A robot journey into cognition:
The role and implications of augmentative manipulation in child development

by

Liliana Alvarez-Jaramillo

A thesis submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

in

REHABILITATION SCIENCE

Faculty of Rehabilitation Medicine
University of Alberta

ABSTRACT

BACKGROUND: The strong relationship between motor and cognitive development suggests that the limited motor experience of children with physical disabilities can impact their cognitive and perceptual development. The assessment of their cognitive skills is also compromised due to limited verbal communication and motor gestures. Robots have been used to give children with disabilities an opportunity to independently manipulate objects and to reveal their cognitive skills when they use the robots. Although studies have shown that children with physical disabilities can benefit from the use of robots as augmentative manipulation systems, certain critical aspects of this interaction remain unclear. Using the robot as a tool is not the same as direct manipulation. The use of robots as tools and their operating interfaces requires a deeper understanding of developmental considerations. Understanding the additional cognitive and perceptual demands that the use of the robot imposes on the child is crucial. This can guide the selection and adaptation of the control interfaces, robot characteristics and programming to match the needs, skills and developmental age of the child as well as the task and goals.

OBJECTIVE: This dissertation is the result of a review of the literature, two studies and a case study developed in order to: 1) determine the behavioral differences between typical and augmentative manipulation and their implications in the performance of a cognitive task by young children; 2) establish the technical feasibility of studying the neurophysiological differences between robot mediated manipulation and typical manipulation, given the characteristics of the robot and the available technology; and 3) determine the neurophysiological differences between typical manipulation and robot augmented manipulation.

METHODS: A review of the literature and a theoretical complexity analysis of using robots as manipulation tools were used to establish the implications of augmentative manipulation. A method for technical implementation of behavioral and neurophysiological comparison of typical and augmented manipulation was designed and tested through a pilot study with adult participants. A study was then conducted with 18 – 30 month old typically developing children. Children participated in two versions of the A not B with invisible displacement task. In one version, children used direct reaching and manipulation of the objects and containers; in the other, they used a robotic arm to access the task. Finally, a child with a bilateral brachial plexus injury resulting in limited independent manipulation of objects participated in the robot version of the task, as well as a gaze direction version. Behavioural and neurophysiological data were collected and analyzed.

RESULTS: Technical feasibility was established. The technical implementation made it possible to study the two conditions and their neurophysiological correlates. In the study with children behavioural and neurophysiological differences were observed between the two conditions. Children were motivated to use the robot and they attributed animacy and agency to it. Differences in the motor and cognitive demands of both tasks were found. Event related potentials were analyzed and differential activity between the robot and the reaching conditions in frontal, central and parietal electrodes. Response modality (robot vs. typical manipulation) was found to have an effect on cognitive processes underlying successful performance of the task. Advantages, disadvantages, and results obtained from this method for technical implementation are presented. Implications for the study of alternative manipulation are discussed.

PREFACE

This thesis is an original work by Liliana Alvarez Jaramillo, under the supervision of Professor Albert Cook. The two research projects that form part of this thesis received research ethics approval from the University of Alberta Research Ethics Board:

"Neural correlates of robot use for manipulation activities", Pro00032410, September 27, 2012

"Neural and behavioral correlates of the role of motor experience and augmentative manipulation in infant cognition", Pro00035724, January 18, 2013.

The technical apparatus referred to in chapter 4 and chapter 5 was designed by the student and Dr. Albert Cook, with the assistance of Al Fleming, technician in the Faculty of Rehabilitation Medicine.

Chapter 4 of this thesis has been accepted for publication as:

Alvarez, L., Wiebe, S.A., Adams, K, Hope, A., Cook, A. (In press) "The Neurophysiology of augmentative manipulation: A method for technical implementation", *Technology & Disability*.

The student was responsible for the design of the study, ethics application, data collection and analysis as well as the manuscript composition. A. Hope assisted with data collection and data analysis. Professor Albert Cook was the supervisory author and was involved in the concept formation, data collection, manuscript composition and edition. Professor S.A. Wiebe was involved with the concept formation, data collection, data analysis and manuscript edits. Professor Kim Adams was involved with concept formation and manuscript edition.

DEDICATION

To the one and only.

"It is the glory of God to conceal a matter; to search out a matter is the glory of kings." Proverbs 25:2.

And to my great 300, who have been more than enough for me to step beyond the oak tree:

My husband Denis, who's sacrificial and enduring love, persistent patience, and unwavering humour, have gotten me through the hardest part of this PhD process with a stronger faith and a big smile.

My mother, Cris and my father, who's immense love and pride in me has never been altered by what I do, but always by what is in my heart.

My aunts, uncle and cousins, who have believed in me every day and have loved me always.

Erin & Jana, who have kept me honest, grounded and faithful to the task at hand. Who have inspired me to live by truth and love by choice.

ACKNOWLEDGEMENTS

I would like to thank a number of individuals and institutions for their support in this journey. First of all I would like to thank my supervisor, Dr. Albert Cook. Dr. Cook has taught me everything I know about everything I want to be. He believed in me always, pushed me kindly, and taught me patiently. Without his commitment, support, leadership, patience and passion for knowledge and people, this would have not been possible. Being his mentoree has shaped me, and it will always be an honour. I would like to thank Dr. Kim Adams, my co-supervisor, for her support, trust and her interest and commitment to make my PhD and my time in Canada an always enriching and memorable experience. I thank Nancy and Darrell, for opening their homes to this Colombian student and making sure my years here where filled with joy and adventure.

I would also like to thank Dr. Sandra Wiebe. Dr. Wiebe's mentorship, knowledge, admirable generosity and commitment to my program have forever shaped my knowledge and my character as a researcher and teacher. I will be forever grateful for taking me in as one of her own students. I want to thank Dr. Johanna Darrah, for her critical, honest, challenging and stimulating feedback and advice through this process. Her questions and conversations have increased my passion for rigor and my commitment to continue to grow as a researcher and clinician. A special thank you to my external examiners, Dr. Jeff Bizanz and Dr. Jeffrey Lockman for their time and their willingness to support this important step of my process and their commitment to the education of future researchers.

Thank you to the leadership team and staff of the Faculty of Rehabilitation Medicine, for their support and patience. Special thanks to Angela Libutti, who has made sure every Rehabilitation Sciences' student, has everything they need to devote themselves passionately to research. I also extend special thanks to Al Fleming, who patiently makes the ideas in our heads come to life.

I want to thank my lab mates and the the Lab's collaborators, especially Dr. Pedro Encarnação, for their advice, support and sharing of knowledge and experiences. Martha Funabashi and Brea Chouinard, my colleagues and friends and the people with whom I have walked this PhD journey. You have both kept me honest, I admire you both greatly and couldn't have asked for better partners in the unpredictable adventures of doing life and research.

Throughout this process, and through the generous mentorship of Dr. Cook and Dr. Wiebe, I have come to collaborate with a number of students in the Department of Psychology. I want to

specially thank the members of the Alberta Brain and Cognitive Development Lab (ABCD Lab) for taking me in as one of their own and sharing their time, knowledge and resources with me. Specially Mahsa Khoei and Sarah Elke, for their knowledge, kindness and commitment to team building and work. What a great example they have been. I thank Alex Hope and Colyn Wasylynuk, who patiently and committedly grew to appreciate Samantha the robot, and without whom data collection would not have been possible. I will hear from you in the future, proudly and happily.

My PhD program funding was possible thanks to the support of the Colombian Government through the Francisco Jose de Caldas Scholarship awarded to me by COLCIENCIAS; and the support and commitment of Universidad del Rosario, in Colombia. Thank you to all my colleagues and the leadership team at Universidad del Rosario, for believing in me and investing in my education.

Finally, I want to thank all my family. My mother whose sacrifices made it possible for me to dream big and make it happen, and my father who has never let go off of his girl. My aunts, uncle and cousins for their unconditional love. David & Nicole who have been my family in Canada and have made sure I had a place to call home in their hearts. I thank my husband Denis for his support and patience. For marrying the PhD student who came with a half-human size robot included… and its implications.

To all the adults, children and families that participated in this research: Thank you for your time, your patience and your support of science. Your willingness to support my research will always remind me of why we do what we do.

And to Samantha the robot… because we did it, although you will never really know that!

Table of Contents

List of Tables

List of figures

Chapter 1
Introduction and Overview

Introduction and Overview

Motor experience plays a central role in cognitive and perceptual development of typically developing children. As a critical part of motor experience, object manipulation has been identified as a motor behaviour that enables the child to acquire skills required for learning, emergence of symbols, referential communication and the understanding of relations between objects and interactions with the environment (Bates, 1979; Greenfield, 1991; Piaget 1952; McCarty, Clifton & Chollard, 2001; Affolter, 2004). Children with physical impairments can lose opportunities for meaningful exploration or manipulation of objects (Ruff, McCarton, Kurtzburg & Vaughan, 1984). The lack of meaningful opportunities for exploration and manipulation may be impacted by two elements. First, the physical disability limits the ability of the child to physically manipulate objects (Jennings & MacTurk, 1995). Children with severe physical disabilities have limitations in the manipulation of objects that can compromise the quality of their play and learning skills (Cook, Adams, Encarnação, Alvarez, 2012). Second, parenting styles and perceptions of parents about the child's performance in manipulation tasks can also limit the child's access to exploration opportunities (Jennings & MacTurk, 1995). This suggests that children with physical impairments are vulnerable to cognitive developmental delays (Riviere & Lecuyer, 2003).

Assistive technologies (AT) can provide opportunities for young children with disabilities to interact and explore their environment (Judge, Floyd & Wood-Fields, 2010). AT can also facilitate communication (Schlosser & Raghavendra, 2004), mobility (Millborne, Campbell & Wilcox, 2004) and facilitate manipulation to enhance cognitive development and learning (Cook, Adams, Encarnação, Alvarez, 2012). Children with disabilities can benefit from early exposure to AT because it gives them access to early experiences (Rosen et al., 2009; Wiart & Darrah, 2002; Cook, Liu & Hoseit, 1990). AT gives children with disabilities opportunities to engage in different kinds of social, cognitive and communicational activities, by increasing, maintaining, improving or compensating for their functional limitations (Cook & Polgar, 2008). For example, children who are unable to move independently can benefit from the use of powered mobility in order to promote the development of the skills that, in the study of typical development, have been proven to be related with self-produced mobility (Tefft, Guerette & Furumasu, 1999).

The case of augmentative manipulation

In the same way that powered mobility is an alternatively to walking, an alternative to typical manipulation can help children with physical disabilities access the early cognitive and perceptual advantages of upper extremity exploration. Robots have been used to provide an alternative to typical manipulation for children with disabilities. In the rehabilitation setting, robots can be used as augmentative manipulation systems due to their capability for picking, placing and exploring objects (Tejima, 2000). Several studies report the use of robots by children with severe physical disabilities. A study conducted by Cook, Bentz, Harbottle, Lynch & Miller (2005) reported an increase in children with disabilities' participation in the classroom, expressive language and interest (as reported by teachers) as a result of the use of a robotic arm system. Also, a study conducted by Cook, Howery, Gu & Meng, (2000), revealed that children who are unable to directly manipulate objects in their environment can use a robotic arm to handle objects and engage successfully in play experiences.

Through the use of switches children can gain control over the robot, which in turn, increases their independence and control over manipulative tasks and the environment (Isabelle, Bessey, Dragas & Blease, 2002). A study conducted by Cook, Liu & Hoseit (1990) revealed that very young children with disabilities can use a single switch-controlled robot as a tool. Six developmentally delayed children with chronological ages less than 38 months participated, along with three typically developing children. A switch was placed in front of the child and the robotic arm held a cookie that was in sight for the child but out of reach. Pressing the switch shortened the distance between the cookie and the child. Children as young as 8 months (developmental age) were able to use the robotic arm as a tool to retrieve the object of interest.

In infancy and early childhood cognitive testing has a very strong motor component (Thelen, 2000). Standardized developmental tests often require either motor responses or speech, which makes them hard to use with children with physical disabilities in order to determine their developmental or cognitive level (Poletz, Encarnação, Adams & Cook, 2010). Augmentative manipulation can provide children who have disabilities with the opportunity to perform different manual tasks and reveal and further develop their understating of the tasks and cognitive skills. For example, the use of a robot as a tool to perform a task can allow the exploration of a child's transition from an egocentric frame of reference (i.e. body-centered) to an allocentric frame of reference (i.e. object centered) (Barca et al., 2010). The use of the robot as a tool implies that the child needs to determine where the objects are and select an action in relation to the frame of reference of the robot for it to successfully grasp or reach an object (Cook et al., 2012).

The present study

Children with disabilities can accomplish manipulative tasks through the use of robots because robots compensate for their functional limitations by decreasing the motor demand of the task. Although studies have shown that children with physical disabilities can benefit from the use of robots as augmentative manipulation systems, certain critical aspects of this interaction remain unclear. Using the robot as a tool is not the same as manipulating objects with one's hand (Poletz et al., 2010; Cook et al., 2012). Action mediated by a tool can add additional cognitive demands to the task (Keen, 2011; Vygotsky, 1978) that in the case of augmentative manipulation can result in poor robot operational competence, rather than actual poor performance of a task. Operational competence refers to the development of skills required for successful device operation, including access methods (Light, 1989) (e.g. learning how to use the switches to produce the desired responses in the robot). Studies that have explored the use of robots as a way to compensate for functional limitations have also found that there are certain robot-operation skills required to successfully use the robot (For a review, See Cook, Adams, Encarnação, Alvarez, 2012). For example, children need to understand that pressing the switch causes the robot to move in a certain way (cause and effect) or that when using two or more switches the robot can move in sequences that give the child more control over the step by step movement of the robot (Cook et al., 2005; Poletz et al., 2010). Robots may decrease the motor demand while at the same time increase the task's cognitive complexity.

If robots have the potential to assist children with disabilities in the development of early cognitive concepts that result from independent interaction with objects then the robots must be accessible to young children (Cook et al., 2012). Therefore it is critical to understand the additional cognitive and perceptual demands that the use of the robot imposes on the child. On one hand, this can guide the selection and adaptation of the control interfaces. Control interfaces are the hardware elements that a person can use to control a device such as switch or a joystick (Cook & Polgar, 2008).

On the other hand, robot characteristics and programming can also be adapted to match the needs and skills of the child as well as the task and goals. One way to explore the ways in which robot augmented manipulation is different from typical manipulation and the resulting motor and cognitive implications, is to explore the use of robots by typically developing children. Several studies have explored the skills that typically developing children display when using robots and the ages at which they emerge (Forman, 1986; Stanger & Cook, 1990; Poletz et al., 2010; Cook et al., 2012). However the differences between robot augmented manipulation and typical manipulation with a similar goal or task have not been evaluated. Such a comparison requires a task for which the robot can be adapted but in which only the response modality would be changed.

Comparing children's typical manipulation with robot augmented manipulation in the performance of a cognitive task can provide insight into the specific implications of using augmented manipulation. The readily available behavioral data provided by this comparison can illustrate the ways in which decreasing the motor demands while potentially increasing the cognitive complexity (as with the robot) can alter children's performance. In addition, the use of neurophysiological data can further reveal the perceptual and cognitive processing demands involved in both versions of the task.

Neurophysiological Data

Neurophysiology provides a well-suited method for the study of brain activity in relation to behavioural responses (De Hann, 2002). Electroencephalographic (EEG) recordings are considered the most suitable method for the study of cognitive and perceptual processing during task performance in children: 1) they are non-invasive (Taylor & Baldeweg, 2002), since electrical activity is measured at the scalp; 2) They are among the few options that are safe and do not require sedation when used with children (De Hann, 2002); 3) They have high temporal resolution, on the order of 1 ms or greater (Luck, 2005). Cognitive processing can be studied in synchrony with the process of the task. Neurophysiological data can offer complementary data regarding the cognitive and perceptual processes that give rise to a particular behavioral response, and processes of which the subject is unaware (Dimoka et al., 2011). These data have been largely used to explore the substrates of child cognition, perception and emotion, especially because children cannot verbally reflect about the choices or salient information in the task that influenced their performance (Picton & Taylor, 2007; Thierry, 2005; Nelson & Bloom, 1997; Taylor & Baldeweg, 2002). The task used in these studies and discussed throughout this dissertation is the A-not-B task, perhaps the most studied task in developmental psychology (Dalenoort & De Vries, 2004).

The A-not-B task

In the classic version of the A-not-B task a child watches as a toy is hidden at one location (A). The child is then allowed to search for the toy. After several hidings and retrievals at location A, the toy is then hidden at the opposite location (B). When allowed to search for the toy, children between 8 and 12 months often reach back to location A, in spite of having seen the object being hidden at the new location (B). This perseverative behavior is referred to as the A-not-B error (Piaget, 1954; Berger, 2010).

The A-not-B task is considered a classic measure of cognitive development in early childhood (Diamond & Goldman-Rakic, 1989). An adaptation of the A-not-B was selected as the task for these studies because of the rich body of literature behind it and the different interpretations of the A-not-B that make it valuable for testing novel implementations. Of particular relevance for this study, is the relation between motor and cognitive skills in the performance of this task, an interaction which in fact gave origin to the task. Throughout his account of children's cognitive development, Piaget viewed motor experience and manipulation as the source of cognitive development (as cited by Rochat, 1989). For Piaget (1954) development is an active process, in which the child transforms his environment. Motor experience allows the child to progressively explore, manipulate and transform his environment. As the child acts on the world, he assimilates his experiences expanding his cognitive skills (Morabia, 2004).

Piaget & Inhelder (1969) proposed cognitive development as a process that occurs in a steady progression in which the child gradually goes through several stages of development. The experiences encountered by the child in one stage of development, were considered by Piaget as foundational for the development of further complex skills in the next stage (Ojose, 2008). The sensorimotor stage, the first of Piaget's developmental stages, encompasses the cognitive development of children in their first two years of life (Piaget & Inhelder, 1969). Referring to the construction of knowledge and representations of reality by the child in the first two years of life, Piaget (1969, p. 4) stated: "in the absence of language or symbolic function, these constructions are made with the sole support of perceptions and movements and thus by means of a sensory-motor coordination of actions without the intervention of representation or thought".

As described by Ormrod (2008) Piaget considered the sensorimotor stage particularly critical for the emergence of intentionality and object permanence. Intentionality refers to the ability of the child to act in a goal oriented manner (Piaget, 1969). Object permanence refers to the ability of the child to understand that an object continues to exist even when the object is hidden or out of view (Munakata, 1998). Piaget (1954) proposed the A-not-B task as a way to study object permanence and intentionality throughout the sensorimotor stage. By adding invisible displacement Piaget increased the complexity (Baird et al., 2002) of the task to make it more appropriate for testing the A-not-B error in older children (in their second year of life) (Diamond, 1997). In this version, children see an attractive toy hidden in a container at midline and the container is then moved to location A (i.e. the toy is invisibly displaced since what the child sees is the container being displaced not the toy). A screen is placed in front of the child to block his view and a delay period is introduced. During the delay an exact and empty container is placed in the opposite side, location B. After the delay, the screen is lifted, and the child is encouraged to search for the object (Wiebe, Lukowski & Bauer, 2010). The A-not-B with invisible displacement has been shown to share the same elements as the classical version (remembering where the object is hidden, inhibiting the previously successful response and reaching towards the object) (Diamond et al., 1997; Morasch & Bell, 2011).

If a child cannot successfully retrieve the object from the new location in the classical A-not-B task, Piaget (1969) hypothesized that the child believes the position of the object depends on his previously successful reaching behavior (i.e., the action of the child gives rise to the existence of the object), rather than depending on changes of the object's position in space. When a child successfully retrieves the object in both locations his actions reveal intentionality in the sense that the child is able to understand that in order to achieve the goal (e.g., retrieving the object) he needs to remove the cover. When invisible displacement is added, the child needs to further understand the interaction between objects in space: the object's location depends on its displacement and its new position in space and that the displacement of the container causes the displacement of the object as well (Piaget & Inhelder, 1969). Nevertheless, the A-not-B task has been used in laboratories all around the world (Diamond et al., 1997) and several alternative explanations have been provided for the A-not-B error. Table 1-1 summarizes alternative explanations that have been reported in the literature for why children display the A-not-B and the different versions of the task that have been used to do so.

Although the A-not-B error is a consistent and robust replicable finding in developmental research, the nature and meaning of the A-not-B error has been the focus of great debate (see Table 1-1). This perseverative error has been interpreted from different perspectives (for a meta-analysis see Marcovitch & Zelazo, 1999): as an illustration of developmental failure to understand object permanence (Piaget, 1954); an error derived from an egocentric frame of reference (Acredolo, 1985); limited working memory and inhibitory control as a result of immature neurological development (Diamond, 1990; Cuevas & Bell, 2010). Another possible explanation is that children perseverate due to the repetition of the motor plan and reaching kinematics that create a motor habit that the child cannot inhibit (Clearfield et al., 2006). In opposition to a cognitive account of the perseveration error, this approach advocates for a difficulty of the child in the inhibition of the motor pattern in spite of having full knowledge of the response. Alternatively, from a cognitive load perspective, children's A-not-B error results from a trade-off between the cognitive resources allocated to refined motor control and those required for complex cognitive performance (Berger, 2004; Berger, 2010). When exposed to a task that demands increasing effort, children sacrifice their weakest skill to carry out the task as best as they can (Kahneman, 1973).

One element that remains constant throughout the study of the A-not-B task (and its adaptations) is the extent to which motor and cognitive skills contribute to the A-not-B error. The fact that a motor response is required by the child in order to reveal the understanding of the task is a challenge to determining if the perseveration in the task is motor or cognitive in nature. Motor experience appears to be both demanding and leading to the contingencies for cognitive development (Smith et al., 1999). A looking version of the task has been used in order to explore the influence of motor behavior in the error (Bell & Adams, 1999; Bell & Adams, 1999; Bell, 2001). Bell and collaborators found comparable responses in both the reaching and the looking versions of the task in infants 8 months and older. However, children between 5 and 8 months of age performed better in the looking version of the task (Cuevas & Bell, 2010). These findings raise an interesting question regarding the motor demands of the task. Younger children, who are not yet very skilled at reaching (Smith et al., 1999) may not be able to overcome the motor demands of the reaching task (Berger, 2010). On the other hand it has been suggested that older children who have more stable reaching skills may be building more strong memories of the reach's motor planning and therefore perseverate (Clearfield et al., 2006). The role of alternative manipulation can offer additional insight into this question by providing an alternative means of independent motor control over the objects.

The interaction between motor and cognitive skills that seems to underlie the performance in the task, and the fact that a robot can be programmed to allow a child to perform the task in addition to typical reaching, makes the A-not-B task an ideal candidate for the study of augmentative manipulation.

Table 1-1 Summary of different reported accounts of the AnoB error

Account of A-not-B error origin	Description	Task versions used	References
Object Permanence and mental representation	Child displays the A-not-B error because he believes the existence of the object is contingent to his reaching. The child does not have an accurate mental representation of the object.	A-not-B classical version with cloths covering objects A-not-B with invisible displacement version	Piaget (1954) Piaget & Inhelder, (1969)
Spatial orientation and self-produced locomotion	Children display the A-not-B error because they fail to code the position of the object in space in relation to the previous location (A). In order to overcome perseveration children need to switch from an egocentric frame of reference to an allocentric frame of reference. These skills are developed as a result of self-produced locomotion. Notes: 1. Bell & Fox (1997) provide supporting evidence for both self-produced locomotion and brain maturation as etiologies of the A-not-B error. However, no three way interaction between the two and performance was found. 2. In Lew et al. (2007), perseveration is attributed to children's immature spatial orientation which in turn	A-not-B with changes in: - the position of the child and the task (180° rotation of the table before the B trial or changing the position of the child from seating to standing) -the toy used in A and B trials -The positions of A and B locations	Bremner & Bryant (1977) Evans & Gratch (1972) Butterworth (1975) Kermoian & Campos (1988) Bertenthal et al., (1994) Bell & Fox (1997) Lew et al. (2007)

	affects motor planning		
Brain maturation (and its relation to executive functions)	Children have accurate mental representations of the object, but their prefrontal cortex is not mature enough yet. This causes the child to not be able to successfully hold the memory of where the object is and inhibit the previously successful response simultaneously.	A-not-B and A-not-B with invisible displacement classical versions; versions of both with increased number of search locations; and looking version of the tasks (children respond by looking instead of reaching)	Diamond & Goldman-Rakic (1989) Cummings & Bjork (1981) Diamond (1990) Diamond (1997) Bell (2001) Cuevas & Bell (2010) Morasch and Bell (2011)
Parallel Distributed Processing	The A-not-B error is a result of a competition between latent memory traces of previously relevant information (A trial) and active memory traces of the current situation (B trial). In order to overcome perseveration, children must maintain active memory traces for the B location, that can compete with the strong repeatedly reinforced latent traces that bias the child's reach towards A.	A-not-B task altering the characteristics of lids and toys. In some versions no objects are hidden.	Munakata (1997) Munakata (1998) Munakata (2001)
Dynamic Field Account	Children perseverate in this task (that is they display the A-not-B error) due to the convergence of several processes (visual perception, motor planning, posture and spatial discrimination). The error results from the	Adaptations that altered the reaching kinematics of the task (such as adding weights, changing the position of the child, etc.)	Smith et al. (1999) Diedrich et al. (2000) Thelen et al. (2001) Clearfield et al. (2006)

	formation of a strong motor memory that builds over the reaching trials toward A. These memories are stronger than the visual memory of seeing the object being hidden at B. In this account perseveration is considered a developmental achievement towards a balance between stable and flexible motor and perceptual behavior.		
Cognitive Capacity account	In the A-not-B task, children's performance is dependent on the allocation of finite cognitive resources into the motor and cognitive demands of the task. Both motor and mental demands can tax cognitive capacity. Increased motor demands results in a greater difficulty to inhibit the response and impacts their cognitive processing.	Adapted versions in which children crawl, walk, or descend stairs to reach visible or non-visible targets for A and B trials.	Berger (2004) Berger (2010)
		Another manual search task termed "the CnotB task" where there are three hiding locations and children observe the hand of the researcher displaced under all three.	Riviere & Lecuyer (2003)

Research Questions

The following dissertation is the result of a review of the literature and the collection of data in order to answer the following questions:

1) How does the use of typical manipulation and robot mediated manipulation by young children differ in the performance on the A-not-B with invisible displacement task?

2) Is it technically feasible to study the neurophysiological differences between robot mediated manipulation and typical manipulation, given the characteristics of an electrically driven robot and the available technology?

3) What are the neurophysiological correlates of typical manipulation and robot mediated manipulation in young children's performance of the A-not-B with invisible displacement task?

The Papers

The following dissertation is a collection of four papers that together aim at answering the questions described above. A final general discussion and conclusions chapter is also included.

Paper 1: Grasping the opportunity for augmentative manipulation

This prospectus review provides an overview of the developmental approaches to the role of independent motor experience, specifically manipulation, in cognitive development. This paper establishes the relevance of manipulation for children's development and therefore the need for providing children with disabilities with an alternative to typical manipulation.

