“THE IMPACT OF REPEATED SENSORY-MOTOR EXPERIENCE WITH MULTIMODAL OBJECTS UPON THE EMERGENCE OF INFANT REACHING”

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Dedication

To my loving and supportive wife. Unconditional.

Acknowledgments

Primarily, I thank the parents and infants for their participation in this study. I appreciate their willingness to commit to such a rigorous developmental study.

Secondly, I wish to thank my family for their encouragement throughout my graduate career. Without such encouragement the road to earning my Ph.D. surely would have been quite longer. I especially thank my wife, Ellen, who has provided so much support that I would have been unable to complete my work without her. Whether it was traveling to infants' homes to help with data collection, helping with recruitment, providing feedback on statistics and talks, she was there and I am forever grateful. Secondly, I thank my parents, Howard and Cathy Williams, for providing me with every opportunity available to foster the pursuit of my goals. In addition, I want to thank Mike and Cathy Harvey for their prayers and support.

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Abstract

Previous studies found that providing infants with repeated opportunities for reaching improved the emergence and quality of the behavior, presumably via exploratory and selective processes (Bojczyk & Corbetta, 2004; Lobo et al., 2008). Here we further examined the effects of opportunities for reaching by exposing infants to multimodal objects that were activated either continuously by a hidden motor or contingently by hand-toy contact. We asked if such objects would motivate infants to try to reach for them even more than still and silent objects.

Forty-four pre-reaching infants were recruited within the week prior to turning three months of age and were seen for 16 consecutive days. Three groups received daily exposure to objects that either moved and made noise continuously (continuous), moved and made noise only on hand-object contact (contingent), or did not move or make noise when touched (repeated task exposure). A control group received no daily experience. On day 1, all infants were assessed in the laboratory to ensure they were not reaching. From days 2-15, an experimenter tested the repeated groups in the home. On day 16, all infants' reaching was reassessed in our laboratory. Arm kinematics were recorded during laboratory visits. All testing was the same: infants were seated in an infant chair behind a table and an experimenter placed 1 toy on the table at midline for one minute. Infants received ten trials per day. We measured amount of intentional reaches, hand-toy distance, and peak movement speed.

Intentional reaching significantly increased for all repeated groups. Examination of infants that improved showed that the contingent group displayed a significantly higher gain in reaching over time relative to the repeated task exposure and continuous groups. Kinematic measures indicated that these young infants modulated the speed of their reaching movements to

match task demands. Specifically, infants in the continuous group displayed increased peak speeds of their movements in order to contact a moving object. Results suggest that repeated opportunities to reach for objects underlies the emergence of reaching; however this process may be aided by providing a salient, multimodal link that highlights the effects of successful action.

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Introduction

Background and theoretical considerations

Reaching is a crucial behavior to emerge in an infant's behavioral repertoire around three to five months of age (Thelen et al., 1993; von Hofsten, 1991). The emergence of reaching permits infants to interact with their environment in many novel ways and has profound effects on multiple domains of infant development. More specifically, with the onset of reaching, infants begin to explore the dynamic biomechanical aspects of their bodies and through such exploration they gain the motor control necessary for further improvements in reaching behavior (Bhat, Heathcock, & Galloway, 2005; Konczak, Borutta, Topka,& Dichgans, 1995; Thelen et al., 1993; Thelen, Corbetta, & Spencer, 1996; Thelen & Smith, 1994). Also, concomitant with the ability to bring the hands into contact with objects are new possibilities to explore and learn about object properties (Bushnell & Boudreau, 1993; Corbetta & Snapp-Childs, 2009; Gibson, 1988). Similarly, exploratory behaviors become more sophisticated following the onset of reaching, which allows infants to combine afferent information arising from different sensory modalities, and subsequently aid intermodal learning (Eppler, 2005; Rochat, 1989). Prior work has also found that the early emergence of reaching facilitates the development of successful means-end behavior (Lobo & Galloway, 2008). Finally, the ability to reach for objects induces changes in the emotional-social context. For instance, once they become successful at contacting objects, infants begin to direct more visual attention toward their surroundings instead of parents' faces (Fogel, Dedo, & McEwen, 1992; Ruff & Rothbart, 1996). In conjunction with infant behavioral changes, parents alter their own behavior by providing more opportunities for infants to use their novel ability, which facilitates improvements in all areas connected with reaching

behavior (Fogel, 1997). Taken together, these findings indicate that reaching is critical to development in all domains of infants' lives. Despite the onset of reaching being such an important behavior, developmental psychologists still lack a complete understanding of the processes and early sensory-motor experiences that underlie its emergence.

Historically, many investigators have tried to determine how infants learn to reach and to examine the processes that underlie the emergence of the behavior. However, these attempts have only yielded small pieces to a much larger and complex puzzle. Over the past 50 to 60 years, theoretical perspectives on how infants begin to reach have changed considerably to accommodate the many disparate pieces of the puzzle. In adapting to these changes, contemporary developmental scientists have made some headway in their attempts to gain a clearer understanding of the emergence of reaching. A review of these perspectives will illustrate the changes that have taken place over this relatively short period of time.

In the early to middle 1900s pioneers in developmental science such as L. Halverson, A. Gesell, and M. McGraw began to show interest in early motor behaviors such as reaching, crawling, and walking, among many others. At that time, the main objective of these researchers was to intensely describe and catalog the motor behaviors of young children. The ensuing descriptive works provided current developmental psychologists with an invaluable knowledge base of the typical sequence and timing of motor behaviors in young children. However, in addition to their descriptive contributions, these researchers made profound, and long-lasting, theoretical contributions. In general, each of these pioneers viewed the development of motor behaviors from a maturationist standpoint, in which progress in motor development was ultimately regulated by the genetically-determined growth plan of the nervous system (Thelen &

Adolph, 1992). The foundation of this theoretical viewpoint may be found in the animal research conducted by G. E. Cogdill. According to Carmichael (1970), "Cogdill must be remembered as the investigator who first charted the relationship between the detailed growth of the nervous system and the consequent alterations which occur in behavior (p. 456)." Cogdill concluded from his work with the salamander *Amblystoma punctatum* that changes in behavior were concurrent with growth in the structure of the nervous system (Coghill, 1930, 1936). Specifically, the observed behaviors of the salamander were direct readouts of the nervous system and only when changes in the nervous system occurred would behavioral change be apparent (Carmichael, 1970; Coghill, 1930, 1936; Thelen & Adolph, 1992).

Both Gesell and McGraw followed in this tradition and applied it to explain the emergence of reaching in infants. The basic premise of their argument was that connections between the nervous and musculoskeletal systems must form for infants to attain a certain level of maturity before novel, more voluntary behaviors such as reaching may occur (Thelen & Adolph, 1992). When the novel behaviors did begin to emerge, it was inferred that those neuromuscular connections had shifted from subcortical (reflexive) control to more cortical (voluntary) control (Gesell, 1952, 1988; Halverson, 1933; McGraw, 1945). The prevailing view of the time was that motor development was linear and proceeded through strictly-defined developmental steps, with the sequence ultimately being controlled by innate rules (Thelen & Smith, 1994). Although this theoretical viewpoint dominated the field for many years, it focused most attention on "what" and "when" aspects of development, while diverting attention away from questions that dealt directly with the processes of "how" behaviors emerge.

In contrast to the neuromaturational perspective were strict associationist accounts of behavioral development. This perspective purported that behavior in humans, as well as nonhuman animals, was controlled by external stimuli and situations. Thus, there was little need to refer to mental processes to explain behavior (Malone, 1991). A few of the key proponents of this movement were E. R. Guthrie, C. L. Hull, and E. L. Thorndike. The work of E. L. Thorndike had a significant impact on the field of motor learning with his proposition of the Law of Effect (Schmidt & Lee, 1999). The Law of Effect stated that the likelihood of producing behavioral responses in a particular situation would either increase or decrease based on the effects that they produced (Thorndike, 1927, 1949). This law was developed from his examination of the behavior of cats, amongst other animals, placed in problem boxes. The problem boxes were specially-designed so that only one specific action performed by the animal was required in order to escape from the box (e.g. pull a string, push a floor board). Thorndike discovered that animals learned how to escape from the problem box in a gradual fashion rather than immediately making the association between the prior behavior and escape. The Law of Effect provided the basis for Thorndike's idea of "selecting and connecting," which further stated that the associations between "satisfying" behavioral consequences and the particular situation within which those consequences occurred were "stamped in," or strengthened (Green & Piel, 2002; Malone, 1991; Thorndike, 1927; 1949). Although Thorndike never directly applied this idea to the emergence of infant reaching, it may be extended to do so. Based on the Law of Effect, associations between arm movements leading to "satisfying" consequences, presumably hand-object contact, and the reaching situation, would gradually be strengthened over time, therefore leading to a greater likelihood of performing the successful arm movements

in future, similar reaching situations. In general, despite the Law of Effect being broadly applied to many behaviors in many different situations, there was very little attention paid to the cognitive aspects involved in behavioral learning processes as much of behavior was presumed to be triggered by an external stimulus.

Piaget, a constructivist, proposed a different perspective on how infants began to reach for objects. He believed that voluntary behaviors were constructed from the set of reflexes with which infants entered the world. With regard to the emergence of reaching, reflexive grasping and reflexive looking behaviors were the building blocks of future voluntary reaching and grasping (Piaget, 1952). Piaget believed that each of the reflexes corresponded to separate schemata, or cognitive structures representing particular actions or concepts, and were unconnected from one another at birth. Thus, before infants were able to reach for objects successfully it was necessary for them to integrate the separate schemata (e.g. link grasping schema with looking schema) through active interactions with the environment. To be more specific, infants needed to properly integrate movements of the hand and arm (proprioception) with vision of the hand as well as with vision of the desired object in order to successfully reach for objects. This perspective was supported by work from White, Castle, and Held (1964) when they observed that institutionalized infants performed alternating looks between their hand and a desired object near the onset of reaching, which seemed to suggest an active integration process. Until recently there has been continued support for the idea that vision was necessary to actively guide the hand to the object (Bushnell, 1985); however, work from Clifton and her colleagues, which will be discussed in detail later, has challenged this idea by showing that infants do not need to see their hand in order to contact an object. For instance, infants are able to transport

their hand(s) to glowing objects as well as to sounding objects in a dark room without altering the kinematic structure of their movements (Clifton, Muir, Ashmead, & Clarkson, 1993; Clifton, Rochat, Robin, & Berthier, 1994; Corbetta, 2009). Despite this incongruence with recent empirical evidence, the fact that Piaget emphasized the importance of infants' active exploration within the environment provided a starkly different perspective from that of Halverson, Gesell, and McGraw. Specifically, infants were seen as active participants in driving their own perceptual-motor development rather than prisoners of their own rate of neural maturation. Also, the specification of cognitive structures, or schemata, set Piaget's theory apart from the associationist theories. However, one thing that has been considered by contemporary developmental scientists is that even before the time that Piaget, as well as White and his colleagues, observed alternating glances between hand and object near the onset of reaching, infants had already figured out how to transport their hand near the desired object (Thelen & Smith, 1994). This consideration highlighted the fact that the question of how infants initially discovered a solution to transporting their hand(s) to a desired object remained unanswered.

In the mid 1970s, the concept of schemata was applied to information processing models of human motor behavior, which quickly became the most popular perspective to explain the acquisition of motor skills (Clark, 1995; Gabbard, 2004; Newell, 1991, 2003; Schmidt, 1975). Primarily, the information processing theory is one with a cognitive approach that views the mind as a collection of structures, which process information serially from input to output. Gradually over time, the structures (e.g. schemata, motor programs, etc.) extract and compile rules from motor performance to the point where those rules may be more or less automatically applied in future, similar situations in a top-down fashion (Clark, 1995; Gabbard, 2004; Schmidt,

1975). The integration of schemata into the information processing approach was forged by R. A. Schmidt in 1975, with his proposal of a schema theory of motor learning. It is worthwhile to discuss this theory in further detail as it is the most widely used theoretical perspective in the adult motor learning and control field.

Schmidt (1975, 2003) defined a schema as, "an abstract memory representation thought of as a rule, concept, or generalization," which he adopted from F. Bartlett and applied to his theory of motor learning (Bartlett, 1932; Schmidt & Lee, 1999). Prior to a discussion on the specific functions performed by the schemata, it is important to discuss Schmidt's proposal of a generalized motor program (GMP). The GMP was defined as a memory structure, which contained information about the specific features of a particular class of actions (e.g. reaching, kicking, etc.). Each class of actions possessed a unique pattern of activity, of which the GMP contained information about the common aspects of the pattern within each class. When this program was called from memory, that specific pattern of motor activity was executed (Schmidt, 1975, 2003; Schmidt & Lee, 1999; Summers & Anson, 2009). However, simply activating the GMP was not enough as each situation within which the action was to be performed varied. Therefore, according to Schmidt (1975), the performer needed to apply specific parameters to the GMP prior to movement execution. This information was proposed to be specified by two separate schemata: the recall schema (rules for movement production) and the recognition schema (rules for movement evaluation). These rules were thought to be extracted and compiled into memory from four types of information available after the production of each movement: 1) Initial conditions information, 2) Specific parameters assigned to the GMP, 3) Feedback about the movement outcome, and 4) Sensory consequences of the movement (Schmidt & Lee, 1999).

Over time as the performer produced many movements, the rules for movement production and evaluation were stored in the recall and recognition schemata, thereby facilitating the input to output flow of information. Thus, as the rules were stockpiled into memory, when presented with a similar situation in which the same class of actions was needed, the rules were recalled from memory to scale the action in a new way.

As noted, this has been a very attractive perspective used to explain motor behavior, especially with adult motor behavior (Clark, 1995; Newell, 1991, 2003; Schmidt, 1975, 2003). However, it has been much more difficult to apply this theory in the motor development domain. Most of the work conducted in the tradition of Schmidt's schema theory has been with adult motor learning and the presence of a GMP has simply been assumed. The developmental origins of the GMP have yet to be specified (Schmidt, 2003; Thelen & Smith, 1994). In addition, despite the lack of knowledge of GMP origins, some contemporary motor developmentalists acknowledge that the motor learning process is most likely quite different between adults and infants (Berthier, Rosenstein, & Barto, 2005; Thelen & Smith, 1994, 2006). Another area of concern when applying this perspective to motor development, especially with respect to the emergence of reaching in infants, is that it lacks a clear explanation as to how infants transition to new forms of movement. Schema theory has only provided an explanation as to how the rules contained in the recall and recognition schemata may explain a new way of scaling already existing movement forms, rather than how the rule may be applied to novel, different movement forms (Newell, 1991, 2003; Schmidt, 2003; Schmidt & Lee, 1999).

In recent years, many developmentalists have begun to view behavioral development, especially the emergence of novel movement forms, from a more multicausal perspective. This

framework acknowledges that all aspects of the developing system, including internal factors, external factors, in addition to the system's own developmental history interact and cooperate to impact the development of behavior. The foundation of this viewpoint, commonly referred to as the epigenetic/developmental systems perspective, has its roots in the work of developmental psychobiologists and comparative psychologists such as T. C. Schneirla, Z. Y. Kuo, and G. Gottlieb. Rather than assigning primary importance to neural maturation or to the environment, Schneirla, Kuo, and Gottlieb argued that behavioral development was much more complex in that neural processes interact with other endogenous factors as well as factors arising from the periphery (Gottlieb, 2009; Gottlieb, Wahlsten, & Lickliter, 2006; Kuo, 1970; Schneirla, 1966). Kuo (1970) highlighted the developmental systems viewpoint quite well when he stated, "In every stage of ontogenesis, every response is determined not only by the stimuli or stimulating objects, but also by the total environmental context, the status of anatomical structures and their functional capacities, the physiological (biochemical and biophysical) condition, and the developmental history up to that stage (p. 189)." These influential theorists made it commonplace for contemporary developmental scientists to recognize that the properties of the nervous system, body, and environment cooperate to drive the emergence of behavior (Chiel & Beer, 1997; Corbetta, 2009; Thelen, 2000).

From the back-drop of general developmental systems theory, dynamic systems theory has emerged as one of the more popular perspectives, especially in the realm of motor development. This particular perspective places a stronger emphasis on the processes of transition and change that lead to the emergence of novel behaviors. Accordingly, new behaviors become assembled through the multiple and continuous interactions among the many

interconnected, and continuously changing, levels of an organism's system. The system includes all components within (genetics, structure, early sensory-motor experiences, etc.) and surrounding that particular organism (contextual demands, environmental factors, etc.). Through these interactions, not pre-determined rules, new behaviors self-organize (Thelen, 1989, 1992, 1995).

When viewing the emergence of reaching from a dynamic systems standpoint, one must acknowledge that there are many factors both within and around infants that contribute to this process. It certainly is no easy task to specify all factors that impact the emergence of reaching; however, Clearfield & Thelen (2001) have proposed a few to highlight the confluence of factors involved. One important necessity is the ability to localize an object in the environment (via the visual and/or auditory modality) and subsequently be motivated to touch or obtain it. Additionally, the infant must possess the muscular control of the arms to lift and move them within the gravitational force-field, make online movement corrections through the use of sensory modalities, as well as control their posture. From a dynamic systems perspective, the organization of these variables to successfully reach for objects is an extremely complex task for young infants and does not happen all of a sudden. Rather, the learning to reach process begins at birth through multiple experiences rooted in early interactions and sensory-motor behaviors. Here, learning refers to changes in behavior as a result of infants' active exploration of the capabilities of their bodies and subsequent selection of successful movements relevant to the context and task at hand. Exploration is specifically defined as repeated cycles of action and perception, during which infants attend to and perceive the consequences of their actions. Utilization of this perspective means that novel behaviors are rooted in prior experiences.

Specifically, newly assembled behaviors emerge from previously assembled behaviors and in turn, the new behavioral assemblies provide the basis for future ones (Berthouze & Goldfield, 2008; Corbetta & Vereijken, 1999; Goldfield, Kay, & Warren, 1993;Thelen & Corbetta, 2002; Thelen & Smith, 2006). Specifically with regard to reaching, current reaching behavior is assembled, via selective processes, from prior spontaneous/non-reaching and reaching behaviors and thus, current reaches provide the substrate for subsequent reaching development.

Retrospectively, most prior theoretical proposals have highlighted the notion that the nervous system plays a role in behavioral development. Indeed, recent theories do not discount that the nervous system is an integral part of the development of behavior; however, through nonhuman primate work and recent technological advances, developmental scientists now have a better understanding of nervous system development, which in turn has fostered a better understanding of the contribution that the nervous system makes to behavior (Stiles, 2009).

Much of the knowledge about the human nervous system has come from work with nonhuman animals, especially nonhuman primates such as rhesus monkeys and chimpanzees (Huttenlocher, 2002). Over the course of primate evolution, certain differences have been discovered with regard to nervous system development. For instance, the evolution of the primate brain has been shown through the rate and pattern of developmental growth. Specifically, at birth human primate brains are small compared to the adult brain size. At birth, human primate brains are approximately 25% of the adult brain weight (Sacher & Staffeldt, 1974). This is in contrast with other primates such as rhesus monkeys and chimpanzees, whose brains are at 60% and 46% of adult brain weight at birth, respectively (Holt, Cheek, Mellits, & Hill, 1975; Passingham, 1982). Furthermore, the rates of brain growth among the various

primates are starkly different. The rate of brain growth tends to slow just prior to birth for rhesus monkeys and just after birth in chimpanzees. In human primates, however, the rate of brain growth remains high for the first few years of life (Passingham, 1982).

Another difference in neural growth between primate species has been found in the phases of synaptogenesis, or the creation of synaptic connections between neurons. This is especially true with regard to the length of phase three synaptogenesis, which corresponds to increases in synaptic connections as a function of typically-occurring and unique experiences within the environment. Specifically, Bourgeois (2001) has found the length of this particular phase to become protracted over the course of primate evolution. For example, this phase is typically completed by 61 days after birth in rhesus monkeys with the total length of the phase being approximately 136 days. In contrast, phase three is typically complete by about 310 days after birth in human primates with the total length of the phase being approximately 470 days (Bourgeois, 2001). Despite the observed differences across primate species, the pattern of growth has been shown to be quite similar, albeit much quicker in nonhuman primates (Bourgeois, 2001; see Huttenlocher, 2002 for a review). Thus, many researchers have taken advantage of nonhuman primate work to better understand the human primate nervous system.

One of the key understandings of the nervous system gained from nonhuman primate, and nonhuman animal work in general, is that the nervous system is continuously changing in response to behavioral activity. Evidence of multidirectional effects between brain and behavior has been found across a number of nonhuman animal species, such as rats (Greenough, Black, & Wallace, 1987) and monkeys (Dorris, Pare, Munoz, 2000; Martin, Choy, Pullman, & Meng, 2004; Merzenich et al., 1983; Merzenich, Grajski, Jenkins, Recanzone, & Peterson, 1990).

Specifically, Greenough et al. (1987) found that rats provided with the opportunity to be motorically and socially active displayed a significantly higher synaptic density relative to rats that were kept in isolation. Dorris et al. (2000) discovered activity-dependent changes in neuronal activity in rhesus monkeys when engaged in an oculomotor reaction time task. With repeated presentations of a stimulus in the same location, the reaction times of the monkeys decreased in conjunction with increased neural activation of the superior colliculus, a brain region associated with eye movement preparation. The observed changes in underlying neural activity were immediate and continuous based on the use of peripheral structures. Furthermore, classic work with multiple species of nonhuman primates from Merzenich and his colleagues has shown topological neural representations of peripheral body structures to be continuously evolving based upon the ongoing activity of those structures. For example, when a particular digit of the hand is removed, the cortical representations of the adjacent digits expand into the area that was previously associated with the removed digit. Also, when two fingers are sutured together to only allow simultaneous movement of the digits, the representational areas of those two digits merge during the sutured period. Following removal of the sutures, which permits independent digit movement, the representational areas become clearly demarcated again (Merzenich et al., 1983, 1990). Similar findings have been discovered in human infants as well. For instance, Bell & Fox (1996) utilized EEG to measure coherence, or connectivity, between brain regions over the time period when infants were learning to crawl. They found a dramatic rise in coherence, or connectivity, between multiple brain regions while infants were actively attempting to discover a solution to crawling. As infants became more proficient crawlers, coherence between brain regions declined. This pattern of neural activity is indicative of

continuous interactions between overt behavior and underlying brain activity. These empirical findings indicate that the nervous system is simply one component of the infant's ever-changing and continuously interacting system that contributes to behavior, rather than being the ultimate source of behavior (Corbetta, 2009).

