human Development, University of Maryland, College Park, MD 20742

CHILD HOME AND CARE Info:

20. Who lives in the child's household? Please include yourself and the child.

First Name	Relationship to Child	Age	Sex

21a. Do you use any type of childcare for your child?

______ Yes

______ No

b. If yes, which of the following best describes your current childcare arrangement?

_____ Relative (other than parent) cares for child

_____ Child care provider in child's own home

_____ Child care provider out of child's home (unlicensed)

_____ Licensed family day care

_____ Day care center

_____ Other (please describe): ________________________________

c. If yes, about how many hours per week does your child spend in childcare?

_____________ (number of hours per week)

Parent reported child vocabulary measure

MacArthur-Bates Short Form Vocabulary Checklist: Level I

Please circle who filled out this form:
mother father
other (specify relation to child)

____

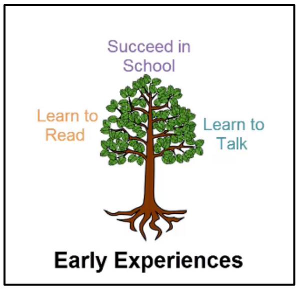
VOCABULARY CHECKLIST

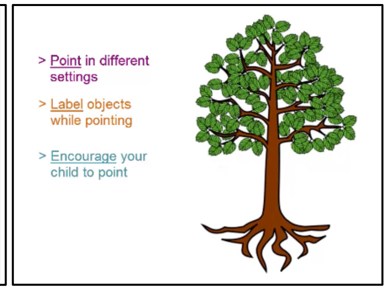
For words your child understands but does not yet say, mark the first column (understands). For words that your child not only understands but also says, mark the second column (understands and says). If your child uses a different pronunciation of a word, mark it anyway.

	Understands	Understands and says		Understands	Understands and says		Understands	Understands and says
choo choo	O	O	chair	O	O	wait	O	O
meow	O	O	couch	O	O	break	O	O
ouch	O	O	kitchen	O	O	feed	O	O
uh oh	O	O	table	O	O	finish	O	O
bird	O	O	television	O	O	help	O	O
dog	O	O	blanket	O	O	jump	O	O
duck	O	O	bottle	O	O	kick	O	O
kitty	O	O	cup	O	O	kiss	O	O
lion	O	O	dish	O	O	push	O	O
mouse	O	O	lamp	O	O	sing	O	O
car	O	O	radio	O	O	smile	O	O
stroller	O	O	spoon	O	O	night	O	O
ball	O	O	flower	O	O	today	O	O
book	O	O	home	O	O	all gone	O	O
doll	O	O	moon	O	O	big	O	O
bread	O	O	outside	O	O	broken	O	O
candy	O	O	plant	O	O	dark	O	O
cereal	O	O	rain	O	O	fast	O	O
cookie	O	O	rock	O	O	hurt	O	O
juice	O	O	water	O	O	pretty	O	O
toast	O	O	babysitter	O	O	soft	O	O
hat	O	O	girl	O	O	I	O	O
pants	O	O	grandma	O	O	me	O	O
shoe	O	O	mommy	O	O	how	O	O
sock	O	O	bath	O	O	who	O	O
eye	O	O	don't	O	O	away	O	O
head	O	O	hi	O	O	out	O	O
leg	O	O	night night	O	O	other	O	O
nose	O	O	patty cake	O	O	some	O	O
tooth	O	O	please	O	O		O	O

Appendix B. Pointing to Success Training Materials

Still shots from training video

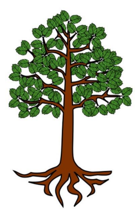




Pamphlet

Why Pointing?

- Pointing is important for babies to learn **language**.
- Babies learn to point first by watching others, so the **more you point** the more your baby will point too!
- By pointing in a variety of different settings, **labeling** while you point, and **encouraging** your child to point you can give your child the foundation he or she needs to do well!



The early experiences babies and toddlers have at home with you will help them grow and learn. That means that what you do as a parent to shape the early experiences for your child can have a big impact on their later successes.

Have questions or comments?
Child Development Lab
301-405-2835

POINTING to SUCCESS

When to Point:

- While **reading** – point to and label pictures in the book.
- During **play time** – you can point to and talk about the toys with your child.
- **Anytime** throughout your day!
  - At the park or playground
  - At the grocery store
  - Walking around the neighborhood

What **YOU** do is just as **important** as what your **child** is doing to help them **learn and communicate**.

Important Tips:

- Remember to talk while pointing!
  - **Labeling** helps your child connect the word with the object and to grow his or her vocabulary.
- Encourage your child to point!
  - Ask **questions** like "Where is the red block?" and give **positive feedback** by saying something like, "Good job pointing to the red one!"

Training log

Parent Name: ______________________________ Child Name: ______________________ Month: ________________________

Daily Play and Pointing Log

As you spend time playing with your child and pointing, check off the boxes and keep a record to see your child's progress!