Paper 2: Robotic Tools: Quantifying the complexity of using robots as augmentative manipulation tools

Because of the critical role that manipulation plays in child development, robots can be used as an alternative to typical manipulation to provide young children who have physical disabilities with independent exploration experiences. However, using a robot as a tool may add cognitive demands to the task when compared with direct manipulation or the use of more common tools (i.e., a hook). This paper provides a theoretical approach to the assessment and quantification of the complexity of children using the robot as a tool. The complexity number hypothesis first proposed by Van Leeuwen, Smitsman & Van Leeuwen (1994) for common tools was used to assess the complexity of a robot mediated task performed by an infant with a disability and compared with the demands encountered by a typically developing infants when using a common tool.

Paper 3: The neurophysiology of augmentative manipulation: a method for technical implementation

Little is known about the neural correlates that subtend robotic augmentative manipulation and the ways in which using a robot to manipulate objects may change the task's cognitive and perceptual demands. Several technical considerations pose a challenge to such studies. After exploring the theoretical differences in the previous paper, this paper presents a methodology for the technical implementation of neurophysiological exploration of robot-augmented manipulation and presents a preliminary comparison between augmented manipulation and direct manipulation as response modalities in the A-not-B task with invisible displacement (i.e. this additional level of complexity was added in order to make the task more appropriate for older participants).

Preliminary results of this adult pilot were presented at the 12th European Association for the Advancement for Assistive Technologies in Europe (AATE) Conference (September 19 to 22, 2013 in Vilamoura, Portugal). The presentation was awarded a "Highly Commended Distinction" in the Young researcher award category. A complete extended and revised version (Chapter 3) was submitted and accepted as a paper in the journal Technology and Disability.

Paper 4: The role of augmentative manipulation in infant cognition: the case of the A-not-B task

This final paper presents the results of a study conducted with 15 typically developing children between 18 to 30 months. Additionally, it presents the results of a case study with a 28 month old child with a severe physical disability. Children in this study were exposed to the typical reaching version of the A-not-B task with invisible displacement and a robot mediated version of the task. Behavioural and neurophysiological data were recorded and compared. Implications for the use of robot augmented manipulation are discussed.

Chapter 2

Paper 1: Grasping the opportunity for augmentative manipulation

Introduction

Motor experience plays a critical role in cognitive and perceptual development for typically developing children. Through physical manipulation, exploration and interaction with the environment a child develops perceptual, cognitive and social skills (McCarty, Clifton, & Chollard, 2001; Flanagan, Bowman, & Johansson, 2006). Further, motor skills allow insight into a child's developing cognitive and perceptual skills (McCarty, Clifton, & Chollard, 2001), providing the first window to observe developmental changes in the young child (Thelen, 2000). Children with physical impairments often have limited opportunities for meaningful exploration or manipulation (Ruff, McCarton, Kurtzburg, & Vaughan, 1984) and this limitation may restrict the observance and development of their cognitive and perceptual skills (Jennings, & MacTurk, 1995).

Motor development is one of the most studied topics in developmental theory (Haywood & Getchell, 2009). The study of typical motor development has focused on the emergence of locomotion and manipulation and their importance in development (Karasik et al., 2011). The emphasis on these motor behaviors in typical child development has influenced rehabilitation and educational approaches with children who have motor disabilities (Fetters & Ellis, 2006). As a result, development of children with disabilities has been approached clinically (Herbert, 2003) and rehabilitation has been extensively focused on an appearance of normalcy, as derived from the medical model of disability and its focus on the amelioration of impairment (Phelan et al., 2014). For children with physical disabilities, the rehabilitation focus has been on restoring "typical patterns of movement", under the assumption that more "typical patterns" will lead to improvements in function and ultimately participation (Butler & Darrah, 2001). Although there are certainly physiological benefits that result from impairment-focused remediation approaches (e.g. walking results in maintenance of muscle length and bone density, Larkin & Summers, 2004) the evidence supporting improvement of function and increased participation is inconclusive (Law et al., 2007). In a randomized control trial, Law et al. (2011) found that, in terms of goal attainment, the effects of a therapy approach based on environmental adaptations were similar to those of an approach based on remediation of the child's impairment.

The focus on remediation for children with physical disabilities is supported by the medical concept of normalcy and societal preference for a non-disabled body (Gibson et al., 2012). Since the mid-1800s, when the statistical distribution concept of norm was first used as an imperative of "what should be" and then applied to the human body (McKenzie, 1981; Davis, 1995), the notion of normal was followed by the concept of an abnormal or disabled body (McKenzie, 1981; Norrgard, 2008). With the introduction of ranked physical traits (e.g. weight & height), greater emphasis was placed on the lower and higher ranks of a certain trait, which led to the current conception of tests like intelligence quotient (IQ) (David, 1995; Goldstein, 2012). This placed the characteristics of people with disabilities as "lower" and therefore undesired and the positive extremes as desirable traits that were to be preserved as a "normal" ideal (Goldstein, 2012). Variations in children's bodies that are outside of the "norm" lead to exclusion by the medical and developmental communities (James, 1995). Great amounts of public and family financial and time resources are put into the rehabilitation goal of remediation for children with disabilities even though it has been established that many children will not achieve or maintain typical independent functional ability and will use assistive technologies (AT) (Gibson et al., 2012).

The three aims of this paper are to 1) explore the theoretical, practical and historical elements that contribute to our understanding of atypical development, the goals of rehabilitation and the consideration of assistive technology alternatives; 2) provide an overview of the relevance of manipulation for children's development; 3) demonstrate the importance of providing children with physical disabilities with an alternative to typical manipulation.

The "typically" informed understanding and approach to childhood disability

The understanding of atypical development around its characteristic deviation from the norm continues to be predominant (Landsman, 2009). Several fields of research and theoretical perspectives have contributed to the medical concept of clinical normality and the implications of such concepts. Clinical approaches that emphasize "normalcy" may be resistant to alternative means to provide children with disabilities with early experiences because of the concern that seeking the use of

Assistive Technologies (AT) as an alternative to typical motor patterns will interfere with the potential and desire of the child to achieve typical skills (Rosen et al., 2009).

For years, power mobility was viewed as a last resource in the rehabilitation process of children with physical disabilities. It was believed that providing a child with a power wheelchair would suppress the child's desire and potential for walking (Wiart et al., 2004). Similarly, augmentative and alternative communication (AAC) devices were viewed as a last resort because of concern that they would prevent a child from talking (Romski & Sevcik, 2005). The value of walking and talking was emphasized rather than the importance of achieving mobility and communication by a variety of means.

Normality and the Neuromaturational Approach

In the first year of life, changes in the child's ability to interact with the environment through manipulation and mobility constitute the readily available evidence of an expected or normal trajectory of development. The observable and progressive nature of motor behaviour in infancy allowed early scientists to establish the relationship between development and neurological maturation. Deeply rooted in biology and neuromaturation, development was attributed to the maturation of the central nervous system (CNS) with environmental interactions having little influence (Gesell, 1929; McGraw, 1930). Neural maturation was described as the result of a progressive decline in the expression of reflexes by cortical inhibition, followed by cortical control in which various neural centers are functionally integrated (McGraw, 1930)). Historically the clinical approach to atypical development was based on this neuromaturational approach to development.

The neuromaturational approach contributed a definition of norm-based motor development milestones as evidence of the maturation of the CNS. Norm based milestones in motor development have allowed the identification of atypical development and the early detection of neurological disorders (Howle, 2002; Heriza, 1991). The detailed description of the neuromaturational developmental norms made it possible for deviations to be noted early (Aylward, 1994). These norm-based milestones are used as profiles of typical time points and characteristics of emerging motor behaviors that are used to determine the presence or absence of expected motor patterns or the presence of atypical motor behaviors. Many of the norms developed by Gesell and his contemporaries are used widely in developmental scales and battery assessments, and his initial reports on child development continue to be widely cited in developmental books and publications (e.g. Gesell

Developmental Observation-Revised, Bayley Scales of Infant Development). The neuromaturational approach's description of infantile reflex-based motor behaviour in the child was seen in children and adults with motor disabilities, which led to the use of the neuromaturational developmental theory as a model for rehabilitation and recovery (Kamm, Thelen, & Jensen, 1990). For years, this approach influenced theoretical backgrounds and therapeutic interventions with atypically developing children aiming at inhibiting postural reflexes and achieving more typical voluntary movements (Miyahara & Reynders, 2003). However, in Gesell's detailed and confident descriptions of child development "the typical child was a quasistatistical amalgam, every parent's child would naturally deviate" (Thelen & Adolph, 1992, p. 374) and rehabilitation and clinical practices have since moved towards more comprehensive views of development.

The paradigm shift: new perspectives on typical and atypical development

The historical trajectory and evolution of the understanding of development has resulted in different conceptions around atypical development and rehabilitation approaches. Due to the complexity of the developmental process it is not surprising that multiple interpretations and assumptions around children's development have emerged. More recent theories of development lead to our understanding of children's development as a dynamic process with continuous interactions among motor, cognitive and perceptual skills (Thelen, 2005). The emergence of new developmental theories that have recognized the need for developmental views that can encompass both typical and atypical development and that recognize variability and adaptation as integral to the nature of human development, have prompted a paradigm shift in rehabilitation and disabilities services.

Traditional approaches to how children develop their movement skills are insufficient to explain certain new patterns that can emerge as a result of changes in the environment and the flexibility of motor behavior (Spencer et al., 2006). An example of the latter is the disappearance of the stepping reflex (Thelen & Fisher, 1982). Neuromaturational approaches had traditionally explained the disappearance of the stepping reflex (i.e. at around three months of age infants will stop making walking motions with legs and feet when held in upright position with their feet touching the ground) as a result of brain maturation leading to cortical control over voluntary movement or as a result of an evolutionary adaptation (Oppenheim, 1981; Touwen, 1976). However, Thelen and her colleagues (Thelen & Fisher, 1982; Thelen, Johanson, & Ridley-Johnson, 1984) showed that the disappearance of the stepping reflex is due to a critical fat: muscle ratio and the increased muscle strength a child requires to lift his legs in the upright position as he gains weight (Spencer et al., 2006). This better explains why kicking in the supine position with the same pattern of movement increases during the first 6 months and the stepping reflex disappears.

Understanding the development of children with disabilities has been viewed as a process that starts with understanding what typical or so-called "normal" development looks like (Herbert, 2003). However, defining what is typical in child behavior has also proven to be challenging because of the variable nature of development (Vereijken, 2010). For example, Thelen and colleagues (1996) showed that infants display very different patterns of reaching behaviour. Children adapt to both the unique characteristics of the environmental demands of a reaching task and their innate skills for movement (Spencer et al., 2006). Each "typically developing" child, if studied closely, displays highly variable trajectories. From the standpoint of developmental research data, variability would lead to the conclusion that measurement was not reliable (Vereijken, 2010). However, variability could actually reveal control mechanisms that govern child behavior and could provide more valuable information about the process of development. In line with this suggestion, Thelen & Smith (2000, p. 343) remarked, "traditionally, variability in behavioral data is a researcher's nightmare […] researchers deliberately choose tasks to make people look alike. But real behavior in real children is not like that".

Exploring variability in development has led to the reconceptualization of atypical development as part of a developmental continuum. Herbert (2003) distinguishes between five types of development. *Delayed development* refers to developmental patterns of typically developing children that are slow in emergence. *Abnormal development* refers to behaviors that are not seen in typically developing children because the developmental process is different from normal. *Absence of development* occurs in some categories or domains in which the child fails to develop a certain skill. *Expected behavior within atypical development* refers to aspects in the development of children with disabilities who develop within the range of variation reported in non-disabled children. These first four categories in the classifications still reflect the legacy of norm-based deviation for the categorization of developmental milestones of children with disabilities. These categories draw clear distinctions that derive from a child's neurophysiological condition and the resulting observable outcomes. Further, Herbert acknowledges in this account that some aspects of the development of a child with a disability are within the range of what is considered "normal".

A fifth category proposed by Herbert is called *compensatory development*. Children with disabilities may take routes in their developmental process that differ from those of typically developing children although the end point is the same. Unlike abnormal development, this category reflects behaviours that have a similar functional end goal than those seen in typical child development but through different means. The idea that children with disabilities can have different trajectories of development to achieve the same point resembles the concept of “developmental detours” proposed by Vygotsky (1929) in his accounts of the study of disability.

Vygotsky’s defectology

The conception around typical patterns of motor development expands beyond the boundaries of clinical interventions and into the educational approach towards children with physical disabilities. Limited experiences and opportunities are provided for children with disabilities due to the expectations of society towards normality (Gindis, 1995).In his works “Fundamentals of Defectology” Vygotsky proposed what at the time was a unique vision of education for children with disabilities (Gindis, 2003). Vygotsky suggested that positive capabilities and strengths of the child should be emphasized by including them in educational and therapeutic settings that recognize their potential and the areas in which they need support. He referred to this practice as inclusion based on positive differentiation (Vygotsky, 1931/1993). A similar approach is advocated by the social model of disability (Barnes & Mercer, 2004).

Defectology, originally *defectologia* in Russian, was a term used to describe the study of disability and the methods and processes of evaluation, education and upbringing of children with disabilities (Gindis, 1995). Within defectology Vygotsky proposed the concept of developmental detours. Vygotsky (1978) stated that the diagnosis of a child with a disability constitutes only a disorder, in the sense that it is an *organic impairment* (Gindis, 2003). An organic impairment is a medical description of the child’s condition whereas a disability is the result of the exclusion from social, cultural and educational interactions that the child suffers as a consequence of his primary disorder that Vygotsky refers to as the secondary disability (Vygotsky, 1931/1993). Because an organic impairment does not necessarily result in a disability, development of children with disabilities should not be studied as a quantitative problem, in the sense that it is not a matter of a child having fewer skills compared to a typically developing child who has more. For Vygotsky, the study of development of children with disabilities needed to go beyond the quantitative skill differences into developmental detours. For example, one cannot simply imply that the development of a blind child is equal to the development of a typically developing child after subtracting visual perception and all that relates to it. Development is a sequence of inter-related events that cannot be isolated from each other. In the same way a typically developing child has unique ways to deal with environmental demands based on his unique organic and functional structures, a child with a disability has a qualitatively different development that can lead to the same functional end point as the typically developing child. Therefore, educational strategies should recognize the functional end point of a certain behavior and encourage alternative means to achieve it (Vygotsky, 1931/1993).

Dynamic Systems Theory (DST)

The relevance of the functional end point of children's behaviors (over the means through which they achieve them) suggested by Vygotsky, is consistent with findings from the Dynamic Systems Theory (DST) that has permeated more recent rehabilitation approaches. In the studies of Thelen (1996) typically developing children who showed variable behaviors in the acquisition of their skills, showed stability in the functional end point. For example, children with variable reaching patterns arrived at more coordinated reaching patterns and trajectories for object grasping as they gained experience. Similarly, a developmental detour represents the possibility that a child with a disability can accomplish a functional task that has meaning for him, through a different developmental pathway in comparison to typically developing peers (Vygotsky, 1931/1993). It is the interaction between the organic components of a system and the environment that causes a pattern to emerge (Smith & Thelen, 2003).

In DST, the child's characteristics coupled with task related and environmental demands are all fundamental to motor development (Thelen, 2005). This theoretical framework has major implications in both typical and atypical development. Modifying the task or the environment can allow the child to perform an activity that he couldn't before (Darrah et al., 2011). For example, reaching behaviors emerge around three months, and yet, when provided with the appropriate characteristics of the task and environmental opportunities, children use their feet in a coordinated purposeful way to interact with toys (Galloway & Thelen, 2004). The study of variability as a source for development in dynamic systems theory is comprehensive enough to support both typical and atypical development studies (Thelen, 2005). The interactions between the child, the task and the environment, provide the input to explore several options of movement and find the most efficient motor solution (Darrah & Bartlett, 1995).

Ecological Realism approach

DST resembles the principles of ecological realism proposed by Gibson and Gibson (1955). Eleanor and James Gibson's approach focused on perceptual development as coupled to action and in the last two decades has been adapted to further explore motor development (Haywood & Getchell, 2009). Gibson et al. (1987) demonstrated that children select the movement pattern that allows them to successfully complete the task based on the information provided by the environment.

The emphasis of the ecological approach is the relationship between two elements: the individual and the environment upon which the individual acts (Kirst-Ashamn & Lull, 2009). DST can be considered as more broad, in the sense that it considers elements within the individual and elements within the task and environment as crucial parts of the system, for example, the child's biomechanical, physiological, emotional characteristics as well as the physical and/or social constraints of the environment (Thelen, 1995). However, both DST and Gibson's Ecological realism approach establish that the role of the interaction between the environment and the child is critical for development. For this reason, they are often considered as highly compatible and complementary theories (Bertenthal & Clifton, 1998).

The Neuronal Group Selection Theory (NGST)

The Neuronal Group Selection Theory (NGST) conceptualizes the influence of the environment in brain connectivity as well as the neural correlates of individuality in development (Howle, 2002). NGST portrays brain development as the result of the dynamic organization of neuronal networks as determined by behavior and experience (Edelman, 1987).The NGST conceptualization of brain mechanisms is consistent with DST (Thelen, 1995). The child encounters environmental information that affords him different possibilities of action (Gibson J. , 1979). These possibilities are the result of the neuronal primary repertoire (a variety of movement opportunities the child can explore in order to meet environmental demands) (Edelman, 1987). This repertoire opens the possibility to several alternative combinations and degrees of freedom (Thelen, 1995). The selected motor actions are assembled in self-organizing patterns that are dependent on the task and environmental constraints (Thelen, 2000). Experience and environmental information then promote selection among neuronal groups and a new repertoire that has proven successful is assembled (Howle, 2002). Successful behaviors provide feedback that strengthens these connections (Thelen, 1995).

An initial pattern variability is followed by selection. The system settles into more stable and successful patterns of behavior that reduce variability as the behavioral response of the child becomes more skilled and stable (Hadders-Algra, 2008). The repeated experience of a successful pattern allows the child to master the skill, and the neuronal group connectivity is strengthened. The variability increases in the form of ability to adapt these patterns to different situations or to shift to patterns that can be successful with other environmental constraints (Howle, 2002).

Impact of the new perspectives on rehabilitation practices

From Vygotsky's perspectives on childhood disability, all the way to DST, Neuronal Group Selection Theory and Ecological Realism, behavior is conceived as a result of the interaction between anatomical, physiological, environmental and experiential factors. Their influence on the therapeutic strategies for children with disabilities has increased (Thelen, 1995), partially motivated by inconclusive evidence supporting functional improvement resulting from traditional approaches such as neurodevelopmental treatment (Blauw-Hospers & Hadders-Algra, 2005; Butler & Darrah, 2001). These perspectives also advocate for exploring alternative means through which children with disabilities can achieve functional goals. For example, a context-focused intervention approach for children with cerebral palsy based on the principles of the DST promotes a focus on the functional performance of a task rather than in the attainment of a "normal" pattern of movement (Darrah et al., 2011). Therapists are trained to identify goals along with families and to focus on changing the task or the environment as a way to achieve the established goals instead of attempting remediation of the child's skills. If the goal of a child is achieving independent self-feeding of cereal with limited hand control, the focus is on modifying the task. For example, the therapist put peanut butter on the child's fingers so that the cereal would stick to the child's hand. This approach led to immediate achievement of the functional goal. The repeated independent practice of this successful pattern can potentially lead to modification of the child's constraints so that he can progress to self-feeding without this adaptation (Darrah et al., 2011). A similar strategy based on the family's needs, the Coping and Caring for Infants with Special Needs (COPCA) program has been developed following the principles of NGST (Dirks et al., 2011). Parents are coached on strategies that can help the child achieve his or her functional goals. Using different movement patterns that differ from those of typically developing children is reinforced and promoted as a strategy for achieving a goal.

Neither the context-focused intervention approach nor the COPCA program, aim at achieving normalization of movements or inhibiting the child's movement patterns. Instead they focus on the functional goal and they value trial and error behaviors as a source of learning. Both programs have been compared with traditional impairment remediation therapies that are commonly based on neurodevelopmental treatment (NDT) (Law et al., 2007; Dirks et al., 2011). Both programs report positive outcomes on functional performance and parent involvement (Darrah et al., 2011; Dirks et al., 2011).

Assistive Technologies for children with physical disabilities

Providing inclusive and meaningful educational and social participation opportunities for children with disabilities requires a comprehensive understanding of their developmental potential, the challenges that they face and the compensatory mechanisms and alternative means that they can use and develop. Assistive Technologies (AT) constitute an alternative through which children can achieve the functional end points of motor patterns (e.g. powered mobility, as an alternative to walking, enables locomotion). AT gives people with disabilities the means through which they can interact with others, perform daily activities, express and develop their individuality, be more independent and participate in their community (Tefft, Guerette, & Furumasu, 1999; Mankoff, Hayes, & Kasnitz, 2010). In the same way, AT can allow children with disabilities to interact and explore their environment (Judge, Floyd, & Wood-Fields, 2010), facilitate communication (Schlosser & Raghavendra, 2004), facilitate mobility (Millborne, Campbell, & Wilcox, 2004) and facilitate manipulation to enhance cognitive development and learning (Cook, Encarnação, & Adams, 2010). One example of the ways in which AT can provide an alternative to typical motor patterns is powered mobility.

The case of power mobility

It is clear in typical development that functional mobility and exploration contributes to cognitive and perceptual development (Held & Hein, 1963). The lack of functional independent mobility can cause compromised spatial knowledge, learned helplessness, poor performance in object permanence tasks, compromised weariness of heights, and increased dependence of vision for postural control (For a review see Rosen et al., 2009). Children with physical disabilities can also have poor self-initiation and persistent feelings of helplessness if they are not given means to explore and interact (Millborne, Campbell, & Wilcox, 2004). Therefore, alternative means for early independent environmental exploration should be provided (Butler, 1986). An appreciation of the negative consequences of a lack of independent locomotion and exploration prompted advances in self-produced locomotion for children with disabilities (Butler, 1991). Power mobility is an example of AT that can be used to either augment or compensate for a function, and increase functional capabilities (Cook & Polgar, 2008).

The exploration and early adoption of power mobility has provided children who have disabilities access to the cognitive, perceptual and social benefits of functional independent exploration of their environment (Furumasu, Guerette, Teft, 1996; Butler, 1991; Rosen et al., 2009). For children who are unable to move independently power mobility has been shown to promote the development of skills that are related to self-produced mobility in typical development (Tefft, Guerette, & Furumasu, 1999).

Although the cognitive, social and emotional benefits of power mobility were established, concerns were raised regarding whether or not very young children could learn how to use power mobility safely (Kermoian, 1998), and children's access to AT devices is often delayed until they are school-aged based on cognitive readiness, and safety concerns (Tefft, Guerette, & Furumasu, 1999; Chen, Ragonesi, Galloway, & Agrawal, 2011). Current, evidence shows that a child's age is not what determines the ability of the child to operate a power wheelchair, and that cognitive readiness occurs at an age far younger than school age (Rosen et al., 2009). Infants and young children with physical impairments can benefit from power mobility (Butler, 1988; Chen et al., 2011; Butler, 1986; Rosen et al., 2009). Therefore, the frequency with which AT devices are being prescribed for young children is increasing (Lovarini, McCluskey, & Curtin, 2006).

Other types of motor experience: the case of manipulation

Due to their motor impairments, children with motor disabilities can have difficulties in manipulation which can affect the quality of their play and learning skills (Cook, Adams, Encarnação, Alvarez, 2012). Clinical development of manipulation skills has not been as responsive as mobility to the paradigm shift from remediation of movement patterns to focus on functional mobility.

Manipulation plays a major role in development, learning and interaction. Therefore a focus on functional manipulation rather than on typical reaching and grasping patterns can allow children to benefit from the opportunities for cognitive development afforded by independent manipulation.

Object manipulation is a critical part of motor experience that enables the child to acquire skills required for learning, emergence of symbols, referential communication and the understanding of interactions between multiple objects and the environment (Bates, 1979; Greenfield, 1991; Piaget 1952; McCarty, Clifton, & Chollard, 2001; Affolter, 2004). Object manipulation starts a few months after birth and is the first means through which the human infant acts on the world, emerging before independent locomotion (Vauclair, 1984). The child perceives objects and their properties and starts exploring different ways of interacting with them (e.g. bangs objects against each other (Kahrs et al., 2012)). Also, the child starts exploring ways of interacting with others (e.g. the child throws an object that is picked up by an adult) (Haywood & Getchell, 2009).

Performance of object manipulation in typically developing children can indicate that early milestones of cognitive and perceptual development have been reached (Vauclair, 1984; Affolter, 2004). Through object manipulation, a child progressively starts to relate to objects and discovers how objects can be used to achieve a goal (Lockman, 2000). This development by the human child gives rise to tool use (the use of an object to produce a physical modification of the environment (Greif & Needham, 2011), which in cognitive theory has also been related to representational means-end planning (Bates, 1979; Lockman, 2000; Keen, 2011). Tool use has been identified as a landmark cognitive skill (Parker & Gibson, 1977) that involves understanding of the properties of objects and how they can relate to each other as a means to achieve a goal (Buttelmann, Carpenter, Call, & Tomasello, 2008). For example, at around 18 months, a child is able to execute a planned strategy if he/she notices an awkward orientation of the handle of a spoon. The strategy is used to guide the selection of which hand to use or how to change the grasp for successful self-feeding (McCarty et al., 1999; Keen, 2011). During the first two years, the child actively manipulates objects, explores them individually and sequentially and finally realizes that one object can be used as a means to reach the other (Piaget, 1954). For example, a child can use a stick (McCarty, Clifton, & Chollard, 2001) or a string (Chen, Sanchez, Campbell, 1997) to retrieve an object out of reach.

The exploration and understanding of objects in the environment progressively exposes the child to cognitive conflict (Piaget, 1954). A cognitive conflict arises when a child's present concepts and knowledge of the world are not enough to solve a new situation or understand a new element of action (Shayer, 2003). This conflict forces the child to accommodate his previous cognitive structures (Piaget, 1954) in order to internalise the new experiences (Vygotsky, 1986). This, in turn, leads the child to further develop his/ her cognitive skills (Sayce, 2009).

Object manipulation and tool use also have great implications in the child's social development. Object manipulation is influenced by the way adults and peers use objects in a particular context and how they respond to a child's exploration of a particular object (Vygotsky, 1978). For example, a child may use a string to pull an object. The adult naturally observes the child while he performs the action and provides feedback by correcting or praising the child (Vygotsky, 1978). The child observes and imitates the use of objects and therefore how he relates to objects depends on the context (Vygotsky, 1978).

There are major implications of manipulation for a child's social, and cognitive development making it crucial to find alternatives when typical motor patterns are not available in children with disabilities. Evidence suggests that although manipulation as a form of motor experience plays an important role in cognitive and perceptual development, typical motor experience may not be necessary for the acquisition of skills (Riviere & Lecuyer, 2003;; Riviere & Lecuyer, 2002). Children with disabilities can explore alternative ways of manipulating objects as a result of adaptive behaviors in response to environmental demands. Alternative means through which children can reveal and develop their skills in the absence of typical manipulative skills can allow a further understanding of atypical development.

Robots: The case for augmentative manipulation

Clinically, great emphasis is placed on the kinematic and kinetic characteristic of the grasp of children with motor disabilities (Cope & Trombly, 1998; Coluccini et al., 2007; Mackenzie et al., 2009). However, the early benefits of independent exploration of the environment on cognitive and perceptual skills may be missed when the achievement of typical motor patterns is the paramount goal (Wiart & Darrah, 2002; Tefft et al., 1999). The benefits of early exposure to AT for children have been explored, revealing that young children can use AT and have independent access to early experiences (Rosen et al., 2009; Wiart & Darrah, 2002; Cook, Liu, & Hoseit, 1990).