Overall, the increased understanding of the nervous system has fostered the generation of theoretical perspectives on the relationship between brain and behavioral development, which have been combined with dynamic systems theory to provide a more complete picture of the emergence of reaching. In particular, dynamic systems theory has been complemented by the theory of neuronal group selection (TNGS) proposed by Gerald Edelman (Edelman, 1987, 1992, 2004; Hadders-Algra, 2000; Sporns & Edelman, 1993) as well as by approximate optimal control theory (Barto, 2002; Berthier et al., 2006). Both of these neural perspectives illuminate the multidirectional effects between brain and behavior, which solidifies their compatibility with a dynamic systems view of behavioral development. Furthermore, both perspectives, which will be covered in turn, are in agreement with current empirical literature on the dynamics of nervous system development.

During early nervous system development, connective redundancy in the nervous system has been shown to be driven by the overproduction of unspecified synaptic connections in response to typically-occurring experiences (Bertenthal & Campos, 1987; Bourgeois, 2001; Greenough et al., 1987). As a result of such complex and widespread connectivity, and the fact that the connections do not arise pre-specified for particular functions, multiple neuronal networks are activated when similar behavior patterns are produced (Edelman, 1987; 1992; Huttenlocher, 2002). The process of neuronal selection has been proposed to stabilize certain

patterns of synaptic connectivity when those activated connections coincide with the successful completion of a goal-directed behavior that is functionally adaptive to the task-at-hand. This stabilization of active synapses has been termed experience-dependent plasticity by Greenough et al. (1987). Furthermore, according to Edelman and his colleagues, the generation of successful goal-directed movements, such as reaching, does not occur strictly via computational strategies, during which the nervous system first computes a complete movement trajectory and then activates the behavior (e.g. Hollerbach, 1982; Schmidt, 1975; 2003; Schmidt & Lee, 1999). Rather, Edelman and his colleagues purport that the discovery of a successful reaching movement occurs through the exploration of variable arm movements, which ultimately leads to the selection of the proper reaching movement (see also Thelen & Corbetta, 1994 and Thelen & Smith, 2006). The solution that infants discover satisfies two tenets. First, the discovered solution is appropriate to the task-at-hand. Second, it possesses functional value. The functional value of a behavior, it has been proposed, is discovered through neuronal activation of what Edelman (1987) has termed innate value systems, which extend and receive connections to and from nearly all areas of the nervous system. These innate value systems, proposed to be contained within the brain regions responsible for important bodily functions (e.g. heartbeat, respiration, etc.), do not actually produce the behavior, but interact and dynamically work with multiple brain regions to determine its appropriateness, or functional value, for the particular context within which the behavior occurs. Discovering the functional value of the behavior fosters selection of those behaviors appropriate for the task-at-hand. From a selectionist standpoint, infants enter the world with a set of neural constraints, which allows the infant to produce a set of movement patterns that have been evolutionarily selected because of adaptive,

or functional, value (Berthier, Clifton, McCall, & Robin, 1999). These neural constraints work to decrease the state space an infant has available to motorically explore and discover a successful action (Schlesinger, Parisi, & Langer, 2000). With each movement produced, multiple neuronal networks are activated and subsequent selection of movements proceeds based on the activity of the proposed value systems in response to the particular movement and its outcome. For example, as an infant reaches out and contacts an object, the value system shows increased activation to the neural networks involved to indicate that the behavior just performed was functionally adaptive. Thus, a more positive response of the value system to a given behavior would serve to strengthen the synaptic connections that were involved in that behavior. Through this strengthening process, the likelihood of activating those particular synaptic linkages would be greater in similar future situations (Edelman, 1987, 1992; Sporns & Edelman, 1993).

Recently, through the use of modeling technology, approximate optimal control theory has further specified the notion of value as it relates to the functioning of neural networks and the emergence of reaching. Building upon the notion of Edelman's value systems contained in the brain, which are inherently available to detect and evaluate the functionality of the performed behavior, work from Berthier and his colleagues (Berthier et al., 2005) have proposed specific mechanisms involved in learning the functional value of a behavior. This modeling work is based on Reinforcement Learning algorithms, which work by utilizing feedback signals to evaluate performance. Rather than relying only on externally provided feedback signals, Berthier et al. (2005) propose that the feedback is most likely something internal such as the infant's evaluation of the behavior. For instance, in the case of reaching, the evaluation could be whether the reach was successful based on their goal. However, in furthering the ideas of

Edelman, it has been proposed that it would be difficult to determine which specific actions in an exploratory sequence led to the valuable, or functionally adaptive, outcome. Instead, and in line with research highlighting the continuous, multidirectional interplay between movement and nervous system activity (Dorris et al., 2000; Greenough et al., 1987; Martin et al., 2004; Merzenich et al., 1983, 1990), a value function is learned through continuous associative processes that map each state of the system with a value, or judgment of how good it is to be in that particular state when the child has a particular goal in mind. The value function, which is learned through repeated exploratory activity, serves as a prediction mechanism of the expected "reward." As an example, if the "reward" is related to the goal of contacting an object within reaching space, then the states explored in which the hand is closer to the goal of object contact correspond to higher values. Thus, with this particular goal in mind and based on the current state of the system (i.e. the proximity of the hand to the object) action selection proceeds based on the value function (Barto, 2002; Berthier et al., 2006; Fagg, Barto, & Houk, 1998).

In a short amount of time there has been considerable evolution in theories of how infants learn to reach. It is also clear that traces of the prior theories may be found in the more contemporary viewpoints. However, the specific combination of dynamic systems theory, Edelman's TNGS, and approximate optimal control theory highlights the importance of exploratory activity, and more specifically, the importance of early arm movements, to the emergence of infant reaching. It is these early arm movements, fostered through repeated opportunities to attempt reaches for objects, which aid the selective process of learning to reach.

Early reaching behavior

Most studies that have examined the early motor behavior of nonhuman primate infants have focused mainly upon the onset and offset of infant reflexive behavior, such as the grasping reflex (Hallock, Worobey, & Self, 1989; Sackett, Gunderson, & Baldwin, 1982; Schneider & Suomi, 1992). To gather information about these behaviors, comparative researchers have utilized behavioral assessments designed to test human infant behavior in the first weeks of life, such as the Neonatal Behavioral Assessment Scale (Brazelton, 1973), or modified neurobehavioral assessment scales designed specifically for nonhuman primates (Sackett et al., 1982; Schneider & Suomi, 1992). Studies such as these have documented that the majority of primate infants display reflexive behaviors such as rooting, sucking, and grasping. The grasping reflex in particular is present at birth in the majority of nonhuman primates, however, the offset times differ between species. For instance, in rhesus monkey infants, the offset of the grasping reflex is typically around one month of age, which coincides with the onset of voluntary motor control (Sackett et al., 1982). However, in human infants, the offset of the grasping reflex typically occurs around three months of age, which coincides with the approximate onset of successful reaching (Sackett et al., 1982; Thelen et al., 1993; von Hofsten, 1991). Despite an interest in documenting the early reflexive behaviors of nonhuman primates, there has been relatively little work focusing on the different arm movements that precede the emergence of reaching in nonhuman primates and how these movements may impact the formation of reaching behavior. One recent comparative analysis of infant reaching behavior conducted by Nelson (2010) focused on the development of hand preference across rhesus monkey and human infants; however, this analysis focused only on arm movements at or following the onset of goal-directed

reaching. Although the study by Nelson (2010) was the first to examine goal-directed reaching behavior in infant rhesus monkeys with kinematics, she did not specifically examine the different arm movements prior to the emergence of goal-directed reaching. Thus, relatively little is known about specific arm movements, aside from reflexive behaviors, prior to reaching onset in nonhuman primates. As noted, recent theories of human infant reaching emphasize the importance of early arm movements for discovering a solution to the reaching task; therefore many studies have documented the various phases of arm movements through which human infants typically move prior to the emergence of reaching.

Before infants begin to consistently reach and touch objects in the environment, they perform what have been termed spontaneous movements, which were originally noted by William Preyer (as cited in Kessen, Haith, & Salapatek, 1970). These movements have been defined as arm movements, sometimes repetitive, that are prevalent in the apparent absence of any known stimuli (Gabbard, 2004; Thelen, 1996). The important, exploratory function, of these behaviors has been highlighted more recently; however, even some early developmental scientists, such as Preyer, had suggested that there must be some relation between these early spontaneous movements and later adaptive behavior (as cited in Kessen et al., 1970; Thelen et al., 1993). Despite the historical suggestion of their importance, spontaneous arm movements have been described by pioneers in motor development in such ways as random, unintentional, writhing, and non-functional (Gesell & Armatruda, 1947; Hadders-Algra & Prechtl, 1992; Piaget, 1952; White et al., 1964). All of these terms insinuate that these early arm movements are randomly generated through space, possess no organization at all and serve no function. However, multiple studies have examined the spontaneous arm movements of young infants and

have shown these movements to possess properties present in all movements such as accelerations and decelerations, which have been termed movement units. In one study, von Hofsten & Ronnqvist (1993) found that these early arm movements possess a temporal and spatial patterning such that within each unit arm movements tend to be straight, while the timing and location of changes in movement direction are coupled with transitions between movement units. Furthermore, findings from van der Meer, van der Weel, & Lee (1995) contradict the view that neonatal spontaneous arm movements are purposeless and unintentional. When newborns' hands are attached to a pulley system, they will voluntarily counteract a pulling force in order to keep their hand within their visual field. Thus, these findings indicate that the arm movements generated by neonates may not be completely random as many had previously thought.

In addition to spontaneous movements, multiple studies have found changes in upper limb behavior with the introduction of an object into infants' reaching space. One such early visuomotor behavior observed in newborn infants has been termed pre-reaching, which involves an extension-flexion synergy between the arm and hand (von Hofsten, 1982; 1984; 1989). Specifically, von Hofsten (1982, 1984) found that neonates tend to extend their fingers during arm extension and flex their fingers while they flex their arms. With the observation of such a seemingly sophisticated reaching behavior in the newborn, came new perspectives on how infants learned to reach. One perspective, espoused in the 1970s by T. G. R. Bower, seemed to propose that the ability to reach for objects was some form of inborn knowledge from which neonates are capable of using vision to direct their hands to objects in the environment (Bower, 1974; Bower, Broughton, & Moore, 1970; Thelen & Smith, 1994). Bower and his colleagues concluded from a series of reaching studies that if specific conditions are met, such as alertness

and postural support, neonates possess the ability to visually-direct their arm movements to objects. In Bower et al. (1970), for instance, newborns were presented with objects in five various locations. The researchers found that 40% of all forward arm extensions culminated in direct hand-object contact (Bower, 1974; Bower et al., 1970). Due to the general agreement that this type of behavior was too sophisticated for neonates, many studies attempted to replicate these results, but they were unsuccessful (Dodwell, Muir, & DiFranco, 1976; Ruff & Halton, 1978). Von Hofsten (1982) utilized a more sophisticated methodology to examine eye-hand coordination in the newborn and, rather than a sophisticated eye-hand coordinative relationship like that found by Bower and his colleagues, he concluded that the relationship is more rudimentary in nature. He discovered that when infants visually fixated an object they performed more forward arm extensions relative to when they did not visually fixate the object. Although, von Hofsten (1982) discovered few successful hand-object contacts, he found the forward extensions during visual fixation of the toy to be better aimed and ended closer to the object relative to non-fixated forward movements. Also, when the object was fixated, the speed of the hand slowed down as it neared the object. It was evident from this work that even in neonates there is some sort of link between the visual system and arm movements; however, it is not fully developed as successful contacts are extremely infrequent (von Hofsten, 1982).

With the conclusion by von Hofsten (1982) that reaching in the neonate is rudimentary at best, he conducted detailed examinations of early reaching behavior and was one of the main researchers to document the phases of arm movements after the pre-reaching phase leading up to and through the emergence of reaching in infants (von Hofsten, 1984; 1986; 1991). After the pre-reaching phase, at approximately two months of age, infants typically exhibit a decreased

frequency of forward arm extensions; however, it is around this time that researchers have discovered some of infants' first object-directed swipes. The forward extensions performed tend to be unilateral with no attempt to grasp the object as the majority of the movements are performed with a fisted hand (White et al., 1964; von Hofsten, 1984). After two months, von Hofsten (1984) found a significant increase in the number of non-fisted, forward arm extensions. Just prior to three months of age, he also noted an increase in the amount of hand opening during reaches to the object, which was only observed when infants visually fixated the object. Between three and four months of age researchers have documented an increase in bilateral arm movements toward objects presented at midline. These bilateral arm movements are accompanied by alternating glances between the hands and target objects as the hand-object distance decreases. These alternating glances between hands and object indicate that infants utilize vision to guide their hand to the object for contact (Bushnell, 1985; Piaget, 1952; White et al., 1964). Unilateral arm movements tend to re-appear around four months and continue to be accompanied by alternating glances between hand and object. Overall activity, in the form of number of arm movements and arm movement speed, has been shown to increase just prior to the first week of consistent success at reaching for and contacting objects (von Hofsten, 1984; Bhat, Heathcock, & Galloway, 2005). In addition, just prior to reaching onset, the distance from hand to object changes relatively little; however, at the emergence of reaching this distance tends to decrease and infants bring their hands to the midline more often (Bhat et al., 2005; Spencer & Thelen, 2000). On average, around five months of age infants begin to exhibit object-directed reaches characterized by one quick arm movement without the alternating glances between hand and object (White et al., 1964). Accounts of infant reaching behavior, especially those by Piaget

(1952) and White et al (1964), which stress the alternation of glances between hand and object, suggest that early in the learning to reach process infants are dependent upon vision to get their hand to the object for contact and led to the visual guidance perspective on infant reaching.

Visually-guided reaching refers to the idea that infants need to have continuous vision of their hand and the object in order to "guide" their hand to the object. Specifically, while the hand and object are visible, infants need to repeatedly glance back-and-forth in order to bring their hand into contact with the desired object (Bushnell, 1985). There have been a plethora of studies, as mentioned above, that seem to provide evidence that this notion is accurate. It was proposed by Bushnell (1985) that infants first progress through a period of visually-guided reaching, which allows them to successfully learn to reach and touch objects. Then, as infants become better at reaching and contacting objects, simultaneous vision of the hand and object is no longer necessary for transporting the hand to the object. Visually-elicited reaching is the term used to describe those reaches that do not require visual guidance of the hand during the reach. In other words, infants see an object within reaching space, which elicits a reach to that object without the use of vision to monitor the hand to its final destination. Thus, over time and with proficiency, infants move from a visually-guided approach to a visually-elicited one (Bushnell, 1985). The visual guidance hypothesis was an attractive explanation for the observations in the literature at the time; however, it is not in accord with recent empirical findings beginning with studies conducted by R. K. Clifton and her colleagues (Corbetta, 2009).

Clifton et al. (1993) designed a study that further examined the notion that vision of the hand is important early in the process of learning to reach and contact objects. They tested infants longitudinally from six to 25 weeks of age and compared reaching onset times to objects

presented in full light (vision of the hand) versus in the dark (vision of object, but no vision of the hand). If vision of the hand was necessary to the emergence of reaching, then reaching onset should have occurred in the light before it occurred in the dark. If vision of the hand was not crucial for the onset of reaching then the onset times for the light and dark conditions should have been equal. The findings supported the idea that young infants did not need to see their hand to guide arm movements to the object. All infants began reaching in the light around the same time they began reaching in the dark. Clifton et al. (1993) suggested that the proprioceptive modality had been underestimated as infants in their studies were just as successful at the reaching task without vision of the hand as they were with it. They did not conclude that the visual modality is unimportant in the learning to reach process; however, they proposed an alternative developmental progression than had most previous researchers. They suggested that early in the development of reaching, reaching movements are visually-elicited, while visually-guided reaching develops later when more sophisticated and precise movements of the hand are necessary for grasping. A recent study by Carrico & Berthier (2008) has supported this hypothesized progression. In this study, reaching behavior in dark conditions only seemed to be negatively impacted in 15-month-old infants and adults, while the reaching of younger infants seemed to be more resilient to the perturbation (Carrico & Berthier, 2008). Overall, Clifton and her colleagues point out that learning to reach is not driven by utilization of a single modality, but requires the coordination of multiple modalities.

In general, previous research that examined infants' upper limb behaviors during the time prior to the onset of consistent reaching highlights the fact that the learning to reach process is a complex and protracted one. The extant literature indicates that infants exhibit many different

early arm movements, both in the absence and presence of an object, and utilize multiple sensory modalities in the process. While the behavioral progression mentioned above is a "typical" one, it is important to note that individual differences are abundant. Individual differences in spontaneous and pre-reaching behaviors have been shown to impact future reaching behavior, thus stressing the importance of individual infants' developmental histories (Thelen et al., 1993). Specifically, these unique, early sensory-motor experiences tend to shape the developmental histories of infants, and thus, impact the formation of infants' first reaches. Based on this notion, and the recent theoretical emphasis on exploration and selection of movements through early sensory-motor experience, many researchers have manipulated infants' early upper limb experiences in order to understand the processes underlying the learning and development of reaching behavior.

Exploration and selection through early sensory-motor experience

The notion that young infants are able to modify ongoing behaviors based upon changes that occur in their surroundings has been demonstrated in multiple studies. These studies provide foundational support for the idea that even very young infants are able to discover the consequences of their actions through exploratory behavior and subsequently select those actions that are adaptive for the task-at-hand. The basis of these studies was centered on the provision of reinforcement, or the presentation of an interesting effect to the infants. When the infants modify their behavior in response to the presented effect, the researchers conclude that the infants have discovered the contingency between their actions and the environmental consequences of those actions.

One group of studies analyzed infants' modification of non-nutritive sucking behavior in response to varied environmental effects. Milewski & Siqueland (1975) discovered that newborn infants modify their sucking rate in order to view novel colors and patterns on a television monitor. Specifically, in order to continue viewing the novel visual stimulus, the infants increased and maintained their sucking rate, thereby not only demonstrating their ability to discriminate between familiar and novel stimuli, but that they also discovered the relationship between their sucking actions and consequences and utilized this discovery to modify their actions (Milewski & Siqueland, 1975).

Another study (Rochat & Striano, 2000) utilized non-nutritive sucking behavior to examine two-month-olds' responses to varied types of contingent auditory feedback. One group of infants, called the contingent-analog group, was permitted to orally explore a nipple and once infants reached a specific sucking force threshold, they heard different tones. The tones heard were different based upon the force with which the infants applied to the nipple. A second group of infants, the contingent-only group, was permitted to explore a nipple and once a specific force threshold was met, they heard tones. These tones did not vary based upon the sucking force of the infants in this particular group. The results from this study demonstrated that the two-month-olds did actively modify their sucking behavior to hear the tones as both groups displayed sucking forces around the necessary threshold. However, the contingent-analog group, which received varying tones with each sucking force applied to the nipple, showed significantly longer sucking pressures and more variations in the force applied to the nipple (Rochat, 1998; Rochat & Striano, 2000). Thus, results from studies that utilized non-nutritive sucking behavior

demonstrate the ability of very young infants to detect and capitalize upon the visual and auditory consequences of their sucking actions.

Another set of studies (Bahrick & Watson, 1985; Rochat & Morgan, 1995) utilized a different paradigm to examine this ability specifically between the proprioceptive and visual modalities. Three- to five-month-old infants were situated in front of two television monitors. On one monitor, infants were able to view a real-time recording of their ongoing kicking movements. Therefore what they viewed matched what they felt in real time. On the second monitor, infants were able to view a recording of their leg movements, which had been manipulated such that what infants viewed did not match what they currently felt. The main measure was the amount of time spent looking to each monitor. If the infants displayed a looking preference toward the video that was incongruent with what they felt, it would indicate that they were able to discriminate between the videos based on the visual-proprioceptive relationship. Results showed that infants displayed a clear looking preference for the video that did not match what they currently felt. In addition, the infants tended to look back-and-forth between the videos, something akin to exploration, prior to displaying a clear looking preference. The researchers argued that the infants were able to discover the contingent relationship between the visual and proprioceptive modality, which allowed them to select the appropriate action (Bahrick & Watson, 1985; Rochat & Morgan, 1995).

A now classic experimental paradigm, the conjugate reinforcement mobile procedure, has also provided evidence of infants' early ability to discover the consequences of their actions and subsequently modify those actions to obtain desired environmental results (Rovee & Rovee, 1969). In this procedure, infants lie on their backs with one ankle connected to an overhead

mobile via a string. Movement of that particular leg induces movement in the overhead mobile. In the many studies conducted by Rovee-Collier and her colleagues, they have demonstrated that infants as young as two months of age discover the relationship between their leg movements and the mobile movements. Not only do these studies show that infants discover these contingencies but they use them to modify their kicking movements, such as displaying increased leg movement amplitude to increase the mobile's movement amplitude (Rovee-Collier, Morrongiello, Aron, & Kuperschmidt, 1978; Rovee & Rovee, 1969).