Day 1 - Date:	Day 2 - Date:	Day 3 - Date:	Day 4 - Date:	Day 5 - Date:	Day 6 - Date:	Day 7 - Date:
☐ I played with my child for 15 minutes today **Did you point during playtime?** ☐ Yes ☐ No (or I don't remember) **Today my child pointed…** ☐ Not at all ☐ Some ☐ Many times	☐ I played with my child for 15 minutes today **Did you point during playtime?** ☐ Yes ☐ No (or I don't remember) **Today my child pointed…** ☐ Not at all ☐ Some ☐ Many times	☐ I played with my child for 15 minutes today **Did you point during playtime?** ☐ Yes ☐ No (or I don't remember) **Today my child pointed…** ☐ Not at all ☐ Some ☐ Many times	☐ I played with my child for 15 minutes today **Did you point during playtime?** ☐ Yes ☐ No (or I don't remember) **Today my child pointed…** ☐ Not at all ☐ Some ☐ Many times	☐ I played with my child for 15 minutes today **Did you point during playtime?** ☐ Yes ☐ No (or I don't remember) **Today my child pointed…** ☐ Not at all ☐ Some ☐ Many times	☐ I played with my child for 15 minutes today **Did you point during playtime?** ☐ Yes ☐ No (or I don't remember) **Today my child pointed…** ☐ Not at all ☐ Some ☐ Many times	☐ I played with my child for 15 minutes today **Did you point during playtime?** ☐ Yes ☐ No (or I don't remember) **Today my child pointed…** ☐ Not at all ☐ Some ☐ Many times
Day 8 - Date:	Day 9 - Date:	Day 10 - Date:	Day 11 - Date:	Day 12 - Date:	Day 13 - Date:	Day 14 - Date:
☐ I played with my child for 15 minutes today **Did you point during playtime?** ☐ Yes ☐ No (or I don't remember) **Today my child pointed…** ☐ Not at all ☐ Some ☐ Many times	☐ I played with my child for 15 minutes today **Did you point during playtime?** ☐ Yes ☐ No (or I don't remember) **Today my child pointed…** ☐ Not at all ☐ Some ☐ Many times	☐ I played with my child for 15 minutes today **Did you point during playtime?** ☐ Yes ☐ No (or I don't remember) **Today my child pointed…** ☐ Not at all ☐ Some ☐ Many times	☐ I played with my child for 15 minutes today **Did you point during playtime?** ☐ Yes ☐ No (or I don't remember) **Today my child pointed…** ☐ Not at all ☐ Some ☐ Many times	☐ I played with my child for 15 minutes today **Did you point during playtime?** ☐ Yes ☐ No (or I don't remember) **Today my child pointed…** ☐ Not at all ☐ Some ☐ Many times	☐ I played with my child for 15 minutes today **Did you point during playtime?** ☐ Yes ☐ No (or I don't remember) **Today my child pointed…** ☐ Not at all ☐ Some ☐ Many times	☐ I played with my child for 15 minutes today **Did you point during playtime?** ☐ Yes ☐ No (or I don't remember) **Today my child pointed…** ☐ Not at all ☐ Some ☐ Many times

References

Antognini, K., & Daum, M. M. (2017). Toddlers show sensorimotor activity during auditory verb processing. *Neuropsychologia*. http://doi.org/10.1016/j.neuropsychologia.2017.07.022

Aravena, P., Delevoye-Turrell, Y., Deprez, V., Cheylus, A., Paulignan, Y., Frak, V., & Nazir, T. (2012). Grip Force Reveals the Context Sensitivity of Language-Induced Motor Activity during "Action Words" Processing: Evidence from Sentential Negation. *PLoS ONE*, *7*(12), e50287. http://doi.org/10.1371/journal.pone.0050287

Arnstein, D., Cui, F., Keysers, C., Maurits, N. M., & Gazzola, V. (2011). mu-Suppression during Action Observation and Execution Correlates with BOLD in Dorsal Premotor, Inferior Parietal, and SI Cortices. *Journal of Neuroscience*, *31*(40), 14243–14249. http://doi.org/10.1523/JNEUROSCI.0963-11.2011

Avanzini, P., Fabbri-Destro, M., Dalla Volta, R., Daprati, E., Rizzolatti, G., & Cantalupo, G. (2012). The Dynamics of Sensorimotor Cortical Oscillations during the Observation of Hand Movements: An EEG Study. *PLoS ONE*, *7*(5), e37534. http://doi.org/10.1371/journal.pone.0037534

Bates, E., Benigni, L., Bretherton, I., Camaioni, L., & Volterra, V. (1979). *The emergence of symbols: Cognition and communication in infancy*. New York: Academic Press.

Bates, E., Camaioni, L., & Volterra, V. (1975). The acquisition of performatives prior to speech. *Merrill-Palmer Quarterly of Behavior and Development*, *21*(3), 205–226.

Berger, H. (1929). Über das Elektrenkephalogramm des Menschen. *Arch Psyiat*

Nervenkr, *87*, 527–570.

Brooks, R., & Meltzoff, A. N. (2008). Infant gaze following and pointing predict accelerated vocabulary growth through two years of age: A longitudinal, growth curve modeling study. *Journal of Child Language*, *35*, 207–220. http://doi.org/10.1017/S030500090700829X

Brooks, R., & Meltzoff, A. N. (2015). Connecting the dots from infancy to childhood: a longitudinal study connecting gaze following, language, and explicit theory of mind. *Journal of Experimental Child Psychology*, *130*, 67–78. http://doi.org/10.1016/j.jecp.2014.09.010

Brune, C. W., & Woodward, A. L. (2007). Social cognition and social responsiveness in 10-month-old infants. *Journal of Cognition and Development*, *8*(2), 133–158. http://doi.org/10.1080/15248370701202331

Camaioni, L., Caselli, M. C., Longobardi, E., & Volterra, V. (1991). A parent report instrument for early language assessment. *First Language*, *11*(33), 345–358. http://doi.org/10.1177/014272379101103303

Camaioni, L., Perucchini, P., Bellagamba, F., & Colonnesi, C. (2004). The role of declarative pointing in developing a theory of mind. *Infancy*, *5*(3), 291–308. http://doi.org/10.1207/s15327078in0503_3

Cameron-Faulkner, T., Theakston, A., Lieven, E., & Tomasello, M. (2015). The Relationship Between Infant Holdout and Gives, and Pointing. *Infancy*, *20*(5), 576–586. http://doi.org/10.1111/infa.12085

Cannon, E. N., Simpson, E. A., Fox, N. A., Vanderwert, R. E., Woodward, A. L., & Ferrari, P. F. (2016). Relations between infants' emerging reach-grasp competence and event-related desynchronization in EEG. *Developmental Science*, *19*(1), 50–62. http://doi.org/10.1111/desc.12295

Cannon, E. N., Woodward, A. L., Gredebäck, G., Hofsten, C. Von, & Turek, C. (2012). Action production influences 12-month-old infants' attention to others' actions. *Developmental Science*, *15*(1), 35–42. http://doi.org/10.1111/j.1467-7687.2011.01095.x.Action

Cannon, E. N., Yoo, K. H., Vanderwert, R. E., Ferrari, P. F., Woodward, A. L., & Fox, N. A. (2014). Action experience, more than observation, influences mu rhythm desynchronization. *PloS ONE*, *9*(3), e92002. http://doi.org/10.1371/journal.pone.0092002

Capirci, O., Contaldo, A., Caselli, M. C., & Volterra, V. (2005). From action to language through gesture: A longitudinal perspective. *Gesture*, *5*(2005), 155–177. http://doi.org/10.1075/gest.5.1.12cap

Capirci, O., Iverson, J. M., Pizzuto, E., & Volterra, V. (1996). Gestures and words during the transition to two-word speech. *Journal of Child Language*, *23*(3), 645–673. http://doi.org/10.1017/S0305000900008989

Carpenter, M., Nagell, K., & Tomasello, M. (1998). Social cognition, joint attention, and communicative competence from 9 to 15 months of age. *Monographs of the Society for Research in Child Development*, *63*(4).