Robots can be used as an alternative to early manipulative behaviors in the same way that power mobility is an alternative to walking. Children in different age ranges can benefit from the use of robots, and children as young as 8 months have used a robot as a tool to retrieve an object out of reach (Cook, Liu, & Hoseit, 1990). In the rehabilitation setting, robots can be used as augmentative manipulation systems due to their capability for picking, placing and exploring objects (Tejima, 2000). Robots can be programmed in several ways throughout a continuum of autonomy from fully autonomous to teleoperated (Sheridan & Verplank, 1978). At one end of this continuum the autonomous robot performs a complete action when it receives an initial high level command. The teleoperated robot at the other end of the continuum requires that the user provide all the commands. The flexibility of robot autonomy results in an advantage for their use with children when usability and cognitive readiness are unknown or variable. Children with disabilities can control the robots independently through switches adapted to their physical capabilities increasing their independence and control over the task (Isabelle, Bessey, Dragas, & Blease, 2002).

Several studies report the use of robots by children with severe physical disabilities (For a review see Cook et al., 2010; Cook, Adams, Encarnação, Alvarez, 2012). The use of robots as an alternative to manipulation has been shown to increase children's participation in the classroom where expressive language and interest increased as reported by teachers (Cook, Bentz, Harbottle, Lynch, & Miller, 2005). Children who are unable to directly manipulate objects can use a robotic arm to engage in play activities (Cook, Howery, Gu, & Meng, 2000). In addition robots can also provide a tool through which children with disabilities can reveal their understanding of cognitive skills (Poletz, Encarnação, Adams, & Cook, 2010; Cook, Adams, Volden, Harbottle, & Harbottle, 2010).

Conclusions

Considering that developmental theory shapes the way we interpret, understand and approach childhood, the way we interact with children in clinical and educational settings is impacted by our understanding of how they develop and learn, how different skills and behaviours emerge, and how this process is enhanced or constrained by environmental factors (Thelen, 2005). The framework under which children's development is interpreted can have great implications in terms of the opportunities, facilitators or constraints that the child encounters (Santrock, 2008).

Motor experience has been related to the development of early cognitive skills. Through manipulation and locomotion the child interacts with his environment and progresses in the acquisition of cognitive and perpetual skills. However, it is the functional goal of motor experience rather than the means through which children typically achieve it that can have an impact on the development of children with severe physical disabilities. Manipulation constitutes such a crucial experience for children, that alternatives to typical reaching and grasping should be identified. Children can use robots to perform manipulative tasks and benefit from the cognitive and perceptual components of manipulation. Augmentative manipulation can also provide insight into the child's cognitive skills by proving observable evidence of the child's understanding of concepts and environmental demands. However, robot augmented manipulation is not the same as typical manipulation. Understanding the cognitive and perceptual demands that are presented to the child when using the robot as a tool is critical. Comparing augmentative manipulation and typical manipulation can provide useful information in this regard. Both theoretical approaches to the analysis of complexity of augmented manipulation (See Alvarez & Cook, 2014, *chapter 3 in this document*) and experimental comparisons of typical and robot augmented manipulation support this goal (See Alvarez et al., 2014, chapter 4 in this document; Alvarez et al., 2014, Chapter 5 in this document).

Chapter 3

Paper 2: Robotic Tools: Quantifying the complexity of using robots as augmentative manipulation tools

Introduction

Through physical manipulation and exploration of the environment a child develops perceptual and social skills that allow learning and interaction (McCarty, Clifton & Chollard, 2001; Flanagan, Bowman & Johansson, 2006). As a critical part of motor experience, object manipulation has been identified as a motor behaviour that enables the child to acquire skills required for emergence of symbols, referential communication and the understanding of relations between objects, and interactions with the environment (McCarty et al., 2001; Bates, 1979; Greenfield, 1991; Piaget, 1954; Affolter, 2004). Object manipulation starts developing a few months after birth, as the child perceives objects and their properties and explores the relation of these objects to self and other´s actions (Haywood & Getchell, 2009). Object manipulation indicates that early milestones of cognitive and perceptual development have been reached (Affolter, 2004). Through object manipulation, a child progressively starts to relate to objects and discovers how objects can be used to achieve a goal (Lockman, 2000). This development by the human child gives rise to tool use, which in cognitive theory has been related to representational means-end planning (Bates, 1979).

Tool use has been identified as a landmark cognitive skill (Parker & Gibson, 1977) that involves the understanding of the properties of objects and how they can relate to each other as a means to achieve a goal (Buttelmann, Carpenter, Call & Tomasello, 2008). For example, at around 18 months, a child is able to execute a planned strategy if he/she notices an awkward orientation of the handle of a spoon. The strategy is used to guide the selection of which hand to use or how to change the grasp for successful self-feeding (McCarty et al., 2001; Keen, 2011). The use of objects as tools extends the physical capability of the child enhancing his interactions with the environment (St. Amant & Horton, 2008).

Children with physical disabilities lose opportunities for meaningful exploration or manipulation due to their motor impairments (Ruff et al., 1984). The physical disability limits the ability of the child to physically manipulate objects (Jennings & MacTurk, 1995). Further, the perceptions of parents about the child's performance in manipulation tasks can also limit how much they encourage the child to interact with the environment. Parents of children with physical disabilities have been found to encourage less exploration by the child and perceive their child as seeking more adult approval and help, being less motivated and preferring very easy and familiar tasks (Jennings & MacTurk, 1995).

The use of assistive technologies (AT) allows children with disabilities access to early experiences by increasing, maintaining, improving or compensating for their functional capabilities (Cook & Polgar, 2008; Jones, McEwen, Hansen, 2003; Wiart & Darrah, 1999; Cook, Liu & Hoseit, 1990). Assistive technologies such as power mobility or augmentative and alternative communication devices give children with disabilities opportunities to explore their environment through independent mobility (Wiart & Darrah, 1999), or interact with others and participate in social activities (Cooley, 2010). In a similar way, robots represent an alternative to typical manipulation (Cook et al., 2012).

Robots: Augmentative manipulation systems

A robot is "an automatically controlled, reprogrammable, multipurpose, manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications" (International standard ISO 8373, 2012). Even though the International Standard emphasizes the industrial use of robots, they can and are used in other fields such as rehabilitation (Cook, Encarnaçao & Adams, 2010).

In the rehabilitation setting, robots can be used as augmentative manipulation systems due to their capability for picking, placing and exploring objects (Tejima, 2000). In that sense, robots supplement (augment) the existing manipulation skills of the child and compensate for the limitations in manipulation. Robots can be programmed in several ways on a continuum from fully autonomous to teleoperated so that children with disabilities can use them for assistive manipulation (Cook, Encarnaçao, Adams, 2010). At one end of this continuum the autonomous robot can perform a complete action when it receives an initial high level command and does not request any intervention of the human user (Cook, Encarnaçao, Adams, 2010). On the other end of the continuum, to use the teleoperated robot the user has to provide all the commands and has absolute control (Cook, Encarnaçao, Adams, 2010). Children can control the robots independently through the use of switches adapted to their physical capabilities and needs. For autonomous action this can be a single switch that generates a complete robotic movement to complete a task. A teleoperated robot might require switches for each degree of freedom of the robot. This independent control over the robot, through switches, increases the independence and control of the child over the task and the environment (Isabelle et al., 2002).

Several studies report the use of robots by children with severe physical disabilities. Robots have been shown to increase children with disabilities' participation in the classroom, expressive language and interest as reported by teachers (Cook et al., 2005). Children who are unable to directly manipulate objects in their environment can use a robotic arm to handle and manipulate objects and engage successfully in play experiences (Cook et al., 2000). Robots can also provide a tool through which children with disabilities can reveal their understanding and use of cognitive skills (Cook et al., 2011; Poletz et al., 2010).

Although robots have been used by children with physical disabilities in different activities, the perceptual and cognitive demands of using a robot to manipulate objects and those involved in typical manipulation using only the child's body are not equivalent. Understanding the additional cognitive and perceptual demands that the use of the robot imposes on the child is crucial. This can guide the selection and adaptation of the control interfaces (e.g. switches), robot characteristics and programming to match the needs and skills of the child as well as the goals and task. However, identifying how much more complex the task is with the robot compared to direct motor action of the child and what factors determine the likelihood of the child to succeed in a robot mediated task is challenging. Our exploration of the complexity of robots used for augmentative manipulation is based on conceptualizing the robot as a manipulation tool and then evaluating the developmental considerations that can be derived from that perspective.

Different types of robots have been used with children with physical disabilities (for a review see Cook, Adams, Encarnaçao, Alvarez, 2012). The analysis presented in this paper focuses on the Microbot teach mover ® (Questec Inc.) robotic arm shown in Figure 3-1. The Microbot teach mover robot has several characteristics that make it ideal for exploring tool use in robot-augmented manipulation. It is an anthropomorphic half human size robotic arm with six degrees of freedom (Patterson & Katz, 1992). Anthropomorphism in robots is a characteristic that facilitates interaction because it helps humans to rationalize and relate to the robot's actions (Duffy, 2003). The motors enable base rotation, flexion and extension of robot shoulder and elbow, wrist flexion, extension, supination and pronation, and a gripper that can open or close (Cook & Polgar, 2008).

The robot control mechanism can be adapted so that the child can control it via single switches. There are different types of commercially available single switches that can be used by people with disabilities depending on their needs and skills (For a summary see Cook & Polgar, 2008, p, 260). Children can activate button-type switches because they require only a light force (i.e. pressing the button) (Cook & Polgar, 2008). The robot can be programmed so that a one or a number of switches allow the child to control the actions. This control includes the following modalities: pressing and holding a switch initiates and continues an action; pressing a switch once replays a preprogramed complete movement; or pressing several switches to control the robot, where each switch is related to a movement of a specific joint in the three dimensional Cartesian coordinates system (Cook & Polgar, 2008). The switch or switches can be adapted to the child's motor skills and placed in the site(s) of best motor control for the child. The Microbot has been previously used to explore tool use by very young children with physical disabilities (Cook et al., 1990; Cook & Cavalier, 1999), reporting successful use of the robot as a tool by infants.

Figure 3-1 Microbot Teachmover Robotic Arm

Tools, Tool Use and Robots

Robots as augmentative manipulation tools

Several definitions of a tool have been adopted in the tool use literature (For a review see St. Amant & Horton, 2008). For the purposes of this analysis, a tool refers to an item that expands the functional range of a human limb allowing an individual to manipulate some aspect of the environment (Greif & Needham, 2011). There are two uses of “tool” that are excluded from this definition: 1) sometimes another person can be used as a resource or tool, through which an individual can reach a goal (Greif & Needham, 2011). Children with disabilities may have to tell others, often with the help of assistive technologies, how they want them to manipulate an object to achieve a task (Schlosser et al., 2004). For example, a child can tell her mother to retrieve an out of reach cookie for her. However, in Greif & Needham’s definition a tool is restricted to a non-human object; 2) There are items, such as computers, that can alter one’s state of knowledge and as such can be considered tools (Garland & Noyes, 2004). Note that the abovementioned definition relates specifically to manipulation and physical interaction with the environment as goals of the tool. By this definition, a robot that is operated by the child in order to manipulate objects, by extending or augmenting the functional capabilities of the hand and arm can be considered a tool.

The robot can be classified as a compound tool. Compound tools are man-made artifacts that have multiple parts that together facilitate object manipulation (Frey, 2007; Greif & Needham, 2011). Tool use can be classified into simple and complex (Greif & Needham, 2011). Compound tools are involved in complex tool use. A simple tool enhances or amplifies the motor output of the upper limb to attain a goal (e.g. using a stick to retrieve an object out of reach) (Frey, 2007). On the other hand, in complex tool use the tools are used to produce transformations in the environment that convert the movements of the hand into qualitatively different mechanical actions. For example the handle on a tool that acts to increase force through leverage, also positions the hand to optimize task performance (Greif & Needham, 2011).

When considered as a tool, a robot allows children with physical disabilities to increase their independent interaction with the physical environment. As described above, previous studies that have shown robots to be useful for children with disabilities in play and academic tasks have been configured so that the child can control the robot through simple switches .As such, the robot does not merely "extend the length, strength, grip angle or posture of a limb" (Greif & Needham, 2011, p. 52) as common tools do (e.g., stick, pliers, etc.). The robot extends the reaching and grasping ability of the child, by means of the child's operation of a simple mechanical object, namely the switch. However, the child must understand the relationship between the switch, the robot and the manipulative action- a different cognitive skill than directly reaching for an object with his/her arm. To describe these elements in terms of tool use, we will refer to the "tool effect" as described by Michotte (1991). Michotte (1991) studied how the attributes that make humans perceive an object as a tool. In his experiments, one object launched another object, and the latter in turn launched a final object. Michotte found that participants who observed this sequence perceived the first object as the motor object (i.e. the initial motor of the action), the intermediary object as the tool and the final object as the target. Figure 3-2 illustrates and defines the role of each of the objects involved in the tool effect. The action of the second object was perceived as passive and contingent on the action performed by the first object.

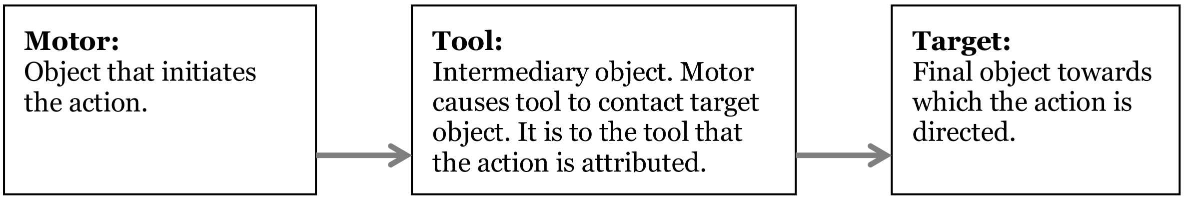


Figure 3-2 Objects as defined in the tool effect (Based on definitions by Michotte, 1991). The order in which they are presented refers to the order of the actions sequence.

Although, Michotte's study only had participants passively observe the sequence of events, the study revealed that tool use can be perceived in terms of a hierarchically organized sequence of events with a time sequence structure. Regarding the robot and the switches, it is possible then, to consider that in the perception of a robot mediated task, the robot would act as the tool, and the switches as the motor object, contingent on action by a child.

Tool use and affordances: the case of robots

Having defined a tool and focusing on the specific manipulative intention for the purposes of this analysis, tool use can then be defined as the alteration of the physical environment that results from the individual (from here on referred to as actor) and the tool (Greif & Needham, 2011). Further, when manipulation is the goal, tool use occurs when the actor (e.g. typically developing child) uses his hand to control a tool in order to affect a target (Greif & Needham, 2011) (from here on referred to as the target). For example, a child can use a toy hammer to drive a peg into a peg-board (Kahrs, Jung &

Lockman, 2013). Or a child with a disability can control a robotic arm to retrieve a cookie out of reach (Cook, Liu & Hoseit, 1990). Figure 3-3 illustrates an example of the tool effect in the case of a child using the robot, via a single switch, as a tool to retrieve a cookie out of reach. Note that in addition to the roles defined by Michotte, the human is included as an actor in the sequence of events.

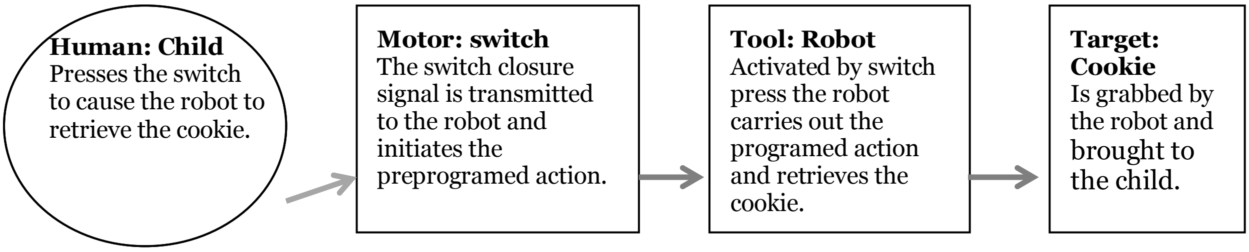


Figure 3-3 Example of robot mediated tool effect

Several developmental approaches have described tool use as the result of cognitive or evolutionary achievements (See McCormack, Hoerl & Butterfill, 2011). From a perception-action approach, tool use is described as the result of perception-action behaviors that the child explores in order to gain information about his environment (Lockman, 2000). According to this approach, the development of tool use is related to the ability of the child to recognize and understand relationships between objects and to detect affordances (Lockman, 2000).

In his development of the ecological realism approach to perceptual development, Gibson coined the term affordances to refer to the specific combination of properties of an object and it´s surfaces that gives information to the individual about the possibilities of acting on that object (Gibson, 1979). In other words, affordances communicate to an individual what can be done with an object given its properties. They provide information on how that object can interact with the surfaces on which it stands and with other objects in the environment (these interactions are referred to as complementarities) (Humphreys, 2001). For example, a door knob affords "turning", and the buttons of a TV remote control afford pressing. Affordances constitute a direct link between the visual properties of an object and the action that can be performed with it (Humphreys, 2001). Several studies have been able to associate the realization of affordances with the development of problem solving and causal cognition in children and adults (Lockman, 2000; Pepping & Li, 2005; Van Leeuwen, Smitsman & Van Leeuwen, 1994).

Affordances are perceived by the person based on properties of the object and by detecting which motor skills are required to operate or manipulate the object. These motor skills, such as push or turn, are often referred to as motor effectivities (Gibson, 1999). Sometimes, a person can identify actions that can be performed with an object (e.g. such as push or turn) just by seeing the object, and based on previous manipulation of similar objects (Van Leeuwen et al., 1994). An object can also be used correctly or its function can be understood even if this object has not been previously encountered. A person can identify the effectivities required to handle an object based on contextual or associative knowledge, as well as on previously stored knowledge of this object or similar objects. For example, an adult can identify an unfamiliar tool as “graspable” based on its visual characteristics (Vingerhoets, Vandamme, Vercammen, 2009). This last condition is determined by the ability of the person to detect the affordance of the object based on perceptual properties (Humphreys, 2001) and on adequate design characteristics (Norman, 2002). The design and visual characteristics of the tool make it easier for the person to interact successfully with the target. “When affordances are taken advantage of, the user knows what to do just by looking: no picture, label, or instruction needed" (Norman, 1988, p.9). This is consistent with anthropomorphism of the robot being a facilitator for interaction, as observing a robot with human like characteristics makes it easier for an individual to relate the robot’s actions to his/her own actions (Duffy, 2003).

Neuropsychological evidence shows how particular categories of action can be cued due to affordances, even if not related to previous experience (Humphreys, 2001; Vingerhoets, Vandamme, Vercammen, 2009). In the case of the TV remote buttons and the knob, or even other novel “pushable” or “turnable” objects, the individual realizes an action that can be performed with the object. The structure of this sequence of events is very straightforward, and only requires the detection of one action and the required interaction (complementarity) between the person and the target. This is also known as a first order complementarity between the actor (i.e., who acts on the object) and the target (i.e., the final target object) (Van Leeuwen, Smitsman & Van Leeuwen, 1994) and it is the most basic form of affordance (See Figure 3-4).

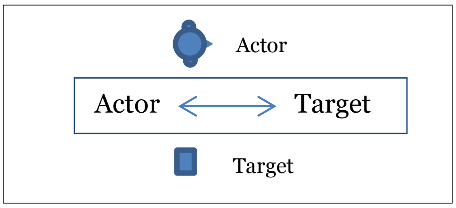


Figure 3-4 First order complementarity between the actor and the target (The child only needs to realize how to reach, grasp, or grab the target).

First order complementarities allow a child to understand and use an object. The child only needs to realize how the target can be reached, grasped or grabbed. However when using a tool, the child needs to perceive the properties of the tool as well as understand how it can be used to manipulate a target. For this reason, the use of tools implies prospective planning of the action in order to relate a sequence of events to the objects and their properties (Keen, 2011). Van Leeuwen et al. (1994) introduced a higher order affordance structure (integrating more than one complementarity) in order to understand the events taking place when using a tool. With this approach tool use can be described in terms of the mutual constraints and dual complementarities between the actor and the tool, the actor and the target and the tool and the target. Figure 3-5 presents the structure of complementarities that need to be detected when using a tool (with illustrations providing an example of using a hook to retrieve an object out of reach). First order complementarities between actor and target and actor and tool need to be detected as well as the complementarity between tool and target (i.e. how can the tool manipulate the object). These three first order complementarities need to also be related to each other in order for the child to plan prospectively how to manipulate the tool so that the final action on the target object can be achieved. These relations between first order complementarities are known as second or higher order complementarities. As seen in Figure 3-5, three lower order complementarities and three the higher order complementarity structures need to be perceived and understood by the child in order to use a tool:

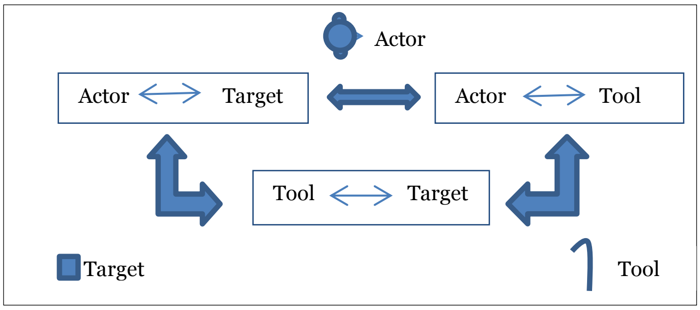


Figure 3-5 First order complementarities (represented by the small straight arrows) and higher order complementarities (represented by the big arrows). Illustrations provide an example of the actor (a child), the target (a squared cookie) and a tool (a hook). Adapted from Van Leeuwen, Smitsman & Van Leeuwen, 1994.

The complementarity structure of a robot mediated task

The understanding of the complementarities that the child needs to perceive in order to use a tool gives us some information about the cognitive and perceptual demands. However, it does not take into account the unique characteristics of the tool, the task or the actor. Having an understanding of only these complementarities does not allow us to quantify the complexity, make comparisons between tasks or tools or predict the complexity of a certain tool use. In the case of a child with a severe disability using a robot as a tool, unique traits of this interaction such us the additional interface (e.g., switches) required by the child to operate the robot, are not captured. When using an interface such as a switch to operate the robot, new complementarities between switch and actor, target and robot are added.

Consider the task mentioned above where children used a robot as a tool to retrieve a cookie out of reach (Cook, Lui, and Hoseit, 1990). Six developmentally delayed children with chronological ages less than 38 months participated along with three typically developing children. The Microbot used in the study (Figure 3-1) was programmed so that playback of the stored movement (bringing the cookie closer to the child) occurred as long as a single switch was activated.

The experimental sessions began with a familiarization period in which the reaction of the child to the robotic arm was observed. A switch was placed in front of the child and the robotic arm held a cookie that was in sight of the child but out of reach. The child had to repeatedly press the switch in order to bring the cookie close enough to grasp it. Pressing the switch shortened the distance between the child and the robot arm holding the cookie. The child then reached for the cookie in an attempt to grasp it. If the cookie was still out of reach, the child needed to repeat pressing the switch to bring it closer. **Error! Reference source not found.** shows the affordance structure of this cenario where: the child is the actor, the switch is added to the structure as the motor object on which the child acts, the tool is now a robot, and the cookie is the target object**.**

Figure 3-6 Affordance structure of the cookie retrieval task when using a robotic arm. First order complementarities are represented by the small straight arrows and higher order complementarities are represented by the big solid arrows.

Table 3-1 provides a summary of the first and second order complementarities implicated in this task and their definitions.

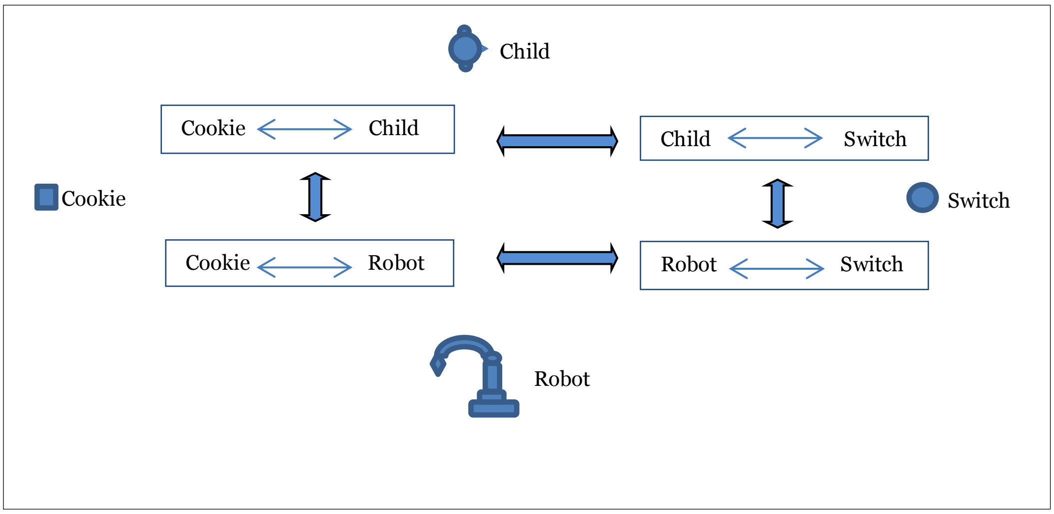


Figure 3-6 Affordance structure of the cookie retrieval task when using a robotic arm. First order complementarities are represented by the small straight arrows and higher order complementarities are represented by the big solid arrows.

Table 3-1 First and second order complementarities and their meaning in the context of the cookie retrieval task

FIRST ORDER COMPLEMENTARITIES	SECOND ORDER COMPLEMENTARITIES
Cookie-Child: Child wants to grab the cookie.	*Cookie-Child / Cookie- Robot:* Child wants the cookie but the cookie is too far to reach. However, the robot arm is holding it, so it can bring it closer.
Cookie-Robot: Robot grip is holding the cookie.	*Cookie-Robot/ Robot-Switch:* Robot can bring the cookie closer. The robot arm is too far but there is a button in front of the child that may make robot move

	and bring the cookie with it.
Robot-Switch: Switch controls the robot.	*Robot-Switch/ Child-Switch*: Robot may be controlled by button in front and the button can be pressed. This may cause robot to come closer.
Child-Switch: Switch is "pushable"	*Child-Switch/ Cookie-Child*: in order to grab the cookie, the robot needs to be moves towards the child, therefore the switch needs to be pressed in order to get the cookie.

In their analysis of the task with children with disabilities, Cook et al. (1990) revealed several elements relevant to this higher order affordances structure. First, children with disabilities as young as 8 months could use a robotic arm to retrieve an object of interest. Studies with typically developing children have shown that starting at around 8 months children can successfully retrieve objects out of reach (Noland, 2008; Munakata, 2004). Second, children performed behaviors that indicated they knew their actions resulted in a desired consequence. Based on a correspondence criteria, Cook et al. (1990) determined that observable behaviours of a child were related to switch activation if they occurred during a five second window before or after the switch was activated by the child. For example, the child would activate the switch and then immediately look up at the robot. This time frame was consistent with observations by Goldenberg (1979) that those responses occurring within 3 to 5 seconds are the most motivating for the child, and they also reflected temporal proximity. A repeatability criterion was defined as "the times during the experimental session that the correspondence criterion was met as a percentage of the total number of times the switch was pressed" (Cook, Liu & Hoseit, 1990).