With this particular set-up, many different leg movements cause movements in the mobile. Thus, no specific leg movement needs to be selected in order to induce the interesting effects of mobile movement. Thelen (1994) modified the conjugate reinforcement paradigm in such a way that three-month-old infants need to select a specific kicking pattern in order to fully activate the overhead mobile. Based on prior research, when supine, three-month-olds typically show a preference for single-leg or alternating-leg kicking rather than simultaneous, in-phase kicking (Thelen, 1985). Thelen (1994) attached infants' legs to one another with an elastic band and set up the conjugate reinforcement task such that in order to fully activate the overhead mobile, the infants needed to perform simultaneous, in-phase kicking. She discovered that infants who had their legs attached together broke their preferred alternating kicking pattern and learned to perform more simultaneous kicks, which was the specific behavior required to fully activate the mobile (Thelen, 1994). This line of research was furthered by Angulo-Kinzler (2001), who discovered that three-month-olds could discover and select very precise leg movements in order to activate an overhead mobile. In her study, Angulo-Kinzler fitted infants' legs with a goniometer to measure joint angle, which was fed through a computer and attached to

the overhead mobile. When infants' legs were in a particular posture, indicated by the goniometer, the computer activated the mobile. Results showed that the infants discovered the particular leg posture required to activate the mobile and spent more time with their legs near that posture (Angulo-Kinzler, 2001). The results from studies that use the conjugate reinforcement paradigm not only indicate that infants are capable of discovering contingent relationships in their environment through exploratory movements, but they are also able to capitalize on these relationships to select leg movements specific to the task-at-hand. Specifically, through the generation of various exploratory leg movements, the infants perceive particular consequences as valuable, or functional to the task (e.g. activating the mobile), and select those movements expected to result in that consequence.

Recently, studies examining such exploratory and selective processes have been applied to the emergence and development of reaching behavior. In a study conducted by Lobo, Galloway, & Savelsbergh (2004), researchers attempted to understand how particular types of experiences affect the emergence of reaching in infants. Non-reaching infants were provided with two different types of arm movement experience: general movement and task-related experience. The general movement experience condition was set up in much the same way as that of Rovee-Collier's conjugate reinforcement experiments (Rovee-Collier, 1991; Rovee-Collier et al., 1978; Rovee & Rovee, 1969); however, in this study infants' arms were tethered to the mobile. For this general movement experience group, a wide range of arm movements activated the mobile in rewarding ways. On the other hand, infants in the task-related experience condition were provided only with opportunities to actively reach for objects placed within their reaching space. Thus, in the task-related condition, only certain types of arm movements

produced a rewarding outcome. Following the training, changes in hand-object contacts were assessed in a reaching context. Infants in the general movement experience condition exhibited significantly more hand-object contacts than infants who did not receive additional experience, while the task-related experience group produced the greatest increase in hand-object contacts. This increase was significantly higher than that of the general movement experience group as well. Lobo and her colleagues concluded that the infants who received the general movement experience were able to explore a wider range of arm movements that resulted in rewarding activation of the mobile, through which they gained better control over many different arm movements. This better control allowed them to perform more generalized arm activity in the reaching context, which increased the likelihood of success. However, infants in the task-related condition were able to practice within the reaching context and actively utilized arm movements necessary for success in the reaching situation, which aided in the selection of those particular reaching movements.

This task-related result was recently replicated in a study by Lobo & Galloway (2008). In this study, parents were instructed to spend time each day for three weeks instructing their infant on how to reach for objects presented at midline. As part of the daily experience parents were first asked to direct their infant's attention to his or her own hands as well as to an object presented at midline. Next, parents were to move their infant's hands into contact with the object. Following this, parents allowed their infant to actively attempt to reach for and contact the objects. Infants who received this daily, object-directed experience displayed earlier reaching onsets when compared to a group that only received additional social experience without objects. It seems that in both the Lobo et al. (2004) and Lobo & Galloway (2008)

studies, those movements ending in successful hand-object contact within the specific reaching situation are more valuable, or functional to the reaching task, and aid the selection process. Thus, through specific practice in the reaching context the infants gain better control over arm movements specific to the reaching situation.

Some researchers have proposed that repeated exposure within a task context alone could be enough to induce improvement in behaviors related to that specific task. Work in the area of nonhuman animal learning has supported this idea and may be found in classic studies conducted by E. L. Thorndike (1927) and H. Harlow (1949) with cats and monkeys, respectively. Both found that these nonhuman animals were capable of learning to solve a task through basic repeated exposure to that task over time. Not only did the animals become successful at the task to which they were repeatedly exposed, but Harlow (1949) discovered that the monkeys were forming what he termed learning sets, which signified that the monkeys were learning how to learn. This in turn allowed them to transfer what they learned on one task to another, similar task. In a more recent study, Schneider & Suomi (1992) provided rhesus monkey newborns with differential rearing environments to examine the progression in early behavioral activity. Rhesus monkey infants who were provided with a cloth surrogate and repeated opportunities to reach for and manipulate small infant toys displayed significantly higher scores on measures of reaching, grasping, and motor coordination relative to other groups that did not receive such repeated opportunities to interact with objects (Schneider & Suomi, 1992). This work from the nonhuman animal literature highlights the notion that the learning processes that underlie animals' capability to take advantage of repeated opportunities to discover task solutions may be continuous across evolutionary history.

More recently with human infants, Bojczyk & Corbetta (2004) provided one group of six and a half month-olds with limited, but repeated, exposure (six trials per week) to an object retrieval task until they were successful at retrieving the objects from within the box. Another group, which was age-matched to when infants in the repeated exposure group were successful at retrieving objects from within the box, only experienced the task once. In addition, when the task was presented to the infants, experimenters offered no specific training or cueing to aid the infants in discovering a solution to the task. The researchers found that infants who were repeatedly exposed to the task significantly outperformed infants who were only presented with the task once. They argued that repeated exposure without specific training procedures, which permitted repeated and active exploration of specific actions and the associated consequences, enhanced infants' selection of those actions resulting in more valuable consequences, and subsequently performance on the task (Bojczyk & Corbetta, 2004).

The findings from Lobo et al. (2004), Lobo & Galloway (2008), and Bojczyk & Corbetta (2004) fit well with the dynamic systems, neuronal group selection, and approximate optimal control frameworks. These studies suggest that providing the opportunity for infants to actively explore solutions to particular perceptual-motor problems, which allows for the discovery of the functional value of these actions when hitting the object or seeing the object when opening the box, suffices to provide valuable experience and enhance the development of specific reaching behaviors. With regard to the emergence of reaching, as hand-object contact may be considered an indicator of a successful reach, it is plausible to consider whether it may be possible to highlight that functional consequence, and enhance the process of learning to reach.

This question has recently been explored by Needham and her colleagues (Libertus & Needham, 2009, 2010; Needham et al., 2002). Needham and colleagues created "sticky" mittens to explore the effects of simulated grasping experience upon object-directed activity, especially object engagement and exploration (Needham et al., 2002), and the development of reaching (Libertus & Needham, 2009, 2010). The function of the "sticky" mittens was to provide pre-grasping infants with the sensation of successful grasping. Infant mittens were altered by placing the "soft" side of Velcro on the palm area while the corresponding "hard" side of the Velcro was placed on desired objects. If the infants happened to make hand-object contact, the object adhered to the mitten as if the infant had performed a successful reach and grasp. Experience with the "sticky" mittens was provided to infants of three months and nine days of age by the parents for 12-14 consecutive days. After receiving the "sticky" mittens experience, infants displayed significantly more object-directed activity when compared to an age-matched control group that did not receive any additional experience. Specifically, Needham et al. (2002) found significantly more visual, oral, and manual exploration of objects as well as more intentional attempts to reach for objects in the "sticky" mittens experience group than in the control group. Libertus & Needham (2009) found similar results excluding a significant increase in visual exploration of the objects. Overall, Needham and her colleagues concluded that the simulation of grasping provided by the "sticky" mittens experience drove the increases in object-directed activity.

The conclusion posed by Needham and her colleagues seemed to be a logical one if the act of grasping an object is considered to be a valuable consequence. In continuing this line of thought, through the provision of this valuable sensation infants began to select the arm

movements that successfully led to "grasping." However, the Needham group did not address whether the increased object-directed activity was driven by the simulated grasping per se or whether the repeated exposure to the reaching context, which fostered the opportunity to explore actions and their consequences within the reaching space, brought about the observed increases.

Williams & Corbetta (2011) recently examined this topic in detail. In particular, the problem of dissociating between simulated grasping experience and repeated reaching exposure was addressed by the addition of a "non-sticky" mittens group. Thirty pre-reaching infants were randomly assigned to one of three groups: "sticky" mittens (seen for 16 consecutive days with 14 days of in-home repeated task exposure with simulated grasping), "non-sticky" mittens (seen for 16 consecutive days with 14 days of in-home repeated task exposure without simulated grasping), or control (seen only on days 1 and 16 with no mittens). Results suggested that the provision of simulated grasping did not offer a distinct advantage to the "sticky" mittens group when learning to reach for objects. All groups showed increased amounts of intentional hand-object contacts when comparing days 1 and 16. However, only the infants in the "sticky" and "non-sticky" groups showed significant increases. In more detail, when the 16 consecutive days were analyzed for the "sticky" and "non-sticky" groups, only the "non-sticky" group showed a sustained increase in the amount of intentional contacts over time. Overall, these findings indicate that basic repeated exposure to the reaching context, which both mittens groups received, seems to underlie the progressive discovery of appropriate reaching movements and object-directed activity.

Findings such as those from Williams & Corbetta (2011), in conjunction with Lobo et al. (2004), Lobo & Galloway (2008), and Bojczyk & Corbetta (2004), highlight the notion that no explicit guidance is necessary for infants to discover appropriate solutions to novel perceptual-motor tasks. Instead, self-guided exploration, fostered by repeated exposure to the particular reaching context, seems to be an important mechanism driving the exploration and selection of successful reaching behaviors. Furthermore, the body of evidence that has highlights young infants' ability to discover and capitalize on contingencies embedded in the environment, supports the idea that varied action outcomes available for discovery during repeated task exposure may impact the emergence and development of reaching in different ways.

Focus of the current study

As shown by Williams & Corbetta (2011), the action outcome of "grasping" is not the driving force behind improvements in object-directed activity, and more specifically, in the emergence of reaching. One possible explanation as to why the simulated grasping experience is not advantageous to the process of learning to reach may be that the grasping of an object is not perceived by the young infants as a valuable, or functional, consequence as these infants are just beginning to figure out how to contact objects. This idea fits with prior work on infant reaching and grasping development, which indicates that the first perceptual-motor problem infants need to figure out is how to get their hand(s) near the desired object for contact (Thelen et al., 1993; von Hofsten, 1984; White, Castle, and Held, 1964). Grasping an object typically occurs a few months after infants are able to contact objects (Gabbard, 2004; von Hofsten & Lindhagen, 1979). Therefore, action outcome manipulations should be tailored to enhancing infants' ability

to bring their hand(s) into contact with desired objects if we want to enhance the process of learning to reach. These manipulations may be designed from two different standpoints.

Primarily, in the mastery motivation literature, researchers have found higher task persistence in six-month-old infants if a greater amount of objects in their typical environment are responsive to their actions (Jennings, Harmon, Morgan, Gaiter, & Yarrow, 1979). This early exposure to responsive objects in six-month-olds was also related to infants' task persistence when they were 12 months of age. Thus, infants who are exposed to objects that highlight the contingent relationship between actions and consequences show greater persistence when presented with a task that requires a search for a solution. Jennings et al., (1979) defined persistence as the continued search for feedback from objects. Thus, persistence may be considered a form of exploration when presented with certain mastery tasks, and in turn, may also be applied to the task of learning to reach. Therefore, since repeated exposure to responsive objects has been shown to increase task persistence (e.g. exploration), then providing pre-reaching infants with the opportunity to interact with these types of objects may aid the discovery of contingent relationships between specific arm movements and their consequences, and thus facilitate the selection of those successful movements. Specifically, objects that produce multimodal stimulation (move and make a sound) contingent upon infants' successful arm movements may highlight the functional value of those arm movements. This, in turn may increase infants' persistence at exploring and repeating such behaviors resulting in a functionally adaptive, or valuable, consequence and in this way efficiently discover a solution to the particular task-at-hand. Indeed, we know from prior work that even young infants are sensitive to contingencies between their actions and outcomes and are able to modulate their behavior

based upon those contingent relationships that prove to be the most rewarding, or functional to the task-at-hand (Angulo-Kinzler, 2001; Rochat, 1998; Rovee-Collier, 1991; Rovee-Collier et al., 1978; Thelen, 1994).

Secondly, it is possible that persistence in searching for a task solution, may be enhanced through the provision of continuous multimodal stimulation, independent of action-outcome contingencies. Research has shown that young infants, when given a choice, allocate more visual attention toward objects that move rather than static objects (Gibson, 1988; Ruff & Rothbart, 1996). In addition, according to the intersensory redundancy hypothesis proposed by Bahrick & Lickliter (2000), when object motion is synchronously paired with sounds, infants selectively attend the multimodal event and ignore other items present in the visual scene (Bahrick, Lickliter, & Flom, 2004). Work conducted in the framework of the intersensory redundancy hypothesis has shown that the synchronous presentation of motion and sound serve to capture and maintain infants' attention, which facilitates the perceptual learning of amodal properties present in the multimodal event such as rhythm, rate, and location (Bahrick & Lickliter, 2000). Furthermore, recent work conducted by Gibson, Tsolo, Libertus, & Needham (2009) illustrated that infants who received brief, simulated grasping experience with sounding objects showed greater visual attention to objects when compared to infants who received the experience with non-sounding objects. This particular selection of research brings about the idea that simply being exposed to multimodal objects, despite objects' responsiveness being non-contingent upon infants' actions, may serve to drive more object-directed behavior (e.g. visual attention, reaching attempts), which would in turn increase the likelihood of hand-object contact and the discovery of functional consequences.

In this study I examined the effects of repeated exposure to contingent, multimodal action outcomes and continuous multimodal stimulation, relative to basic repeated exposure to the reaching situation, upon the emergence of reaching in infants. I asked the following questions: 1) If infants received repeated reaching experience with objects that moved and made sound only upon successful hand-object contact, would this experience serve to accentuate the value, or functionality, of the successful reaching movements and subsequently enhance infants' persistence to explore and select similar successful movements?; and 2) If infants were simply provided with repeated opportunities to reach for objects that continuously moved and produced sound, independent of hand-object contact, would infants be more persistent at exploring and discover a solution to the reaching task?

Consistent with previous studies that highlighted the impact of early, repeated reaching experience upon the emergence and development of reaching, I expected to see increased amounts of reaching behavior in the contingent and continuous multimodal group, as well as in the basic repeated exposure group. However, I predicted that despite the increases observed in all groups that received repeated opportunities to reach for the objects, the infants in the contingent multimodal group would display the highest amount of successful reaching behavior. This prediction was rooted in the theoretical notion that the functional value of successful hand-object contacts would be highlighted and/or increased by infants' discovery of the embedded contingent, multimodal stimulation. Therefore, infants who received this repeated, sensory-motor experience would exhibit a more persistent and efficient exploration and selection process, and thereby demonstrate a greater amount of successful reaching behavior over time relative to

infants who received continuous multimodal stimulation and basic repeated exposure to the reaching situation.

In addition, I expected that infants' persistence to perform object-directed behavior would be enhanced through repeated opportunities to attend and reach for continuously moving and sounding objects. Based on the principles of the intersensory redundancy hypothesis, infants in the continuous multimodal group would be more likely to direct their visual attention to the moving and sounding object and display the highest amount of visual attention toward the objects. This increased visual attention would facilitate their persistence to attempt to reach and contact the object. In addition, through attending the synchronous multimodal stimulation, infants in this group may gain a better understanding of object location, an amodal property contained in the multimodal event, and demonstrate more directed reaching movements relative to infants in the basic repeated exposure group and control group.

Method

Participants

Forty-four infants were recruited within the week prior to turning three months of age (*M* = 85.65 days, *SD* = 2.43 days) from the Greater Knoxville, Tennessee area via formal letter and follow-up phone calls. The names and addresses were obtained through a Tennessee government-supplied database of birth records. Each infant was randomly assigned to one of four groups: 1) Contingent multimodal (n = 11; 6 females, 5 males), 2) Continuous multimodal (n = 11; 6 females, 5 males), 3) Repeated task exposure (n = 11; 5 females, 6 males), or 4) Non-repeated control (n = 11; 6 females, 5 males). The repeated task exposure and control groups were infants utilized in a prior study (Williams & Corbetta, 2011). All infants included in the

final sample were full term and possessed no known sensory, motor, or neurological impairments based upon parental report. In addition, all infants were unable to successfully reach and contact objects at the start of the study. Infants who met these criteria were followed longitudinally for 16 consecutive days (excluding the control group) as per Williams & Corbetta (2011).

Material

During all testing sessions infants were supported in a custom-designed infant seat reclined ten degrees from the vertical. A foam strap was secured around infants' torsos in order to provide full postural support and permit a full range of motion of the limbs. The infant seat was situated behind a small, wooden table (15" wide x 25" long x 15" high). Atop the table was a custom-made wooden cover, which contained a central hole through which objects were presented. The table height (including the custom-made wooden cover) was approximately waist-high for all infants.

Objects used for all sessions were a mixture of small, colorful plastic objects, which were comprised of non-toxic materials. These objects, which did not move nor make sound even upon hand-object contact, were used for all sessions held in the laboratory and for the repeated task exposure condition.

For the contingent multimodal condition, objects moved and made sound only upon hand-object contact. The original objects were modified by placing a bell inside and were placed onto a small, Velcro-covered platform atop a 1 ½ inch stiff spring. The spring was mounted to the top of a 3 ½" tall x 4 ½" wide wooden block which was situated beneath the custom-made wooden table cover and was flush with the top of the cover. Thus, only the object atop the

spring protruded through the table cover. With this particular set-up infants could be presented with different objects on each trial.

For the continuous multimodal condition, objects oscillated and made sound regardless of hand-object contact. The original objects were modified in the same way as for the contingent group. However, the objects were placed onto a small Velcro-covered platform mounted to a stiff plastic rod atop a 3 ½" tall x 4 ½" wide custom-designed object motor. The object motor was situated beneath the custom-made table cover so that the top of the motor was flush with the table cover. The motor was activated by a button located on the side of the outer casing. Once the button was depressed, the motor remained activated for one minute, oscillating the objects in a left-right motion and then shut off on its own. All parts of the object motor were encased in a hard plastic cover to prevent infants from contacting any moving part of the motor's machinery.

During all laboratory sessions, three video cameras were used to capture the looking and reaching behavior of the infants. One camera was placed directly across the table in front of the infant at eye level in order to capture gaze behavior. The two remaining cameras were situated 90 degrees to the left and right of the infant in order to capture the reaching movements of each arm. The two lateral cameras were fed through a digital video switcher (Datavideo Corporation, Whittier, CA), which merged the two camera views into a split-screen arrangement. This split-screen view was then sent into a VCR where it was recorded onto a VHS tape with a frame counter (Horita, Mission Viejo, CA). During all home sessions, one video camera was used to capture both the looking and reaching behavior of the infants. The camera was situated directly across the table from the infant at eye level. All of the behavior for home sessions was recorded directly onto VHS-C video tapes.

Arm movement kinematics were captured through the use of the Flock of Birds motion analysis system (Ascension Technology Corporation, Burlington, VT) during all laboratory sessions. Two mini bird markers (8 mm) were applied to the dorsal side of each wrist with Johnson & Johnson hypoallergenic tape. The wires for the markers were taped at the shoulder and behind the infant seat so as to prevent them from interfering with arm movements. The Flock of Birds sampled movement data at 120 Hz. Arm kinematics were not collected during the home sessions.

Design and procedure

Testing proceeded in three phases: 1) Reaching assessment (day one in the laboratory), 2) Sensory-motor experience (days 2 – 15 in the home), and 3) Learning assessment (day 16 in the laboratory). The contingent, continuous, and repeated task exposure groups participated in all three phases while the control group only participated in phases one and three (see figure A1; all figures and tables may be found in the appendix).

Reaching assessment phase (day one; laboratory session)

All infants participated in this phase of the study. This first laboratory visit was designed to assess infants' reaching behavior and to establish baseline measures of visual attention and arm movement kinematics. First, infants were placed securely in the infant seat and situated behind the waist-high wooden table. Prior to applying the Flock of Bird markers to infants' wrists, one trial was collected with one marker placed on the table-top where objects were to be located on each trial so as to encode object position. Then, the markers were applied to the infants' wrists. Trials began with one experimenter seated across the wooden table from the infant with one object in hand. The experimenter captured the infants' attention to the object and

then placed it on the pre-encoded position at midline and approximately 12 ½ cm in front of the infants. A second experimenter triggered the Flock of Birds and kept track of trial duration. Once the object was placed on the table-top, the experimenter situated across from the infant remained silent and did not interfere with infants' behavior in the presence of the object. Ten, one minute trials were collected. Only infants that performed zero hand-object contacts on day one were permitted to continue to the next phase of the study as per Williams & Corbetta (2011).

Sensory-motor experience phase (days two through 15; home sessions)

Infants in the contingent, continuous, and repeated task exposure groups received daily sensory-motor experience sessions in their homes. Two experimenters traveled to infants' homes to administer the sensory-motor experience for 14 consecutive days. The home sessions were conducted in a quiet area of the home and in a similar manner as the laboratory sessions. Once infants were secured in the infant seat behind the wooden table, one experimenter sat directly across the table from the infants, captured the infants' attention with one object, and then placed it within infants' reaching space at midline. After the object was in place, the experimenter across the table remained silent while the second experimenter monitored the trial duration. Just as for the laboratory visits, ten, one minute trials were collected. During each one minute trial, all infants received the opportunity to repeatedly attempt to reach for and contact objects.

Learning assessment phase (day 16; laboratory session)

All infants participated in this final session. The purpose of this session was to reassess infants' looking and reaching behaviors after the 14 consecutive days of sensory-motor experience and to compare these measures with those of the control group, which did not receive

the repeated sensory-motor experience. Once infants were secured in the infant seat and the Flock of Bird markers were applied, the session was conducted in the same manner as the reaching assessment phase on day one.