Carr, L., Iacoboni, M., Dubeau, M.-C., Mazziotta, J. C., & Lenzi, G. L. (2003). Neural mechanisms of empathy in humans: A relay from neural systems for imitation to limbic areas. *Proceedings of the National Academy of Sciences*, *100*(9), 5497–5502. http://doi.org/10.1073/pnas.0935845100

Cartmill, E. A., Demir, Ö. E., & Goldin-Meadow, S. (2012). Studying Gesture. In E. Hoff (Ed.), *Research Methods in Child Language: A Practical Guide* (1st ed., pp. 208–225). Blackwell Publishing Ltd.

Caspers, S., Zilles, K., Laird, A. R., & Eickhoff, S. B. (2010). ALE meta-analysis of action observation and imitation in the human brain. *NeuroImage*, *50*(3), 1148–67. http://doi.org/10.1016/j.neuroimage.2009.12.112

Cattaneo, L., Fabbri-Destro, M., Boria, S., Pieraccini, C., Monti, A., Cossu, G., & Rizzolatti, G. (2007). Impairment of actions chains in autism and its possible role in intention understanding. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(45), 17825–30. http://doi.org/10.1073/pnas.0706273104

Cattaneo, L., Sandrini, M., & Schwarzbach, J. (2010). State-Dependent TMS Reveals a Hierarchical Representation of Observed Acts in the Temporal, Parietal, and Premotor Cortices. *Cerebral Cortex*, *20*(9), 2252–2258. http://doi.org/10.1093/cercor/bhp291

Charman, T., Baron-Cohen, S., Swettenham, J., Baird, G., Cox, A., & Drew, A. (2000). Testing joint attention, imitation, and play as infancy precursors to language and theory of mind. *Cognitive Development*, *15*(4), 481–498. http://doi.org/10.1016/S0885-2014(01)00037-5

Cohen, M. X. (2014). *Analyzing neural time series data: theory and practice.* Cambridge, MA: MIT Press.

Colonnesi, C., Stams, G. J. J. M., Koster, I., & Noom, M. J. (2010). The relation between pointing and language development: A meta-analysis. *Developmental Review*, *30*, 352–366. http://doi.org/10.1016/j.dr.2010.10.001

Corballis, M. C. (2010). Mirror neurons and the evolution of language. *Brain and Language*, *112*(1), 25–35. http://doi.org/10.1016/j.bandl.2009.02.002

Corballis, M. C. (2012). How language evolved from manual gestures. *Gesture*, *12*(2), 200–226. http://doi.org/10.1075/gest.12.2.04cor

Cuevas, K., Cannon, E. N., Yoo, K. H., & Fox, N. A. (2014). The infant EEG mu rhythm: Methodological considerations and best practices. *Developmental Review*, *34*(1), 26–43. http://doi.org/10.1016/j.dr.2013.12.001

D'Ausilio, A., Pulvermüller, F., Salmas, P., Bufalari, I., Begliomini, C., & Fadiga, L. (2009). The Motor Somatotopy of Speech Perception. *Current Biology*, *19*(5), 381–385. http://doi.org/10.1016/j.cub.2009.01.017

D 'ausilio, A., Bufalari, I., Salmas, P., & Fadiga, L. (2012). The role of the motor system in discriminating normal and degraded speech sounds. *CORTEX*, *48*, 882–887. http://doi.org/10.1016/j.cortex.2011.05.017

da Silva, R. L., Labrecque, D., Caromano, F. A., Higgins, J., & Frak, V. (2018). Manual action verbs modulate the grip force of each hand in unimanual or symmetrical bimanual tasks. *PLOS ONE*, *13*(2), e0192320. http://doi.org/10.1371/journal.pone.0192320

de Klerk, C. C. J. M., Johnson, M. H., Heyes, C. M., & Southgate, V. (2015). Baby steps: investigating the development of perceptual-motor couplings in infancy. *Developmental Science*, *18*(2), 270–280. http://doi.org/10.1111/desc.12226

de Klerk, C. C. J. M., Southgate, V., & Csibra, G. (2016). Predictive action tracking without motor experience in 8-month-old infants. *Brain and Cognition*, *109*, 131–

139. http://doi.org/10.1016/j.bandc.2016.09.010

Debnath, R., Salo, V. C., Buzzell, G. A., Yoo, K. H., & Fox, N. A. (under review). Mu rhythm is specific to action execution and observation: Evidence from time-frequency and connectivity analysis.

Delorme, A., & Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neurosience Methods*, *134*, 9–21.

Desrochers, S., Morissette, P., & Ricard, M. (1995). Two perspectives on pointing in infancy. In C. Moore & P. J. Dunham (Eds.), *Joint attention: Its origins and role in development* (pp. 85–101). Hillsdale, NJ: Lawrence Erlbaum Associates.

Di Cesare, G., Errante, A., Marchi, M., & Cuccio, V. (2017). Language for action: Motor resonance during the processing of human and robotic voices. *Brain and Cognition*, *118*, 118–127. http://doi.org/10.1016/j.bandc.2017.08.001

di Pellegrino, G., Fadiga, L., Fogassi, L., Gallese, V., & Rizzolatti, G. (1992). Understanding motor events: a neurophysiological study. *Experimental Brain Research*, *91*(1), 176–180. http://doi.org/10.1007/BF00230027

Egorova, N., Shtyrov, Y., & Pulvermüller, F. (2016). Brain basis of communicative actions in language. *NeuroImage*, *125*, 857–867. http://doi.org/10.1016/j.neuroimage.2015.10.055

Engel, A. K., Maye, A., Kurthen, M., & König, P. (2013, May). Where's the action? The pragmatic turn in cognitive science. *Trends in Cognitive Sciences*. Elsevier. http://doi.org/10.1016/j.tics.2013.03.006