Children demonstrated use of the robotic arm as a tool as determined by the correspondence and repeatability of behaviours along each trial. These children would look at the switch, hit it, and then look at the robotic arm; the study reported activation of switch meeting the correspondence criterion 96% of the time. Children's strategies could be analyzed through behavioural analysis and coding: For example, children often activated the switch, looked at the robot and then tried to reach for the cookie. If the cookie was still out of reach they would repeat the behaviours that caused the robotic arm to bring the cookie closer.

For the analysis presented in the current paper, a similar set-up as the one used by Cook et al. (1990) was presented to 10 adult non-disabled participants, in order to test their perception of the role of the robotic arm and the switch. Participants were presented with the same robot and task, except the cookie was replaced with an object to be grasped. All participants indicated that the robotic arm was the tool. When asked about the role of the switch, participants described as being "what makes the robot work". In terms of Michotte's (1991) tool effect described above, the switch was perceived as the motor object and the robot as the tool.

Robots and the complexity number hypothesis

The affordance structure also provides a framework to determine the sequence of events that the actor, in this case the child, needs to carry out. Gibson (1999) pointed out that events have a structure consisting of units of action, actions within the sequence that can be identified by a specific beginning and end. When observing events, subjects segment a sequence of actions into smaller more concrete units (Newtson, 1973). Thus, a sequence of actions could be perceived and described in terms of smaller units (Cutting, 1981). For example, when the goal is eating and a spoon is used as a tool, grasping the spoon is one unit of the sequence that has a beginning (i.e. initiation of hand movement) and an end (i.e., realization of contact between hand and spoon) (Van Leeuwen et al., 1994). However, in order to define the boundaries of a unit, namely its beginning and end, it is necessary to take into account the skills of the actor and the context in which the action is taking place. Whether the actor is very skilled or is an expert user of a tool determines whether units can be broader or not (Van Leeuwen et al., 1994). For example, an adult is used to eating with a spoon and can grasp the handle of a spoon adequately without a lot of thought. Therefore, the units of action that the adult needs to perceive could probably be described as grasping the spoon, load it with food, bring it to the mouth and empty the spoon. On the other hand, an 18 month old child (less skilled in the action of self-feeding) may need to break the action into smaller units: reach towards the spoon, detect the orientation of the handle of the spoon, adjust the grasp according to orientation, load the food, lift spoon with added weight of the food, etc.

The smaller units of action required by the child illustrate another characteristic of affordance perception. Sometimes, as the actor is performing the sequence of actions, new relations between objects and their affordances are perceived by the actor. For example, the child may not notice the awkward orientation of the spoon (Keen, 2011) until he tries to lift the spoon and bring it to his mouth. Only then does the child realize that the orientation needs to be adjusted. This can be useful for a child actor since it implies that not all components of the sequence need to be prospectively planned. Only some of them are planned in advance whereas others emerge as the action unfolds. In order to understand the events that need to be perceived prospectively, one needs to understand which units of the sequence are enough to elicit the action, and which units will emerge as the person acts on the object. In other words, some complementarities need to be detected before the action starts in order to plan prospectively; others emerge in sequence as a result of the actor's manipulations. This can be determined by analyzing the action and trying to describe it with the least amount of units that are in fact absolutely necessary to understand the sequence (Cutting, 1981).

As illustrated in the previous examples, the higher order affordance structure relies on two assumptions that are critical for the interpretation of the analysis. First, the analysis of the tool use event includes the minimum number of units required for the action to take place. Second, there is no affordance structure complexity analysis that can be independent from the context or the particular characteristics of the specific actor (Van Leeuwen et al., 1994). The affordance structure analysis provides a basis to understand the complexity of the task itself, which is why it uses the minimum required elements to which additional complexity may be added by the characteristics of the actor or the context. It is critical to keep in mind these assumptions when interpreting the results.

The number of events or units of perception and the kind of temporal integration (in parallel or in sequence) required provides a way to quantify the complexity of the tool use task and compare different situations (Van Leeuwen et al., 1994). The more units of complementarities needed to understand and achieve the goal, the more complex the task is. In this way, Van Leeuwen et al. (1994) developed a quantitative analytical notation of the complexity of a tool use task. This quantitative notation (referred to as the complexity number) can be used as a measure of the complexity of the task that incorporates the analysis and prediction of different constraints, spatial relations and time relations needed to use the tool. Table 3-2 presents the notation assigned to each factor in the Complexity number hypothesis.

Table 3-2 Notation for complexity hypothesis components

Notation	Meaning
A (stands for Actor).	Used when referring to a complementarity between the actor and the tool; or the actor and the target.

	Note: Aend refers to the complementarity between the Actor and the target. Aend is the ultimate goal of the tool use action.
O (stands for Objects, either the tool or the target)	Used when referring to complementarities between the tool and the target.
. (Parallel units)	Events that need to be detected in parallel or at the same time.
, (Units in sequence)	Events that emerge in sequence, one after the other, as a result of the actor's manipulations.

In the case of tool use, units have two different types of temporal integration: in sequence, represented in the notation by a comma, or in parallel, represented by a period. Parallel integration is considered to be more complex since it requires prospective understanding of complementarities, while in sequence integration, performing one action allows the actor to understand a new complementarity.

Complexity number: reaching, tools and robots

Let us again consider the situation described in Cook et al. (1990) study where a small child is trying to reach for a cookie. A typically developing child would reach for the cookie, and grasp it if it was within reach. This scenario would have no higher order affordances since there is only one complementarity between actor and target. In the notation this scenario would be represented just by:

$$A_{end}$$

Consider the same typically developing child in a situation where the cookie is now out of reach. This constraint introduces the need for a tool. If the tool were a hook located strategically with the handle within reach of the child and the crook part surrounding the cookie, the child would only need to pull the hook to retrieve the cookie. A similar configuration was presented as an example in Van Leeuwen et al., (1994). In order to use the tool, the child must recognize that the use of the tool changes two spatial relations between actor, target and tool by realizing two affordances. The first affordance is the reachability of the target which is the goal (Aend), and the other affordance is the "pullability" of the hook (A1). Since Aend can't be achieved without understanding A1, they need to be perceived prospectively (i.e., before starting the action) and simultaneously (i.e., the two events need to be realized in parallel). The period that connects A1 and Aend in the formula represents the parallel temporal integration required. The higher order affordance structure that could describe this use of the tool would be:

$$A^2_1 = (A_1 \cdot A_{end})$$

As represented in this formula, the cookie can be reached (Aend) if the actor pulls the hook (A1) and both complementarities need to be perceived at the same time in order to use the tool. The exponent "2" represents the second order of affordance structure resulting from the integration of the first order structures. This event would have a complexity number of 1, since only one second or higher order affordance structure results from the integration of two first order structures. Therefore only one second order relation needs to be integrated temporally for the desired configuration to be successful. This simple form of tool use could also turn into a more complex sequence of events. For example, if the spatial orientation of the hook was altered (e.g., the crook were turned away from the cookie) then the child would need to flip the hook to use it to bring the cookie closer (Van Leeuwen et al., 1994).

Reaching or using a tool such as a hook in order to retrieve an object out of reach are two scenarios in which , although the child has the motor skills to do both, it is the distance and configuration of objects that determines the use of one or the other. However, when the actor is a child with a severe physical disability, reaching or using tools such as a hook is not possible. For this scenario, the use of a robotic arm to retrieve the cookie as described above (Cook et al., 1990) becomes an alternative for independent manipulation. For the robot mediated task, Table 3-3 describes the First order and second order complementarities of this task.

Table 3-3 Complexity Number Hypothesis for robot-cookie task

child-switch	Robot-switch	cookie-robot	cookie-child
As_1	Or_1	Oc_1	Ac_1
			A_{end}

Where:

As1= First child-switch complementarity= Switch can be pressed by child

Or1= First robot-switch complementarity= Switch makes robot move closer

Oc1= First cookie-robot complementarity= Robot is holding cookie and moves it

Ac1= First cookie-child complementarity= Distance from child to cookie

A-end= Grab cookie

In this case, five complementarity units are needed. First, the child needs to realize that the cookie is out of reach but that the switch, which is at hand, can be pressed (Ac_1, As_1). Then, in a sequential way, the child needs to realize that when the switch is pressed the robot moves closer (As_1,

Or_1). Then the child realizes that by pressing the switch to move the robot closer, the robot brings the cookie towards him (Or_1,Oc_1). The child then needs to perceive that as robot brings cookie the distance between himself and the cookie decreases (Oc1,Ac1). Finally the child detects that pressing the switch makes it possible to take the cookie from the robot (As1. Aend). The higher order affordance structure that could describe this use of the tool would be:

$$A^2_2 = (Ac_1, As_1), (As_1, Or_1), (Or_1,Oc_1), (Oc1,Ac1) ,(As1. Aend)$$

The robot mediated task is more demanding than reaching for the cookie but it decreases the motor demands so that it is possible for children with disabilities to perform it independently.

Conclusions

Manipulation has been related to spatial knowledge, causal cognition, object permanence, and symbolic communication (Cohen, 1985; McCormack, Hoerl, Butterfill, 2011; Piaget, 1954; Greenfield, 1991). Children with physical disabilities can lose opportunities for independent manipulation of objects around them and the exploration of object's attributes (Jennings & MacTurk, 1995). Robots can be used as augmentative manipulation systems that assist manipulation and provide a way through which children with physical disabilities can interact with their physical environment. When used as tools, robots provide a way through which children with severe physical disabilities can access independent manipulation and exploration. This has developmental advantages and provides meaningful learning opportunities.

Certain characteristics of robots, make them ideal candidates for augmentative manipulation: their ability to pick, reach, grasp and place objects; the flexibility in the use and adaptation of different control systems such as switches; and the flexibility in terms of autonomy that they provide. However, they also have certain limitations that restrict their usability and efficacy. Robots can be big, expensive, and they place additional cognitive demands on the child. Cook and collaborators (for a review see Cook et al., 2012) have explored different alternatives to overcome these challenges, such as using Lego Robots that are less expensive, adapting the number of switches and the control that they give to the child over the task, and further exploring the cognitive demands of using robot-augmented manipulation. Understanding these cognitive demands can provide insight into design modifications and task adaptation.

One of the strategies used to explore the cognitive demands placed on the child by the use of robot-augmented manipulation has been determining the age at which typically developing children can successfully operate the robot to achieve a goal (Poletz et al., 2010). In a study with typically developing children between 3 and 6 years of age, Poletz et al. (2010) presented children with a sequence of robot tasks that were thought to increase in complexity (cause & effect, inhibition, laterality and sequencing). A Lego robot similar to a toy truck was used. The tasks involved the following: 1) cause and effect: the child was required to press a single switch (only switch presented) to make the robot go forward and knock over a tower of blocks. 2) Inhibition: the child was required to release the switch in order to stop at a certain point next to a pile of blocks. 3) Laterality: two towers of blocks were presented and the child needed to pick one, and press the switch that would make robot turn to that side (two switches were added. One switch made the robot turn left, the other one right and the switch that made it go forward was kept). 4) Sequencing: after making the choice of which tower of blocks to knock over, the child was required to press the switches in sequence to turn the robot and then make it go forward to knock over the tower. The performance of children in these tasks revealed a significant positive correlation between age and successful performance in the more complex tasks. The older the child, the better his performance in increasingly complex tasks. For example, all three year olds were able to successfully complete the cause and effect task, but only some were able to complete the inhibition task.

The characteristics of the robot and the switches, as well as the number of switches and the strategies used to familiarize the child with their effects on the robot have a great impact on the likelihood of the child succeeding in the task. The complexity number provides a way through which task complexity can be quantified. This allows modifying the task or the robot characteristics such as the control interface or mechanical capabilities in order to decrease complexity. Understanding and comparing the complexity of robot mediated tasks also allows researchers and professionals to understand what is being asked of the child. One could easily be tempted to use the robot as an alternative to manipulation and then ask the child to complete certain tasks exactly as a typically developing child would by reaching and grasping, ignoring the fact that robot operation is already evidence of certain cognitive and perceptual skills.

The affordance structure complexity number can constitute a tool for the analysis of task complexity when using robots as tools. This can also provide some foundational information for the experimental comparison of robot mediated manipulation in children.

This analysis is only based on the minimum required sequence of events needed for the action to unfold and the affordances that the child needs to perceive and understand to achieve the task. Using this theoretical approach to the quantification of complexity can enhance the experimental testing and exploration of robot augmentative manipulation. A strategy through which the additional cognitive and perceptual demands of robot augmented manipulation can be tested, is the comparison of typically developing children's performance on robot augmented manipulation vs typical manipulation versions of well-defined tasks. Such an approach can help define the parameters of the task and the robot that are more likely to allow children to succeed with the robot, and children with disabilities to use it as a tool to reveal their skills and develop new ones.

Chapter 4
Paper 3: The Neurophysiology of augmentative manipulation: A method for technical implementation[1]

Introduction

Motor experience plays a central role in children's cognitive and perceptual development. Through physical manipulation, exploration and interaction with the environment a child develops perceptual and social skills that will allow him/her to learn and act on the world [1, 2]. In the absence of language during the early years, motor behaviour has also allowed insight into the child's developing cognitive and perceptual skills [1].

Object manipulation is a critical part of motor experience that enables the child to acquire skills required for symbolic and referential communication, the understanding of relationships between objects and their environmental interactions, and causal and spatial knowledge [1, 3, 4, 5]. Object manipulation starts evolving a few months after birth, as the child perceives objects and their properties and explores the relation of these objects to self and other´s actions [6].

Performance of object manipulation indicates that early milestones of cognitive and perceptual development have been reached [7,8]. Through object manipulation, a child progressively starts to relate to objects and discovers how objects can be used to achieve a goal [8]. This development by the human child gives rise to tool use, which in cognitive theory has been related to representational means-end planning [8,9]. Tool use has been identified as a landmark cognitive skill [10] that involves the understanding of the properties of objects and how they can relate to each other as a means to achieve a goal [11]. For example, at around 18 months, a child is able to execute a planned strategy if he/she notices an awkward orientation of the handle of a spoon. The strategy is used to guide the selection of which hand to use or how to change the grasp for successful self-feeding

---

[1] This paper has been accepted for publication as: Alvarez, L., Wiebe, S.A., Adams, K, Hope, A., Cook, A. (In press) "The Neurophysiology of augmentative manipulation: A method for technical implementation", Technology & Disability. The original reference list and citation format of the paper has been kept as per FGSR, University of Alberta guidelines for published material included in a dissertation. Therefore references for chapter 4 are presented immediately after the chapter and are also included in the general reference list.

[1, 9]. The use of objects as tools extends the influence of the child on the environment and enhances his interactions [12].

The strong relationship between motor skills and cognitive development suggests that a lack of motor experience can result in cognitive and perceptual delays [13]. Children with congenital or early acquired severe physical disabilities can lose opportunities to develop and demonstrate their cognitive and perceptual skills if the physical disability limits the ability of the child to physically manipulate objects [14]. This limitation in object manipulation can compromise the quality of their play and learning skills [15].

There are benefits of early exposure to assistive technology for children. Young children can use assistive technology in order to have access to early independent interaction with their environment and the objects in it [16, 17, 18]. Assistive technologies allow these children to engage in different kinds of social, cognitive and communicative activities, by increasing, maintaining, improving or compensating for their functional capabilities [19]. Assistive technology gives children with disabilities opportunities to explore their environment through independent mobility [17], interact with others as part of their social construction of the world [20] and explore and participate in learning and play activities [15, 21, 22, 23].

As an assistive technology, robots can be used as augmentative manipulation systems due to their capability for picking, placing and exploring objects [21]. Several studies report the use of robots as augmentative manipulation systems by children with severe physical disabilities [21, 24, 25, 26, 27]. In these studies children independently controlled robots using switches adapted to their capabilities and needs. Robots can be programmed in several ways throughout a continuum of autonomy from fully autonomous (i.e., the robot carries out a complete task without human intervention) to tele-operated (i.e., the human operator controls the robot throughout a task) [15]. The characteristics of switches, such as simplicity, portability and safety, make it possible for the child to independently control the task and their influence over the environment increases [28]. By using robotic systems for augmentative manipulation, children's participation in academic and play activities, expressive language and level of engagement increased as reported by parents and teachers [24].

So far, studies of children's use of robotic augmentative manipulation systems has largely focused on outcome measures such as the perceptions of parents and teachers, and the attainment of academic, play or therapeutic goals. The required cognitive and perceptual skills of direct manipulation of objects and of robotic augmentative manipulation are not equivalent. Providing a robot for children with physical disabilities can give them access to independent object manipulation. However, adding the robot as a tool may change the way the child perceives the tasks at hand and the relation between objects. Also, the characteristics of the additional cognitive and perceptual skills required to operate the robot remain unclear. These skills add complexity to what for typically developing children constitutes a natural manipulative behaviour. A better understanding of what is being asked of the child when providing this alternative manipulation system is required.

In the absence of verbal responses, cognitive assessments in early childhood often require hand dexterity and object manipulation to solve problems (e.g. building towers with blocks) [29]. Children with disabilities can use a robot to perform these manipulative tasks. However, the skills required for successful robot operation and control may be of greater complexity than those that can be revealed by the completion of the task itself. This can also contribute valuable information regarding the skills that these children can reveal by using the robots.

The comparison of direct manipulation and robot augmentative manipulation in similar tasks constitutes the first step in understanding the cognitive and perceptual demands of robot augmentative manipulation systems for children. Using both behavioural data (e.g. performance, success rate, reaction time, response time, etc.) and neuroimaging data can provide a broader understanding of the potential differences between direct and augmented manipulation. The use of neuroimaging techniques to support the study of augmentative manipulation can provide insight into the associated cognitive representation and complexity.

Comparing the direct and augmentative version of a manipulation task and exploring its effects with the use of neuroimaging techniques presents two distinct challenges. First, children with severe physical disabilities cannot manipulate objects independently and a comparison of direct and augmented manipulation of objects cannot be obtained. Second, the integration of a robotic augmentative manipulation system and electrophysiological measurement creates technical challenges related to electrical interference due to robot motors and control circuitry as well as movement artefact due to the movement required to activate the robot control system.

Conducting pilot studies with non-disabled adults and typically developing children who can use direct and robot-mediated manipulation can help overcome the first challenge by revealing the comparative aspects of the human-device interaction. When referring to other types of assistive technologies, Higgenbotham and Bedrosian [30] describe how selecting non-disabled participants in the initial phases of an assistive technology investigation can allow for the construction of performance distributions that can later be compared and tested for generalizability. Also, this approach can control for the variability that naturally exists between participants with different degrees of motor compromise and skills [30]. Selecting non-disabled participants in the pilot phases can also reveal the cognitive processes necessary for the acquisition of device performance competence [31]. Therefore, a method for technical implementations needs to allow the comparison of both typical manipulation as well as robot augmented manipulation in order to serve the purposes of pilot studies as well as studies with people with disabilities.

To overcome the second challenge, a method for technical implementation that allows the exploration of robot augmented manipulation is required. In addition, the use of electroencephalography (EEG) signal and the resulting event related potentials (ERP) provides an alternative for the functional analysis of brain function while allowing the use of artefact reduction computational methods, which are useful in situations where artefact is increased. These non-invasive neurophysiology measures [32] are widely used to safely explore the substrate of cognitive and perceptual function [33]. They have high temporal resolution, in the order of 1 ms or better [34]. Cognitive processing can be studied in synchrony with the process as it happens. EEG and ERP are also inexpensive compared to other neuroimaging methods [34].

Objectives

This paper presents the design of a custom made platform interface for the neurophysiological exploration of robot-augmented manipulation and presents an evaluation of the technical feasibility of performing a comparison between augmented manipulation and direct manipulation as response modalities in a cognitive task. It is divided in two parts: first, the need for an interface method is presented as well as the platform and its technical characteristics. Second, pilot testing conducted with 10 adults is presented. This allowed for the evaluation of the technical feasibility of neurophysiology comparison of robot augmented manipulation and typical manipulation.

Methods

Robot augmentative manipulation system

The half human size MiniMover-5[2] robotic arm [Figure 4-1] with six degrees of freedom was used. The robot stepper motors enable base rotation, flexion and extension of shoulder and elbow, wrist flexion, extension, supination and pronation, and a gripper that can open or close [19]. The robotic arm was programmed and controlled by a notebook computer running Microbot Control Center software[2].

The varying degrees of severity of the motor impairment of the children that can benefit from using these robots as augmentative manipulation, makes switches a versatile and customizable alternative control interface. Switches can be adapted to the best control site for the child. The robot was programmed so that playback of a complete stored movement occurs when a switch is activated. Participants used two switches to activate the pre-stored robot movements. The switch placed at the left of the participant's midline made the robot move towards the container on the left, lift it, drop it and go back to home position. The switch placed at the right side of the participant's midline made the robot move towards the container on the right, lift it, drop it and go back to home position.

Figure 4-1 Microbot Teachmover Robotic Arm

---

[2] Quest Technologies, Farmington Hills, Michigan

Customized Platform for technical implementation

Typically, exploration of neurophysiological substrates of cognitive function are obtained by designing an experimental task in which stimuli are presented on a screen and the participant responds by using a keyboard, or a response box with a set number of switches. These responses subsequently flag the EEG ongoing signal, making it easier to then extract the segments of interest. In the case of robot augmentative manipulation systems, the tasks and stimuli are dynamic and three-dimensional in nature, and therefore not suitable for screen based response experimental designs. In the case of the A-not-B task (described in more detail below), several events of interest replaced the standard screen presented stimuli: (1) when the barrier is lifted marking the beginning of a trial, (2) when the participant hits a switch to choose either side A or B for robot retrieval of the object, (3) when either cup is lifted, recognizing both the lifting and the presence or not of the object.

A custom-made interface is required that can translate the stimuli described above into input signals that E-Prime[5] can detect and use as markers for the EEG signal. For this purpose a custom-built wooden platform was designed to monitor the responses of the participant using three magnetic switches wired into the platform, and two switches controlled by the participant. E-Prime extensions for Net Station[3] flagged the EEG signal for each of these events. The three magnetic switches marked the lifting of the barrier, and when one of the two cups was lifted. The participant switch responses were connected to the robot to replay the stored movements (see Figure 4-2). The wooden platform was wired through a common DB-9 connector typically used for the switch response box so that events were registered by E-prime as keyboard inputs (see Figure 4-3).

Figure 4-2 Platform and Robot set-up showing the two containers in position on the platform and the two participant switches used to control the robot arm.

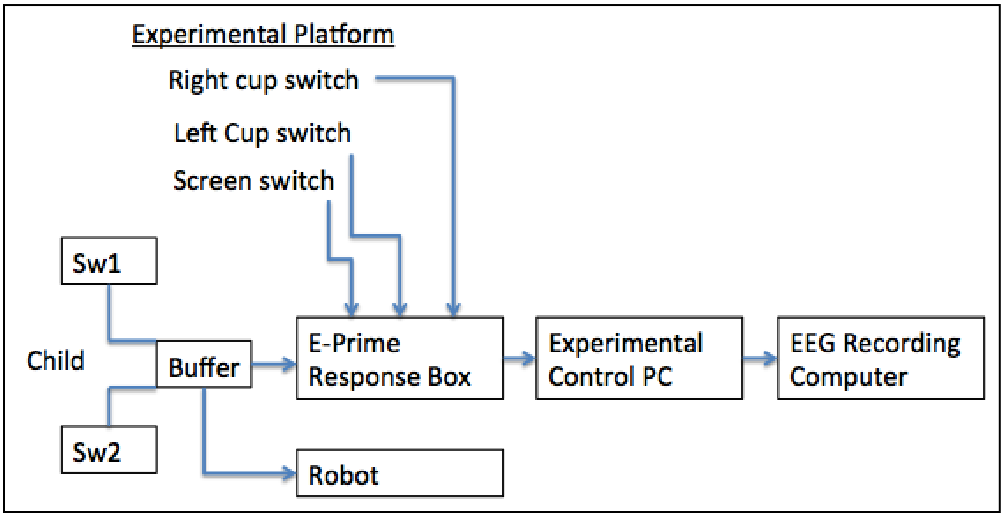


Figure 4-3 Experimental set-up

In order to facilitate consistent recording of trial information by E-Prime, during direct manipulation condition, the robot was programmed to stay in the home position regardless of switch closure. The researcher pressed the switch to signal the cup towards which participant began reaching. This way the channelling of the signal was still done through the automated platform but with no response from the robot. Figure 4-4 illustrates the electrophysiological set up with E-Prime® and NetStation®.

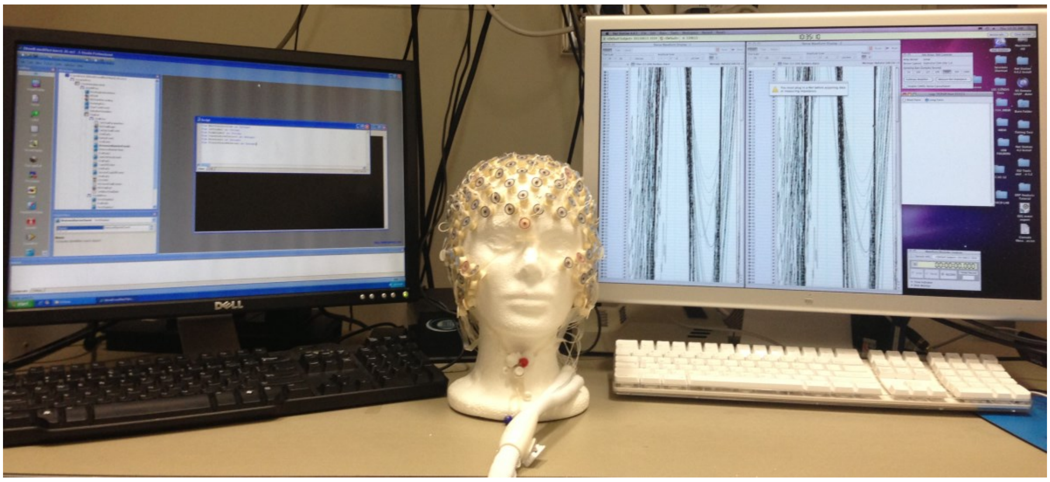


Figure 4-4 Neurophysiological measures set-up showing electrodes in a cap worn on the participant's head, the presentation software (E-Prime) screen and the signal acquisition (Net Station) screen.

Testing of technical implementation

Participants

Ten right-handed adults participated in this pilot testing (5 females and 5 males; mean age: 29.3 years, range: 23-34). All participants had normal or corrected vision. None of the participants reported having a previous history of neurological or psychiatric disorders, or taking any medications at the time of testing.

The Task

The A not B task is considered a classic measure of cognitive development in early childhood [35] and perhaps the most studied task in developmental psychology [36]. Developed by Piaget [4], this task was chosen as a cognitive and perceptual task with very specific motor requirements (i.e. requires patterns of reaching, grasping and lifting small objects). This made it suitable for adaptation to the robot-mediated version. Also the great amount of literature available on this task, allows further comparison of our results and provides the basis for the interpretation of the task's complexity. Since this task could be used in future studies with children, it was used in this testing phase for the purpose of consistency.