Analyses

All video recordings of looking and reaching behavior were scored using the Noldus Observer XT-9 (Noldus Information Technology b.v., Wageningen, The Netherlands). The kinematic data was processed through the use of a custom-made Matlab program (The Mathworks, Inc., Natick, MA). Dependent measures were divided into three categories: reaching behavior, looking behavior, and movement kinematics. All analyses were performed only on times when objects were within infants' reaching space. Parametric analyses were utilized only when data met assumptions of normality, otherwise non-parametric statistics were employed.

Reaching behavior

Analyses on the reaching behavior included the average number of intentional hand-object contacts per trial and the average percent of trials with intentional hand-object contact. Intentional hand-object contact was coded when an infant looked at the object both prior to, during, and at hand-object contact. If the infant shifted their gaze away from the object during any part of this time period, the contact was coded as unintentional. Two independent coders scored the number of intentional contacts and trials with intentional contact from the behavioral videos on twenty percent of the sample. Interobserver reliability for all reaching measures reached at least 91% agreement.

Average number of intentional hand-object contacts per trial

This variable allowed for a continuous measurement of the amount of intentional hand-object contacts over the course of the study. For all infants on each day of the study, all intentional hand-object contacts were tallied and then divided by the total number of trials collected on that day. Averages were then calculated for each group by day.

Average percent of trials with intentional hand-object contact

The average percent of trials with intentional hand-object contact was calculated for all infants on each day of the study by dividing the number of trials during which infants performed at least one intentional hand-object contact by the total number of trials collected. Averages were then calculated for each group by day.

Looking behavior

Analysis of the looking behavior included the percent of time spent looking to each of five categories: object, experimenter, right hand, left hand, or elsewhere. Elsewhere was coded when infants looked anywhere other than the four categories such as looking at the table or the ceiling. This code was also used when the coder was unable to determine gaze location. The percent of time spent looking to each category was computed by dividing the look duration value corresponding to each category by the total trial duration. An average percent of total trial duration spent looking to each of the five categories was calculated for all infants and groups by day. Using the Noldus Oberver XT, two independent coders scored the number of gaze shifts and look durations amongst the five looking categories from the behavioral videos on twenty percent of the sample. Interobserver reliability for all looking measures reached at least 85% agreement.

Movement kinematics

All kinematic data collected with the Flock of Birds motion analysis system was imported into a custom-designed Matlab program, which first filtered the data with a zero-phase, second-order Butterworth filter with a 6 Hz cut-off. This program was used to process and calculate the following variables: average resultant distance between hand and object, resultant displacement and average velocity of arm movements, average peak velocity of arm movements, average number of movement units, and the average amount of time that the hands spent within 10 cm, 20 cm, 30 cm, and 30+ cm of the object. Descriptions on specific calculations for each variable are covered in turn.

Average resultant distance between hand and object

The resultant distance between hand and object was calculated by determining the distance between the x, y, and z coordinates of the pre-defined object position and the x, y, and z coordinates of the position of each hand. The square root of the summed squared distances was then computed to obtain the resultant distance. This value was then divided by the length of the data in order to obtain an average value.

Resultant displacement and average velocity

The average resultant displacement was calculated for each hand by taking the square root of the summed squared x, y, and z coordinates. In order to compute the average velocity of the resultant displacement, the program computed the absolute difference in resultant displacement with a three point technique and then multiplied by the sampling rate (120 Hz). Following this computation the value was divided by the length of the data to obtain an average value.

Average peak velocity

The custom-made Matlab program searched the velocity time series in a three point technique to detect the peaks in the velocity profile. The average peak velocity was calculated by dividing the values of the velocity peaks by the total number of velocity peaks in the time series.

Average number of movement units

The average number of movement units was computed from the velocity time series using a three point technique. The program counted a movement unit when it approached a change in direction (i.e. acceleration and deceleration) in the velocity time series. Movement units were only counted when changes in velocity were greater than five cm per second. Then, averages were computed for each group by day.

Average percent of time the hands were within 10 cm, 20 cm, 30 cm, or 30+ cm of object

In order to calculate the percent of time the hands were within 10 cm, 20 cm, 30 cm, or 30+ cm of the pre-defined object location, the program analyzed the resultant hand-object distance and calculated the proportion of time spent within each of these distance divisions. The proportions were then multiplied by 100 to obtain a percentage value. These values were then averaged by group and day.

Results

Due to sporadic fussiness not all infants received the full ten trials on all days of the study. Thus, it was important to ensure that infants in the contingent, continuous, and repeated task exposure groups all received equivalent amounts of task exposure. Exposure times for the groups were calculated for days two through 15 in total minutes. A one-way ANOVA indicated

that there was no significant difference in total exposure times between the contingent (M = 103.5, SD = 8.48), continuous (M = 107.5, SD = 13.74), and repeated task exposure (M = 114.64, SD = 12.39) groups ($F(2,30) = 2.550$, $p = .095$).

Reaching behavior

All analyses of reaching behavior were conducted first on the entire sample. Next, analyses were focused on infants from the repeated sensory-motor experience groups (contingent, continuous, repeated task exposure) who were consistent performers at the end of the study. Consistent performers were defined as those infants who performed at least one intentional contact on days 13, 14, 15, and 16 of the study. Based on this criterion, there were six performers in both the contingent and continuous groups and five in the repeated task exposure group.

Average number of intentional hand-object contacts per trial

Figure A2 depicts the average number of intentional contacts per trial on days one and 16 for individual infants in each group. As may be seen, all infants in all groups performed zero contacts on the first day of the study and there was a wide range of performance for this measure on day 16. A total of 17 infants performed zero intentional contacts on the final day of the study (contingent, N = 4; continuous, N = 3; repeated task exposure, N = 3; control, N = 7). The contingent and repeated task exposure groups displayed a larger range of performance, with the infants in each group performing on average more than two intentional contacts per trial. In contrast, the majority of infants in the continuous and control groups displayed values of less than two intentional contacts per trial. All groups appeared to exhibit an increase when comparing day one with day 16. A modified Wilcoxon Signed-Ranks test was used to examine

within group change. A first modification to the test was to count infants who did not show improvement from the first to the final day of the study as negative ranks with values matching the lowest positive value of infants who improved. Secondly, to conform to a symmetrical distribution of difference scores, the maximum value for infants was set to 0.5 intentional contacts per trial. This maximum value was chosen such that the number of infants above 0.5 intentional contacts per trial equaled the number of infants who performed zero intentional contacts on the final day. Subsequently, any infant who performed 0.5 intentional contacts per trial or more on the final day received a value of 0.5. The test revealed significant increases from day one to 16 in the contingent (M_{Day16} = 2.28, SD_{Day16} = 3.11; Z = -2.076, p = .038), continuous (M_{Day16} = .63, SD_{Day16} = .67; Z = -2.430, p = .015), and repeated task exposure (M_{Day16} = 1.46, SD_{Day16} = 1.96; Z = -2.430, p = .015) groups, while the control group did not display a significant increase (M_{Day16} = .96, SD_{Day16} = .2.64; Z = -0.458, p = .647).

Group averages for this measure over time may be seen in figure A3. To examine the progression in the average number of intentional contacts per trial in the repeated groups over time, linear regression analyses were used. Figure A4 depicts the average daily values for the contingent, continuous, and repeated task exposure groups with associated linear trends. Significant linear increases were exhibited by the contingent (F (1, 14) = 79.51, p < .0001, R^2 = .85), continuous (F (1, 14) = 7.64, p = .015, R^2 = .35), and repeated exposure (F (1, 14) = 26.83, p < .0001, R^2 = .66) groups. Summary statistics for individual linear regressions for each group may be seen in Table A1. Based on the non-normality of the data, no repeated measures analyses were appropriate for the full data set.

Figure A5 displays the average number of intentional contacts per trial for the subset of infants in the contingent, continuous, and repeated task exposure groups who were considered consistent performers. A 3(Group) x 16 (Day) repeated measures ANOVA revealed a significant effect of day ($F(1,15) = 4.785$, $p < .0001$, $\eta_p^2 = .255$) and a marginally significant difference between groups at the alpha = .05 level ($F(2,14) = 3.666$, $p = .052$, $\eta_p^2 = .344$). Specifically, performing infants in the contingent group exhibited a significantly higher average number of intentional contacts per trial relative to the continuous group ($p = .02$) and a trend toward a higher amount relative to the repeated task exposure group ($p = .086$). There was no significant group by day interaction.

Average percent of trials with intentional hand-object contact

Figure A6 depicts the average percent of trials with intentional contact on days one and 16 for individual infants in each group. As for the previous reaching measure, it is apparent that there was a large range of performance for this measure on day 16. All groups appeared to exhibit an increase when comparing day one with day 16. Again, a modified Wilcoxon Signed-Ranks test was used to examine within group change. A first modification was to count infants who did not show improvement from the first to the final day of the study as negative ranks values matching the lowest positive value of infants who improved. Secondly, to conform to a symmetrical distribution of difference scores, the maximum value for infants was set to 50 percent. This maximum value was chosen such that the number of infants above 50 percent equaled the number of infants who performed zero intentional contacts on the final day. Subsequently, any infant who performed intentional contacts on 50 percent or more of the trials on the final day received a value of 50. The test revealed significant increases from day one to

16 in the contingent (M_{Day16} = 45.68, SD_{Day16} = 13.85; Z = -2.076, p = .038), continuous (M_{Day16} = 28.08, SD_{Day16} = 7.03; Z = -2.419, p = .016), and repeated task exposure (M_{Day16} = 41.34, SD_{Day16} = 11.62; Z = -2.430, p = .015) groups, while the control group did not display a significant increase (M_{Day16} = 18.48, SD_{Day16} = 33.25; Z = -0.458, p = .647).

Group averages for the percent of trials with intentional contact over time may be seen in figure A7. To examine the progression in the average percent of trials with intentional contact in the repeated groups over time, linear regression analyses were used. Figure A8 depicts the average daily values for the contingent, continuous, and repeated task exposure groups with associated linear trends. Significant linear increases were exhibited by the contingent (F (1, 14) = 28.04, p < .0001, R^2 = .67), continuous (F (1, 14) = 8.01, p = .013, R^2 = .36), and repeated exposure (F (1, 14) = 50.74, p < .0001, R^2 = .78) groups. Summary statistics for individual linear regressions for each group may be seen in Table A2. Based on the non-normality of the data, no repeated measures analyses were appropriate for the full data set.

Figure A9 displays the average percent of trials with intentional contact for the subset of infants in the contingent, continuous, and repeated task exposure groups who were considered consistent performers. A 3(Group) x 16 (Day) repeated measures ANOVA revealed a significant effect of day (F(1,15) = 6.966, p < .0001, η_p^2 = .332) and a significant difference between the three groups (F(2,14) = 4.534, p = .03, η_p^2 = .393). Specifically, performing infants in the contingent group exhibited a significantly higher percentage of trials with intentional contact relative to the continuous (p = .013) and repeated task exposure (p = .041) groups. There was no significant group by day interaction.

Looking behavior

Primarily, analyses were focused on the amount of looking directed toward the object. Figure A10 depicts the average percent of trial duration that infants in all groups spent looking at the object. A 4 (Group) x 2 (Day) repeated measures ANOVA indicated that infants in the four groups did not display a significant change in time spent looking at the toy when only comparing days one and 16. In addition, no significant differences were observed between the four groups on these days. However, as may be seen in figure A10, the three groups that received repeated exposure appeared to exhibit a decline in the amount of looking directed to the toy over time. A 3 (Group) x 16 (Day) repeated measures ANOVA was utilized to examine this change over time in detail. Indeed, the repeated measures ANOVA revealed a significant main effect of day with the groups displaying a decline in the amount of time spent looking toward the objects over time ($F(8.51, 255.37) = 4.055$, $p < .0001$)[1]. An examination of the 14 consecutive in-home sessions indicated significant linear decreases over time for the contingent (F (1, 13) = 10.40, p = .0073) and continuous groups (F (1, 13) = 19.69, p = .0008), but not for the repeated exposure group (F (1, 13) = 2.17, p = .1662). Summary statistics for individual linear regressions for each group may be seen in Table A3. There were no other significant differences or interactions observed between the groups.

Figure A11 depicts the average percent of trial duration by day that infants spent looking toward each of the five pre-specified categories (object, experimenter, right hand, left hand, elsewhere) for the continuous, contingent, and repeated task exposure groups. The 16-day averages for each repeated group may be seen in Table A4. Within all groups, no significant

[1] Assumption of sphericity was violated and the epsilon value for the test was less than .75. Based on Girden (1992), the Greehouse Geisser correction on the degrees of freedom was utilized.

change over time was observed for the amount of looking directed toward the experimenter, right hand, and left hand. Wilcoxon Signed-Ranks tests performed between categories on the 16-day averages within groups revealed that all infants directed more looking toward the objects relative to the experimenter (Z = -2.934, p = .003 (2-tailed); right hand (Z = -2.934, p = .003 (2-tailed)); and left hand (Z = -2.934, p = .003 (2-tailed).

Movement kinematics

All kinematic analyses were performed only on the preferred reaching hand and the time series corresponding to periods when infants were looking at the object. First, we defined the preferred reaching hand as the hand infants used most frequently for contacting the objects on the final day of the study. If infants did not contact objects enough to determine a distinct hand preference on the final day, we used the hand that contacted objects most frequently over the course of the study for the repeated groups. For the non-repeated control babies, we used the hand that exhibited the lowest movement speed during the reaching task on day 16 as the preferred reaching hand. This speed-based criterion was utilized based on prior research indicating that as infants approach the emergence of reaching, movement speed during the reaching task tends to decline (Bhat & Galloway, 2005). Then, the time series corresponding to when infants looked at the object was determined by synchronizing the lateral reaching cameras, which contained the superimposed kinematic time codes, with the gaze camera, which was utilized to code the times when infants looked at the object.

Hand preference

Based on these criteria, hand preferences by group were as follows: contingent (2 right, 9 left); continuous (1 right, 10 left); repeated exposure (2 right, 9 left); and control (3 right, 8 left). When all infants' hand preferences were pooled, 36 out of 43 infants displayed a left hand preference, a proportion that was significantly greater than chance (.50) according to a binomial test ($p < .0001$, 2-tailed).

Average resultant distance between hand and object

The average resultant distance between infants' preferred reaching hand and the object by group may be seen in Figure A12. A 4 (Group) x 2 (Day) repeated measures ANOVA indicated that infants in the contingent (M_{Day1} = 15.73, SD_{Day1} = 3.97; M_{Day16} = 11.97, SD_{Day16} = 4.38), continuous (M_{Day1} = 14.66, SD_{Day1} = 3.44; M_{Day16} = 13.39, SD_{Day16} = 2.63), repeated task exposure (M_{Day1} = 15.31, SD_{Day1} = 2.66; M_{Day16} = 11.41, SD_{Day16} = 4.10), and control (M_{Day1} = 17.03, SD_{Day1} = 3.41; M_{Day16} = 13.37, SD_{Day16} = 4.00) groups all decreased the average resultant distance between hand and object between day one and 16 ($F(1,40) = 16.6$, $p < .0001$, η_p^2 = .290). No other significant differences or interactions were observed between the four groups.

Average peak velocity of reaching movements

The average peak movement velocity of the preferred reaching hand by group on the first and last day of the study may be seen in Figure A13. According to this figure, infants in the continuous (M_{Day1} = 11.01, SD_{Day1} = 1.43; M_{Day16} = 13.46, SD_{Day16} = 2.88) and control (M_{Day1} = 12.68, SD_{Day1} = 1.77; M_{Day16} = 12.82, SD_{Day16} = 2.76) groups displayed an increase in peak movement speed while infants in the contingent (M_{Day1} = 12.69, SD_{Day1} = 1.35; M_{Day16} = 12.36, SD_{Day16} = 1.84) and repeated task exposure (M_{Day1} = 12.54, SD_{Day1} = 2.28; M_{Day16} = 11.38,

SD_{Day16} = 1.77) groups displayed a decrease. A 4 (Group) x 2 (Day) repeated measures ANOVA revealed a day by group interaction ($F(3,40) = 4.106$, $p = .012$, $\eta_p^2 = .235$). To explore this interaction further, pairwise comparisons were used and indicated that the continuous group showed a significant increase in peak movement speed when comparing day one to 16 ($p = .022$). No other significant differences were observed between the four groups.

Average number of movement units

The average number of movement units for the preferred reaching hand by group on the first and last day of the study may be seen in Figure A14. A 4 (Group) x 2 (Day) repeated measures ANOVA indicated that infants in the contingent (M_{Day1} = 474.15, SD_{Day1} = 272.03; M_{Day16} = 346.86, SD_{Day16} = 224.63), continuous (M_{Day1} = 261.46, SD_{Day1} = 211.55; M_{Day16} = 365.91, SD_{Day16} = 187.11), repeated task exposure (M_{Day1} = 534.13, SD_{Day1} = 321.80; M_{Day16} = 362.41, SD_{Day16} = 251.81), and control (M_{Day1} = 521.84, SD_{Day1} = 366.09; M_{Day16} = 465.25, SD_{Day16} = 255.76) groups did not display any significant change over time in the average number of movement units of the preferred reaching hand. No other significant differences were observed between the four groups.

Average percent of time preferred hand within 10 cm of object

The average percent of time that infants' preferred reaching hand was within 10 cm of the object by group may be seen in Figure A15. A 4 (Group) x 2 (Day) repeated measures ANOVA indicated that infants in the contingent (M_{Day1} = 12.99, SD_{Day1} = 18.63; M_{Day16} = 40.81, SD_{Day16} = 33.02), continuous (M_{Day1} = 18.23, SD_{Day1} = 27.95; M_{Day16} = 27.27, SD_{Day16} = 24.51), repeated task exposure (M_{Day1} = 11.65, SD_{Day1} = 16.80; M_{Day16} = 41.57, SD_{Day16} = 37.84), and control (M_{Day1} = 5.88, SD_{Day1} = 10.05; M_{Day16} = 25.97, SD_{Day16} = 29.40) groups increased the amount of

time spent near the object between day one and 16 ($F(1,40) = 21.785$, $p < .0001$, $\eta_p^2 = .353$). No other significant differences or interactions were observed between the four groups.

Discussion

Learning to reach is a process that is viewed as one of discovery that emerges through infants' self-generated actions within the reaching context. Recent theoretical approaches aimed at understanding this complex process have argued that through early exploratory arm movements, such as spontaneous and pre-reaching movements, infants may sporadically perform successful hand-object contacts. These arm movements culminating in contact with the object are presumed to be more functionally valuable to the task-at-hand relative to movements that do not result in hand-object contact. Thus, the arm movements that correspond to greater functional value will increase infants' persistence at trying to repeat that valuable experience. As a result, the emergence of reaching is a gradual process of exploration and selection that occurs within the task context and proceeds based on the functional value of particular reaching actions, whereby the most valuable actions become reinforced and eventually selected (Berthier et al., 2006; Edelman, 1987; Thelen & Smith, 2006).

Based upon this contemporary framework, it is through repeated exposure to the reaching context, which provides infants with the opportunity to explore different arm movements and their consequences, and subsequently permits the gradual selection of those movements appropriate for the reaching task. The importance of repeated task exposure has been highlighted by prior work with findings that showed infants who were provided with repeated opportunities to actively explore the consequences of their actions within a reaching context selected the movements appropriate to the task-at-hand, and thus exhibited improved reaching

behavior (Bojczyk & Corbetta, 2004; Lobo et al., 2004, 2008; Williams & Corbetta, 2011). The primary goal of the current study was to further examine the impact of repeated exposure to a reaching task upon the emergence of reaching in infants. Specifically, three-month-old infants were provided with in-home, experimenter-led, repeated exposure to a reaching task, which contained objects that moved and produced sound in a contingent or continuous fashion, or that did not move nor make sound. I explored whether the provision of repeated exposure to contingent and continuous multimodal objects enhanced the exploratory and selective processes involved in learning to reach beyond basic repeated task exposure.

Based on the prior work just discussed, it was expected that all groups that received repeated opportunities to reach, despite the type of object to which they were exposed, would display significant increases in the amount of intentional reaching over time. However, infants who were provided with exposure to the contingent multimodal objects were expected to display the greatest amount of intentional reaching due to the direct multimodal link between a successful arm movement and the outcome. In particular, arm movements that resulted in the activation of the contingent multimodal objects, which was presumed to be perceived by the infant as a salient and interesting consequence, would result in a heightened functional value designation for that particular behavior, which would increase the frequency of attempts to repeat that experience and aid the selective process.

The results obtained on the amount of intentional reaching behavior were consistent with prior work (Bojczyk & Corbetta, 2004; Lobo et al., 2004, 2008; Williams & Corbetta, 2011) and the proposed predictions. In general, through repeated task exposure, infants exhibited improved reaching behavior. Specifically, on measures of both the average number of intentional contacts

per trial and the average percent of trials with intentional contact, only infants in the repeated exposure groups (contingent, continuous, repeated exposure) displayed a significant increase when day one and day 16 were compared (see figures A2 and A6). The control group, which did not receive daily exposure to the reaching task, failed to display a significant increase in the amount of intentional reaching behavior. In addition, on both measures, all repeated groups displayed significant linear increases over time when all days were considered (see tables A1, A2 and figures A3, A4, A7, A8).