Fadiga, L., Craighero, L., Buccino, G., & Rizzolatti, G. (2002). Speech listening specifically modulates the excitability of tongue muscles: a TMS study. *European Journal of Neuroscience*, *15*(2), 399–402. http://doi.org/10.1046/j.0953-816x.2001.01874.x

Fenson, L., Pethick, S., Renda, C., Cox, J. L., Dale, P. S., & Reznick, J. S. (2000). Short-form versions of the MacArthur Communicative Development Inventories. *Applied Psycholinguistics*, *21*(1), 95–115. http://doi.org/10.1017/S0142716400001053

Ferrari, P. F., Tramacere, A., Simpson, E. A., & Iriki, A. (2013). Mirror neurons through the lens of epigenetics. *Trends in Cognitive Sciences*, *17*(9), 450–457. http://doi.org/10.1016/J.TICS.2013.07.003

Filippi, C. A., Cannon, E. N., Fox, N. A., Thorpe, S. G., Ferrari, P. F., & Woodward, A. L. (2016). Motor System Activation Predicts Goal Imitation in 7-Month-Old Infants. *Psychological Science*, *27*(5), 675–684. http://doi.org/10.1177/0956797616632231

Fischer, M. H., & Zwaan, R. A. (2008). Embodied Language: A Review of the Role of the Motor System in Language Comprehension. *Quarterly Journal of Experimental Psychology*, *61*(6), 825–850. http://doi.org/10.1080/17470210701623605

Foglia, L., & Wilson, R. A. (2013). Embodied cognition. *Wiley Interdisciplinary Reviews: Cognitive Science*, *4*(3), 319–325. http://doi.org/10.1002/wcs.1226

Fox, N. A., Bakermans-Kranenburg, M. J., Yoo, K. H., Bowman, L. C., Cannon, E. N., Vanderwert, R. E., … van IJzendoorn, M. H. (2016). Assessing human mirror activity with EEG mu rhythm: A meta-analysis. *Psychological Bulletin*, *142*(3), 291–313. http://doi.org/10.1037/bul0000031

Gallese, V. (2001). The "'shared manifold'" hypothesis: From mirror neurons to empathy. *Journal of Consciousness Studies*, *8*, 33–50.

Gallese, V. (2005). “Being like me”: Self-other identity, mirror neurons, and empathy. In S. Hurley & N. Chater (Eds.), *Perspectives on imitation: Mechanisms of imitation and imitation in animals* (pp. 101–118). Cambridge, MA: MIT Press.

Gallese, V., Gernsbacher, M. A., Heyes, C., Hickok, G., & Iacoboni, M. (2011). Mirror Neuron Forum. *Perspectives on Psychological Science*, *6*(4), 369–407. http://doi.org/10.1177/1745691611413392

Goldin-Meadow, S., & Butcher, C. (2003). Pointing toward two-word speech in young children. In S. Kita (Ed.), *Pointing: Where language, culture, and cognition meet* (pp. 85–107). Mahwah, NJ: Erlbaum.

Goldin-Meadow, S., Mylander, C., de Villiers, J., Bates, E., & Volterra, V. (1984). Gestural Communication in Deaf Children: The Effects and Noneffects of Parental Input on Early Language Development. *Monographs of the Society for Research in Child Development*, *49*(3/4), 1. http://doi.org/10.2307/1165838

Goodwyn, S. W., Acredolo, L. P., & Brown, C. A. (2000). Impact of symbolic gesturing on early language development. *Journal of Nonverbal Behavior*, *24*(2), 81–103. http://doi.org/10.1023/A:1006653828895

Hart, B., & Risley, T. R. (1992). American Parenting of Language-Learning Children: Persisting Differences in Family-Child Interactions Observed in Natural Home Environments. *Developmental Psychology*, *28*(6), 1096–1105. http://doi.org/10.1037/0012-1649.28.6.1096

Hart, B., & Risley, T. R. (1995). *Meaningful differences in the everyday experience of young American children*. Baltimore: Paul H Brookes Publishing.

Hauk, O., Johnsrude, I., & Pulvermüller, F. (2004). Somatotopic Representation of

Action Words in Human Motor and Premotor Cortex. *Neuron*, *41*(2), 301–307. http://doi.org/10.1016/S0896-6273(03)00838-9

Heimann, M., Strid, K., Smith, L., Tjus, T., Ulvund, S. E., & Meltzoff, A. N. (2006). Exploring the relation between memory, gestural communication, and the emergence of language in infancy: A longitudinal study. *Infant and Child Development*, *15*, 233–249. http://doi.org/10.1002/icd.

Hewes, G. W. (1973). Primate communication and the gestural origin of language. *Current Anthropology*, *14*(1–2), 5–24.

Heyes, C. (2010). Where do mirror neurons come from? *Neuroscience & Biobehavioral Reviews*, *34*(4), 575–583. http://doi.org/10.1016/j.neubiorev.2009.11.007

Heyes, C. (2013). A new approach to mirror neurons: Developmental history, system-level theory and intervention experiments. *Cortex*, *49*(10), 2946–2948. http://doi.org/10.1016/j.cortex.2013.07.002

Hickok, G. (2009). Eight problems for the mirror neuron theory of action understanding in monkeys and humans. *Journal of Cognitive Neuroscience*, *21*(7), 1229–1243. http://doi.org/10.1162/jocn.2009.21189

Huttenlocher, J., Haight, W., Bryk, A., Seltzer, M., & Lyons, T. (1991). Early vocabulary growth: Relation to language input and gender. *Developmental Psychology*, *27*(2), 236–248. http://doi.org/10.1037/0012-1649.27.2.236

Iacoboni, M. (2009). Imitation, Empathy, and Mirror Neurons. *Annual Review of Psychology*, *60*(1), 653–670. http://doi.org/10.1146/annurev.psych.60.110707.163604

Iacoboni, M., & Wilson, S. M. (2006). Beyond a single area: Motor control and language within a neural architecture encompassing Broca's area. *Cortex*, *42*, 503–506. http://doi.org/10.1016/S0010-9452(08)70387-3

Iverson, J. M. (2010). Developing language in a developing body: The relationship between motor development and language development. *Journal of Child Language*, *37*(2), 1–25. http://doi.org/10.1017/S0305000909990432.Developing

Iverson, J. M., & Goldin-Meadow, S. (2005). Gesture paves the way for language development. *Psychological Science*, *16*(5), 367–371. http://doi.org/10.1111/j.0956-7976.2005.01542.x

Johnson, S. C. (2003). Detecting agents. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *358*(1431), 549–59. http://doi.org/10.1098/rstb.2002.1237

Kayser, J., & Tenke, C. E. (2006). Principal components analysis of Laplacian waveforms as a generic method for identifying ERP generator patterns: I. Evaluation with auditory oddball tasks. *Clinical Neurophysiology*, *117*, 348–368.