In the A not B task the participant is exposed to an object hidden in a container. The container is moved to location ***A***. In the standard version of this task the object is placed inside the container already located at either left or right. However, the chosen version for this testing included the addition of invisible displacement [37] (i.e. the object is first hidden inside the container and then the container is moved instead of the object directly being placed at either side containers), which makes the task more complex and therefore more suitable for older children. A screen is then placed in front of the participant and after a delay the participant is allowed to search and retrieve the object. After two successful trials, the object is hidden and moved to the opposite side, location ***B***. This time, after a screen is placed between the participant and the container, an equal but empty container is placed on the opposite side, location ***A***. The participant is encouraged to search for the object [38]. For adult participants, this task is not demanding and a 100% success rate was expected.

In this pilot testing, participants had to find and retrieve the object in two conditions (order was counterbalanced across participants): 1) Robot condition: using a robotic arm for manipulation (i.e. the participant operates a robot to perform the manipulative behaviours); 2) direct reaching condition: reaching for and grasping the objects with their hands (as typically developing children would). Each participant completed 40 trials in each condition. It was hypothesized that only an attention and working memory demand would be placed on the adults, not interfering with success rate, but providing comparable electrophysiological results between the two conditions of the task.

Neurophysiology recordings and analysis

EEG was recorded with the use of a high-density 256 channel Geodesic Sensor Net®[3] referenced to the central vertex electrode. Data analysis was conducted in NetStation®[3], MATLAB®[4] custom scripts and EEGLAB 7.14 open source toolbox that runs in MATLAB. Recording took place in an electrically shielded and sound attenuated chamber where the designed platform was placed and interfaced with E-Prime®[5] presentation software version1.2. E-Prime presentation software allows the design of a computerized experiment where stimulus can be presented to the participant and key presses or touch screen responses can be tracked, resulting in the automatic coding of several dependant variables (e.g. reaction time, success rate, errors, etc). The platform was wired so that events in the task were identified as specific key presses in E-Prime (and were presented in a screen only for the researcher to see) and marked in the EEG signal in NetStation.

Electrode impedances were maintained under 50 kΩ and the signal was sampled at 250 Hz and filtered and amplified at a gain of 1000. Offline, the EEG signal was 0.1-30Hz bandpass filtered as per recommendations by [34]. Artefacts were corrected via independent component analysis (ICA) [39]. Although EEG was initially referenced to the vertex electrode (Cz), a digital average re-reference was conducted. Trials were referred to a 100-ms pre-stimulus baseline. The continuous EEG was segmented into epochs from 1000 ms before either the barrier was lifted or the switch was pressed to 1000 ms post target onset. Only trials with correct responses (i.e. where the participant correctly identified the location of the object) were retained for analyses. A channel was marked bad for the entire session if it was deemed bad in more than 20% of the trials.

Results

Two events of interest were selected for analysis:

---

[3] Electrical Geodesics Inc., Eugene, OR

[4] Mathworks, Natick, MA

[5] Psychology software Tools, Inc., Sharpsburh, PA.

1) Barrier lifting: this event signals the beginning of a trial for the participant and prompts participant to proceed.

2) Switch Closure: This event signals the participant's response.

Exploration of ERPs was first attempted around these two events, with the use of Scripted NetStation Waveform tools (filtering, artefact rejection, bad channel removal, signal segmentation, etc.). An initial waveform exploration also revealed an artefact around the vertex electrode (Cz) that was consistent across participants, and across conditions (

Figure 4-5). This graphic corresponds to the switch press event of interest. A pronounced negative deflection is observed around the vertex, consistent across electrodes around the vertex. We hypothesized that this artefact was related to electrical interference that results from switch closure.

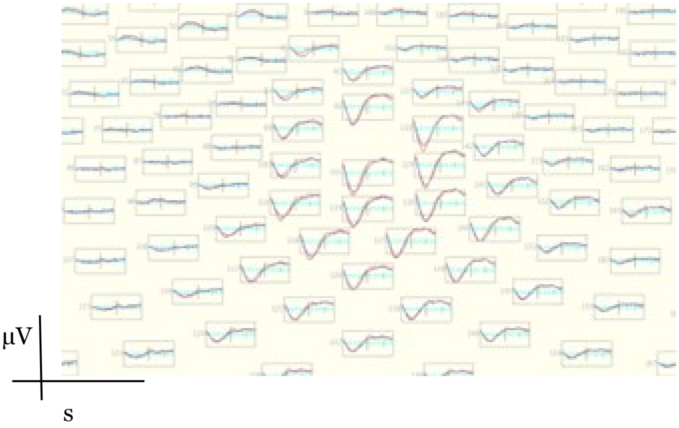


Figure 4-5 Topo-plot of electrodes corresponding to the switch press event of interest

In order to examine this artefact, the same process was applied to the delay events (i.e. the 5 seconds where the participant is being distracted and the barrier is in place). Also, additional testing of a participant performing different movements that resembled switch closure but without actually pressing the switch was conducted. When no switch closure occurred, the vertex artefact was absent from these segments, the initial waveform's artefact source being electrical interference (

Figure 4-6).

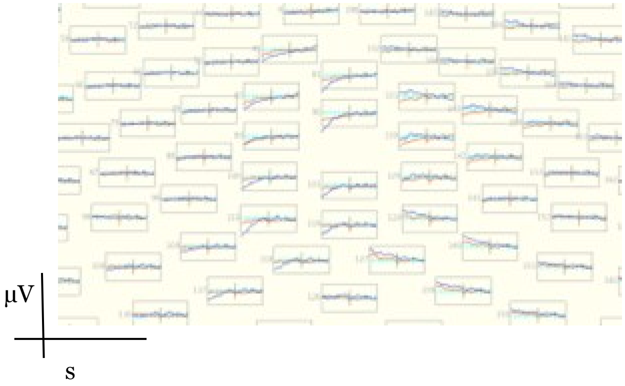


Figure 4-6 Topo-plot of electrodes when using the delay period as the event of interest.

Independent Component Analysis was selected to segregate this artefactual component. The Independent Component Analysis algorithm (ICA) [39] enables the separation of statistically independent signals by source. Although it does not localize the source of the components, it identifies the different sources and allows separation of artefactual components like eye blinks, head movements, etc. [40]. By using this technique, removal of the switch closure artefact was possible. Figure 4-7 shows the signal processing process that was used starting with the NetStation ® tools, and ending with the use of EEGLAB ® in order to use ICA for artefactual component rejection.

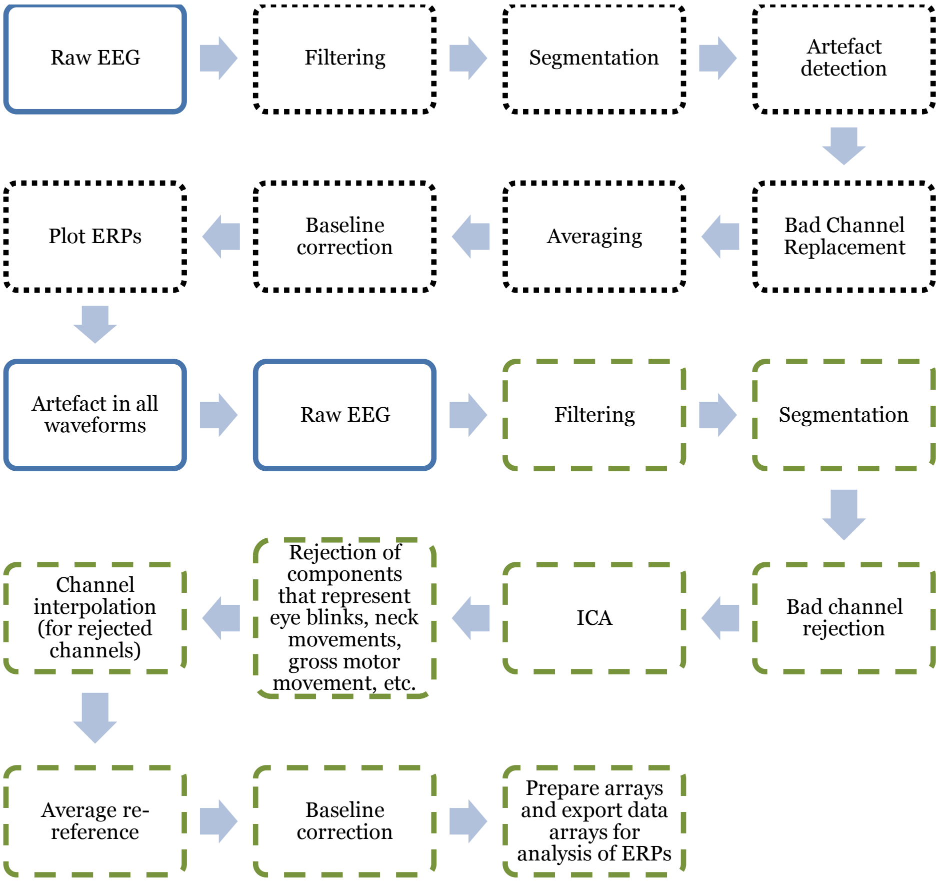


Figure 4-7 Diagram of signal processing stages. The black boxes represent stages completed in NetStation. The green boxes represent the stages completed with EEGLAB.

After ICA was performed, four groups of electrodes representing frontal, central, parietal, and occipital areas in both hemispheres were chosen for further analyses to determine if waveforms could be obtained from these representative sites. The electrodes were identified by finding the 10-20 international system [41] correspondence as described by Luu, Ferree [42] (Table 4-1). The group of electrodes around the corresponding Fz, Cz, Pz and Oz was averaged to obtain these representative sites [43, 44]. Figure 4-8 presents a schematic view of the HydroCel Geodesic Sensor Net, illustrating the distribution of the chosen electrodes. The electrodes chosen for extraction are circled.

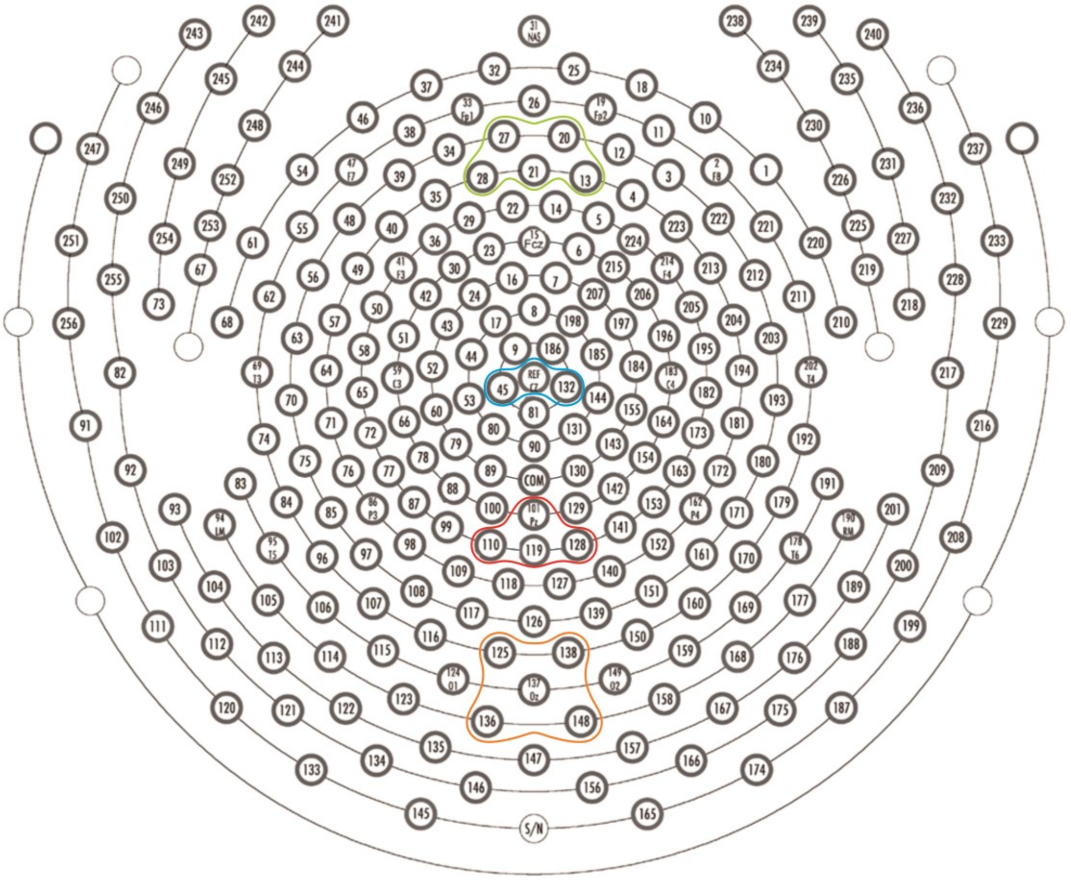


Figure 4-8 Electrode map of the Hydrocel Geodesic Sensor Net – 256 channels

In this schematic view the nose points up. The electrodes that were selected for analysis for each area are grouped together. This figure shows the distribution of each representative area along the scalp. Table 4-1 enumerates the electrodes and their corresponding 10-20 system channel [43].

Table 4-1 Electrode number and correspondence with the 10-20 system

10-20 system	Electrode number	Electrodes chosen for each area
Fz	21	21, 27, 27, 20, 13
Cz	Cz (REF)	45, REF, 132
Pz	101	101, 110, 119, 128
Oz	126	125, 138, 137, 136, 148

Individual trials were averaged and mean amplitudes and peak latencies for each electrode were recorded for each participants. In the robot condition a total of 397 correct trials was averaged; in the reaching condition 399 correct trials were used. For each participant, and each condition (robot and reaching) the mean amplitude and peak latencies for each event (barrier lifted and switch pressed) were averaged together across the electrode groups to represent the ERP components at the frontal, central, parietal and occipital sites.

Figure 4-9 and Figure 4-10present the resulting waveforms for the barrier lifting event and the switch pressing event, for both the reaching and the robot condition in each area. Because this study was a test of the technical setup, no typical experimental manipulations to elicit specific components were done, and no previous knowledge of the waveforms was available. Therefore the waveforms for all four areas in the two conditions were extracted and plotted and visual inspection was used to evaluate the feasibility of ERP analysis and potential components that may be elicited by the task. Interpretation and identification of potential components is to be done with caution.

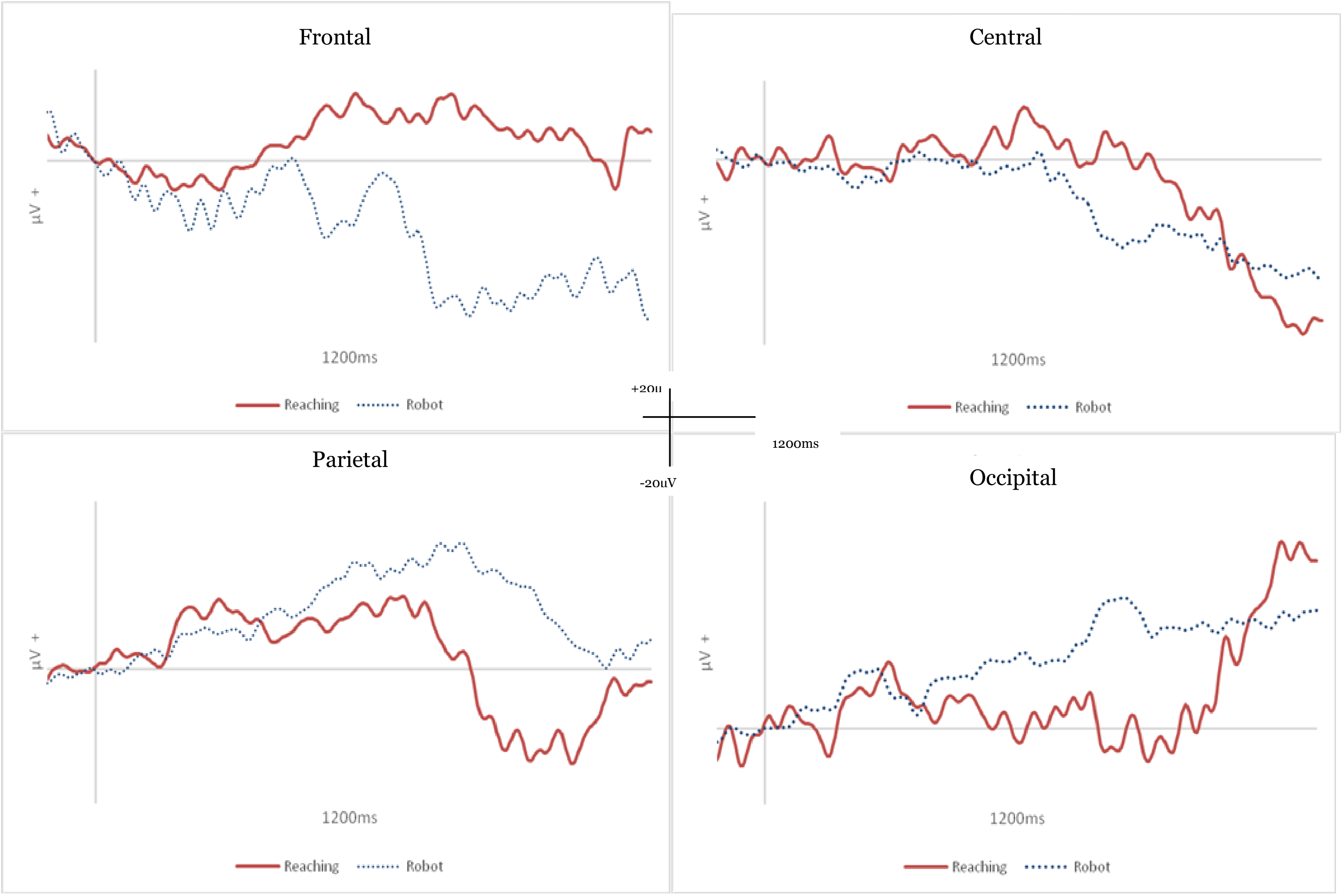


Figure 4-9 Waveforms around barrier lifting event at Fz, Cz, Pz, Oz for robot and reaching condition.

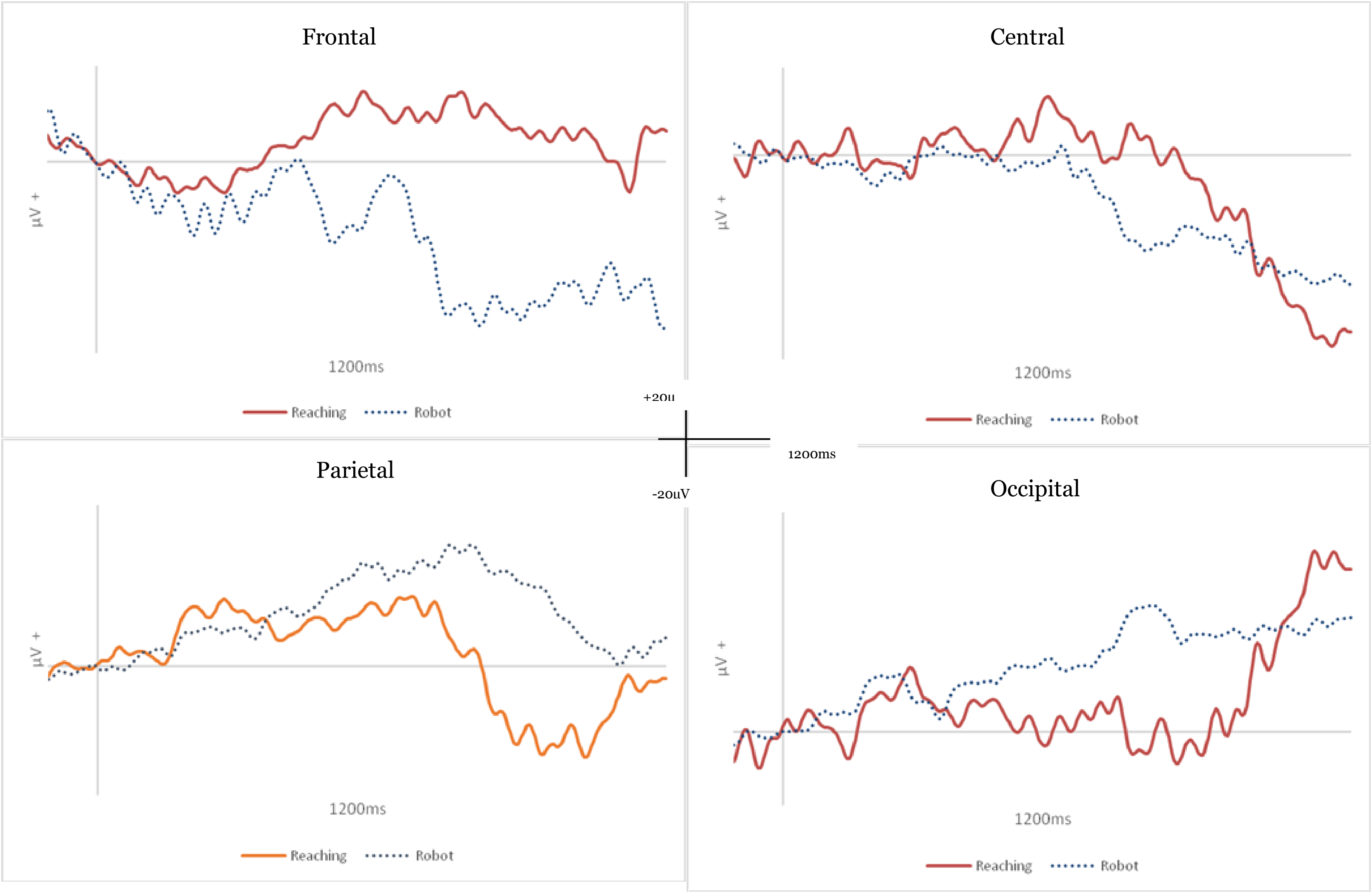


Figure 4-10 Waveforms for switch press event at Fz, Cz, Pz, Oz for robot and reaching condition

A visual inspection of the waveforms reveals several elements: In both events some differential activity can be found between the robot and the reaching conditions, in relation to the amplitude of the waveform. This differential activity can be best seen in Cz and Oz after the barriers is lifted. However, there is weaker differential activity in other sites. When the barrier is lifted, a positive deflection emerges at around 100 ms followed by a negative deflection and then another positive peak at around 200 ms for the reaching condition. For the robot condition this effect is weaker and there is less amplitude of the waveform at these latencies. Because of their early latency, these components may be related to late sensory and early perceptual and attentional processes in adults [45]. For example, in ERP research, a visual N1, a negative component that is typically in the first 100 to 200 milliseconds has been related to visual demands of the task as well as attentional resources [46]. The preceding P1, a positive peak at around 90 to 100 ms has been hypothesized to index perceptual processing [47] (the letter indicates the polarity for the component and the number is usually related to their appearance in the waveform and latency). P1 has also been found to be modulated by visual spatial attention [48]. It is important to note that this testing only establishes technical feasibility and the experimental manipulation is novel thus this experimental manipulation differs substantially from the existing literature on these components (in which well-established experimental conditions are known to elicit certain components) and any association needs further testing to establish correlation between the components reported in the literature with the waveforms elicited in this task.

Results show that robot augmentative manipulation can be controlled in such a way that electrical artefact is minimized and that artefact reduction is possible via ICA.

Discussion

The main purpose of this adult pilot testing was to explore the feasibility of implementing neurophysiological recordings in the performance of a 3D task while using a robotic augmentative manipulation system. The technical implementation presented several challenges. First, the typical 2-dimensional on-screen nature of the tasks involved in neurophysiological data acquisition, makes it hard for 3-dimensional responses to be tracked and marked by the presentation and acquisition software packages. The design of a custom-built platform with hidden wired-in magnetic switches that were programmed into the stimuli presentation software as keyboard responses allowed proper identification of event markers for the signal. However, this can present a challenge for further studies of augmentative manipulation because each task would need a unique interface module so that specific events of interested can be marked.

Second, the nature of the tasks involved in augmentative manipulation poses a challenge to the use of neurophysiological data. Because participants are required to move, stimulus dependant movement inserts an artefact in the signal. Although filtering and the use of ICA aid in the elimination of this source of artefact, the quality of the signal is slightly compromised as seen in the figures. Currently available acquisition and presentation software packages are not optimal for the analysis of signals that are prone to artefact [49]. In such circumstances, filters need to be narrower and alternative methods for the detection of this consistent artefact needs to be explored. For example, Kaatiala et al. [49] recently designed a graphical interface that enables a two-stage approach to the analysis of infant ERP data. This two stage approach aims at providing a systematic way of controlling for stimulus dependant artefacts such as movement. In this approach, video recordings are simultaneously linked with initial exploration of epochs. Initial rejection previous to analysis of the signal is done based on noticeable movement artefact. Then the graphical interface allows for the use of several filters and artefact correction tools. Such approaches can yield promising opportunities for the study of neurophysiological correlates of augmented manipulation, and in tasks that require high manipulative behaviours.

The events chosen for this pilot testing were related to the critical moments of the A not B task. This task will be used for comparison of robot augmented manipulation and typical manipulation in children. This task was used in this pilot testing as a way to determine if a cognitive task could be adapted in such a way that would allow behavioural and neural correlate comparisons. However the cognitive processes in children during the task are fundamentally different from those of adult participants and extrapolation of any correlates is not possible (nor was intended). For example, when the barrier is lifted the child must then evoke the memory of the object, inhibit the previously successful reaching pattern and reach for the correct site. Also, the switch press marks the event in relation to which error monitoring can be observed. However, adult participants may, more likely, hold the memory of the object during the delay. Subsequent analysis should include the segmentation of the delay event and the exploration of potential components during this delay time. Additionally, further manipulations of specific components are required in order to better understand the underlying cognitive demands of the task. A potential component of interest is the Lateralized Readiness Potential (LRP) that has been found to index the preparation of motor activity in a specific side of the body [50]. Since this potential has been reported to relate to motor preparation and motor programming [51] it can provide insight into observed actions of a mechanical augmentative manipulation system that requires the operation of the participant.

Another important alternative for the characterization of augmentative manipulation's neurophysiological substrates, is the analysis of event related potentials and electroencephalographic activity related to observed actions by the robot. Neurophysiological studies of observation of actions performed by others have supported activation similar to that of performing the same actions [52, 53]. For example, the mu rhythm, an electroencephalographic wave present in motor rest, has been found to be suppressed when participants observed someone perform an action. This indicates that similar brain activity is associated with performing and observing the action [53]. The exploration of this component when exposing participants to observing actions performed by the robot may contribute to understanding how the augmentative manipulation is perceived.

The acquisition of neurophysiology data of augmentative manipulation represents a first step for subsequent studies with infants and children with severe congenital physical disabilities. Even though the experimental setup can be challenging in exploratory studies, the custom made platform and method for removing electrical artifact in this paper constitutes a starting point for further investigation of robots and neuroimaging interactions.

Acknowledgements

The authors would like to thank Al Fleming for his invaluable contributions to the development of the instrumentation described in this paper. They would also like to thank Mahsa Khoei, Sarah Elke for the contributions to data processing and analysis.