Although all repeated exposure groups displayed improved reaching behavior over time, data from consistently performing infants suggested that repeated exposure to contingent multimodal objects aided the learning to reach process the most. Infants were considered to be consistent performers if they performed at least one intentional contact on days 13 through 16 consecutively, and were presumed to be the infants who gained the most from their respective object-directed interactions. On both measures of intentional reaching, performing infants from the contingent multimodal group exhibited significantly higher amounts of intentional reaching relative to the continuous and repeated task exposure groups (see figures A5 and A9). Most notably, however, were the results for the average number of intentional contacts per trial, which provided a measure of the amount of repeated intentional hand-object contacts that the infants performed. Consistent with the theoretical notion of selection through the discovery of functional value, infants in the contingent group displayed significantly more intentional contacts per trial relative to the other repeated groups. In other words, it appears that the contingent multimodal action outcome served to highlight the functional value of the behavior leading to that outcome, and in turn, infants increased the frequency of attempts, or persistence, to

reproduce the interesting action consequence. This argument that infants may be more persistent to discover a task solution through exposure to contingently-activated objects fits well with work from Jennings et al. (1979), who found such a result with infants at six and 12 months of age. Thus, through the repeated opportunities to perceive the salient multimodal link between a successful reaching action and its outcome, the infants were able to display an enhanced selective process (Angulo-Kinzler, 2001; Rovee-Collier, 1991; Thelen, 1994).

The examination of infants' looking behavior indicated that no group spent significantly more time than another visually attending the objects. This result was somewhat surprising given that the work conducted from the perspective of the intersensory redundancy hypothesis has found higher levels of attention allocation toward synchronous multimodal events. One possibility, which cannot be resolved from this study, may be that actual looking behavior and level of attention correspond to two different things. Indeed, psychophysiological studies from J. E. Richards and his colleagues have shown that infants shift in and out of different phases of attention (orienting, sustained attention, attention termination) during single looks toward objects and events, with the sustained attention phase corresponding to the time of active information processing (Lansink, Mintz, & Richards, 2000; Reynolds & Richards, 2008; Richards, 1997). To relate this to the current findings, infants in the groups may have displayed similar looking patterns toward the objects; however, the infants may have displayed variations in the amount of time spent in the different phases of attention. Specifically, infants in the continuous group may have spent more time in the sustained attention phase, which potentially would have allowed them to pick up specific information about the multimodal event and map that information onto their reaching attempts. This notion will be addressed further in a later section.

Also with regard to the looking behavior results, there was no change within any group in the amount of looking toward the objects when only days one and 16 were compared. However, when all days were considered for the repeated exposure groups, all groups displayed a decline in the amount of time spent looking toward the objects (see table A3 and figure A10). This result may be due to the fact that over time and with repeated presentation of similar stimuli, responses directed toward those stimuli tend to decrease, as has been shown in many infant habituation studies (Cohen, 1969; Fantz, 1964; Ruff & Rothbart, 1996). However, an alternative explanation is that infants simply became more efficient at mapping their intentions onto their actions rather than losing interest in the task over time (Thelen et al., 1993, 1996). Support for this explanation is evident in the increase in intentional contacts over time despite a decrease in the amount of looking at the objects. If infants were losing interest in the task over time, a decrease in reaching behavior would evident in conjunction with the decrease in object-directed looking.

Over the entire study, the examination of the 16-day averages for the repeated groups indicated that all infants spent significantly more time visually attending the objects relative to the experimenter, right hand, and left hand (see table A4 and figure A11). This distribution of looking fits well with the work conducted by R. K. Clifton and colleagues that stated when infants are first learning to bring their hand(s) into contact with desired objects, they do not visually monitor the approach of their hand to the object in a continuous fashion (Clifton et al., 1993, 1994; Corbetta, 2009). In actuality, as may be seen in figure A11, all infants spent very little time looking at their hands.

The results obtained from the movement kinematic analyses provided a finer look at how infants in each group took advantage of the varied types of sensory-motor experience within the reaching context. First, infants in all groups, including the control group, displayed a significant decrease in the average hand-object distance when days one and 16 were compared (see figure A12). On a related measure, all infants displayed a significant increase in the amount of time spent with their preferred reaching hand near the objects (see figure A15). No differences were observed between the groups on these measures. This particular kinematic result is consistent with prior work, which has shown that over time infants progressively move their arms closer to the midline region (Bhat et al., 2005; Spencer & Thelen, 2000; von Hofsten, 1984; White et al., 1964).

Secondly, results on peak arm movement speed during the reaching task indicated that the selective process was evident even at the level of motor control in these very young infants and was congruent with the type of sensory-motor experience gained in the groups. This was especially true for infants in the continuous multimodal group. Primarily, peak arm movement speed during the reaching situation has been used as a measure of arm control in that higher peak velocities corresponded to less control while lower peak velocities indicated greater arm control (Thelen et al., 1993, 1996; Bhat et al., 2005). The day by group interaction obtained when days one and 16 were compared, indicated that infants in the continuous group learned to select higher movement speeds as those speeds were more likely to result in hand-object contact when the object was in motion (see figure A13). Selection of more rapid arm movements to accommodate the task-at-hand has not been explicitly shown in infants of this age who lack a great deal of general motor control and experience in a reaching situation. However, the fact that infants were

able to contact objects that were moving fits with classic work from von Hofsten & Lindhagen (1979), in which they showed that infants successfully began reaching for moving objects around the same time that they began to reach for stationary ones. Obviously from that particular study we may deduce that infants were able to modify their movement speed to reach out and contact objects in motion. Thus, it was no surprise that the infants in the current study were able to contact the moving objects. However, here we were able to track and demonstrate how these infants were able to modify the control of their early reaching movements in response to the particular sensory-motor experience gained while discovering a solution to the task.

To make a link between looking and reaching behavior, infants in the continuous group did not display significantly more looking toward the objects as was expected. However, as discussed earlier, looking behavior and level of attention may correspond to different things (Lansink et al., 2000; Reynolds & Richards, 2008; Richards, 1997). Therefore, the fact that we did not find the continuous group looking toward the objects more does not necessarily mean that they did not learn and utilize particular perceptual aspects of the multimodal event to select and guide their reaching actions. Based on the work from Richards and his colleagues in conjuction with the intersensory redundancy hypothesis (Bahrick & Lickliter, 2000), it may be that these infants, albeit showing similar amounts of looking toward the objects as the other groups, actually spent more time in the sustained attention phase and were able to pick up such amodal properties from the event as rate of motion and object location. Obviously, the detection of properties such as rate and location would be especially important for infants in the continuous group, as it may have facilitated the selection of more rapid reaching actions

appropriate to contacting the moving objects. This is only speculation as this study did not allow for the psychophysiological measurement of the level of attention.

Study limitations

One limitation of the current study has to do with the total amount of participants. Primarily, based upon the rigorous microgenetic research design, the time commitment was quite large and required many people to complete. Secondly, due to the design of the study, it was sometimes difficult to recruit parents for 16 consecutive days. Finally, with such a small sample size, the use of more powerful statistical analyses is limited; however, by increasing sample size, more statistical options would become available. Thus, additional research with a larger sample size is needed to substantiate the inferences made in the current study. However, despite the small sample size, the results are consistent with studies of similar designs and sample sizes such as Bojczyk & Corbetta (2004) and Lobo et al. (2004, 2008).

A second potential limitation is that this study only examined the short-term consequences that the various early sensory-motor experiences had upon the emergence of reaching. As stated previously, research has shown that the emergence of reaching has an impact on all domains of infant development such as future motor behavior (Bhat et al., 2005; Thelen et al., 1993, 1996), understanding of object properties (Bushnell & Bourdreau, 1993; Corbetta & Snapp-Childs, 2009), intermodal processing (Eppler, 2005), and even social behavior (Fogel, 1997; Fogel et al., 1992). As was demonstrated in this study, infants who received repeated opportunities to gain such early sensory-motor experience showed improved reaching behavior. Further research is necessary to investigate the potential long-term impact of such early experience upon other domains of development.

A final limitation has to do with the lack of movement kinematics for all days of the study, which would have provided a more complete picture of the selection of motor control parameters as a function of repeated experience. To obtain such data, experimenters would have had to set up the Flock of Birds motion analysis system in infants' homes for 16 consecutive days, which was not feasible for the current project.

Concluding remarks

The results of the current study may be sufficiently explained by the combination of dynamic systems (Thelen & Smith, 2006), neuronal group selection (Edelman, 1987), and approximate optimal control theories (Barto, 2002; Berthier et al., 2006). For instance, all infants who were provided with repeated opportunities to actively explore the reaching task displayed significant improvements in reaching behavior. Theoretically, it was through such repeated opportunities to actively attempt to reach and contact objects that successful reaching movements were gradually selected from the background of many arm movements. Furthermore, I believe that the results provide support to the idea that selection proceeds based upon the discovery of functional value. The significantly higher amount of intentional reaching behavior found in infants who discovered the embedded multimodal contingency seems to indicate that those interesting action consequences may have served to accentuate the functional value of the preceding actions and facilitated the repetition and gradual selection of those reaching actions.

This selective process was not only evident in overall intentional reaching behavior, but also at the finer level of movement control. Even these very young infants, who possessed very little experience within the reaching situation, were able to gradually discover and select

reaching movements appropriate for the specific reaching task to which they were exposed. This was especially evident in the peak speed measures of infants who were provided with daily opportunities to reach for moving and sounding objects. After only 14 days of exposure, infants in this group not only learned to contact the object but they also displayed a significant increase in their movement speed, which suggests that they selected those quicker movements to match the task of contacting a moving object. Overall, it was clear from this study that when presented with the challenging task of learning to reach, even very young infants are capable of discovering a solution to the specific task through the provision of repeated opportunities to explore the task space.

Overall, an important message may be gleaned from the current results in tandem with prior work, which highlighted the importance of early opportunities for action to early learning processes (Bojczyk & Corbetta, 2004; Lobo et al., 2004, 2008, Williams & Corbetta, 2011). The applicability of such findings seems very natural when considering that in recent years, researchers have displayed an increased interest in the concept of play and the impact it has upon early learning (Burghardt, 2005; Frost, 1998; Ginsburg, 2007). Burghardt (2005) defined play as, "play is repeated, incompletely functional behavior differing from more serious versions structurally, contextually, or ontogenetically, and initiated voluntarily when the animal is in a relaxed or low-stress setting (p. 82)." The behaviors that young infants perform when exposed to the reaching context conform to each criterion contained within this definition, thus, I believe that learning to reach would be a good model of play and would permit the examination of its impact on general processes of early learning.

Furthermore, a key practical implication to be gained would be to emphasize the need for the opportunity to play, especially to parents, physical therapists, and clinicians. Through such play opportunities, infants may engage in the sensory-motor activity, which induces multidirectional interactions among sensory, motor, and neural systems, and subsequently allows for the gradual learning of adaptive behaviors. Indeed, work from Heathcock, Lobo, & Galloway (2008) began to move in this direction through the design of programs that teach parents, physical therapists, and clinicians who work with at-risk infants (e.g. pre-term, low birth weight) the importance of repeated opportunities to play, or in this specific instance, to reach for objects. The incorporation of this type of play into therapy sessions has resulted in significantly improved reaching behavior in these at-risk populations (Heathcock et al., 2008).

List of References

Angulo-Kinzler, R. M. (2001). Exploration and Selection of Intralimb Coordination Patterns in 3-Month-Old Infants. *Journal of Motor Behavior, 33,* 363-376.

Bahrick, L. E., & Lickliter, R. (2000). Intersensory Redundancy Guides Attentional Selectivity and Perceptual Learning in Infancy. *Developmental Psychology, 36,* 190-201.

Bahrick, L. E., Lickliter, R., & Flom, R. (2004). Intersensory Redundancy Guides the Development of Selective Attention, Perception, and Cognition in Infancy. *Current Directions in Psychological Science, 13,* 99-102.

Bahrick, L. E., & Watson, J. S. (1985). Detection of intermodal proprioceptive-visual contingency as a potential basis of self-perception in infancy. *Developmental Psychology, 21,* 963-973.

Bartlett, F. C. (1932). *Remembering*. Cambridge, England: Cambridge University Press.

Barto, A. G. (2002). Reinforcement learning in motor control. In M. Arbib (Ed.) *Handbook of brain theory and neural networks* (2nd ed., pp. 968-972). Cambridge: MIT Press.

Bell, M. A., & Fox, N. A. (1996). Crawling experience is related to changes in cortical organization during infancy: Evidence from EEG coherence. *Developmental Psychobiology, 29,* 551-561.

Bertenthal, B. I., & Campos, J. J. (1987). New directions in the study of early experience. *Child Development, 58,* 560-567.

Berthier, N. E., Clifton, R. K., McCall, D. D., & Robin, D. J. (1999). Proximodistal structure of early reaching in human infants. *Experimental Brain Research, 127,* 259-269.

Berthier, N. E., Rosenstein, M. T., & Barto, A. G. (2006). Approximate Optimal Control as a Model for Motor Learning. *Psychological Review, 112,* 329-346.

Berthouze, L., & Goldfield, E. C. (2008). Assembly, tuning, and transfer of action systems in infants and robots. *Infant and Child Development, 17,* 25-42.

Bhat, A., Heathcock, J., & Galloway, J. C. (2005). Toy-oriented changes in hand and joint kinematics during the emergence of purposeful reaching. *Infant Behavior & Development, 28,* 445-465.

Bojczyk, K. E., & Corbetta, D. (2004). Object retrieval in the 1st year of life: learning effects of task exposure and box transparency. *Developmental Psychology, 40,* 54-66.

Bourgeois, J. P. (2001). Synaptogenesis in the neocortex of the newborn: the ultimate frontier for individuation? In Nelson & Luciana (Eds.), *Handbook of Developmental Cognitive Neuroscience* (pp. 23-34). Cambridge: MIT Press.

Bower, T. G. R. (1974). *Development in infancy*. San Francisco: Freeman.

Bower, T. G. R., Broughton, J. M., & Moore, M. K. (1970). Demonstration of intention in the reaching behavior of neonate humans. *Nature, 228,* 679-681.

Brazelton, T. B. (1973). *Neonatal Behavioral Assessment Scale* (Clinics in Developmental Medicine No. 50). London: Heinemann.

Burghardt, G. M. (2005). *The Genesis of Animal Play: Testing the Limits*. Cambridge: The MIT Press.

Bushnell, E. W. (1985). The decline of visually guided reaching during infancy. *Infant Behavior and Development, 8,* 139-155.

Bushnell, E. W., & Boudreau, J. P. (1993). Motor Development and the Mind: The Potential Role of Motor Abilities as a Determinant of Aspects of Perceptual Development. *Child Development, 64,* 1005-1021.

Carmichael, L. (1970).The Onset and Early Development of Behavior. In P. H. Mussen (Ed.), *Carmichael's Manual of Child Psychology* (3rd ed., pp. 447-563). New York: John Wiley & Sons, Inc.

Carrico, R. L., & Berthier, N. E. (2008). Vision and precision reaching in 15-month-old infants. *Infant Behavior & Development, 31,* 62-70.

Chiel, H. J., & Beer, R. D. (1997). The brain has a body: adaptive behavior emerges from interactions of nervous system, body and environment. *Trends in Neuroscience, 20,* 553-557.

Clark, J. E. (1995). On becoming skillful: patterns and constraints. *Research Quarterly for Exercise and Sport, 66,* 173-183.

Clearfield, M. W., & Thelen, E. (2001). Stability and flexibility in the acquisition of skilled movement. In Nelson & Luciana (Eds.), *Handbook of Developmental Cognitive Neuroscience* (pp. 253-266). Cambridge: MIT Press.

Clifton, R. K., Muir, D. W., Ashmead, D. H., & Clarkson, M. G. (1993). Is visually guided reaching in early infancy a myth? *Child Development, 64,* 1099-1110.

Clifton, R. K., Rochat, P., Robin, D. J., & Berthier, N. E. (1994). Multimodal perception in the control of infant reaching. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 876-886.

Coghill, G. E. (1930). Individuation versus integration in the development of behavior. *Proceedings of the National Academy of Sciences, 16,* 637-643.

Coghill, G. E. (1936). Integration and motivation of behavior as problems of growth. *Journal of Genetic Psychology, 48,* 3-19.

Cohen, L. B. (1969). Observing Responses, Visual Preferences, and Habituation to Visual Stimuli in Infants. *Journal of Experimental Child Psychology, 7,* 419-433.

Corbetta, D. (2009). Brain, body, and mind: Lessons from infant motor development. In J. P. Spencer, M. Thomas, & J. McClelland (Eds.), *Toward a unified theory of development: Connectionism and dynamic systems theory re-considered*. Oxford University Press.

Corbetta, D. (2009). Perceptual development: Visually-guided reaching. In E. B. Goldstein (Ed.), *Encyclopedia of Perception* (pp. 771-774). Thousand Oak: Sage Publishing, Inc.

Corbetta, D., & Snapp-Childs, W. (2009). Seeing and touching: The role of sensory-motor experience on the development of infant reaching. *Infant Behavior & Development, 32,* 44-58.

Corbetta, D., & Vereijken, B. (1999). Understanding development and learning of motor coordination in sport: The contribution of dynamic systems theory. *International Journal of Sport Psychology, 31,* 515-521.

Dodwell, P. C., Muir, D., & DiFranco, D. (1976). Responses of infants to visually presented objects. *Science, 194,* 209-211.

Dorris, M. C., Pare, M., & Munoz, D. P. (2000). Immediate Neural Plasticity Shapes Motor Performance. *The Journal of Neuroscience, 20,* 1-5.

Edelman, G. M. (1987). *Neural Darwinism: The theory of neuronal group selection*. New York: Basic Books, Inc.

Edelman, G. M. (1992). *Bright Air, Brilliant Fire: On the Matter of the Mind*. New York: Basic Books, Inc.

Edelman, G. M. (2004). *Wider than the sky: The phenomenal gift of consciousness*. New Haven: Yale University Press.

Eppler, M. A. (1995). Development of manipulatory skills and the deployment of attention. *Infant Behavior and Development, 18,* 391-405.

Fagg, A. H., Barto, A. G., & Houk, J. C. (1998). Learning to Reach Via Corrective Movements. *Tenth Yale Workshop on Adaptive and Learning Systems,* 1-9.

Fantz, R. L. (1964). Visual experience in infants: decreased attention to familiar patterns relative to novel ones. *Science, 146,* 668-670.

Fogel, A. (1997). Information, creativity, and culture. In C. D. R. P. Zukow-Goldring (Ed.), *Evolving explanations of development*. Washington, DC: American Psychological Association.

Fogel, A., Dedo, J. Y., & McEwen, I. (1992). Effect of postural position and reaching on gaze during mother-infant face-to-face interaction. *Infant Behavior and Development, 15,* 231-244.

Frost, J. L. (1998). Neuroscience, Play, and Child Development. *Paper presented at the IPA/USA Triennial National Conference*.

Gabbard, C. P. (2004). *Lifelong Motor Development*. San Franciso, CA: Pearson.

Gesell, A. (1952). *Infant Development: The embryology of early human behavior.* New York: Harper & Brothers Publishers.

Gesell, A. (1988). *The Embryology of Behavior: The Beginnings of the Human Mind*. Oxford: Blackwell Scientific Publications LTD.

Gesell, A., & Armatruda, C. S. (1947). *Developmental diagnosis. Normal and abnormal child development: Clinical methods and pediatric applications*. New York: Hoeber.

Gibson, E. J. (1988). Exploratory behavior in the development of perceiving, acting, and the acquiring of knowledge. *Annual Review of Psychology, 39,* 1-41.

Gibson, J., Tsolo, M., Libertus, K., & Needham, A. (2009, April). *Toys that make noise: The effects of multimodal early reaching experiences*. Poster presented at the biennial meeting of the Society for Research in Child Development, Denver, Colorado.

Ginsburg, K. R. (2007). The Importance of Play in Promoting Healthy Child Development and Maintaining Strong Parent-Child Bonds. *Pediatrics, 119,* 182-191.

Girden, E. R. (1992). *Anova: Repeated Measures*. California: Sage Publications, Inc.

Goldfield, E. C., Kay, B. A., & Warren, W. H. (1993). Infant bouncing: The assembly and tuning of action systems. *Child Development, 64,* 1128-1142.

Gottlieb, G. (2009). Environmental and Behavioral Influences on Gene Activity. In L. S. Liben (Ed.), *Current Directions in Developmental Psychology* (pp. 93-97). Boston: Pearson.

Gottlieb, G., Wahlsten, Lickliter, (2006). The Significance of Biology for Human Development: A Developmental Psychobiological Systems View. In R. M. Lerner (Ed.), *Handbook of Child Psychology Vol. 1: Theoretical models of human development* (5th ed., pp. 233-273). New York: John Wiley & Sons, Inc.

Green, M., & Piel, J. A. (2002). *Theories of Human Development: A Comparative Approach*. Boston: Allyn and Bacon.

Greenough, W., Black, J., & Wallace, C. (1987). Experience and brain development. *Child Development, 58,* 539-559.

Hadders-Algra, M. (2000). The Neuronal Goup Selection Theory: a framework to explain variation in normal motor development. *Developmental Medicine and Child Neurology, 42,* 566-572.

Hadders-Algra, M., & Prechtl, H. F. R. (1992). Developmental course of general movements in early infancy. I. Descriptive analysis of change in form. *Early Human Development 28,* 201-213.

Hallock, M. B., Worobey, J., & Self, P. A. (1989). Behavioural Development in Chimpanzee (*Pan troglodytes*) and Human Newborns Across the First Month of Life. *International Journal of Behavioral Development, 12,* 527-540.

Halverson, H. M. (1933). The acquisition of skill in infancy. *Journal of Genetic Psychology, 43,* 3-48.

Harlow, H. F. (1949). The Formation of Learning Sets. *Psychological Review, 56,* 51-65.

Heathcock, J. C., Lobo, M., & Galloway, J. C. (2008). Emergence of Reaching in Infants Born at Less Than 33 Weeks of Gestational Age: A Randomized Clinical Trial. *Physical Therapy, 88,* 310-322.

Hollerbach, J. M. (1982). Computers, brains, and the control of movement. *Trends in Neurosciences, 5,* 189-192.