Kita, S. (2003). *Pointing: Where language, culture, and cognition meet*. Mahwah, NJ: Lawrence Erlbaum Associates.

Kontra, C., Goldin-Meadow, S., & Beilock, S. L. (2012). Embodied Learning Across the Life Span. *Topics in Cognitive Science*, *4*(4), 731–739. http://doi.org/10.1111/j.1756-8765.2012.01221.x

Kuhlman, W. N. (1978). Functional topography of the human mu rhythm. *Electroencephalography and Clinical Neurophysiology*, *44*(1), 83–93. http://doi.org/10.1016/0013-4694(78)90107-4

Kuhn, L. J., Willoughby, M. T., Wilbourn, M. P., Vernon-Feagans, L., & Blair, C. B.

(2014). Early communicative gestures prospectively predict language development and executive function in early childhood. *Child Development*, *85*(5), 1898–1914. http://doi.org/10.1111/cdev.12249

LeBarton, E. S., Goldin-Meadow, S., & Raudenbush, S. (2015). Experimentally Induced Increases in Early Gesture Lead to Increases in Spoken Vocabulary. *Journal of Cognition and Development*, *16*(2), 199–220. http://doi.org/10.1080/15248372.2013.858041

Lepage, J.-F., & Théoret, H. (2006). EEG evidence for the presence of an action observation-execution matching system in children. *European Journal of Neuroscience*, *23*(9), 2505–2510. http://doi.org/10.1111/j.1460-9568.2006.04769.x

Luo, Y., & Baillargeon, R. (2007). Do 12.5-month-old infants consider what objects others can see when interpreting their actions? *Cognition*, *105*(3), 489–512. http://doi.org/10.1016/j.cognition.2006.10.007

MacWhinney, B. (2000). *The CHILDES Project: Tools for analyzing talk, Volume II: The database (Vol. 2)*. Mahwah, NJ: Lawrence Erlbaum Associates.

Makeig, S., Debener, S., Onton, J., & Delorme, A. (2004). Mining event-related brain dynamics. *Trends in Cognitive Sciences*, *8*, 204–210.

Markus, J., Mundy, P., Morales, M., Delgado, C. E. F., & Yale, M. (2000). Individual differences in infant skills as predictors of child-caregiver joint attention and language. *Social Development*, *9*(3), 302–315. http://doi.org/10.1111/1467-9507.00127

Marshall, P. J., Bar-Haim, Y., & Fox, N. A. (2002). Development of the EEG from 5 months to 4 years of age. *Clinical Neurophysiology : Official Journal of the*

International Federation of Clinical Neurophysiology, *113*(8), 1199–208. http://doi.org/10.1016/j.cogpsych.2012.08.001

Marshall, P. J., & Meltzoff, A. N. (2011). Neural mirroring systems: Exploring the EEG mu rhythm in human infancy. *Developmental Cognitive Neuroscience*, *1*(2), 110–123. http://doi.org/10.1016/j.dcn.2010.09.001

Marshall, P. J., Young, T., & Meltzoff, A. N. (2011). Neural correlates of action observation and execution in 14-month-old infants: an event-related EEG desynchronization study. *Developmental Science*, *14*(3), 474–80. http://doi.org/10.1111/j.1467-7687.2010.00991.x

Matthews, D., Behne, T., Lieven, E., & Tomasello, M. (2012). Origins of the human pointing gesture: a training study. *Developmental Science*, *15*(6), 817–29. http://doi.org/10.1111/j.1467-7687.2012.01181.x

Mcneill, D., Duncan, S., Cole, J., Gallagher, S., & Bertenthal, B. (2008). Growth points from the very beginning. *Interaction Studies*, *9*(1), 117–132. http://doi.org/10.1075/is.9.1.09mcn

Meltzoff, A. N. (1995). Understanding the intentions of others: Re-enactment of intended acts by 18-month-old children. *Developmental Psychology*, *31*(5), 838–850. http://doi.org/10.1037/0012-1649.31.5.838

Meltzoff, A. N. (2007). “Like me”: a foundation for social cognition. *Developmental Science*, *10*(1), 126–134. http://doi.org/10.1111/j.1467-7687.2007.00574.x

Meltzoff, A. N., & Gopnik, A. (1993). The role of imitation in understanding persons and developing a theory of mind. In *Understanding other minds: Perspectives from Autism* (pp. 335–366).

Mognon, A., Jovicich, J., Bruzzone, L., & Buiatti, M. (2011). ADJUST: An automatic EEG artifact detector based on the joint use of spatial and temporal features. *Psychophysiology*, *48*, 229–240.

Monroy, C. D., Meyer, M., Schröer, L., Gerson, S. A., & Hunnius, S. (2017). The infant motor system predicts actions based on visual statistical learning. *NeuroImage*. http://doi.org/10.1016/J.NEUROIMAGE.2017.12.016

Montgomery, K. J., Isenberg, N., & Haxby, J. V. (2007). Communicative hand gestures and object-directed hand movements activated the mirror neuron system. *Social Cognitive and Affective Neuroscience*, *2*(2), 114–22. http://doi.org/10.1093/scan/nsm004

Morales, M., Mundy, P., Delgado, C. E. F., Yale, M., Messinger, D., Neal, R., & Schwartz, H. K. (2000). Responding to joint attention across the 6- through 24-month age period and early language acquisition. *Journal of Applied Developmental Psychology*, *21*(3), 283–298. http://doi.org/10.1016/S0193-3973(99)00040-4

Morales, M., Mundy, P., & Rojas, J. (1998). Following the direction of gaze and language development in 6-month-olds. *Infant Behavior and Development*, *21*(2), 373–377. http://doi.org/10.1016/S0163-6383(98)90014-5