References (Chapter 4)

[1] McCarty M. E., Clifton R. K., Chollard R. The beginnings of tool use by infants and toddlers. Infancy. 2001; 2(2): 233-256. doi: 10.1207/S15327078IN0202_8

[2] Flanagan J. R., Bowman M. C., Johansson R. S. Control strategies in object manipulation tasks. Current opinion in Neurobiology. 2006; 16:650-659. doi: 10.1016/j.conb.2006.10.005

[3] Bates E. The biology of symbols: Some concluding thoughts. In E. Bates, L. Benigni, I. Bretherton, L. Camaioni, V. Volterra (Eds.), The emergence of symbols: Cognition and communication in infancy (pp. 315–370). New York: Academic Press; 1979.

[4] Piaget J. The construction of reality in the child. Great Britain: Routledhe; 1954. doi: 10.1037/11168-000

[5] Affolter F. From action to interaction as primary root for development. In I. Stockman, Movement and Action in Learning and development: Clinical implications for pervasive developmental disorders (pp. 169-199). San Diego: Elsevier; 2004.

[6] Haywood K., Getchell N. Life Span Motor Development (5th ed.). Illinois: Human Kinetics; 2009.

[7] Vauclair J. Phylogenetic Approach to Object Manipulation in Human and Ape Infants. Human Development . 1984;Vol. 27, 321-328. doi: 10.1159/000272925

[8] Lockman J. A perception-action Perspective on Tool use development. Child Development. 2000; 71 (1): 137-144. doi: 10.1111/1467-8624.00127

[9] Keen R. The Development of Problem Solving in Young Children: A Critical Cognitive Skill. Annual Review of Psychology. 2011; 62, 1-21. doi: 10.1146/annurev.psych.031809.130730

[10] Parker S. T., Gibson K. R. Object manipulation, tool use and sensorimotor intelligence as feeding adaptations in cebus monkeys and great apes. Journal of Human Evolution. 1977; 6, 623-641.

[11] Buttelmann D., Carpenter M., Call J., Tomasello M. Rational Tool Use and Tool Choice in Human Infants and Great Apes. Child and Development. 2008; 79(3):609 – 626. doi: 10.1111/j.1467-8624.2008.01146.x.

[12] St. Amant R., Horton T. Revisiting the definition of animal tool use. — Anim. Behav. 2008; 75: 1199-1208. doi:10.1016/j.anbehav.2007.09.028

[13] Bertenthal B. I., Campos J.J. New directions in the study of early experience. Child Development. 1987; 58, 560 -567.

[14] Jennings K., MacTurk R. The motivational characteristics of infants and children physical and sensory impairments. In R. MacTurk, G. Morgan, Mastery Motivation: Origins, Conceptualization and Applications (pp. 201-220). New Jersey: Ablex Pusblishing Corporation; 1995.

[15] Cook A., Encarnaçao P., Adams K. Robots: Assistive Technologies for Play, Learning and Cognitive Development. Technology and Disability. 2010; 22, 127-145. doi: 10.3233/TAD-2010-0297

[16] Rosen L. et al. RESNA Position on the Application of Power Wheelchairs for Pediatric Users. Assistive Technology. 2009; Volume 21, Issue 4: 218-226.

[17] Wiart L., Darrah J. Changing philosophical perspectives on the management of children with physical disabilities-their effect on the use of powered mobility. Disability and rehabilitation. 2002; 24(9), 492-498. doi: 10.1080/09638280110105240

[18] Cook A., Liu K., Hoseit P. Robotic Arm used by Very Young Motorically Disabled Children. Assistive Technology. 1990; 2, 51-57. doi: 10.1080/10400435.1990.10132150

[19] Cook A., Polgar J. M. Cook and Hussey's Assistive Technologies: Principles and Practices (3rd ed.). Philadelphia: Elsevier Inc; 2008.

[20] Cooley M. J. AAC Use by Young children at home. Perspectives on Augmentative and Alternative Communication. 2010; 19, 5-11. doi: 10.1163/156855301742003

[21] Tejima N. Rehabilitation robotics: a review. Advanced Robotics. 2000; Vol. 14, No. 7, pp. 551– 564.

[22] Cook A., Cavalier A. Young Children using assistive robotics for discovery and control. Teaching exceptional children. 1999; 31(5), 72-78.

[23] Cook A., Howery K., Gu J., Meng M.. Robot enhanced interaction and learning for children with profound physical disabilities. Technology and Disability. 2000; 13,pp. 1–8.

[24] Cook A., Bentz B., Harbottle N., Lynch C., Miller B. School-Based Use of Robotic Arm System by Children With Disabilities. IEEE Transactions on Neural Systems and Rehabilitation Engineering. 2005; 13(4), 452-460. doi: 10.1109/TNSRE.2005.856075

[25] Besio S., Caprino F., Laudanna E. Profiling Robot-Mediated Play for Children with Disabilities through ICF-CY: The Example of the European Project IROMEC. ICCHP '08 Proceedings of the 11th international conference on Computers Helping People with Special Needs; 2008. pp. 545-552. Berlin: Heidelberg.

[26] Cook A., Adams K., Volden J., Harbottle N., Harbottle C. Using Lego robots to estimate cognitive ability in children who have sever physical disabilities. Disability and Rehabilitation. 2010; 1-9. doi: 10.3109/17483107.2010.534231

[27] Kronreif G., Kornfeld M., Prazak B., Mina S., Fürst M. Robot assistance in playful environment -user trials and results. IEEE International Conference on Robotics and Automation. 2007; pp. 2898-2903. Roma, Italy: IEEE.

[28] Isabelle S., Bessey F., Dragas K. L., Blease P. Assistive Technology for Children with Disabilities. Occupational Therapy in Health Care. 2002; Vol. 16(4). doi: 10.1080/J003v16n04_03

[29] Schum R. Psychological Assessment of Children with Additional Disabilities [STUDY]: Psychological Assessment of Children with Multiple Handicaps Who Have Hearing Loss. The Volta Review; 2004.: available at: http://listeningandspokenlanguage.org/Document.aspx?id=465#sthash.UNYDvLkI.dpuf

[30] Higginbotham J., Bedrosian J. Subject selection in AAC research: Decision points. Augmentative and Alternative Communication. 1995; 11, 11–13. doi: 10.1080/07434619512331277099

[31] Higginbotham D. J. The use of non-disabled subjects in AAC research: Confessions of a research infidel. Augmentative and Alternative Communication. 1995; 11, 2--5.

[32] Taylor MJ, Baldeweg T. Application of EEG, ERP and intracranial recordings in investigation of cognitive functions in children. Developmental Science. 2002; 5, 3, pp. 318-334. doi:10.1111/1467-7687.00372

[33] De Hann M. Infant EEG and Event Related Potentials. Psychology Press; 2002.

[34] Luck S. An Introduction to Event Related Potentials and Their Neural Origins. In S. Luck. Cambridge: MIT Press; 2005.

[35] Diamond A., Goldman-Rakic PS. Comparison of human infants and rhesus monkeys on Piaget's AB task: evidence for dependence on dorsolateral prefrontal cortex. Exp Brain Res (1989) 74:24-40. doi: 10.1007/BF00248277

[36] Dalenoort G., De Vries P. The Essential Role of Binding for Cognition in Living Systems. The Logic of Artificial Life: Abstracting and Synthesizing the Principles of Living Systems (pp. 32-39). Bamberg: IOS Press; 2004.

[37] Wiebe S., Lukowski A., Bauer P. Sequence Imitation and Reaching Measures of Executive Control: A Longitudinal Study Examination in the Second Year of Life. *Developmental Neuropsychology, 2010; 35*(5), 522-538. doi: 10.1080/87565641.2010.494751

[38] Diamond A., Prevor M., Callender G., Drun D. Prefrontal cortex cognitive deficits in children treated early and continuously for PKU. Monographs of the Society for Research in Child Development.1997; 62(4), 1-206. doi: 10.2307/1166208

[39] Bell A.J. and Sejnowski T.J. An information maximisation approach to blind separation and blind deconvolution, *Neural Computation,* 1995; 7, 6, 1129-1159. doi: 10.1.1.61.2871

[40] Makeig S, Bell, A.J., Jung T.P., Sejnowski T.J. Independent Component Analysis of Electroencephalographic Data In: D. Touretzky, M. Mozer and M. Hasselmo (Eds). *Advances in Neural Information Processing Systems*. 1996; 8, 145-151, 1996. doi: 10.1.1.36.4803

[41] Jasper H.H. The ten-twenty electrode system of the International Federation. Electroenceph. Clin. Neurophysiol. 1958; 10, 371-375.

[42] Luu, P., and Ferree, T. Determination of the Geodesic Sensor Nets' Average Electrode Positions and Their 10–10 International Equivalents. Eugene: Electrical Geodesics, Inc. [Technical Note]; 2000.

[43] Classon E., Rudner M., Johansson M., Ronnberg K. Early ERP signature of hearing impairment in visual rhyme judgment. Front. Psychol. 2013; doi: 10.3389/fpsyg.2013.00241

[44] Luu P., Jiang Z., Poulsen C., Mattson C. Learning and the development of contexts for action. Front. Hum. Neurosci. 2011; Volume 5, pp. 1-12. doi: 10.3389/fnhum.2011.00159

[45] Luck S., Kappenman E. The oxford handbook of event related potentials. Oxford Press: New York; 2012.

[46] Mangun G.R., Hillyard S.A. Modulations of sensory-evoked brain potentials indicate changes in perceptual processing during visual-spatial priming. Journal of Experimental Psychology: Human perception and performance. 1991; 17(4): 1057-1074. doi:10.1037//0096-1523.17.4.1057

[47] Woodman G. A brief introduction to the use of event-related potentials in studies of perception and attention. Attention, Perception, Psychophysics. 2010; 72 (8), pp. 2031-2046 doi:10.3758/APP.72.8.2031

[48] Nagamatsu L., Munkacsy M., Liu-Ambrose T., Handy T. Altered visual–spatial attention to task-irrelevant information is associated with falls risk in older adults. Neuropsychologia. 2013; 51, pp. 3025–3032. /10.1016/j.bbr.2011.03.031

[49] Kaatiala J., Yrttiaho S., Forssman L. A graphical user interface for infant ERP analysis. Behavioral Research. 2013; Early online 1-13. doi 10.3758/s13428-013-0404-4

[50] Mordkoff J. T., Gianaros P. J. Detecting the onset of the lateralized readiness potential: A comparison of available methods and procedures. Psychophysiology. 2000; 37, 347-360. doi: 10.1111/1469-8986.3730347

[51] Masaki H., Wild-wall N., Sangals J., Sommer W. The functional locus of the lateralized readiness potential. Psychophysiology. 2004; vol 41, Issue 2, pp. 220-230. doi: 10.1111/j.1469-8986.2004.00150.x

[52] Altschuler EL, Vankov A, Hubbard EM, Roberts E, Ramachandran VS, Pineda JA. Mu wave blocking by observer of movement and its possible use as a tool to study theory of other minds. Poster Session Presented at the 30th Annual Meeting of the Society for Neuroscience; New Orleans: LA. 2000.

[53] Sebanz N, Knoblich G, Prinz W, Wascher E. Twin peaks: an ERP study of action planning and control in co-acting individuals.J Cogn Neurosci. 2006; May;18(5):859-70

Chapter 5
Paper 4: The role of augmentative manipulation in infant cognition: the case of the A-not-B task

Introduction

Manipulation provides infants with opportunities for early independent exploration of the environment (Esseile, Nadel, Fagard, 2010). Children use manipulative behaviors to learn about the world around them and the objects in it. By the end of the first year of life and into their second, children can adapt their movements to specific characteristics of objects (Bourgeois, Khawar, Nea & Lockman, 2005). For example, by 6 months of age, infants attempt to squeeze soft objects more than hard objects (Bourgeois et al., 2005). Also, 19-month old toddlers change the orientation of their grip to match the orientation of the handle of a spoon for self-feeding (McCarty et al., 1999). These manipulative behaviors have been found to be deeply rooted in the interaction between the child's early experiences, their motor skills and the demands of the task (Lobo, Galloway, Savelsbergh, 2004). Motor experience induces and facilitates children's' ability to purposefully interact with objects (Lobo et al., 2004) and to use objects as tools (Sommerville, Hildebrand, Crane, 2008). The ability of the child to understand action goals and the intentions of others when performing an action has been attributed to their ability to relate those actions and intentions to their own previous self-experiences (Sommerville et al., 2008; Metlzoff, 2005).

Children with physical impairments can lose opportunities for meaningful exploration and manipulation of objects (Ruff, McCarton, Kurtzburg & Vaughan, 1984). Children with physical disabilities can't manipulate objects due to fine motor impairments that limit their ability to grasp and reach (Jennings & MacTurk, 1995). Also, they can be perceived as less able to interact independently with objects or overcome frustration (Jennings, Stagg, Connors & Ross, 1995). This in turn, can lead to adults providing fewer opportunities for independent interaction (Dunn et al., 2007). Both the motor nature of their impairment and the ways in which they are perceived, impact the child's ability to explore and learn about the physical environment. In the same way as powered mobility provides an alternative to walking for self-produced locomotion (Rosen et al., 2009), an alternative to typical manipulation can help children with physical disabilities access the early cognitive and perceptual advantages of upper extremity exploration (Cook, Adams, Encarnação, Alvarez, 2012). However typical and robot mediated manipulation are not the same and the ways in which using robots can impact the child's performance as well as the demands added by the robot need to be understood.

This paper presents the results of a study conducted with young typically developing children, in order to compare the use of typical manipulation and robot mediated manipulation when performing a cognitive task. Along with the comparison of behavioral results between the two response modalities, neurophysiological signatures of both were obtained. Their potential and implications for the study of augmented manipulation in children with disabilities are discussed. In line with this, this paper also presents the results of a case study with a 30 month old child with a severe physical disability, who participated in the robot mediated condition and an adapted reaching version.

Augmentative manipulation

Assistive technologies can provide opportunities for young children with disabilities to interact with others and explore their environment (Judge, Floyd & Wood-Fields, 2010; Schlosser & Raghavendra, 2004; Millborne, Campbell & Wilcox, 2004; Cook, Adams, Encarnação, Alvarez, 2012), Assistive technologies can facilitate access to early experiences for children with physical disabilities (Wiart & Darrah, 2002; Cook, Liu & Hoseit, 1990). They can allow children with disabilities to engage in different kinds of social, cognitive and communicational activities, by increasing, maintaining, improving or compensating for their functional capabilities (Cook & Polgar, 2008).

As an assistive technology, robots can be used as augmentative manipulation systems due to their capability for picking, placing and exploring objects (Tejima, 2000). In that sense, robots supplement (augment) the existing manipulation skills of the child and compensate for the limitations in manipulation. The use of a robotic arm system by children with disabilities who are unable to directly manipulate objects has been shown to increase children's participation in play, academic activities, their expressive language and their interest (Cook et al., 2000; Cook et al., 2005). The use of robots has also allowed children with physical disabilities to engage successfully in experiences such as play (Cook et al., 2000) and academic activities such as math (Adams & Cook, 2013) or science (Howell & Hay, 1989) .Through the use of robots children with disabilities have been shown to reveal cognitive skills (Cook, Adams, Harbottle & Harbottle, 2007). In these studies children controlled the robots independently through switches that could be adapted to their physical capabilities and needs.

Although studies have shown that children with physical disabilities can benefit from the use of robots as augmentative manipulation systems, certain critical aspects of this interaction remain unclear. Using the robot as a tool is not the same as direct manipulation (See Alvarez, Adams & Cook, *In preparation*; included as Chapter 3 in this document). Introducing the robot in a task, may change the way the child perceives the task and the relation between objects (Alvarez & Cook, *In preparation*, See Chapter 3 in this document). The use of the robot, which gives children with disabilities access to manipulative tasks by decreasing the motor demand, may at the same time increase the cognitive demand of the task at hand. For example, in a study with typically developing children between 3 and 5 years of age, Poletz et al. (2010) presented children with a sequence of robot tasks that were thought to increase in complexity (pressing the switch to make the robot knock over a tower of blocks, stopping at a marked spot to pick up blocks, choosing between two switches to make the robot turn to a previously chosen side, and making the robot go forward after turning it to one side). The performance of children in these tasks revealed a significant positive correlation between age and successful performance in more complex tasks. All three year olds were able to successfully complete the first task, but only some were able to complete the stopping task and they had difficulties with choosing between two switches. Four year olds were able to master the stopping task, and almost all could select between two switches, but they had difficulties carrying out the sequence. Five year olds mastered all tasks in this study. This example illustrates how the cognitive demand increases, as robot task complexity increases.

Understanding the additional cognitive and perceptual demands that the use of the robot imposes on the child is crucial. This can guide the selection and adaptation of the control interfaces. Control interfaces are the hardware elements that a person can use to control a device, such as switch or a joystick (Cook & Polgar, 2008). On the other hand, robot characteristics and programming can also be adapted to match the needs, skills and developmental age of the child as well as the task and goals. Finally, understanding how using a robot may impact the child's performance on a given task can provide additional insight into the cognitive skills required for robot use and revealed during use.

The A-not-B with invisible displacement task

Comparing children's typical manipulation to robot augmented manipulation in the performance of a cognitive task can provide insight into the implications of using augmented manipulation. The A-not-B task is considered a classic measure of cognitive development in early childhood (Diamond & Goldman-Rakic, 1989) and perhaps the most studied task in developmental psychology (Dalenoort & De Vries, 2004). The A-not-B was selected because of the rich body of literature behind it and the different interpretations of the A-not-B that make it valuable for testing novel implementations. Specifically, for this study, the A-not-B with invisible displacement task (a more complex version of the task as explained below) portrays the relation between motor experience and cognitive skills and is appropriate for children in their second year of life.

In the classical version the A-not-B task, an object is hidden inside a container located at either left or right from the child (location A). After the child retrieves the toy from Location A, the object is then hidden on the other side in the view of the child (location B). According to Piaget (1954) 5 month old infants will not search for the object at either location; from 7 to around 9 months the child successfully retrieves the toy at the first location (A) but when the object is moved to B he often reaches back to location A. This early perseverative error (Diedrich, Thelen, Smith & Corbetta, 2000), is referred to as the A-not-B error (Berger, 2010). Towards the 12th month of age, the child will successfully retrieve the toy at both locations (location A and location B). If a child cannot successfully retrieve the object from the location B in the A-not-B task, Piaget (1969) hypothesized that the child believes the position of the object depends on his previous successful reaching behavior (i.e., the action of the child gives rise to the existence of the object), rather than depending on changes of the object's position in space. When a child successfully retrieves the object in both locations his actions reveal intentionality in the sense that the child is able to understand that in order to achieve the goal (e.g., retrieving the object) he needs to remove the cover.

Piaget (1954) also devised a more complex version of the A-not-B task, in which "invisible displacement" is added. In the A-not-B with invisible displacement task, the toy is hidden inside the container at midline and then the container is moved towards the side (location A) (i.e. the child sees the container that has the toy inside being moved to location A, but does not see the toy directly being moved as in the classical A-not-B task, therefore the toy is being "invisibly displaced"). Then the view of the child is blocked and an identical container is placed at the opposite side (location B). Children in their second year of life will display the A-not-B error too if the A-not-B with invisible displacement task is used (Piaget & Inhelder, 1969; Diamond, 1997; Wiebe et al., 2010). This A-not-B task with invisible displacement shares the same elements of the classical version (remembering where the object is hidden, inhibiting the previously successful response and reaching towards the object)

(Diamond et al., 1997; Morasch & Bell, 2011) but increases the complexity because the toy invisibly displaced and an additional container is placed on the opposite side as a distractor.

Piaget and Inhelder (1969) hypothesized that in addition to the achieved understanding of object permanence necessary to succeed in the classical A-not-B, in the invisible displacement version the child succeeds if he understands that the object's location depends on the displacement of the container in which it was placed, and the child can hold the representation of the object in mind through the displacement (Piaget & Inhelder, 1969). For Piaget, the A-not-B error constituted evidence for a lack of object permanence and the associated mental representation of the object that only emerges towards the end of the first year of life (McCarthy & Reid, 2002). Nevertheless, the A-not-B task has been used in laboratories all around the world (Diamond et al., 1997) and several alternative explanations have been provided for the A-not-B error.

Alternative interpretations of the A-not-B error have resulted from several adaptations and modifications of the A-not-B task designed to further explore the role of motor, cognitive, and perceptual demands on the performance of children. Such adaptations include changing the response modality from reaching to looking or moving across the room; replacing the target object hidden in a container for a continuously visible target; or having the child observe the trials at A and then perform the trials at B (Bell & Fox, 1992; Berger, 2004; Berger, 2010; Boyer et al., 2011). As an alternative to Piaget's explanation of the A-not-B error (object permanence), a spatial orientation account attributes the error to a failure of the child to code the position of the object in space in relation to the previous location (A). In order to overcome perseveration children need to switch from an egocentric frame of reference to an allocentric frame of reference (Acredolo, 1990; Bremner & Bryant, 1977; Evans & Gratch, 1972; Butterworth, 1975). These skills are developed as a result of self-produced locomotion (Kermoian & Campos, 1988; Bertenthal et al., 1994). On the other hand, an immature spatial orientation has also been related to failures in motor planning that can in turn, lead the child to display the A-not-B error (Lew et al., 2007).

Diamond and collaborators (1989; 1990; 1997) have contended that children have accurate mental representations of the object, but their pre frontal cortex is not mature enough yet. This causes the child to not be able to successfully hold the memory of where the object is and inhibit the previously successful response simultaneously (Diamond & Goldman-Rakic, 1989; Diamond, 1990; Diamond, 1997). Bell and collaborators have found evidence of the correlation between the maturation of the frontal cortex and a more accurate performance on the A-not-B task (Bell, 2001;

Cuevas & Bell, 2010; Morasch & Bell, 2011). Bell & Fox (1997) provide supporting evidence for both self-produced locomotion and brain maturation as etiologies of the A-not-B error. However, no three way interaction between the two and performance was found.

According to Munakata (1997; 1998; 2001), the A-not-B error is a result of a competition between latent memory traces of previously relevant information (A trial) and active memory traces of the current situation (B trial). In order to overcome perseveration, children must maintain active memory traces for the B location that can compete with the strong repeatedly reinforced latent traces that bias the child's reach towards A. A similar approach is that of the dynamic field account, according to which children perseverate in this task (that is they display the A-not-B error) due to the convergence of several processes (visual perception, motor planning, posture and spatial discrimination). The error results from the formation of a strong motor memory that builds over the reaching trials toward A. These memories are stronger than the visual memory of seeing the object being hidden at B. In this account perseveration is considered a developmental achievement towards a balance between stable and flexible motor and perceptual behavior (Smith et al., 1999; Diedrich et al., 2000; Thelen et al., 2001; Clearfield et al., 2006).

A more recent model that accounts for the A-not-B error findings across the literature is that of the cognitive capacity account proposed by Berger (2004; 2010). According to this account, children's performance in the task is dependent on the allocation of finite cognitive resources into the motor and cognitive demands of the task. Both motor and mental demands can tax cognitive capacity. Increased motor demands results in a greater difficulty to inhibit the response and impacts the child's cognitive processing. The different accounts of the A-not-B error illustrate the delicate balance between motor and cognitive skills required for a successful response in the task. Although different in their explanation of the origin of perseveration, a constant theme throughout the accounts is the extent to which children are displaying a cognitive skill through a refined reaching pattern and whether it is the cognitive or the motor demands that are driving perseveration.

This study provides an opportunity to explore preservation when the motor demands of the task are decreased. Also, it adds the use of a tool, which may have cognitive implications in the children's performance. Previous studies have shown that children in the first year of life can use the robot as a tool for reaching and retrieving (Cook et al., 1990) but that not all typically developing three year olds can successfully select one of two switches in correspondence with the direction to which they want the robot to turn (Poletz et al., 2010). Poletz et al. (2010) results suggested that children in their first year of life may not be able to successfully use more than one switch to select the direction towards which they want the robot to move. Therefore children in their second year of life (with whom the A-not-B with invisible displacement is appropriate) were recruited for this study. Typically developing children in the second year of life have shown means-end understanding through tool-use behaviour (Lockman, 2000; Keen, 2011).

Studies using the A-not-B with invisible displacement task (with a 5 second delay when the barrier is in place) with 15 and 20 months-old children (Wiebe, Lukowski & Bauer, 2010) and between 24 and 27 month-old infants (Morasch & Bell, 2011) have shown mid-range responses on the A-not-B with invisible displacement task, with room for improvement within the possible range of scores. No significant differences in the proportion of correct searches has been found across participants between the ages of 15 and 20 months (Wiebe et al., 2010) and 24 to 27 months (Morasch & Bell, 2011), and 15 to 30 months (Diamond et al., 1997). These results provide evidence for the use of the task with children between 18 and 30 months since the mid-range results indicate that there is room for further improvement that can still be measured with the task and no differences in perseveration errors have been found across children in this age range.

This paper presents the results of a study conducted to compare toddlers' performance in the A-not-B with invisible displacement task when using direct manipulation and robot augmentative manipulation as alternative methods of response. This study provides both behavioural and neurophysiological data in order to identify the potential differences between direct and augmented manipulation and their associated complexity.

Children with severe physical disabilities cannot manipulate objects independently which limits the possibility of comparing their direct and augmented manipulation of objects. For this reason, Experiment 1 was conducted with typically developing children who each performed the two versions of the task. Experiment 2, a case study of a participant with severe upper limb impairments who participated in the robot augmented manipulation version and an adapted reaching version, is also presented.

Method

Experiment 1

Participants

Fifteen toddlers in their second year of life completed the study (7 males and 8 females; 13 Caucasian, 1 Asian, 1 Arabic). An additional 3 infants were recruited but were excluded due to fussiness of the child during testing and refusal to complete (2) and equipment malfunction (1). Toddlers were between 18 and 30 months (mean age= 24.7; SD= 4.2). All children were born two weeks within their due date, weighed at least 6 pounds at birth, did not require oxygen at birth and had no diagnosis of neurological disorders as reported by parents. Participants were recruited from a data base of families that had indicated their willingness to participate in research (3), through their parents who were University faculty and staff members (5), and from local day care centres and one local children's Sunday school (7). Children visited the laboratory with one of their parents (13 mothers, 2 fathers). Parking expenses were covered and toddlers received a small gift for their participation.

General Procedure

All children in the study participated in three conditions of the A-not-B with invisible displacement task (that differed from each other by how the child was encouraged to response): a typical reaching condition (i.e. the child uses his own upper limbs for reaching and lifting the cups); a robot-assisted condition (children use two different switches placed right in front of them to make the robot reach and lift the cup for them); and a looking version (the cup towards which child looks is coded as the response). Conditions were counterbalanced across participants.

Children visited the lab one time and visits were scheduled at times were they did not conflict with nap or meal times when possible. Testing was conducted by a female researcher who interacted with each child and two male research assistants who were in charge of the technical aspects of each session. On arrival at the laboratory, the researcher waited for the child and parent in the parking lot and blew bubbles as the child arrived to establish rapport and engage the child. Children and their parents were then invited to the laboratory, where parental consent and toddler verbal assent was obtained. There, the experimenter further played with the child while the child became comfortable in the laboratory environment. After playing with the experimenter the child was introduced to the robot. Parents also completed a short questionnaire in which they reported frequency of use and child's perceived skill level with different types of battery operated toys and other devices such as tablets, computers, etc.