Holt, A. B., Cheek, D. B., Mellits, E. D., & Hill, D. E. (1975). Brain size and the relation of the primate to the nonprimate. In D. B. Cheek (Ed.), *Fetal and Postnatal Cellular Growth and Nutrition* (pp. 23-44). New York: Wiley.

Huttenlocher, P. R. (2002). *Neural plasticity: The effects of environment on the development of the cerebral cortex*. Massachusetts: Harvard University Press.

Jennings, K. D., Harmon, R. J., Morgan, G. A., Gaiter, J. L., & Yarrow, L. J. (1979). Exploratory play as an index of mastery motivation: Relationships to persistence, cognitive functioning, and environmental measures. *Developmental Psychology, 15,* 386-394.

Kessen, W., Haith, M. M., & Salapatek, P. H. (1970). Human Infancy: A Bibliography and Guide. In P. H. Mussen (Ed.), *Carmichael's Manual of Child Psychology* (3rd ed., pp. 287-445). New York: John Wiley & Sons, Inc.

Konczak, J., Borutta, M., Topka, H., & Dichgans, J. (1995). The development of goal-directed reaching in infants: hand trajectory formation and joint torque control. *Experimental Brain Research, 106,* 156-168.

Kuo, Z. Y. (1970). The need for coordinated efforts in developmental studies. In L. R. Aronson, E. Tobach, D. S. Lehrman, & J. S. Rosenblatt (Eds.), *Development and evolution of behavior: Essays in memory of T. C. Schneirla* (pp. 181-193). San Francisco: Freeman.

Lansink, J. M., Mintz, S., & Richards, J. E. (2000). The distribution of infant attention during object examination. *Developmental Science, 3,* 163-170.

Libertus, K., & Needham, A. (2009, April). *Short- and long-term effects of simulated reaching experience*. In R.O. Gilmore (Chair), *Just Do It! Infants' Emerging Action Repertoire Shapes Perception, Cognition, Emotion, and Communication*. Symposium conducted at the biennial meeting of the Society for Research in Child Development, Denver, Colorado.

Libertus, K., & Needham, A. (2010). Teach to reach: The effects of active vs. passive reaching experiences on action and perception. *Vision Research, 50,* 2750-2757.

Lobo, M. A., & Galloway, J. C. (2008). Postural and Object-Oriented Experiences Advances Early Reaching, Object Exploration, and Means-End Behavior. *Child Development, 79,* 1869-1890.

Lobo, M. A., Galloway, J. C., & Savelsbergh, G. J. P. (2004). General and task-related experiences affect early object interaction. *Child Development, 75,* 1268-1281.

Malone, J.C. (1991). *Theories of Learning: A Historical Approach*. Belmont: Wadsworth.

Martin, J. H., Choy, M., Pullman, S., & Meng, Z. (2004). Corticospinal System Development Depends on Motor Experience. *The Journal of Neuroscience, 24,* 2122-2132.

McGraw, M. B. (1945). *The neuromuscular maturation of the human infant*. New York: Hafner Press.

Merzenich, M. M., Kaas, J. H., Wall, J., Nelson, R. J., Sur, M., & Felleman, D. (1983). Topographic reorganization of somatosensory cortical areas 3b and 1 in adult monkeys following restricted deafferentation. *Neuroscience, 8,* 33-55.

Merzenich, M. M., Grajski, K. A., Jenkins, W. M., Recanzone, G. H., & Peterson, B. (1990). Functional Cortical Plasticity: Cortical Network Origins of Representational Change. *Cold Spring Harbor Symposium on Quantitative Biology, 55,* 873-887.

Milewski, A. N., & Siqueland, E. R. (1975). Discrimination of color and pattern novelty in one-month human infants. *Journal of Experimental Child Psychology, 19,* 122-136.

Needham, A., Barrett, T., & Peterman, K. (2002). A pick-me-up for infants' exploratory skills: early simulated experiences reaching for objects using 'sticky mittens' enhances young infants' object exploration skills. *Infant Behavior & Development, 25,* 279-295.

Nelson, E. L. (2010). Examining the development of handedness in rhesus monkey and human infants using behavioral and kinematic measures. (Doctoral dissertation). University of Massachusetts Amherst, Amherst, MA.

Newell, K. M. (1991). Motor skill acquisition. *Annual Review of Psychology, 42,* 213-237.

Newell, K. M. (2003). Schema Theory (1975): Retrospectives and prospective. *Research Quarterly for Exercise and Sport, 74,* 383-388.

Passingham, R. E. (1982). *The Human Primate*. San Francisco: Oxford.

Piaget, J. (1952). *The origins of intelligence in children*. NewYork: International Universities Press.

Reynolds, G. D., & Richards, J. E. (2008). Infant heart rate: A developmental psychophysiological perspective. In L. A. Schmidt & S. J. Segalowitz (Eds.), *Developmental Psychophysiology* (pp. 173-212). New York: Cambridge Press.

Richards, J. E. (1997). Effects of Attention on Infants' Preference for Briefly Exposed Visual Stimuli in the Paired-Comparison Recognition-Memory Paradigm. *Developmental Psychology, 33,* 22-31.

Rochat, P. (1989). Object Manipulation and Exploration in 2- to 5-Month-Old Infants. *Developmental Psychology, 25,* 871-884.

Rochat, P. (1998). Self-perception and action in infancy. *Experimental Brain Research, 123,* 102-109.

Rochat, P., & Morgan, R. (1995). Spatial Determinants in the Perception of Self-Produced Leg Movements by 3- to 5-Month-Old Infants. *Developmental Psychology, 31,* 626-636.

Rochat, P., & Striano, T. (2000). Perceived self in infancy. *Infant Behavior & Development, 23,* 513-530.

Rovee, C. K., & Rovee, D. T. (1969). Conjugate reinforcement of infant exploratory behavior. *Journal of Experimental Child Psychology, 8,* 33-39.

Rovee-Collier, C. (1991). The "memory system" of prelinguistic infants. In A. Diamond (Ed.), *The development and neural bases of higher cognitive functions. Annals of the New York Academy of Sciences, 608,* 517-536.

Rovee-Collier, C. K., Morrongiello, B. A., Aron, M., & Kuperschmidt, J. (1978). Topographic response differentiation and reversal in 3-month-old infants. *Infant Behavior and Development, 1,* 323-333.

Ruff, H. A., & Halton, A. (1978). Is there directed reaching in the human neonate? *Developmental Psychology, 14,* 425-426.

Ruff, H. A., & Rothbart, M. K. (1996). *Attention in early development: Themes and variations*. New York: Oxford Press.

Sacher, G. A., & Staffeldt, E. F. (1974). Relation of gestation time to brain weight for placental mammals: Implications for the theory of vertebrate growth. *American Naturalist, 108,* 593-615.

Sackett, G. P., Gunderson, V., & Baldwin, D. (1982). Studying the Ontogeny of Primate Behavior. In J. L. Fobes & J. E. King (Eds.), *Primate Behavior* (pp. 135-169). New York: Academic Press.

Schlesinger, M., Parisi, D., & Langer, J. (2000). Learning to reach by constraining the movement search space. *Developmental Science, 3,* 67-80.

Schmidt, R. A. (1975). A Schema Theory of Discrete Motor Skill Learning. *Psychological Review, 82,* 225-260.

Schmidt, R. A. (2003). Motor Schema Theory After 27 Years: Reflections and Implications for a New Theory. *Research Quarterly for Exercise and Sport, 74,* 366-375.

Schmidt, R. A., & Lee, T. D. (1999). *Motor Control and Learning: A Behavioral Emphasis 4th ed.* Champaign: Human Kinetics.

Schneider, M. L., & Suomi, S. J. (1992). Neurobehavioral Assessment in Rhesus Monkey Neonates (*Macaca mulatta*): Developmental Changes, Behavioral Stability, and Early Experience. *Infant Behavior and Development, 15*, 155-177.

Schneirla, T. C. (1966). Behavioral development and comparative psychology. *Quarterly Review of Biology, 41,* 283-302.

Spencer, J. P., & Thelen, E. (2000). Spatially specific changes in infant's muscle coactivity as they learn to reach. *Infancy, 1,* 275-302.

Sporns, O., & Edelman, G. M. (1993). Solving Bernstein's problem: a proposal for the development of coordinated movement by selection. *Child Development, 64,* 960-981.

Stiles, J. (2009). On Genes, Brains, and Behavior: Why Should Developmental Psychologists Care About Brain Development? *Child Development Perspectives, 3,* 196-202.

Summers, J. J., & Anson, J. G. (2009). Current status of the motor program: Revisited. *Human Movement Science, 28,* 566-577.

Thelen, E. (1985). Developmental origins of motor coordination: Leg movements in human infants. *Developmental Psychobiology, 18,* 1-22.

Thelen, E. (1989). The (re)discovery of motor development: Learning new things from an old field. *Developmental Psychology, 25,* 946-949.

Thelen, E. (1992). Development as a dynamic system. *Current Directions in Psychological Science,1,* 189-193.

Thelen, E. (1994). Three-month-old infants can learn task-specific patterns of interlimb coordination. *Psychological Science, 5,* 280-285.

Thelen, E. (1995). Motor development: A new synthesis. *American Psychologist, 50,* 79-95.

Thelen, E. (1996). Normal infant stereoptypies. In R.L. Sprague & N.M. Newell (Eds.), *Stereotyped movements: Brain and behavior relations*. Hyattsville, MD: American Psychological Association.

Thelen, E. (2000). Grounded in the world: Developmental origins of the embodied mind. *Infancy, 1,* 3-28.

Thelen, E., & Adolph, K. E. (1992). Arnold L. Gesell: The paradox of nature and nurture. *Developmental Psychology, 28,* 368-380.

Thelen, E., & Corbetta, D. (1994). Exploration and selection in the early acquisition of skill. *International Review of Neurobiology, 37,* 75-102.

Thelen, E., & Corbetta, D. (2002). Microdevelopment and dynamic systems: Applications to infant motor development. In N. Granott & J. Parziale (Eds.), *Microdevelopment: Transition processes in development and learning* (pp. 80-108). New York: Cambridge University Press.

Thelen, E., Corbetta, D., & Spencer, J. P. (1996). Development of reaching during the first year: role of movement speed. *Journal of Experimental Psychology: Human Perception and Performance, 22,* 1059-1076.

Thelen, E., Corbetta, D., Kamm, K., Spencer, J. P., Schneider, K., & Zernicke, R. F. (1993). The trainsition to reaching: Mapping intention and intrinsic dynamics. *Child Development, 64,* 1058-1098.

Thelen, E., & Smith, L. B. (1994). *A dynamic systems approach to the development of cognition and action*. Massachusetts: The MIT Press.

Thelen, E., & Smith, L. B. (2006). Dynamic systems theories. In R. M. Lerner (Ed.), *Handbook of child psychology, Vol. 1: Theoretical models of human development* (6th ed., pp. 258-312). New York, NY: John Wiley & Sons, Inc.

Thorndike, E. L. (1927). The Law of Effect. *The American Journal of Psychology, 39,* 212-222.

Thorndike, E. L. (1949). *Selected Writings from a Connectionist's Psychology*. New York: Appleton-Century-Crofts, Inc.

van der Meer, A. L. H., van der Weel, F. R., & Lee, D. N. (1995). The functional significance of arm movements in neonates. *Science, 267,* 693-695.

von Hofsten, C. (1982). Eye-hand coordination in the newborn. *Developmental Psychology, 18,* 450-461.

von Hofsten, C. (1984). Developmental changes in the organization of prereaching movements. *Developmental Psychology, 20,* 378-388.

von Hofsten, C. (1986). Early spatial perception taken in reference to manual action. *Acta Psychologica, 63,* 323-335.

von Hofsten, C. (1989). The organization of arm and hand movements in the neonate. In C. von Euler (Ed.), *The neurobiology of early infant behavior* (pp. 129-142). London: MacMillan.

von Hofsten, C. (1991). Structuring of early reaching movements: A longitudinal study. *Journal of Motor Behavior, 23,* 280-292.

von Hofsten, C., & Lindhagen, K. (1979). Observations on the development of reaching for moving objects. *Journal of Experimental Child Psychology, 28,* 158-173.

von Hofsten, C., & Ronnqvist, L. (1993). The structuring of neonatal arm movements. *Child Development, 64,* 1046-1057.

White, B. L., Castle, P., & Held, R. (1964). Observations on the development of visually-guided reaching. *Child Development, 35,* 349-364.

Williams, J. L., & Corbetta, D. (2011). "Sticky" or "non-sticky" mittens: What really matters for the emergence of reaching? *Manuscript in preparation*.

Appendix

Table A 1. Summary statistics for the average number of intentional contacts per trial over the 16 days from individual linear regression analyses of infants in the contingent, continuous, and repeated exposure groups.

Group	*n*	Mean Slope	*SD*	Min	Max	$p < .05$	(- , +)
Contingent	11	0.14	0.18	-0.01	0.49	4	(4, 7)
Continuous	11	0.03	0.04	-0.02	0.13	2	(3, 8)
Repeated Exposure	11	0.10	0.13	-0.02	0.32	3	(3, 8)

Note. The column "$p < .05$" refers to the number of individual slopes that were significant at the alpha = .05 level. The column "(-, +)" refers to the number of individual slopes that were negative and positive, respectively.

Table A 2. Summary statistics for the average percent of trials with intentional contact over the 16 days from individual linear regression analyses of infants in the contingent, continuous, and repeated exposure groups.

Group	*n*	Mean Slope	*SD*	Min	Max	$p < .05$	(- , +)
Contingent	11	2.15	2.53	-1.06	6.53	4	(3, 8)
Continuous	11	1.07	1.39	-1.26	3.55	2	(2, 9)
Repeated Exposure	11	2.41	2.20	-0.61	6.92	4	(1, 10)

Note. The column "$p < .05$" refers to the number of individual slopes that were significant at the alpha = .05 level. The column "(-, +)" refers to the number of individual slopes that were negative and positive, respectively.

Table A 3. Summary statistics for the percent of trial duration infants spent looking at the object over the 14 in-home sessions from individual linear regression analyses of infants in the contingent, continuous, and repeated exposure groups.

Group	*n*	Mean Slope	*SD*	Min	Max	$p < .05$	(- , +)
Contingent	11	-1.17	1.54	-3.57	2.01	3	(9, 2)
Continuous	11	-1.82	2.00	-4.18	2.14	3	(9, 2)
Repeated Exposure	11	-0.47	1.46	-1.88	1.75	2	(7, 4)

Note. The column "$p < .05$" refers to the number of individual slopes that were significant at the alpha = .05 level. The column "(-, +)" refers to the number of individual slopes that were negative and positive, respectively.

Table A 4. Sixteen-day averages with standard deviations for the percent of trial duration that infants in the repeated groups looked at the object, experimenter, left hand, and right hand.

Group	*n*	Object	Experimenter	Right Hand	Left Hand
Continuous	11	44.57 (*18.64*)	10.89 (*4.96*)	0.33 (*0.37*)	0.51 (*0.62*)
Contingent	11	44.42 (*17.92*)	6.57 (*5.79*)	0.51 (*0.52*)	1.75 (*3.93*)
Repeated Exposure	11	43.90 (*14.07*)	13.15 (*8.67*)	2.63 (*1.81*)	2.51 (*1.94*)

Note. Standard deviations are displayed beneath each grand average in parentheses.

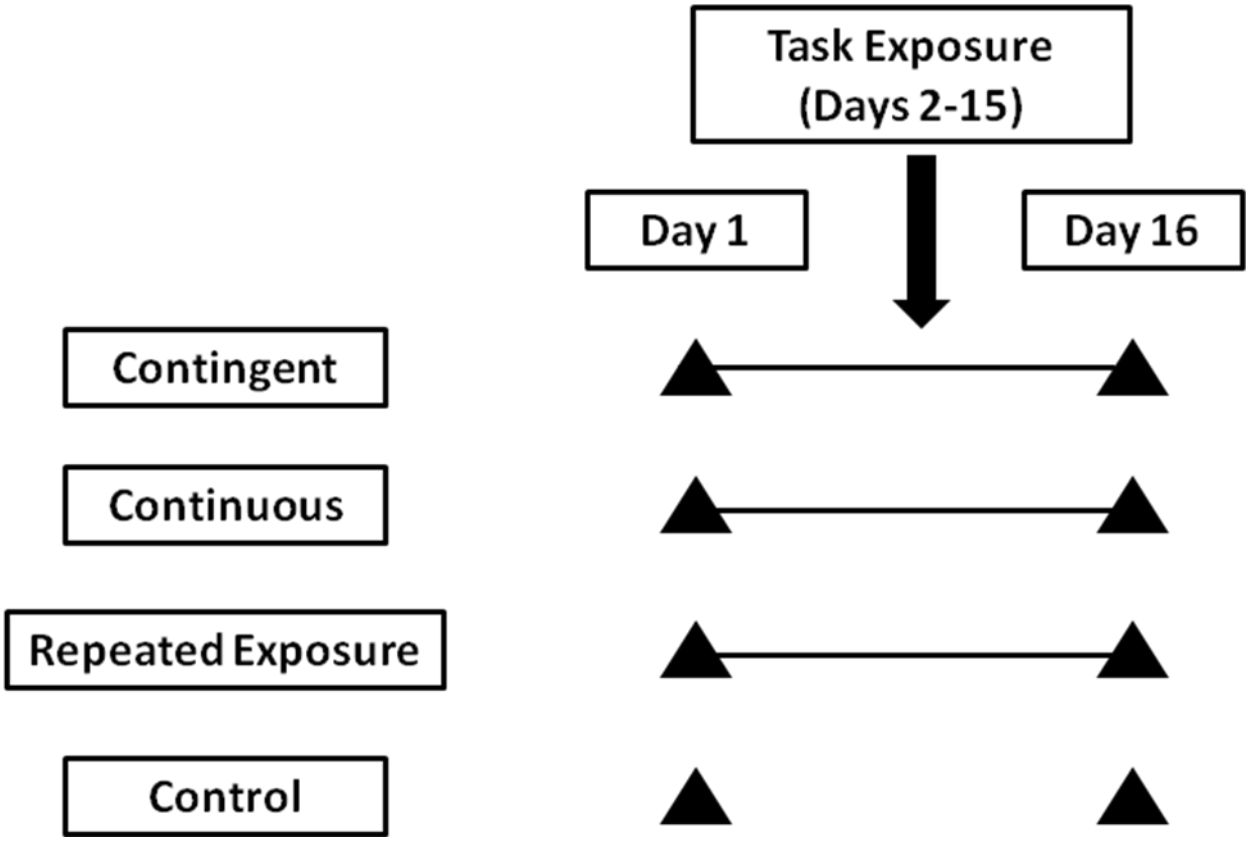


Figure A 1: General diagram depicting the four groups and experimental design. All infants were seen on days one and 16 (assessment days), which are denoted by solid black triangles. Solid lines between the triangles indicate that infants were followed for 14 consecutive days. The absence of a solid line between the triangles indicates that infants were not followed for 14 consecutive days.

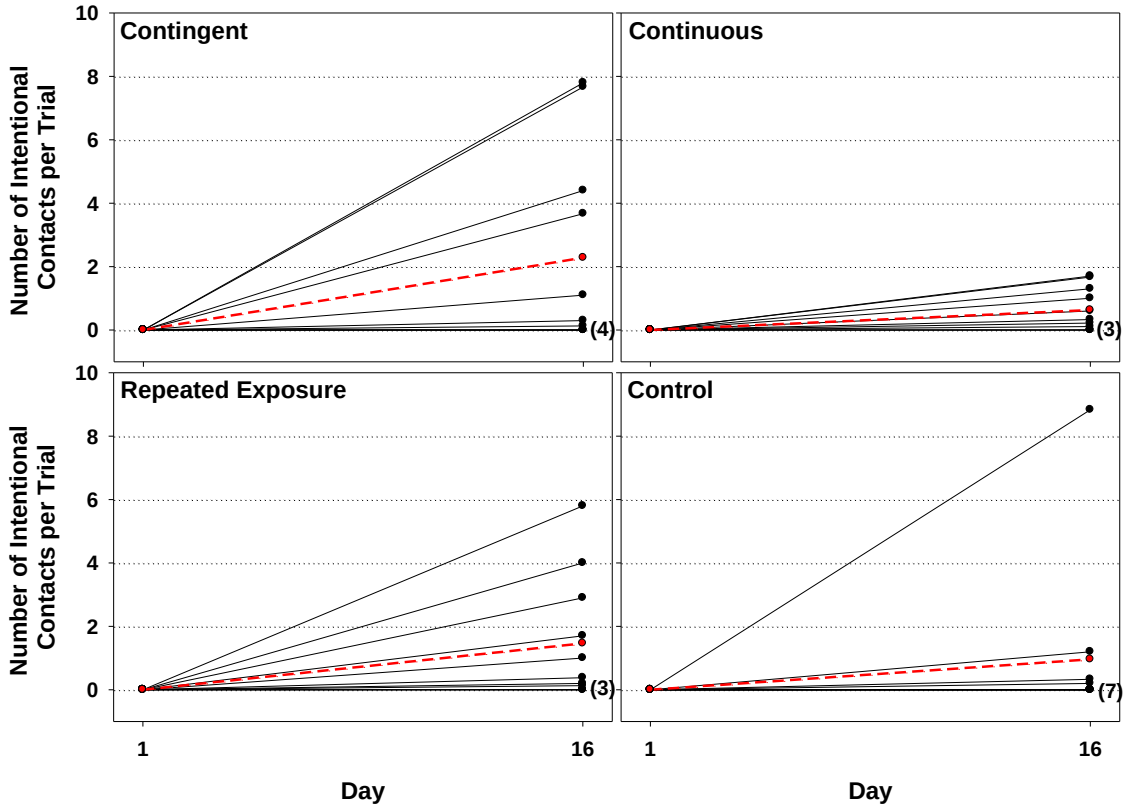


Figure A 2: Trial average of the number of intentional contacts for days one and 16 for all groups. The solid lines depict performances of individual infants in each group. The dashed lines indicate the group averages.