Moreno, I., de Vega, M., & León, I. (2013). Understanding action language modulates oscillatory mu and beta rhythms in the same way as observing actions. *Brain and Cognition*, *82*(3), 236–242. http://doi.org/10.1016/j.bandc.2013.04.010

Moreno, I., de Vega, M., León, I., Bastiaansen, M., Glen Lewis, A., & Magyari, L. (2015). Brain dynamics in the comprehension of action-related language. A time-frequency analysis of mu rhythms. *NeuroImage*, *109*, 50–62.

http://doi.org/10.1016/j.neuroimage.2015.01.018

Morin, O., & Grèzes, J. (2008). What is “mirror” in the premotor cortex? A review. *Neurophysiologie Clinique/Clinical Neurophysiology*, *38*(3), 189–195. http://doi.org/10.1016/j.neucli.2008.02.005

Mukamel, R., Ekstrom, A. D., Kaplan, J., Iacoboni, M., & Fried, I. (2010). Single-neuron responses in humans during execution and observation of actions. *Current Biology*, *20*(8), 750–756. http://doi.org/10.1016/j.cub.2010.02.045

Mundy, P., Delgado, C., Block, J., Venezia, M., Hogan, A., & Seibert, J. M. (2003). Early social communication scales (escs), (305).

Mundy, P., & Gomes, A. (1998). Individual differences in joint attention skill development in the second year. *Infant Behavior and Development*, *21*(3), 469–482.

Murray, L., De Pascalis, L., Bozicevic, L., Hawkins, L., Sclafani, V., & Ferrari, P. F. (2016). The functional architecture of mother-infant communication, and the development of infant social expressiveness in the first two months. *Scientific Reports*, *6*, 39019. http://doi.org/10.1038/srep39019

Muthen, L. K., & Muthen, B. O. (2012). *Mplus User’s Guide. Sixth Edition.* Los Angeles, CA: Muthen & Muthen.

Muthukumaraswamy, S. D., Johnson, B. W., & McNair, N. A. (2004). Mu rhythm modulation during observation of an object-directed grasp. *Cognitive Brain Research*, *19*(2), 195–201. http://doi.org/10.1016/j.cogbrainres.2003.12.001

Neuper, C., & Pfurtscheller, G. (2001). Event-related dynamics of cortical rhythms: frequency-specific features and functional correlates. *International Journal of Psychophysiology*, *43*(1), 41–58. http://doi.org/10.1016/S0167-8760(01)00178-7

Nolan, H., Whelan, R., & Reilly, R. B. (2010). FASTER: Fully Automated Statistical Thresholding for EEG artifact Rejection. *Journal of Neurosience Methods*, *192*, 152–162.

Novack, M. A., & Goldin-Meadow, S. (2017). Gesture as representational action: A paper about function. *Psychonomic Bulletin & Review*, *24*(3), 652–665. http://doi.org/10.3758/s13423-016-1145-z

Nyström, P. (2008). The infant mirror neuron system studied with high density EEG. *Social Neuroscience*, *3*(3–4), 334–347. http://doi.org/10.1080/17470910701563665

Nyström, P., Ljunghammar, T., Rosander, K., & von Hofsten, C. (2011). Using mu rhythm desynchronization to measure mirror neuron activity in infants. *Developmental Science*, *14*(2), 327–335. http://doi.org/10.1111/j.1467-7687.2010.00979.x

Orgs, G., Dombrowski, J.-H., Heil, M., & Jansen-Osmann, P. (2008). Expertise in dance modulates alphabeta event-related desynchronization during action observation. *European Journal of Neuroscience*, *27*(12), 3380–3384. http://doi.org/10.1111/j.1460-9568.2008.06271.x

Overton, W. F. (2006). Developmental Psychology: Philosophy, Concepts, Methodology. In *Handbook of Child Psychology*. Hoboken, NJ, USA: John Wiley & Sons, Inc. http://doi.org/10.1002/9780470147658.chpsy0102

Pan, B. A., Rowe, M. L., Singer, J. D., & Snow, C. E. (2005). Maternal correlates of growth in toddler vocabulary production in low-income families. *Child Development*, *76*(4), 763–82. http://doi.org/10.1111/j.1467-8624.2005.00876.x

Paulus, M. (2012). Action mirroring and action understanding: an ideomotor and attentional account. *Psychological Research*, *76*(6), 760–767. http://doi.org/10.1007/s00426-011-0385-9

Pfurtscheller, G., & Lopes da Silva, F. H. (1999). Event-related EEG/MEG synchronization and desynchronization: Basic principles. *Clinical Neurophysiology*, *110*(11), 1842–1857. http://doi.org/10.1016/S1388-2457(99)00141-8

Piaget, J. (1952). *The origins of intelligence in children*. New York: Norton.

Pineda, J. A. (2005). The functional significance of mu rhythms: translating "seeing" and "hearing" into "doing". *Brain Research. Brain Research Reviews*, *50*(1), 57–68. http://doi.org/10.1016/j.brainresrev.2005.04.005

Pineda, J. A., & Hecht, E. (2009). Mirroring and mu rhythm involvement in social cognition: Are there dissociable subcomponents of theory of mind? *Biological Psychology*, *80*(3), 306–314. http://doi.org/10.1016/j.biopsycho.2008.11.003

Ping, R. M., Goldin-Meadow, S., & Beilock, S. L. (2014). Understanding gesture: is the listener's motor system involved? *Journal of Experimental Psychology. General*, *143*(1), 195–204. http://doi.org/10.1037/a0032246

Pulvermüller, F., Hauk, O., Nikulin, V. V., & Ilmoniemi, R. J. (2005). Functional links between motor and language systems. *European Journal of Neuroscience*, *21*(3), 793–797. http://doi.org/10.1111/j.1460-9568.2005.03900.x

Quandt, L. C., Marshall, P. J., Shipley, T. F., Beilock, S. L., & Goldin-Meadow, S. (2012). Sensitivity of alpha and beta oscillations to sensorimotor characteristics of action: An EEG study of action production and gesture observation. *Neuropsychologia*, *50*(12), 2745–2751. http://doi.org/10.1016/j.neuropsychologia.2012.08.005.Sensitivity

Redcay, E., Velnoskey, K. R., & Rowe, M. L. (2016). Perceived communicative intent in gesture and language modulates the superior temporal sulcus. *Human Brain Mapping*, *37*(10), 3444–3461. http://doi.org/10.1002/hbm.23251

Reid, V. M., Striano, T., & Iacoboni, M. (2011). Neural correlates of dyadic interaction during infancy. *Developmental Cognitive Neuroscience*, *1*(2), 124–130. http://doi.org/10.1016/j.dcn.2011.01.001

Rizzolatti, G., & Arbib, M. A. (1998). Language within our grasp. *Trends in Neurosciences*, *21*(5), 188–194.