In order to playfully introduce the robot (see Figure 5-1), a toy was hidden inside a cup before the child arrived at the laboratory. After introduction to the robot, children were encouraged to "press the button" to see what the colorful switch would do. The robot was programmed to uncover the hidden toy. Two children did not press the switch after they were encouraged, so the researcher pressed the switch and pointed towards the moving robot. The children were encouraged to do the same. This game was repeated several times to ensure the child was comfortable with the robot and understood that pressing the switch caused the robot to move towards the cup. After the child could successfully use one switch, the second switch was introduced and the process was repeated. Children discovered that the two switches made the robot go left and right. After playing with the toys and the robot children were given a picture and some markers to color. In the picture was a character wearing a cap like the EEG net. The researcher pointed out the net in the picture. After coloring the picture the EEG net was placed on the child's head (neurophysiological recording section below). Children were rewarded with stickers after each step of the experiment.

Robot augmentative manipulation system

For the robot condition, the anthropomorphic, half human size MiniMover-5 robotic arm[6] (see Figure 5-1) with six degrees of freedom was used. The robot has stepper motors that enable base rotation, flexion and extension of shoulder and elbow, wrist flexion, extension, supination and pronation, and a gripper that can open or close. The robotic arm was programmed and controlled by a notebook computer running Microbot Control Center software[7] and was adapted to enable switch input.

---

[6] Questec Technologies, Michigan , USA

[7] Questec Technologies, Michigan , USA

Figure 5-1 Microbot Teachmover Robotic Arm

The robot was programmed so that playback of a complete stored movement occurred when a switch was activated. Three movement patterns were stored into the robot: one was programmed to make the robot reach towards a cup place at child's midline (used during familiarization trials); another one made the robot arm reach towards and retrieve the cup placed at child's right (when switch placed at the right of the child was activated), and finally the other one made the robot reach towards and retrieve the cup placed at child's left (when switch placed at left side of the child was activated). When activated, the robotic arm reached towards the chosen target, grasped the cup and uncovered the hidden toy.

In order to facilitate consistent recording of trial information by E-Prime®[8] (the stimuli presentation software system) during the reaching condition, the robot was programmed to stay in the home position regardless of switch closure (in this condition the researcher pressed the switch to indicate the child's response so that the appropriate event marker would be recorded in the presentation software). This way the channeling of the signal was still done through the automated platform but with no response from the robot.

Customized apparatus for technical implementation

A custom-made apparatus (43x38x9 cm) was used for acquisition of behavioral and neurophysiological data during performance of the A not B task. This apparatus allowed the automatic coding of the behavioral events of interest and their marking in the ongoing EEG signal (the apparatus was connected to E-Prime® stimuli presentation software version 1.2 and NetStation®[9] acquisition software). The design and evaluation of the technical feasibility and instrumentation of this apparatus

---

[8] Psychology software Tools, Inc., Sharpsburh, PA.

[9] Electrical Geodesics Inc., Eugene, OR

and its use in a robot version of the A-not-B task is reported in Alvarez et al. (In press) (*see Chapter 4 in this document*). The platform was wired so that the following events in the task were recognized by E-Prime ® as key presses and marked into the EEG signal: (1) when the barrier is lifted marking the beginning of a trial, (2) when the participant hits a switch to choose either side A or B for robot retrieval of the object, (3) when either cup is lifted, recognizing both the lifting and which cup was lifted. The apparatus also served as an interface with the robot. The participant switch responses were connected to the robot to replay the stored movements (See Figure 5-2). Two cylindrical opaque plastic cups (8.8 cm diameter; 12.7 cm height) were placed up-side down, 12 cm apart from each other and used as hiding locations (See Figure 5-2).

Figure 5-2 Platform and Robot set-up showing the two containers in position on the platform and the two participant switches used to control the robot arm.

A-not-B with invisible displacement procedure

Because of EEG recording, the experiment was conducted in an electrically shielded and sound attenuated chamber where the designed platform was placed and interfaced with E-Prime®. Children sat on their parent's lap in front of the apparatus and the researcher sat in front of them on the other side of the apparatus. Several toys that could fit in the cup were available and the child picked which one to use.

Before testing, the toy chosen by the child was placed inside a cup at midline and the child lifted the cup to retrieve the toy. In the robot condition, the child used a single switch that caused the robot to do the same action. Then, invisible displacement was introduced. In view of the child, the toy was placed inside the cup at midline and then moved to one side. If it was unclear for the researcher if the child had observed and attended to the location, the trial was repeated. An opaque plastic barrier was placed between the child and the cup and held in place for 5s. During this delay the researcher enthusiastically counted and distracted the child. The barrier was lifted and the child could then lift the cup and retrieve the toy. In the robot condition the same was done but instead of reaching the child was given a single switch placed towards the same side (left or right) as the container location. This process was repeated two times at each side as pre trials.

Testing trials began with continuous EEG recording. The same procedure as the pre-trials was repeated, except that during the delay period, an exact but empty cup was placed on the opposite side behind the barrier. After delay, the barrier was lifted and the child was allowed to retrieve one of the cups. When a child achieved two consecutive successful trials (retrieved the correct container after the delay) at location A the location was changed for the next trial. In this new trial, the child observed the toy being hidden inside a cup but this time the cup was then moved to the opposite location (location B) instead of location A (this constitutes reversal, and the first trial at this new location is referred to as the "first post reversal trial"). This procedure was repeated until 6 reversals were completed or until the child refused to continue. These dependent variables were automatically recorded in E-Prime: # of reversals completed, # of trials before the criterion for reversal was reached, performance on the first post-reversal, and performance on the second post-reversal trials.

Neurophysiological Recordings

This study is a pilot exploration of ERP signatures of typical and atypical manipulation in the A-not-B with invisible displacement task. If an ongoing EEG signal is time locked to a particular stimulus presented to the child and the signal that results from this response is averaged, the resultant waveforms are referred to as event related potentials (ERPs) (Taylor & Baldeweg, 2002). ERPs provide monitoring of the summation of postsynaptic potentials linked to cognitive processing related to an event (Luck, 2005). Well established experimental manipulations are used to elicit specific changes in the ERP waveform that reflect specific neural or psychological processes (Luck & Kappenman, 2012). However, because a specific ERP experimental manipulation was not used, this study used an ERP component independent experimental design (the waveforms for the robot and reaching conditions are explored but they are not attributed to specific underlying neural process, since several elements may cause overlap between components and changes in the waveform) (Luck, 2005).

EEG signals were recorded with a high-density 128 channel Geodesic Sensor Net®[10] referenced to the central vertex electrode. EEG recording was performed with NetStation®[10] software

---

[10] Electrical Geodesics Inc., Eugene, OR

on a Mac ®[11] computer. This computer also received signals from a PC running E-Prime ®[12] presentation software that inserted time stamps for the critical events of the A-not-B with invisible displacement procedure. Data analysis was conducted in NetStation®, MATLAB®[13] custom scripts and EEGLAB 7.14 open source toolbox that runs in MATLAB ®. The platform was wired so that events in the task (e.g. barrier being lifted, switch presses, cups lifted) were identified as specific key presses in E-Prime ®, marked in the EEG signal in NetStation ® and could then be used as time-locked events around which ERPs could be identified.

Electrode impedances were maintained under 50 kΩ and the signal was sampled at 250 Hz and filtered and amplified at a gain of 1000. Offline, the EEG signal was 0.1-30Hz bandpass filtered, as recommended by Luck (2005) for the recording and analysis of ERPs in children. Artifacts were corrected via independent component analysis (ICA) (Bell & Sejnowski, 1995). In spite of the high motor artifact in the reaching condition and the electrical noise caused by the robot motors in the robot condition ICA was successfully used to remove artifact components (the feasibility testing and procedure of artifact removal has been reported in Alvarez et al. (In press), see Chapter 4 in this document). The EEG was initially referenced to the vertex electrode (Cz) but digital average re-referenced. Trials were referred to a 100-ms pre-stimulus baseline. The lifting of the barrier was used as the time locked event around which analysis was performed. This event signaled the beginning of a trial for the participant and marked the moment where the child was asked to find the toy.

RESULTS

Behavioral Data

Data were obtained from E-prime ® and analyses were conducted in IBM SPSS Statistics for Windows14, Version 20.0. Toddlers in this study almost always responded by attempting to reach during the looking condition and the researcher had to remind the child that he was not supposed to use his hands. Alternatively the parents would hold their children's arms to prevent reaching. This made the "looking" version of this task for typically developing toddlers in this age range artificial and thus it was excluded from the data analysis.

---

[11] Apple Inc., Cupertino, CA

[12] Psychology software Tools, Inc., Sharpsburh, PA.

[13] Mathworks, Natick, MA

14 IBM Corp , Armonk, NY

Table 5-1 summarizes the descriptive statistics for each dependent variable and the range of possible scores for each as reported for the robot and reaching condition. Each dependent variable was analyzed using repeated measures ANOVA to determine whether there were statistically significant differences between the robot and the typical reaching conditions. Effect sizes are reported as eta-squared statistics (η^2). According to Cohen (1988), η^2=.02 can be considered a small effect; η^2=.13 can be considered a medium effect; η^2=.26 can be considered a large effect. Because SPSS reports only partial eta-squared statistics, calculations for eta-squared (η^2) were conducted in Microsoft Office Excel ® [15](2010), using the SPSS reported sums of squares.

Table 5-1 Summary of descriptive statistics for A-not-B with invisible displacement task dependent variables

Descriptive Statistics for performance in the task by condition (n=15; mean age= 24.7; SD= 4.2)					
Dependent Variable	*Range of possible scores*	*Robot Condition*		*Reaching Condition*	
		M	*SD*	*M*	*SD*
Total Reversals Completed	0-6	3.73	1.87	2.40	2.35
Trials required before reaching criterion	≥2	3.60	1.5	2.60	1.18
Proportion of correct responses on First Post-Reversal	0-1	0.30	0.25	0.29	0.33
Proportion of correct responses on Second Post-Reversal	0-1	0.50	0.31	0.31	0.31

The number of reversals in the two conditions was normally distributed as assessed by Saphiro-Wilk's test ($p> 0.5$). Participants completed significantly more reversal sets when using the robot than when typically reaching, $F(1, 14)= 14.737$, $p<0.01$, $\eta2= 0.16$. Children required significantly more trials to reach criterion necessary for reversal trial (two consecutive successful trials a location A) when using the robot than when typically reaching, $F(1, 14)= 5.526$, $p<0.05$, $\eta2= 0.13$.

The proportion of correct responses on the first and second post reversal trials in both conditions were normally distributed, as assessed by Shapiro-Wilk's test ($p = .06$). There were no outliers in the data, as assessed by boxplot inspection. The proportion of correct responses on the first post reversal trials did not change significantly between the robot and the reaching conditions, $F(1, 14)= 0.72$, $p=0.79$. On the other hand, children performed significantly better (made less A-not-B

---

[15] Microsoft , Redmond, Washington.

errors) in the second robot post reversal when compared to the second reaching post reversal, $F(1, 14)= 8.826$, $p<0.05$, $\eta2= 0.09$.In order to have a better characterization of the performance in the first post reversal trials, the proportion of correct responses (successfully retrieval of the toy) were compared against chance (50%) in each condition. In the robot condition, children performed significantly below chance on the first post reversal trial, $t(14)= -3$, $p< .05$. Children also performed significantly below chance in the first post reversal in the reaching condition, $t(14)= -2.44$, $p<.05$. A paired samples t-test was used to determine whether there was a statically significant mean difference between the proportion of correct responses between the first and second post reversal trials in each condition. In the robot condition, there was a 14% increase in the proportion of correct responses in the second post reversal trials when compared with the first post reversal trials, $t(14) = 2.842$, $p < .05$, $d=0.66$. Participants performed better in the second post reversal trials (0.50± 0.31) than the first post reversal trials (0.30 ± 0.24). However, there was no significant difference in the proportion of correct responses between the first and second post reversal trials in the typical reaching condition $t(14) = 0.350$, $p > .05$.

Previous Experience with devices and robot task performance

In order to assess whether the use of battery operated toys and other devices had any effect on the child's performance in the robot condition (i.e. if any skills were possibly being transferred), parents were asked to fill a questionnaire (Poletz et al., 2010) in which they rated the previous experience of their children with different types of toys and games. Using a three point scale, the parent reported the frequency (often= 3, seldom= 2, never=1) and the skill level (task mastered=3, medium=2, trial and error use=1) for each category of toys and devices (switch operated toys such as tickle me Elmo ®; toys with directional controls such as remote control of a toy truck; and computer, tablet or smartphone games).

Table 5-2 summarizes the scores for each child as reported by parents. A Spearman's rank-order correlation was run to assess the relationship between skill and frequency of use of each category of toys and games (as reported by parents) with the # of trials required before reaching criterion in the robot condition, and # of reversals completed in the robot condition. There was a positive correlation between children's skill with switch operated toys and the # of reversals completed with the robot $r_s (13)=0.525$, $p=0.045$. No other significant correlation was found.

Table 5-2 Participants' ages and Proficiency measures

Type of device	**Measure**															
	ID	**206**	**212**	**213**	**203**	**211**	**202**	**210**	**214**	**208**	**204**	**215**	**205**	**201**	**207**	**209**
	Age [months]	18	19	19	22	22	24	25	25	26	27	28	29	30	30	30
Switch operated toys	Frequency	1	3	3	2	3	3	2	2	2	2	2	2	3	2	2
	Skill Level	1	2	3	3	2	3	3	3	2	2	2	2	3	1	3
Directional controls	Frequency	1	2	1	1	1	2	1	2	2	1	2	1	2	2	1
	Skill Level	1	1	1	1	1	2	1	2	1	1	2	1	1	1	1
Personal electronic devises	Frequency	1	2	2	1	2	3	2	2	1	2	3	2	2	1	2
	Skill Level	1	1	1	1	2	2	1	2	1	3	2	2	1	1	3

Neurophysiological data

Out of the 15 children included in the study, two children failed to contribute usable EEG data due to excessive amounts of motor artifact (net refusal). Only 13 children were included in the neurophysiological ERP analysis. As described in Alvarez et al. (In press) (See Chapter 4 in this document), the motor demands of the task and the use of the robot added significant artifact that could not be isolated by means of NetStation Waverform tools. Artifact from electrooculogram (EOG), motor activity, and electrical signal from the robot was removed using independent components analysis (ICA) in EEGLab.

The continuous EEG was segmented into epochs from 100 ms before either the barrier was lifted or the switch was pressed to 1000 ms post target onset. Trials with correct responses (i.e. where the participant correctly identified the location of the object) were analyzed separately from incorrect trials (child failed to correctly identify the location of the toy). A channel was marked bad for the entire session if it was deemed bad in more than 20% of the trials.

For analysis, four groups of electrodes representative of frontal, central, parietal, and occipital areas in both hemispheres were chosen. The electrodes were identified by finding the 10-20 international system (Jasper, 1958) correspondence as described by Luu & Ferree (2000). (Table 5-3 presents the correspondence between the 10-20 system and the 128 electrode net used for this study). The group of electrodes around the corresponding Fz, Cz, Pz and Oz identified by Luu & Ferree was averaged to obtain these representative frontal, central, parietal, occipital sites (Classon et al., 2013; Luu et al., 2011).

Table 5-3 Electrode number and correspondence with the 10-20 system as described by (Luu & Ferree, 2000)

10-20 system	Electrode number	Electrodes chosen for each area
Fz	11	10, 11, 16, 18
Cz	129	31, 80, VREF
Pz	62	62, 67, 72, 77
Oz	75	74, 75, 81, 82

The third column shows the electrodes chosen for each area in this analysis. Figure 5-3 presents a schematic view of the HydroCel Geodesic Sensor Net, illustrating the distribution of the chosen electrodes. The electrodes chosen for extraction are circled.

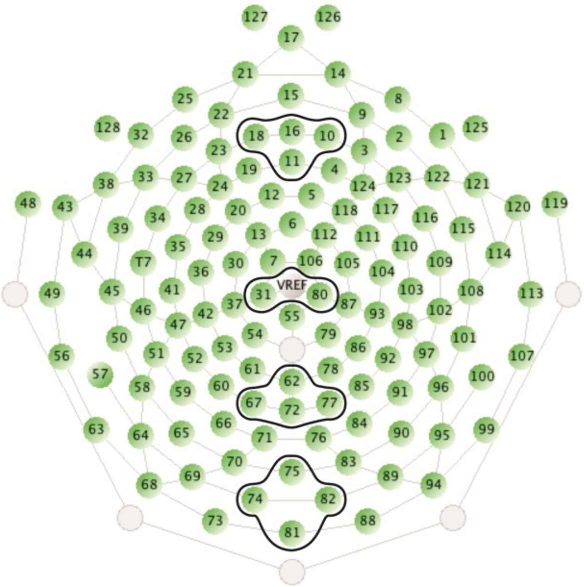


Figure 5-3 Electrode map of the Hydrocel Geodesic Sensor Net – 128 channels

Individual trials were averaged and mean amplitudes and peak latencies for each electrode were recorded for each participant. In the robot condition a total of 206 trials (M=15.8 trials per child) were averaged; in the reaching condition 134 trials (M=10.3 trials per child) were used. For each participant, and each condition (robot and reaching) the mean amplitude and peak latencies for each event (barrier lifted and switch pressed) were averaged together across the electrode groups to represent the ERP components at the frontal, central, parietal and occipital sites.

Figure 5-4 presents the resulting waveforms for the barrier lifting event for both the reaching and the robot condition in each area. These waveforms correspond to 100 ms before to 1200 ms after the barriers is lifted and the child is asked to retrieve the toy. The waveforms for the robot and reaching condition are plotted across the four sites (frontal, central, parietal and occipital).

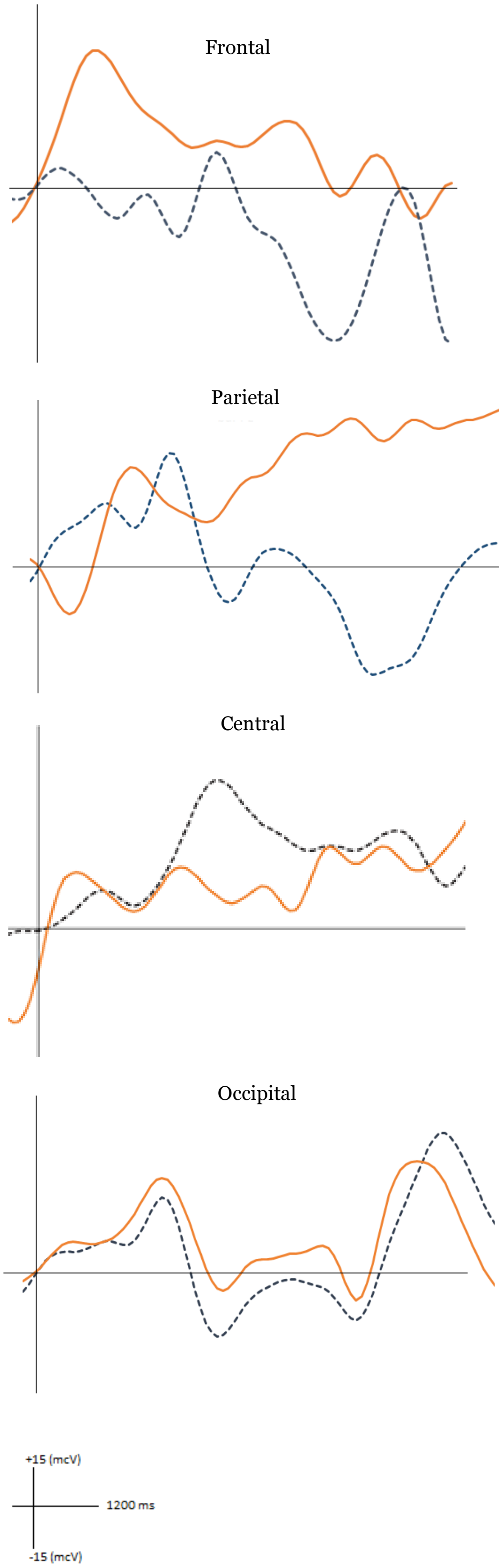


Figure 5-4 Event Related Potential waveforms for the barrier lifting event. The dashed line represents the robot condition and the continuous line the reaching condition. Positive is plotted upwards. Upper left presents the Frontal leads; upper right the Central leads; Bottom left the Parietal leads and bottom right the Occipital leads.

In line with the descriptive and exploratory nature of this study, the approach to analysis as described by Handy (2005) for effect-unspecific hypothesis was used (quantifying differences between waveforms in the absence of a priori predictions of, if, how and where ERP differences will manifest between conditions). The waveform was divided in consecutive time windows of 100 ms of length from stimulus onset until 1000 ms for each waveform in each subject (the topography of the waveforms for the final 200 ms is likely to be influenced by later latency events). The mean amplitude for each time window was entered into a 2 (condition: reaching, robot) x 4 (lead: Fz, Cz, Pz, Oz) within subjects ANOVA. Table 5-4 shows the results as a function of time window and its corresponding p values (≤0.05) for each effect (as recommended by Handy, 2005). There was a significant lead x condition interaction in the 300-500 ms time windows. A significant effect of lead was observed earlier from 100- 600 ms, and the effect of condition was significant between 200 and 400 ms. In addition to the significant time differences in the time windows specified, two important elements emerge from the waveforms. First, the waveforms in the frontal, parietal, and central regions are different (by means of visual inspection and statistical significance). These observed differences in latencies, amplitudes and scalp distribution are consistent with cognitive processes that are qualitatively different (i.e. the components are not the same). Second, in the occipital region, visual inspection reveals similar ERP signatures in this specific area. This is consistent with the fact that visually the conditions would have looked exactly the same for the child, as every object (including the robot) would be in the same location.

Table 5-4 Significance of effect interactions on mean amplitude across time windows

	Time window (ms)									
Effect	0-100	100-200	200-300	300-400	400-500	500-600	600-700	700-800	800-900	900-1000
Lead	--	0.05	0.05	0.05	0.05	0.05	--	--	--	--
Condition	--	--	0.05	0.05	--	--	--	--	--	--
Lead x condition	--	--	--	0.05	0.05	--	--	--	--	--

Discussion

Comparative behavioral data and neurophysiological signatures were used to explore and gain a better understanding of the differences that underlie robot augmented manipulation and typical manipulation in early childhood. The looking condition was excluded from analysis because children in this age range (18 to 20 months) were not able to dissociate the reaching response from the looking. Ruffman et al. (2005) have also reported that children 12 months and older are less likely to glance correctly than they are to reach, resulting in comparable performance in children this age (Cuevas & Bell, 2010; Bell & Adams, 1999). We are not aware of studies exploring the neurophysiological correlates of robot augmented manipulation for young children so this study was a first exploratory analysis to identify the differential neurophysiological signatures of robot augmented manipulation in the performance of a cognitive task.

Previous studies have used EEG power (amplitude measure that reflects excitability of groups on neurons (Nunez, 1981) and coherence (which reflects functional coupling among brain regions (Taylor & Baldeweg, 2002)) to evaluate the relations between frontal cortex maturation and its association with better performance in the A-not-B task (Bell & Fox, 1994; Bell, 2001). Children that exhibited high performance on the task had presented greater power in the frontal and occipital leads and decreased coherence values of the EEG at baseline when compared to children who had a low performance in the task as measured by their behavioural response (BELL, 2001). Studies that have used EEG power and coherence analysis with the A-not-B task have used it either as a baseline measure of brain maturation (Bell & Fox, 1997; Bell & Fox, 1992) or as a baseline to task measure in which case it has only been used in looking versions of the task (Morasch & Bell, 2011; Bell, 2001). Because of the motoric nature of the task and the required time locked events for other analysis, these studies have used EEG (Morasch & Bell, 2011). The current study constitutes a first attempt to include ERP analysis as a way to contribute to the neurophysiological findings of the A-not-B that have been reported in the literature. This perspective adds the specific brain activity related with the decisive time points during the task and the comparison between conditions.

A component-independent design (Luck, 2005) or effect-unspecific hypothesis (Handy, 2005), when no prior information is available to elicit a known component (as in this study), allows inferences in terms of timing (time course), degree of engagement (amplitude) and functional equivalence of the underlying processes conditions (distribution across the scalp) (Otten & Rugg, 2005; Luck, 2005).

Results show that robot and reaching resulting waveforms differ with respect to when the barriers is lifted and the child is asked to find the toy (with a significant interaction of lead condition between 300 and 500 ms and a significant condition effect between 200 and 400 ms). The ERP waveforms in the occipital region were found to be similar, consistent with the fact that the set up and visual information available to the child was maintained across conditions (including the robot which was present in the reaching condition in the same location as in the robot condition). Thus, having the occipital waveforms as a control condition, the differences in the frontal, parietal and central regions reveal that qualitatively different cognitive processes are associated with this event between conditions. Further, the statistically significant effect of condition and lead x condition interaction reveal that these processes begin to differ as early as 200 ms post stimulus. Considering that the event of interest was the lifting of the barrier, where no motor response from the child is being required or performed yet, these differences indicate that just the awareness of response modality is enough to elicit different processes by the child in an object search in the task.

Although no attributions of source localization can be made with the present methodology, frontal, parietal and putaminal neurons have been found to be involved in the incorporation of common tools (e.g. a stick or a rake) into the body schema (i.e. body shape and posture map) in the brain (Maravita & Iriki, 2004). Common tools have been found to be incorporated in the brain's map of the body after repeated use of the tool, with the brain recognizing the tool and the space accessible with it as part of the upper limb (Maravita & Iriki, 2004). But the robot is no common tool. The robot is a novel tool that the child operates by pressing a switch, which alters the extent to which it can be viewed as simply extending the upper limb's space of influence. Thus, the qualitatively different processes elicited in this manipulation provide evidence for differences between the way the robot is perceived and the child's own actions.

These results reveal that the underlying cognitive processes in the performance of the A-not-B task with invisible displacement are different in nature between the robot and typical manipulation conditions. These results provide the basis for exploring the differing neurophysiological components. Further studies should explore the localization of the components and their attribution. These studies should also address the limitations of the study regarding sample size, and children's compliance with net placement.

Analysis of the neurophysiological signatures for the time in which the robot is reaching towards the cup and the child is observing could provide valuable information regarding the way the robot's actions are perceived by the child. When a child observes an action that he has performed before (e.g. an object being reached), activation of his own motor repertoire occurs while observing (Paulus et al., 2011). This in turns facilitates the child's ability to perceive the goals and intentions of others' actions (Woodward, 2011; Sommerville, Woodward & Needham, 2005). The children in this study had no previous experience with the robot and its possible actions and degrees of freedom, but their own reaching experiences may influence the way in which that part of the robot-mediated task is perceived due to the anthropomorphic nature of the arm.

All children involved in the study appeared to be motivated and to enjoy the interaction with the robot. All but two children pressed the button when encouraged to explore what the robot could do. After exploring, children wanted to repeat the task and playing with the robot encouraged them to continue with the session. The motivation and comfort of children when interacting with robots has also been reported in other studies involving typically developing children (Poletz et al., 2010) and children with physical disabilities (Kronreif et al., 2007).