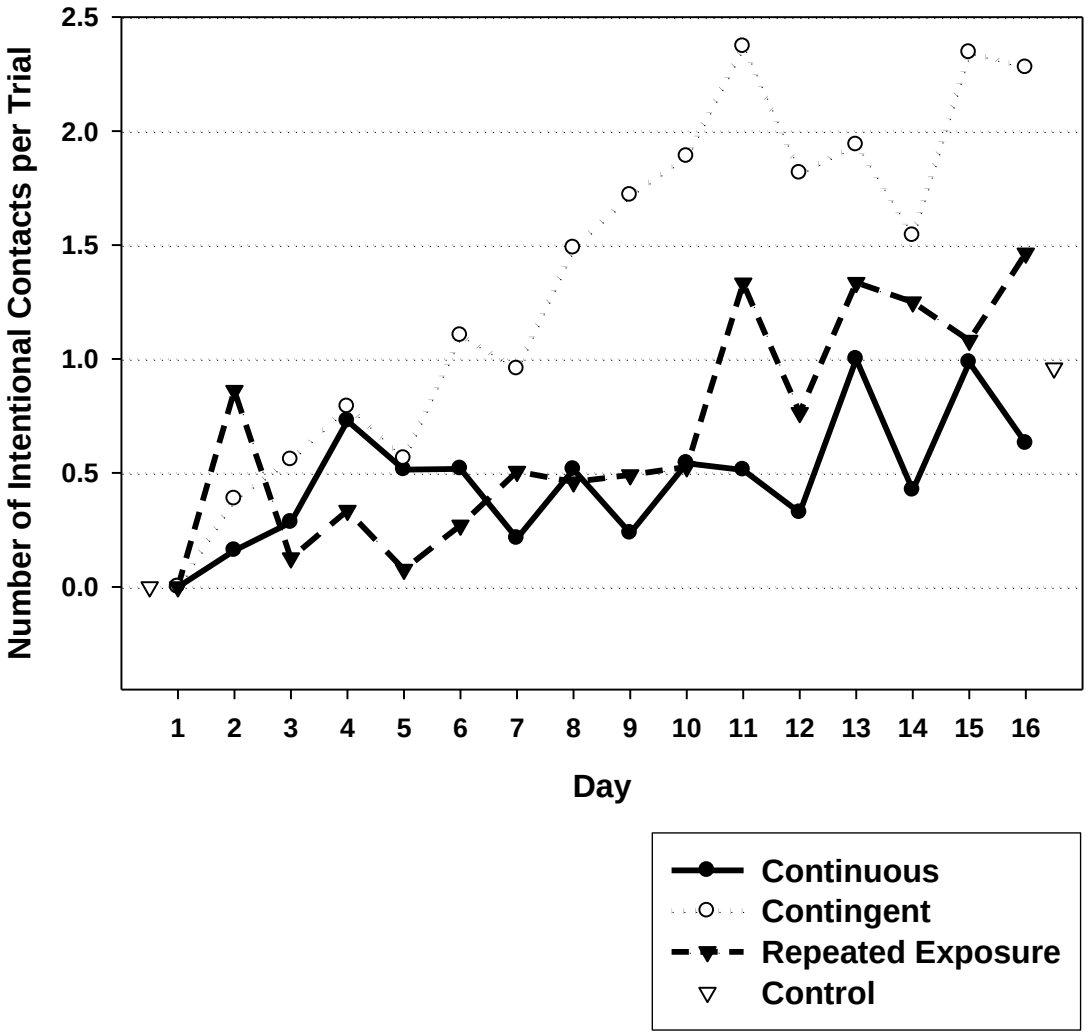


Figure A 3: Average number of intentional contacts per trial by group and day over the sixteen days of the study.

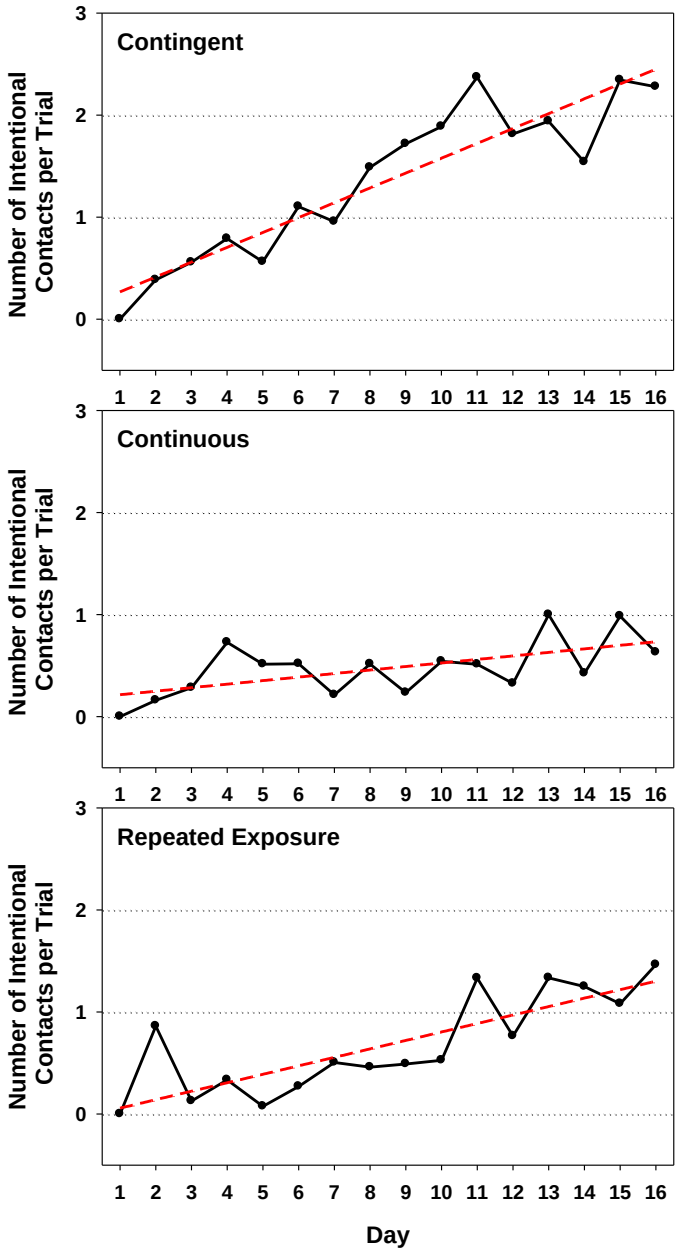


Figure A 4: Average number of intentional contacts per trial by day for the contingent, continuous, and repeated task exposure groups. The dashed lines depcit the linear trends.

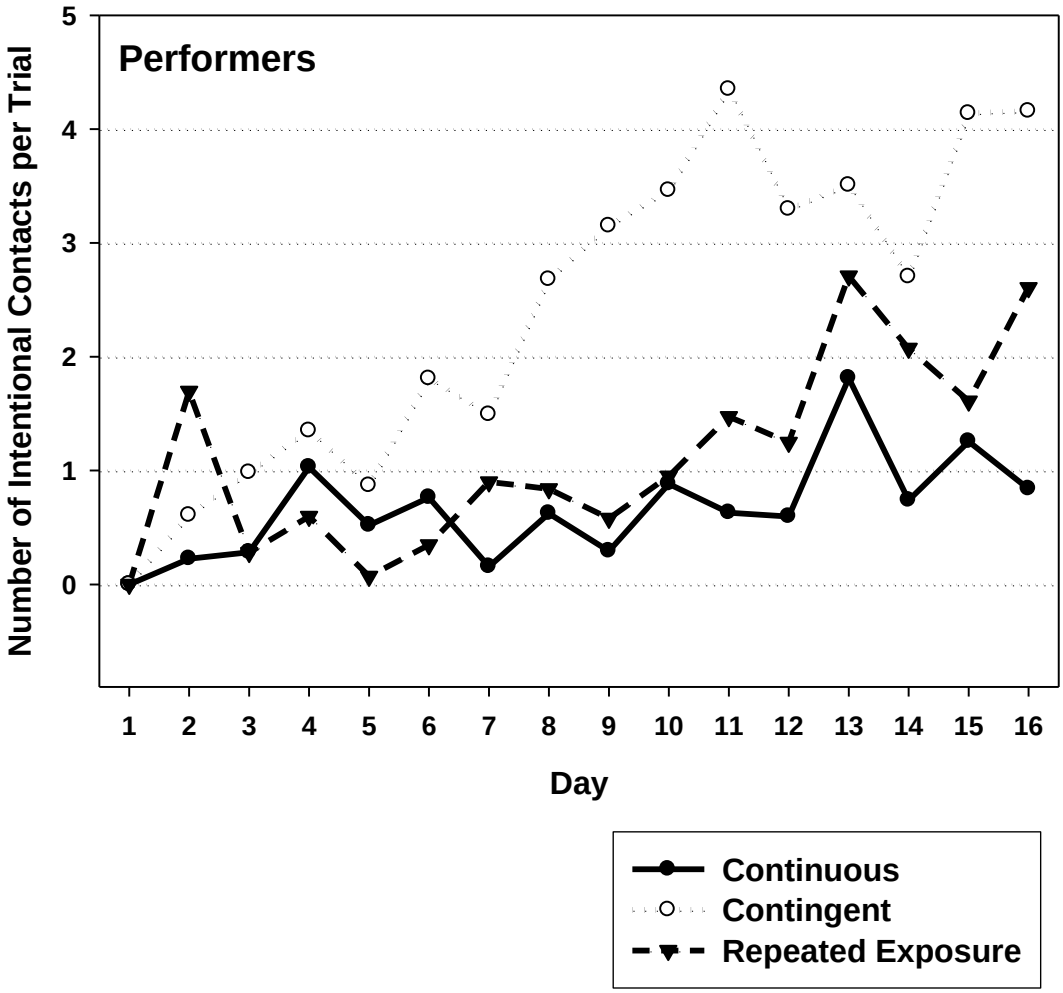


Figure A 5: Average number of intentional contacts per trial by group over the sixteen days of the study for infants classified as performers.

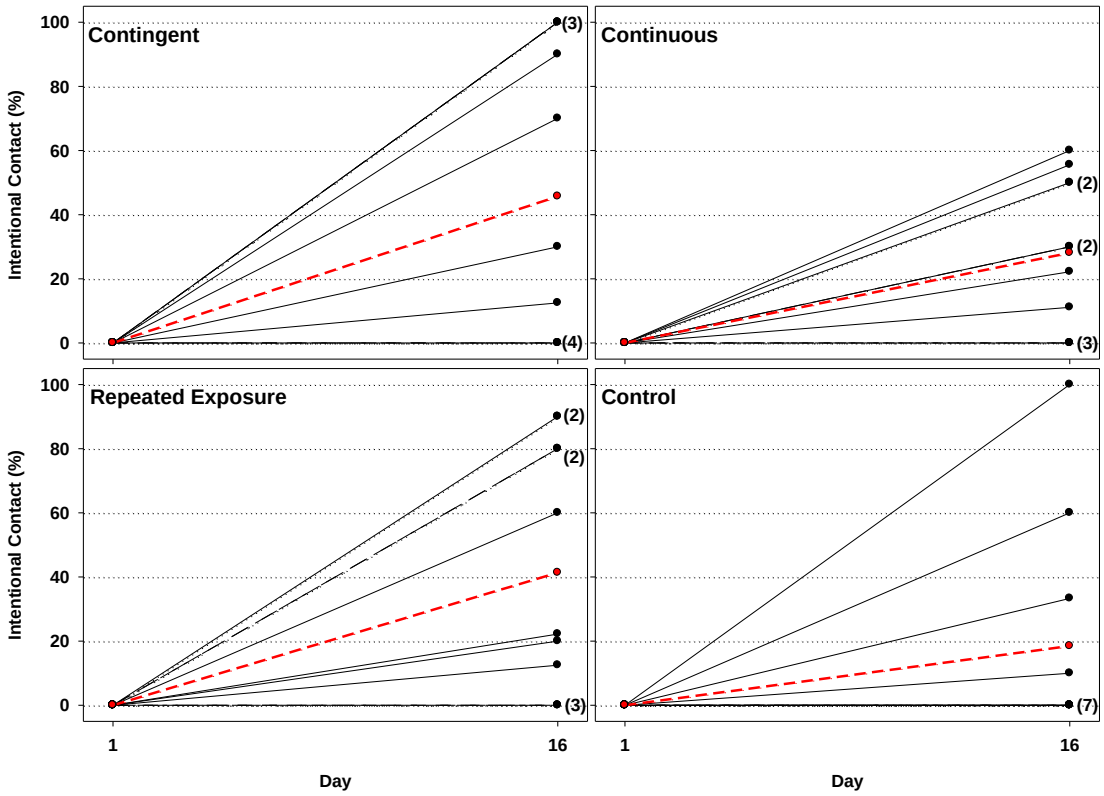


Figure A 6: Percent of trials with intentional contact for days one and 16 for all groups. Performances of individual infants in each group by day are displayed by solid lines. Group averages by day are displayed by a dashed line.

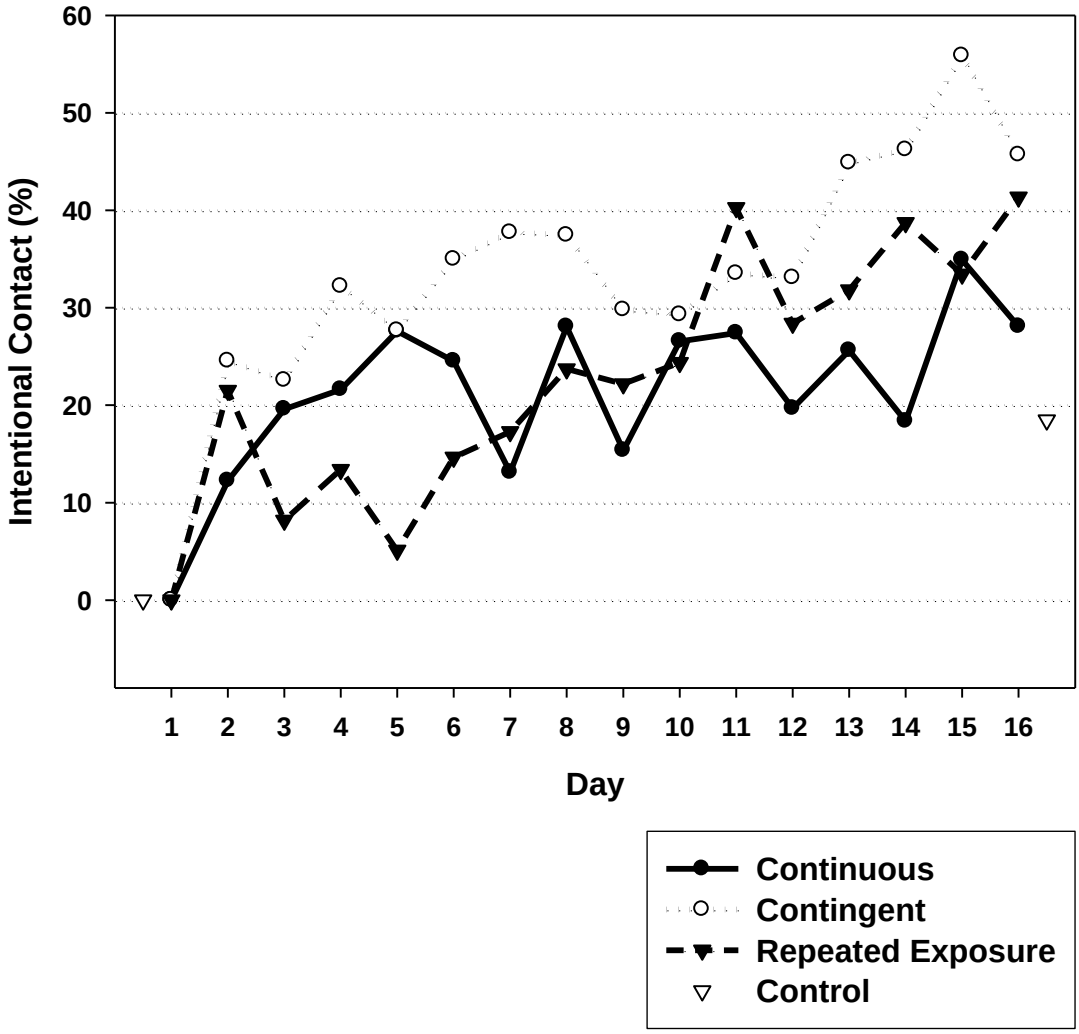


Figure A 7: Average percent of trials with intentional contact by group and by day over the sixteen days of the study.

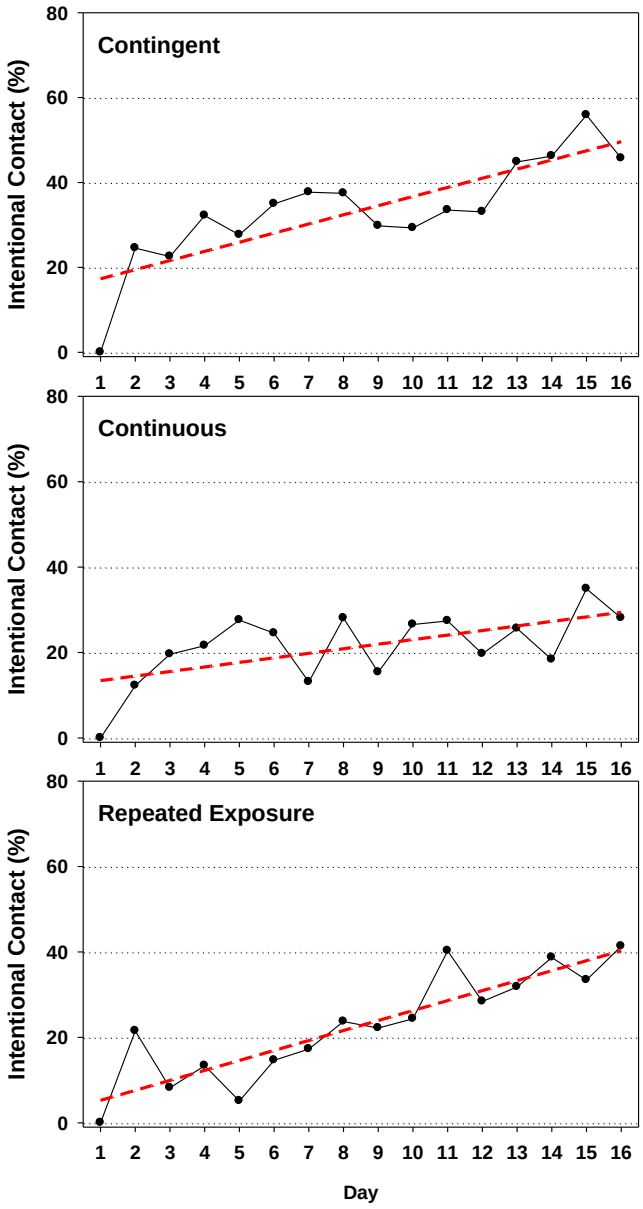


Figure A 8: Average percent of trials with intentional contact by day for the contingent, continuous, and repeated task exposure groups. Linear trends are displayed by the dashed lines.

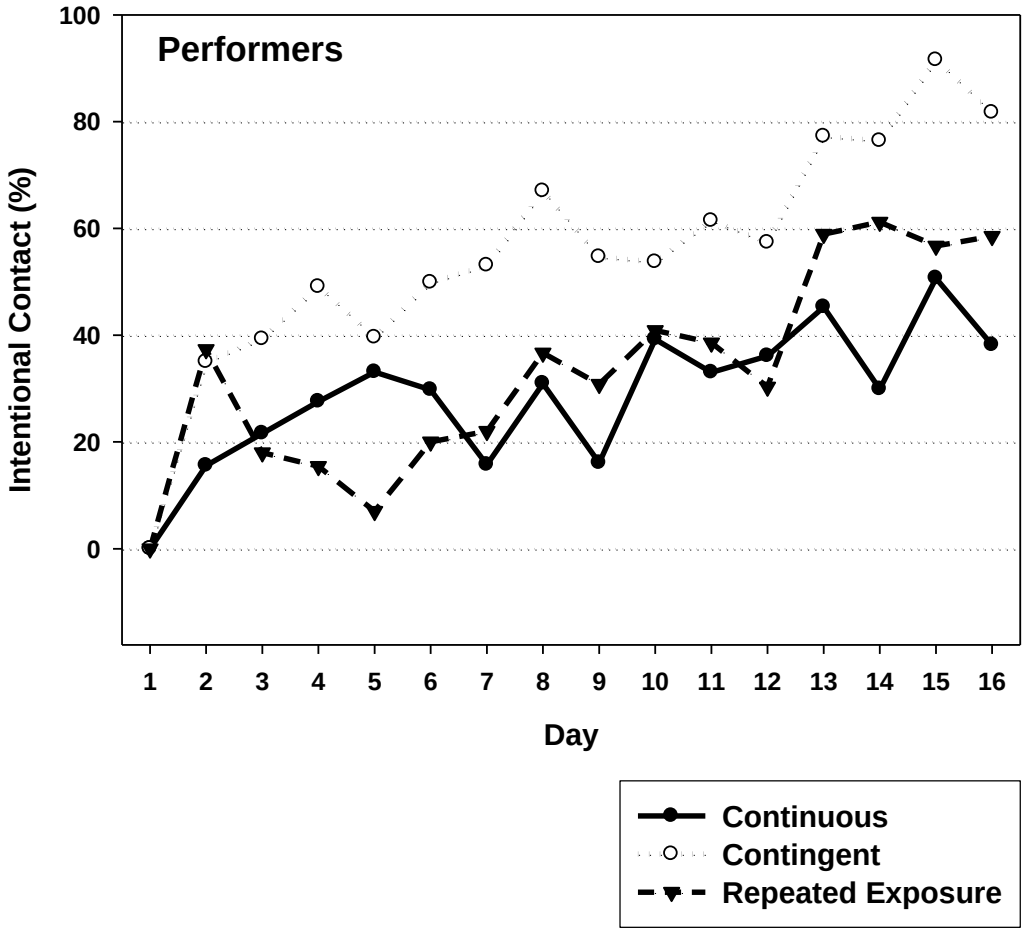


Figure A 9: Average percent of trials with intentional contact by group over the sixteen days of the study for infants classified as performers.