Rizzolatti, G., & Craighero, L. (2004). The mirror-neuron system. *Annual Review of Neuroscience*, *27*, 169–92. http://doi.org/10.1146/annurev.neuro.27.070203.144230

Rizzolatti, G., & Fabbri-Destro, M. (2008). The mirror system and its role in social cognition. *Current Opinion in Neurobiology*, *18*(2), 179–184. http://doi.org/10.1016/j.conb.2008.08.001

Rizzolatti, G., Fadiga, L., Gallese, V., & Fogassi, L. (1996). Premotor cortex and the recognition of motor actions. *Cognitive Brain Research*, *3*(2), 131–141. http://doi.org/10.1016/0926-6410(95)00038-0

Rizzolatti, G., Fogassi, L., & Gallese, V. (2001). Neurophysiological mechanisms underlying the understanding and imitation of action. *Nature Reviews Neuroscience*, *2*(9), 661–670. http://doi.org/10.1038/35090060

Rizzolatti, G., & Sinigaglia, C. (2010). The functional role of the parieto-frontal mirror circuit: interpretations and misinterpretations. *Nature Reviews. Neuroscience*, *11*(4), 264–74. http://doi.org/10.1038/nrn2805

Rodríguez, C., Moreno-Núñez, A., Basilio, M., & Sosa, N. (2015). Ostensive gestures come first: their role in the beginning of shared reference. *Cognitive Development*. http://doi.org/10.1016/j.cogdev.2015.09.005

Rowe, M. L. (2000). Pointing and talk by low-income mothers and thier 14-month-old children. *First Language*, *20*, 305–330. Retrieved from http://fla.sagepub.com/content/20/60/305.short

Rowe, M. L. (2012). A longitudinal investigation of the role of quantity and quality of child-directed speech in vocabulary development. *Child Development*, *83*(5), 1762–1774. http://doi.org/10.1111/j.1467-8624.2012.01805.x

Rowe, M. L., & Goldin-Meadow, S. (2009a). Differences in early gesture explain SES disparities in child vocabulary size at school entry. *Science*, *323*, 951–953. http://doi.org/10.1126/science.1167025

Rowe, M. L., & Goldin-Meadow, S. (2009b). Early gesture selectively predicts later language learning. *Developmental Science*, *12*(1), 182–7. http://doi.org/10.1111/j.1467-7687.2008.00764.x

Rowe, M. L., Leech, K. A. (under review). A parent intervention with a growth mindset approach improves children's early gesture and vocabulary development.

Rowe, M. L., Ozçalişkan, S., & Goldin-Meadow, S. (2008). Learning words by hand: Gesture's role in predicting vocabulary development. *First Language*, *28*(2), 182–199. http://doi.org/10.1177/0142723707088310

Roy, A. C., Craighero, L., Fabbri-Destro, M., & Fadiga, L. (2008). Phonological and lexical motor facilitation during speech listening: A transcranial magnetic stimulation study. *Journal of Physiology Paris*, *102*(1–3), 101–105. http://doi.org/10.1016/j.jphysparis.2008.03.006

Salo, V.C., Debnath, R., Cannon, E.N., Fox, N.A. (in prep). Infants' use of pointing gestures is related to their perception of others' points.

Satorra, A., & Bentler, P. M. (1994). Corrections to test statistics and standard errors in covariance structure analysis. In A. von Eye & C. C. Clogg (Eds.), *Latent variables analysis: Applications for developmental research* (pp. 399–419). Thousan Oaks, CA: SAGE Publications.

Schippers, M. B., Gazzola, V., Goebel, R., & Keysers, C. (2009). Playing charades in the fMRI: Are mirror and/or mentalizing areas involved in gestural communication? *PLoS ONE*, *4*(8), e6801. http://doi.org/10.1371/journal.pone.0006801

Schippers, M. B., Roebroeck, A., Renken, R., Nanetti, L., & Keysers, C. (2010). Mapping the information flow from one brain to another during gestural communication. *Proceedings of the National Academy of Sciences*, *107*(20), 9388–9393. http://doi.org/10.1073/pnas.1001791107

Seibert, J. M., Hogan, A. E., & Mundy, P. (1982). Assessing interactional competencies: The Early Social-Communication Scales. *Infant Mental Health Journal*, *3*(4).

Shapiro, I. (2011). *Embodied cognition*. New York: Routledge/Taylor & Francis.

Shiller, D. M., Bourguignon, N., Frak, V., Nazir, T., Cadoret, G., Robert, M., & Lemay, M. (2013). Word-induced postural changes reflect a tight interaction between motor and lexico-semantic representations. *Neuroscience Letters*, *555*, 129–133. http://doi.org/10.1016/j.neulet.2013.09.021

Sommerville, J. A., & Woodward, A. L. (2005). Pulling out the intentional structure of action: the relation between action processing and action production in infancy. *Cognition*, *95*(1), 1–30. http://doi.org/10.1016/j.cognition.2003.12.004

Sommerville, J. A., Woodward, A. L., & Needham, A. (2005). Action experience alters 3-month-old infants' perception of others' action. *Cognition*, *96*(1), B1-11. http://doi.org/10.1016/j.cognition.2004.07.004.Action

Southgate, V. (2013). Do infants provide evidence that the mirror system is involved in action understanding? *Consciousness and Cognition*, *22*(3), 1114–1121. http://doi.org/10.1016/j.concog.2013.04.008

Southgate, V., Johnson, M. H., Karoui, I. El, & Csibra, G. (2010). Motor system activation reveals infants' on-line prediction of others' goals. *Psychological Science*, *21*(3), 355–359. http://doi.org/10.1177/0956797610362058

Southgate, V., Johnson, M. H., Osborne, T., & Csibra, G. (2009). Predictive motor activation during action observation in human infants. *Biology Letters*, *5*(6), 769–772. http://doi.org/10.1098/rsbl.2009.0474

Stadler, W., Ott, D. V. M., Springer, A., Schubotz, R. I., Schütz-Bosbach, S., & Prinz, W. (2012). Repetitive TMS suggests a role of the human dorsal premotor cortex in action prediction. *Frontiers in Human Neuroscience*, *6*, 20. http://doi.org/10.3389/fnhum.2012.00020

Steinhorst, A., & Funke, J. (2014). Mirror neuron activity is no proof for action understanding. *Frontiers in Human Neuroscience*, *8*, 8–11. http://doi.org/10.3389/fnhum.2014.00333

Streltsova, A., Berchio, C., Gallese, V., & Umiltà, M. A. (2010). Time course and specificity of sensory-motor alpha modulation during the observation of hand motor acts and gestures: a high density EEG study. *Experimental Brain Research*, *205*(3), 363–73. http://doi.org/10.1007/s00221-010-2371-7

Tenenbaum, E. J., Sobel, D. M., Sheinkopf, S. J., Malle, B. F., & Morgan, J. L. (2015). Attention to the mouth and gaze following in infancy predict language development. *Journal of Child Language*, *42*(6), 1173–1190. http://doi.org/10.1017/S0305000914000725

Tenke, C. E., & Kayser, J. (2012). Generator localization by current source density (CSD): Implications of volume conduction and field closure at intracranial and scalp resolutions. *Clinical Neurophysiology*, *123*, 2328–2345.

Thorpe, S. G., Cannon, E. N., & Fox, N. A. (2016). Spectral and source structural development of mu and alpha rhythms from infancy through adulthood. *Clinical Neurophysiology*, *127*(1), 254–269. http://doi.org/10.1016/j.clinph.2015.03.004

Tomasello, M. (1995). Joint attention and social cognition. In C. Moore & P. J. Dunham (Eds.), *Joint attention: Its origins and role in development* (pp. 103–130). Hillsdale, NJ: Lawrence Erlbaum Associates.

Tomasello, M. (2008). *Origins of human communication*. Cambridge, MA: MIT Press.

Tomasello, M., Carpenter, M., Call, J., Behne, T., & Moll, H. (2005). Understanding and sharing intentions: the origins of cultural cognition. *The Behavioral and Brain Sciences*, *28*(5), 675-91-735. http://doi.org/10.1017/S0140525X05000129

Tomasello, M., & Farrar, M. J. (1986). Joint attention and early language. *Child Development*, *57*(6), 1454. http://doi.org/10.2307/1130423

Tomasello, M., Kruger, A. C., & Ratner, H. H. (1993). Cultural learning. *Behavioral and Brain Sciences*, *16*(3), 495. http://doi.org/10.1017/S0140525X0003123X

van Elk, M., van Schie, H. T., Hunnius, S., Vesper, C., & Bekkering, H. (2008). You'll never crawl alone: neurophysiological evidence for experience-dependent motor resonance in infancy. *NeuroImage*, *43*(4), 808–14. http://doi.org/10.1016/j.neuroimage.2008.07.057

Van Overwalle, F., & Baetens, K. (2009). Understanding others' actions and goals by mirror and mentalizing systems: A meta-analysis. *NeuroImage*, *48*(3), 564–584. http://doi.org/10.1016/j.neuroimage.2009.06.009

Virji-Babul, N., Rose, A., Moiseeva, N., & Makan, N. (2012). Neural correlates of action understanding in infants: Influence of motor experience. *Brain and Behavior*, *2*(3), 237–242. http://doi.org/10.1002/brb3.50

Volterra, V., Caselli, M. C., Capirci, O., & Pizzuto, E. (2005). Gesture and the emergence and development of langauge. In D. Slobin & M. Tomasello (Eds.), *Beyond Nature-nurture: Essays in Honor of Elizabeth Bates* (pp. 3–40). Mahwah, NJ: Lawrence Erlbaum Associates.

Vukovic, N., Feurra, M., Shpektor, A., Myachykov, A., & Shtyrov, Y. (2017). Primary motor cortex functionally contributes to language comprehension: An online rTMS study. *Neuropsychologia*, *96*, 222–229. http://doi.org/10.1016/j.neuropsychologia.2017.01.025

Wakefield, E. M., Novack, M. A., Congdon, E. L., Franconeri, S., & Goldin-Meadow, S. (2018). Gesture helps learners learn, but not merely by guiding their visual attention. *Developmental Science*, p. e12664. Wiley/Blackwell (10.1111). http://doi.org/10.1111/desc.12664

Wellman, H. M., Phillips, A. T., Dunphy-Lelii, S., & LaLonde, N. (2004). Infant social attention predicts preschool social cognition. *Developmental Science*, *7*(3), 283–288. http://doi.org/10.1111/j.1467-7687.2004.00347.x

Woodward, A. L. (1998). Infants selectively encode the goal object of an actor's reach. *Cognition*, *69*(1), 1–34. http://doi.org/10.1016/S0010-0277(98)00058-4

Woodward, A. L. (2004). Infants' use of action knowledge to get a grasp on words. In D. G. Hall & S. R. Waxman (Eds.), *Weaving a Lexicon* (pp. 149–172). Cambridge, MA: MIT Press.

Woodward, A. L., & Guajardo, J. J. (2002). Infants' understanding of the point gesture as an object-directed action. *Cognitive Development*, *17*(1), 1061–1084. http://doi.org/10.1016/S0885-2014(02)00074-6

Yoo, K. H., Cannon, E. N., Thorpe, S. G., & Fox, N. A. (2015). Desynchronization in EEG during perception of means-end actions and relations with infants' grasping skill. *British Journal of Developmental Psychology*, 24–37. http://doi.org/10.1111/bjdp.12115

Yoo, K. H., Thorpe, S. G., & Fox, N. A. (2016). Neural correlates of motor learning in infants. Paper presented in N. A. Fox (Chair) Neural correlates of action from infancy to early childhood. The Biennial International Conference on Infant Studies, New Orleans, LA.

Zambrana, I. M., Ystrom, E., Schjølberg, S., & Pons, F. (2013). Action imitation at 1½ years is better than pointing gesture in predicting late development of language production at 3 years of age. *Child Development*, *84*(2), 560–73. http://doi.org/10.1111/j.1467-8624.2012.01872.x