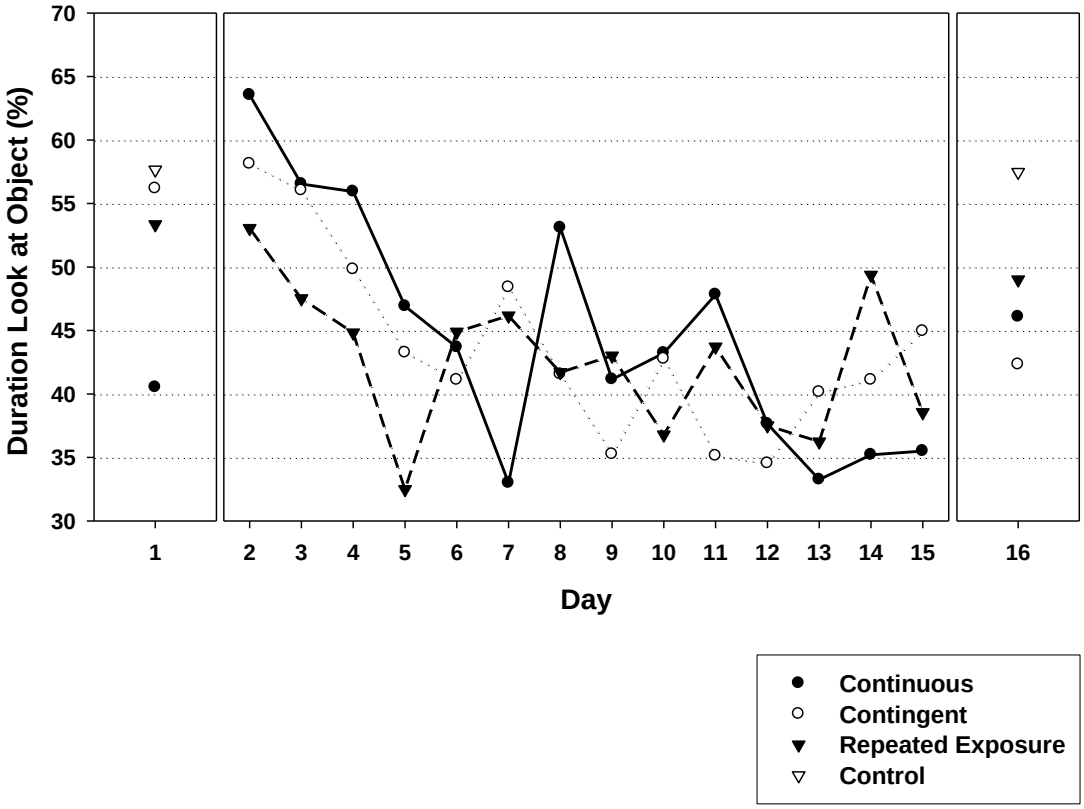


Figure A 10: Average percent of trial duration that infants looked at the object by group. Assessment days one and sixteen are shown in separate panels. Daily averages are displayed with connecting lines for the three repeated groups.

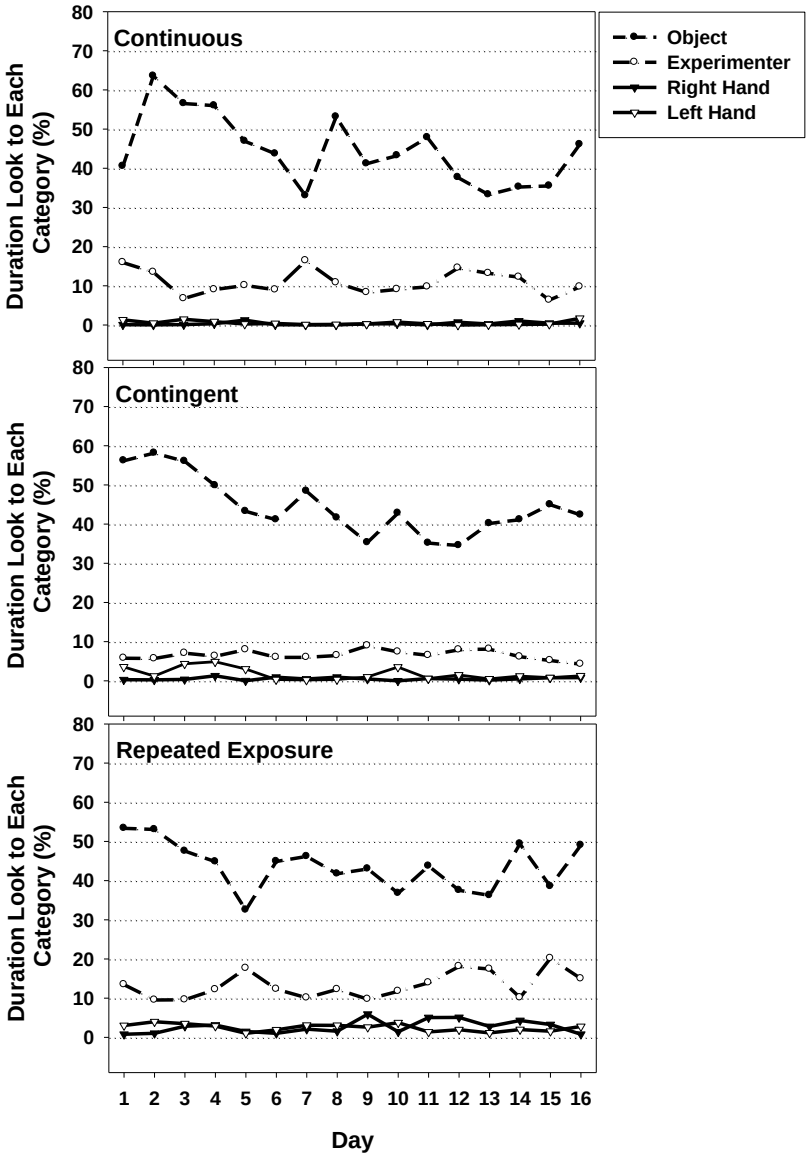


Figure A 11: Average percent of trial duration that infants in the repeated groups looked at the five looking categories over the sixteen days of the study.

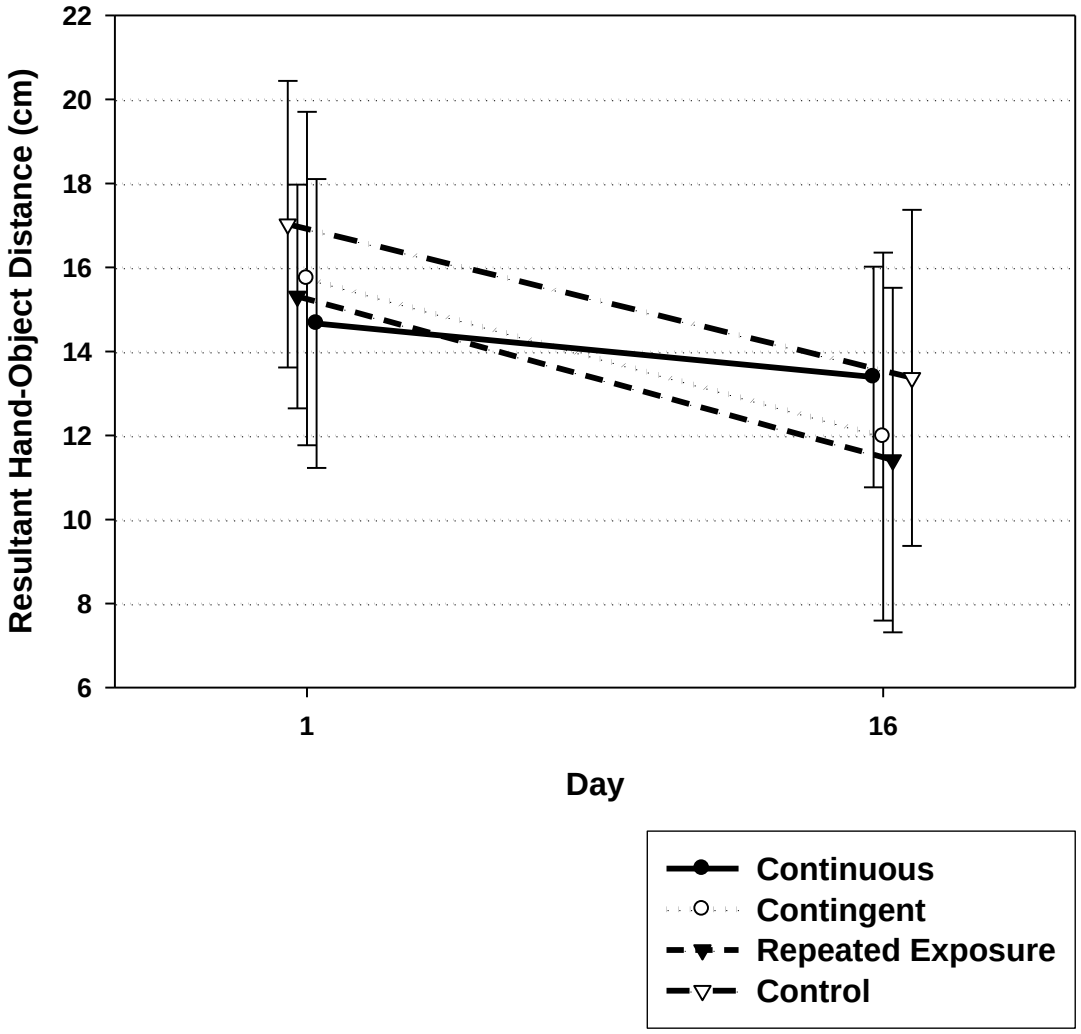


Figure A 12: Average resultant distance between infants' preferred reaching hand and the object by group for the first and last days. Error bars depict standard deviations of the mean.

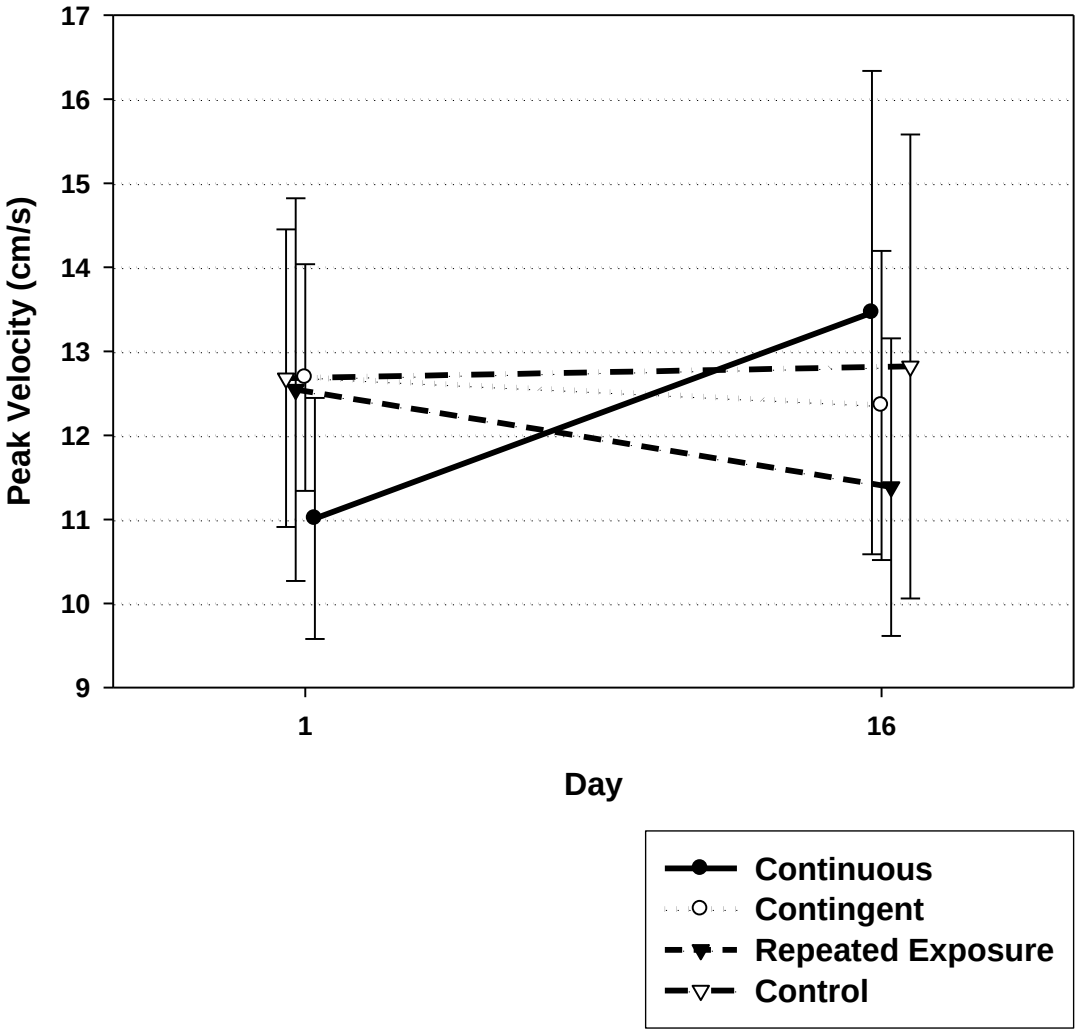


Figure A 13: Average peak velocity of infants' preferred reaching hand by group for the first and last days. Error bars depict standard deviations of the mean.

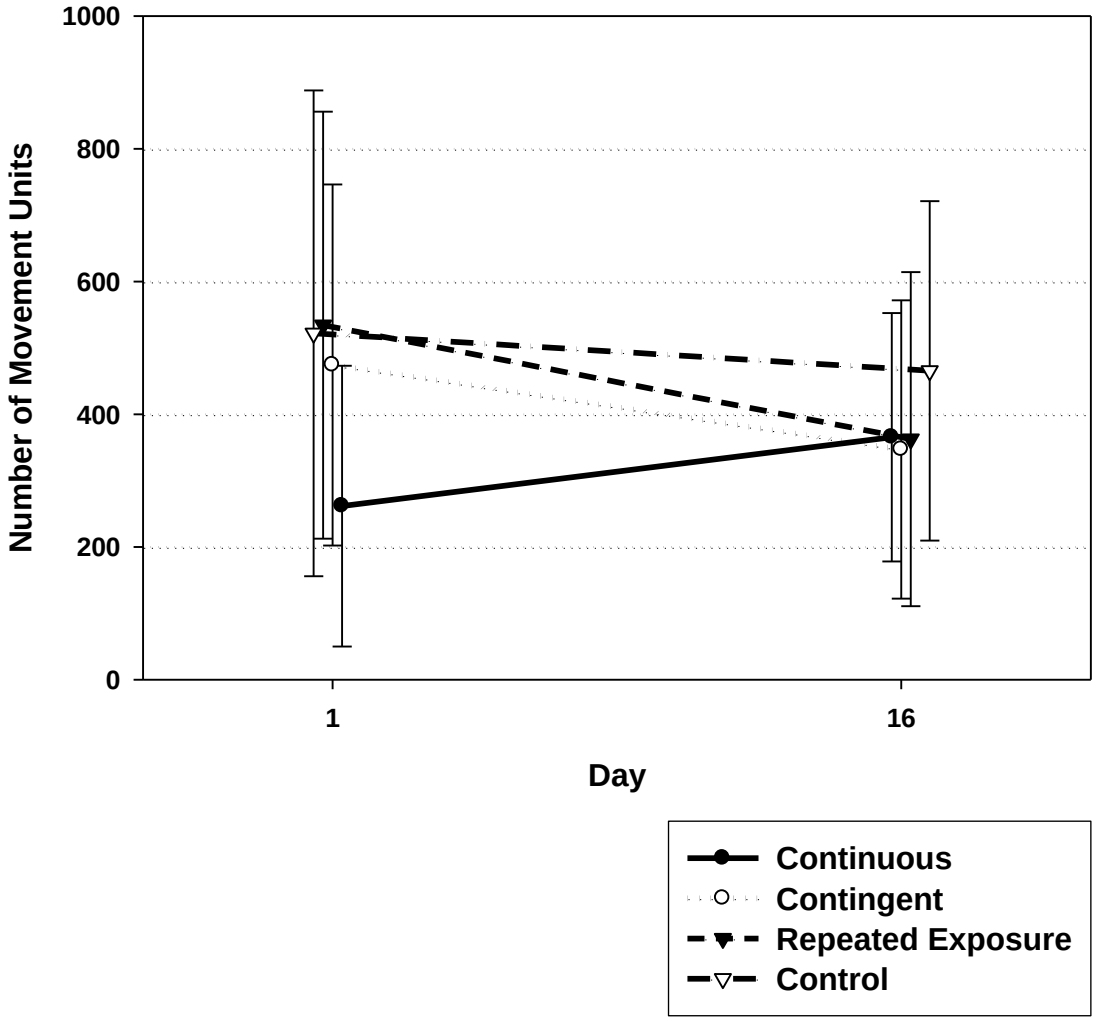


Figure A 14: Average number of movement units of infants' preferred reaching hand by group for the first and last days. Error bars depict standard deviations of the mean.

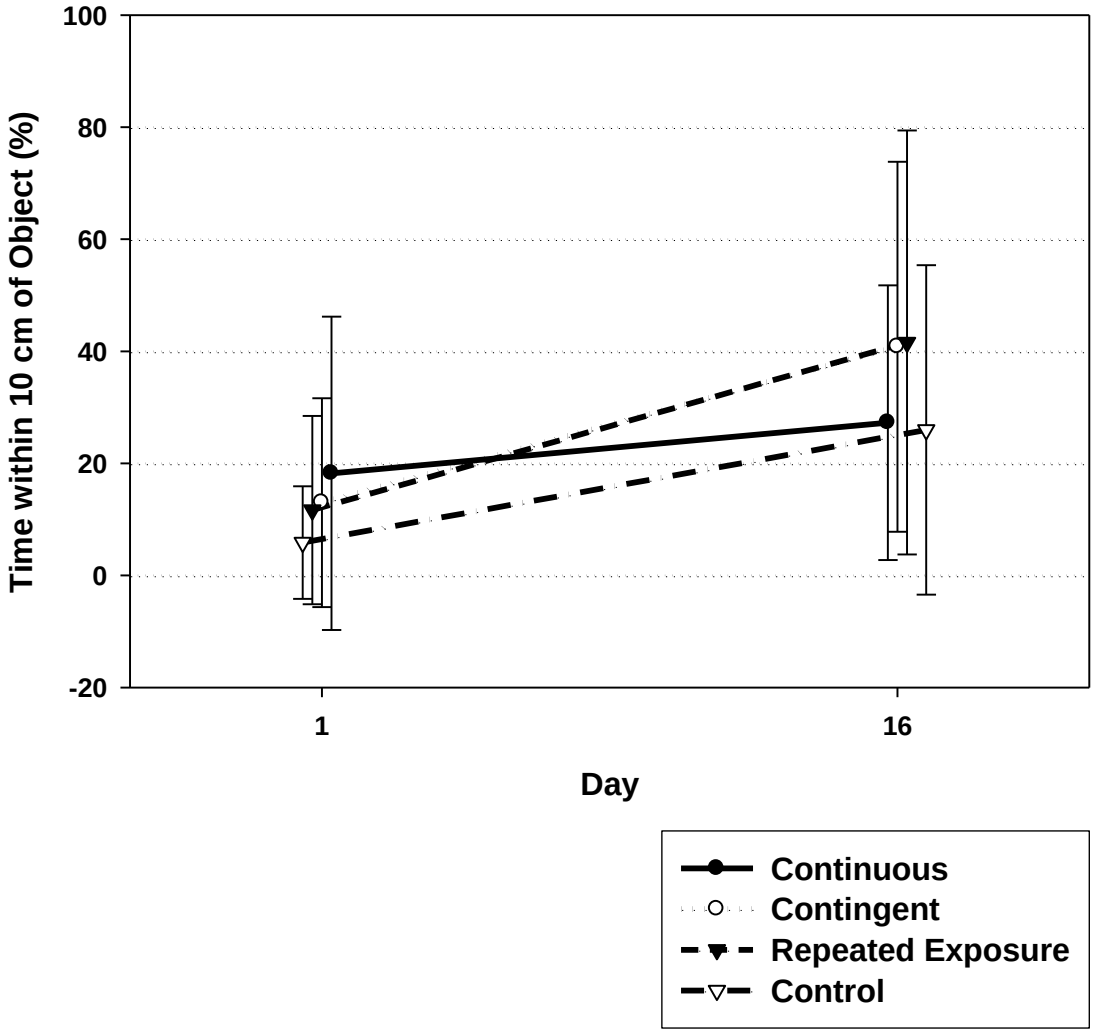


Figure A 15: Average percent of time that infants spent with the preferred reaching hand within 10 cm of object for the first and last days. Error bars depict standard deviations of the mean.

Vita

Joshua L. Williams was born in Indianapolis, Indiana on September 15, 1982. He was raised in Evansville, Indiana. He received his B.A. in Movement and Sport Science from Purdue University in May 2004 and his M.A. in Experimental Psychology with a developmental emphasis from The University of Tennessee in 2009.