Studies with toddlers have shown that compliance with neurophysiological electrode attachment is low in this population (Stifter et al., 1999; Wolfe & Bell, 2007). Electrode compliance is typically an issue that affects the results generalizability (as only more compliant children participate and they may not be representative of the population) (Morasch & Bell, 2011). In this study, the order of condition (robot vs. reaching) was counterbalanced across participants but the robot was introduced at the beginning of the session every time to ensure that the child was comfortable and to motivate the child to wear the net and keep it on through the session (as this would allow them to play with the robot). Introducing the robot helped participants to accept the placement of electrodes. . Results showed that children completed significantly more reversals when using the robot. As part of the procedure, six reversal sets were administered or administration stopped when the child refused to continue. This was the case with the reaching version in which children completed fewer reversals. Children were more willing to overcome frustration and continue when performing the task with the robot. This suggests that robot interaction might be rewarding in and of itself.

Our findings show that children required significantly more trials at A before achieving criterion for reversal when using the robot than when reaching. Although the meaning of trials at the A location before reversal has been largely neglected in the A-not-B literature (Marcovitch et al.,

2002) some research has suggested that it may be indicative of difficulties with initial learning (Diamond, 1997; Wiebe et al., 2010). The number of A trials has been found to have a U-shaped effect on subsequent perseveration (Marcovitch & Zelazo, 1999; Marcovitch et al., 2002). This U-shaped effect is described as follows: as the number of trials at A increases, the likelihood of perseveration increases too but it then decreases after a certain number of trials because it provides opportunity for the child to reflect on the task.

The results obtained in the robot condition, may reflect the additional complexity involved in performing the task with the use of the robot (as shown by increased number of trials required at A before criterion) but also additional opportunities for the child to understand the structure of the task (which may have influenced the performance in the second post- reversal trials). Alvarez and Cook (*In press*, see Chapter 3 in this document) showed, at a theoretical level, the additional levels of complexity involved in using this robotic arm as a tool. The child needs to prospectively relate the desired target with the ability of the robot to retrieve it, and the required switch press to make it happen. Similarly, in this task children need to not just choose the cup in which they believed the toy was hidden, but also select the switch that would correspond with the desired movement towards the selected cup. Switches for each side were placed in front of the child at left and right from midline so that the relation to the robot's reaching was more explicit. In spite of training trials at each location, video recordings showed three of the children pressing the switch and observing the robot move towards the incorrect side (namely the cup that did not have the toy) and then forcefully leaving their parent's lap and quickly attempting to change the toy to the cup towards which the robot was going in at least one of the trials before criterion was reached. They made statements like "the robot was almost wrong but I helped".

Statements and verbal expressions of children during the robot condition provide some insight into children's performance with the robot. When interacting with the robot expressions of children often indicated that they were attributing agency to the robot. Young children have been shown to discriminate between biological and non-biological movement and to differentiate goal-directed actions from random movements (Friedman & Kahn, 1992; Johnson et al., 2001). However, children's ability to discriminate the source of movement is altered when interacting with animate things (Massey & Gelman, 1988). Gelman & Gottfried (1996) conducted a study in which toddlers and pre-school children observed inanimate objects (such as toys) and small animals (e.g. lizard) being carried from one place to another by a human hand. When asked about the source of movement, children expressed that a person had moved the objects (inanimate) but thought that the movement of the animals for transportation was self-generated. These results reveal that for animate objects, young children believe that movement is self-generated regardless of what they see or experience as the source of the movement (Okita et al., 2006). In our study, these findings suggest that children may have attributed the search for the toy to the robot, and believing that they were helping an "independent" robot may have provided a different opportunity to reflect on the task. This may be partly the reason why there were significant differences in the second post reversal trial, where children performed significantly more accurately with the robot than when reaching and why there were observed differences in the ERP waveforms between conditions when children were asked to find the toy. The fact that children only activated the switch once and this would in turn re- play the pre-programmed movement of the robot may have also contributed to the child's perception of the robot as independent. Requiring the child to continue to press the switch in order to complete the movement (i.e. continuous playback mode) can help children gain control over the task and may increase tool use awareness by the child. For example, Cook, Liu and Hoseit (1990) used continuous playback mode to determine if young children would use a robotic arm (the same as in the present study) as a tool to retrieve a cookie out of reach. In this study, where two switches were used, such an approach was not used in order to avoid having children initiate the action with one switch but not completing it or changing to the other switch in the middle of the response. Future studies should expand on the effects of increased robot control on performance, including tasks in which more than one switch is required.

In a study conducted by Okita et al. (2006), 3 to 5 year-olds watched or interacted with different types of robots and were later assessed on whether or not they attributed animate characteristics to the robot. Children in the study attributed more animacy and self-agency to robots with which they interacted by causing them to move than when they simply observed them. In our study, children caused the movement but may have attributed self-agency to the robot. The robot in this study was a robotic arm, which does not have all the anthropomorphic characteristics of a human, in fact 3 of the children posed questions similar to "how can the robot find the toy in the cup if it doesn't have eyes?" The study by Okita et al. (2006), showed that although realism affects the child's perception, it doesn't have a significant effect on whether or not they attribute agency to the robot, which seems to be more related to the movement capabilities of the robot. Elements that allow the child to reflect during the A-not-B task (such as forcing children to pause before responding (Riviere &

Lecuyer, 2003)) or having a very large number of pre-trials at A (Marcovitch et al., 2002) have been shown to decrease perseveration in the A-not-B task. In the present task, children's attribution of agency led older children to often reflect out loud about the correct response after the first post-reversal. Children often made remarks such as "I can help robot, do it again".

No significant differences were found in the proportion of correct responses in the first post-reversal trial between conditions. However limitations of the study may account for this result. A larger sample size is required in order to assess both the behavioral performance and the neurophysiological signatures. Although no differences have been found in the proportion of correct responses in the reaching condition across 18 to 30 months of age (Diamond, 1997) and no correlation was observed in this study between age and performance, there may be differences in how younger and older children in this age range respond to the robot condition. In light of this, data was explored by grouping the children into older (24-30 months) and younger (18-23 months) children. This initial exploration revealed a pattern that requires further exploration with larger sample sizes. In the robot condition, younger children displayed fewer errors, on average, when compared to the reaching condition. The situation was reversed for older children. This pattern could support a cognitive capacity account of perseveration (Berger, 2004; Berger, 2010). Because younger children are less skilled in their reaching behaviors (Smith et al., 1999) the reaching version would represent an increased motor demand-condition (the demand of the task is dependent on the child expertise with a certain skill required by the task (Berger, 2004)). In this situation, where the robot decreases the motor demand, younger children may be more able to devote cognitive resources to the cognitive skills required for remembering the position of the toy and inhibiting the response (Berger, 2010). Alternatively, older children whose cognitive capacity is not taxed by having to skillfully reach towards the cup (Berger, 2004) may find the robot condition too cognitively demanding and distracting for the performance of a task. If this is true, then the robot would be compensating for the motor component of the task for the young children. Older children would be then more challenged by the cognitive elements of robot mediated manipulation, where agency may help them overcome perseveration. There are a number of implications of robots compensating for the motor aspect of the A-not-B task for children with disabilities. In a study of A-not-B performance, Collimore (2011) found that younger children's performance in the A not B task may be affected by the memory of reaching at A, but this seems to not be the case for older children. When younger children encounter greater motor demands their performance in this cognitive task decreases, unlike older children.

It is important at this point to take a step back from performance of children in the robot mediated condition to discuss the implications of motor vs. cognitive demands of the A not B with invisible displacement task. The motor habit that is created by repeatedly searching at A has been the focus of several studies, especially those within the dynamic systems account of the A-not-B error (Diedrich et al., 2000; Clearfield et al., 2006). Also, the motor demands imposed by the task on young children whose patterns of reaching are not yet fully stable and coordinated have been reported to be the potential source of the A-not-B error (Diedrich et al., 2000) (Collimore, 2007). However, the A-not-B with invisible displacement was designed to test perseveration in older children (those in their second year of life). Therefore, children in this age range would be far more skilled at reaching than 8 month olds who perseverate in the classic version of the task and their reaching skills would be beyond the 12 month olds who are able to overcome perseveration in the classical version of the task.

It was Piaget's argument (1954) that older children would perseverate in the A-not-B with invisible displacement task because the increased complexity would challenge their recently formed object permanence skill. However, children in the A-not-B with invisible displacement have been shown to incorrectly search in the B trials after successfully retrieving the object in the A locations (Wiebe et al., 2010; Diamond, 1997). This perseverative behavior in which children fail to retrieve the object only after repeated reaches towards A, even in this more advanced version of the task, supports results by Diedrich et al. (2000), in which the reaching pattern is influenced by the task difficulty and novelty. This holds true also when looking at studies in which adult participants fail to reach skillfully when presented with an altered environment in which artificially created forces caused curved trajectories in participants reaching (Lackner & Dizio, 1994; Shadmehr & Mussa-Ivaldi, 1994). After several training repetitions, adults were able to consistently produce straight reaching patterns in the novel environment. Interestingly, when forces were removed and participants were back to familiar context, the trained pattern remained and they were now making curved trajectories in what used to be the familiar typical reaching field. These studies provide evidence that when faced with a new set up and dynamics of the environment, repetitive behavior can cause perseveration in motorically skilled participants. Further, perseverative behavior (failure to inhibit a previously trained successful response that is no longer appropriate to succeed in the task at hand (Mandler, 1988)) has been shown to be present in older children and even in adults in different types of tasks (Zelazo, Frye & Rapus, 1990). Piaget's different versions of object permanence tasks (object hidden under a single cloth; A-not-B classical version and invisible displacement) have been shown to reveal fewer errors when children don't act upon the objects and only observe (Riviere & Lecuyer, 2003) and can be associated with motor and cognitive mechanisms (Berger, 2004; Berger, 2010). Further, changing the motor and perceptual characteristics of the task has been shown to elicit or suppress A-not-B errors in children from 8 months to 30 months, evidence of the ways in which motor planning and perceptual information provided by the task can alter the reaching behavior of children in this broad age range and that their implications in the A-not-B error cannot be tied to a developmental period (Smith, 2009)

The fact that no significant differences were found in the proportion of correct trials between the robot and the reaching condition could, alternatively, constitute evidence to support the fact that perseveration may occur at the motor planning level (Smith, 2009). There is evidence to suggest that the A-not-B error can be elicited when children observe someone else perform the A trials and then are asked to perform the trial at B (Logo & Bertenthal, 2006). In this situation, children use a common representational code for their own motor planning and the actions they observe others perform (Sommerville & Woodward, 2005). In this context, motor planning, and not motor execution itself, can lead to the A-not-B error after A trials have been successfully repeated (Berger, 2001; Munakata et al., 2001; Lew et al., 2007). Studies that have explored the simulation of actions when observed by adults have shown that when the actions are performed by robots or mechanical devices simulation and mirroring of motor planning decreases, as adults may not be able to relate to a mechanical action as they would to a human one (Tsai & Brass, 2007; Tai et al., 2004). However, recent studies have shown that when additional information is available to the human (such as associative learning of the function of the device or its similarity with human movement) the mirroring system can also be activated by robotic movement (Press et al., 2005; Boyer et al., 2011).

Boyer et al. (2011) explored whether this similar representation extended to non-human agents. In their study, 9 month old infants observed a pair of mechanical claws hide the toy at location A and then were asked to retrieve the toy at location B in experiment 1. In experiment 2, children were first familiarized with the claws and the experimenter that was operating them but not with their function. In experiment 3 children were familiarized with the function of the claws and the human operator. For both experiment 1 and 2, children's A-not-B were found to be at chance levels. However, in experiment 3, children displayed significantly more errors. Children in the third experiment exhibited perseverative behaviour similar to that reported by Logo & Bertenthal (2006). When familiarized with the function of the claws and the human as the operator, infants perceive mechanical actions as goal oriented and can map the actions of the device to their own motor representations (Boyer et al., 2011). In Boyer et al.'s study, children were passive during the A trials and only intervened in B trials. Our results suggest that when children were active in producing the robot movement, the motor planning of the action after having being familiarized with the robot reaching pattern in familiarization trials can elicit the repetitiveness at A that would cause them to perseverate at B. Also, this could support the hypothesis of direct matching (Calvo-Merino et al., 2005; Logo & Bertenthal, 2006). According to the direct matching hypothesis, motor simulation and mapping of actions decreases when observed actions are outside one's own motor repertoire or capabilities of action. According to Boyer et al. (2011) their first two experiments supported that hypothesis because 9 month old children are "motorically unable to operate the claws" (pp. 8). Children in our study caused the robot movement and being actors in the task may have also allowed them to relate to the robot movement. Our findings indicated that the anthropomorphic characteristics of the robot and its movements facilitated children's understanding of the robot's actions. In terms of motor simulation, our study would meet the condition for motor simulation because children were able to relate to the robot and were capable of actions towards the robot that caused it to move. Although getting the robot to move required a different motor action by the child (pressing switch) than that of reaching, the robot reaching movement was within the motor repertoire of the child and the action of pressing the switch to cause it was within their capabilities of action.

It is important to note that the robot in our study was always placed at the left side of the child due to technical requirements of the equipment and the space. This meant that the robot would always come towards the object from the left of the child, and go to the left or right cup. Twelve children out of the total sample were found to have a consistent right hand preference (as reported by parents and confirmed during play time with the researcher). Three had inconsistent preferences. Children with a consistent preference could still hit the switch with either hand but were found to use their preferred hand to do so. Although further research needs to ensure that flexible side placement of the robot allows further exploration of the implications of robot placement, this was not considered problematic. In a study conducted to determine the effects of hand preference on the A-not-B error, Collimore (2011) found that infants with a consistent hand preference who were randomly assigned to conditions in which the A trials were consistent with preferred hand side or not, searched correctly more often at A trials when the A location was consistent with their preferred hand but this did not affect their performance on the reversal trials (perseveration).

Experiment 2 Case-study: Performance of a physically disabled child

This study is the first to compare the use of typical manipulation and augmented manipulation in the performance of a cognitive task and the first to explore the neurophysiological signatures of each of these in relation with typically developing children's performance of a cognitive task. In addition, experiment 2 presents the performance of a child with a physical disability as a case study. The purpose of this case study was to explore the performance of children with physical disabilities in a cognitive task when using robot augmented manipulation. This case study also provides initial information regarding how the interaction of children who have disabilities with the robot and their resulting performance differs from that of typically developing children.

Participant

A 30-month old Caucasian toddler with a bilateral brachial plexus injury and her mother volunteered to participate in the study. The mother was aware of the study through a friend whose typically developing child had participated. The mother expressed interest in the study because of the robot mediated condition. She reported that the child had difficulties playing with off-the-shelf toys that presented high motoric demands for the child.

The brachial plexus is a network of nerves that originate in cervical spinal nerves (C5-C7) and in two thoracic spinal nerves (T1-T2) (Anwar et al., 2012). This network is responsible for innervation of the muscles in the upper limb (except the trapezius muscle) (Moore & Agur, 2007). The participant in this study had a bilateral injury of the brachial plexus as a result of trauma during childbirth. The child had undergone nerve repair surgery at 7 months on the right upper limb and extensive physical therapy. At the time of the visit to the laboratory the child was engaged in play and functional limitations of the upper limb were assessed, following general guidelines of Mallet Scale for assessment of brachial plexus injury in children (Gilbert & Tassin, 1987). The child was found to have restricted shoulder abduction and external rotation of the left shoulder, and could not bring hand to head, back or mouth. She had difficulty grasping objects and mostly used her right arm. On the right upper limb, the child was found to have restricted shoulder abduction, external rotation and could not bring hand to back or mouth. However she could reach towards objects close to her, and grasp light objects. The child was capable of pressing the switches if they were placed close to her.

Procedure

The child participated in the robot and reaching condition of the task. Behavioral data were recorded. For the robot condition, switches were placed close within comfortable reach of the child. For the reaching condition, the task was modified so that child only had to point towards cup and the researcher would lift it. The rest of the procedures were exactly the same as those employed with typically developing children.

Results

Error! Reference source not found..

Table 5-5 Scores obtained by child in Experiment 2

Case study Results by condition			
Dependent Variable	***Range of possible scores***	***Robot Condition***	***Reaching condition***
Total Reversals Completed	0-6	*5*	*3*
Trials required before reaching criterion	2 ≤	*5*	*2*
Proportion of correct responses on First Post-Reversal	0-1	*0.80*	*0.40*
Proportion of correct responses on Second Post-Reversal	0-1	*0.40*	*0.40*

Discussion

The child in experiment 2 also completed more reversals with the robot than in the adapted reaching condition. The child was motivated and expressed excitement over controlling the robot by herself (verbal expressions included statements like “mommy I did it, it was me”). The mother also provided additional encouragement by giving positive feedback in the robot condition as the child was independently controlling the robot. Interestingly, the child did not provide any signs of agency or self-generated movement attributions to the robot. On the contrary, and unlike the typically developing children, this girl repeatedly expressed ownership over the robot’s actions, event when unsuccessful in finding the toy. Similarly, children with disabilities have been found to perceive their power wheelchairs to be an extension of themselves and part of their notion of body and control over it (Gibson & Teachman, 2012).

This child also required more trials at A before reaching criterion, asis did her typically developing pears, indicating overall increased complexity of the robot mediated version of the task. She achieved 80% accuracy in the task when using the robot, compared to the 40% achieved in the adapted reaching (as revealed by the proportion of correct responses in the first post-reversal which indicates the ability to overcome perseveration). We interpret these findings as having two implications. First, decreasing the motor demand gave her access to the task and her cognitive and attention resources were devoted to the cognitive demand of the task decreasing perseveration (Berger, 2004). Children with severe physical disabilities have been found to perform better than their typically developing peers in tasks where inhibiting motor responses interferes with cognitive performance (Riviere & Lecuyer, 2003; Riviere & Lecuyer, 2002). Second, the child did not expect the robot to act independently or perceive it as being animate, which allowed her to better use it as a tool to achieve her goals. The girl's mother reported that the child had undergone extensive rehabilitation processes, which may have provided her with greater exposure to other technologies and tools used in the clinical environment. In fact, the child used switch operate toys very often, as well as toys with directional controls.

The performance of this child provides evidence for the assertion that children with disabilities may access developmental detours in the absence of typical motor experience that is conducing to learning (Riviere & Lecuyer, 2002). For typically developing children, previous action experience has been found to facilitate children's action perception and their understanding of the goals and intentions of someone else's actions (Woodward, 2011; Sommerville, Woodward, & Needham, 2005). When a child observes an action, a corresponding activation occurs in his/ her own motor repertoire (motor resonance) (Paulus et al., 2011). The child in this case study did not have typical previous reaching experience that, in theory, would have allowed her to better understand the robot's reaching action. Yet her previous experience with rehabilitation technologies or having to direct her mother in order to retrieve a desired object may have allowed her to perceive the robot as a tool dependent on her own actions and intentions. Children with physical disabilities for whom reaching behaviors require extensive amounts of energy and effort have been found to pause and reflect more extensively on the task at hand (Riviere & Lecuyer 2002). The girl in this case study would pause every time after the barrier was lifted and reflect for longer period of time.

Future studies that explore the effects of robot augmented manipulation on cognitive performance and demands can also include an adapted manipulation condition. In our study the condition was adapted to be as similar as possible to the typically developing children's reaching condition. However, in light of potential alternative developmental pathways, such a condition should encourage children with disabilities to use their preferred adaptive means of interaction with objects (such as laying on the side in the floor in order to better access the objects, etc.). This can further clarify the alternative means of functional mobility that children develop and that allow them to benefit from the cognitive and perceptual implications of movement.

Conclusions

This study establishes the feasibility of comparing typical manipulation and robot augmented manipulation involving multiple switches, in the performance of a cognitive task by young children. Our findings also reveal behavioral differences between augmentative manipulation and typical manipulation and provide the basis for further exploration of neurophysiological differences and implications.

The data in this study reveal several characteristics of robot-augmented manipulation. Using robots in order to perform manipulative behaviors such as reaching and grasping can give children with disabilities access to the independent exploration of the environment. The fact that young typically developing children found the robot motivating and that this encouraged their persistence in the task and their compliance with other elements of the task is promising for the design of studies and interventions with children with disabilities. Also, these results support the role of augmented manipulation in relation to the child: using the robot as a tool increases the cognitive demands of the task while decreasing the motor demand. The additional cognitive demand placed by the robot can be addressed by adapting the robot and the control interface (e.g. the switches). Also, different cues and training procedures can be used in order to make the robot mediated tasks more accessible to young children. As young typically developing children responded to the task, this study also suggests that children with disabilities may benefit from exposure to early robot augmented tasks and playful activities through which they can use the robot and become more familiar with its constraints and the opportunities it affords. Giving children additional exposure to the robot in manipulating different objects and providing young children with robot mediated experiences may also impact the way the child perceives the robot and may lead to children using the robot as a tool more than expecting it to act independently.

Further research should explore the performance of the A-not-B task of children with severe motor disabilities who lack typical previous motor experiences. The children's own and unique ways of accessing objects should also be explored in order to identify the developmental detours employed by children with disabilities. This could benefit the understanding of the developmental pathways to the acquisition of cognitive skills by children with disabilities. In addition, it could provide further insight into the role of motor experience and motor execution during the A-not-B task. Further studies should also include a larger sample size to assess the differences between younger and older children in the task when using the robot and explore the relation between EEG indices of brain maturation and performance of robot mediated manipulation in the A-not-B task. In addition, the study of augmentative manipulation would benefit from exploring the neurophysiological correlates of children's perceptions of robot actions.

Chapter 6
General Discussion and Conclusions

The preceding four papers were based on review of the literature and data collected in order to explore the differences between augmentative manipulation and typical manipulation, and their implications in the performance of a cognitive task by young typically developing children. Also, the technical feasibility of exploring neurophysiological data as well as behavioral data was evaluated, given the current available technology both for neurophysiological recordings and for augmentative manipulation. Four papers were included that together establish: the relevance of this comparison (the why); the characteristics and implications of using robots as augmentative manipulation tools (the what); a method for technical implementation of the comparison and its technical feasibility (the how); and the differences between young children's use of robot augmented manipulation and typical manipulation in a cognitive task.

Through a review of the literature, chapter 2 established the importance of providing children with physical disabilities with an alternative to typical manipulation that can give them access to early manipulative experiences. The study of typical development offers a deeper understanding of the role of functional movement and its intersection with cognition (Esseile, Nadel, Fagard, 2010; Thelen, 2000). A paradigm shift in the rehabilitation approach to disability and the early use of assistive technologies supports the transition from trying to achieve the most typical patterns of movement, towards function and participation (Thelen, 2005; Law et al., 2007; Mankoff, Hayes & Kasnitz, 2010). It is within this framework, that robots can provide the benefits of functional manipulation.

If robots can provide access to cognitive development opportunities and early independent interaction then they need to be both motorically and cognitively accessible for young children (Cook et al., 2012). The implications of using such robots as tools as an alternative to typical manipulation needs to be understood. Studies that have explored the use of robots with children with disabilities raise concerns regarding the ways in which robot augmented manipulation is different from typical manipulation and the additional cognitive and perceptual demands it requires (Poletz, Encarnaçao, Adams, Cook, 2010; Cook et al., 2010; Cook et al., 2012). The performance of typically developing children, who can manipulate objects and can also access the robot mediated manipulation, can shed light into this questions and concerns (Poletz et al., 2010;). What is it that is being asked of young children when given a robot as a tool for manipulation?

A way to begin answering the question of what is being asked of a young child when giving him a robot for manipulation and how it differs from typical manipulation is the conceptualization of the robot as a tool and the underlying implications. The second paper in this dissertation (presented in chapter 3) presented this conceptualization and used the literature and concepts around tool use to characterize the robot as a compound tool through which children can engage in complex tool use. A complexity analysis strategy proposed by Van Leeuwen, Smitsman & Van Leeuwen, (1994) was used. Within the framework of this analysis, the cognitive complexity of the use of a tool is determined by how many objects and items are involved in the task and how they interact with each other. When using augmentative manipulation, there is a target object that the child wants to manipulate, the robot, and the switch (es) that control the robot. The child needs to perceive how they relate to each other and to himself. The complexity is also determined by how much of this interaction needs to be understood by the child before initiating the action, and how much can be made available as the action unfolds. The analysis in chapter 3 of this dissertation presented the robot that was later used for comparison between typical and augmented manipulation (in chapters 4 and 5) and was intentionally used for its characteristics. As a result of the analysis presented in Chapter 3, it became clear that the robot decreases the motor demands on the task, while increasing its cognitive complexity.

In order to compare augmentative manipulation and typical manipulation and their implications in children's performance of a cognitive task, a task was selected that could be performed with the robot, and in which the motor response was directly related to the cognitive skills being displayed. The A not B task is considered a classic measure of cognitive development in early childhood (Diamond & Goldman-Rakic, 1989) and is perhaps the most studied task in developmental psychology (Dalenoort, De Vries, 2004). This task was chosen as a cognitive and perceptual task with very specific motor requirements (i.e. required patterns of reaching, grasping and lifting small objects). This made it suitable for adaptation to the robot-mediated version. Also the great amount of literature available on this task allows further comparison of our results and provides the basis for the interpretation of the task's complexity.

In order to test the implications of the tradeoff between motor and cognitive demands imposed by the robot for children when performing a task in comparison to typical manipulation, the technical feasibility of such comparison was established. Paper 3 (presented in Chapter 4 of this document) presented a method for technical implementation that was designed for this study and a pilot with adult participants that established the feasibility of its use for the purposes of this research. The dynamic nature of the A-not-B task (as trial by trial locations depend on the child's performance), the motor response required from the child and possible interference from the robot's electrical motors pose a challenge for the exploration of neurophysiological data in this comparison. The method for technical implementation allows the exploration of neurophysiological data and also incorporates an automatic coding of the child's performance on the A-not-B task. Studies that have used this task previously have used video recordings for the scoring of dependent variables in the task (Clearfield et al., 2006; Wiebe et al., 2010; Bell, 2001). The proposed method simplified the coding by automatically inputing the data into the E-Prime ® acquisition software.

The proposed and tested method was then used in a study to compare the augmentative and typical manipulation of 18 to 30 month old children. Initially, this research was designed to also include a comparison of the performance of 18 to 30 month old children with severe physical disabilities. Recruitment of a sample in Edmonton that could meet the criteria for this study was not possible (the need for neurophysiological equipment and compatibility of the tested interface restricted the location to the city). In order to participate in this study, children with disabilities had to have a motor disability that had restricted their independent locomotion and manipulation; a motor disability that was either congenital, or acquired (includes symptom onset) before independent locomotion was achieved; and no known cognitive limitations (e.g. child has a motor disorder with no known effect on cognitive skills). Participants were excluded if they had vision impairments, hearing impairments, or if they were previously involved in robot studies. Most children did not meet the criteria for the study as they had only partial limitations on their ability to manipulate objects (for example only one upper extremity was impaired). The very few children that met all the criteria (for example children diagnosed with Spinal Muscular Atrophy), were very critically ill due to complications and could not participate. For other children who could participate in this study (children with a diagnosis of cerebral palsy) cognitive impairments could not be ruled out as these are typically assessed when children are older. As with other studies exploring the use of robots by children, an initial exploration of typically developing children's performance was conducted (Poletz et al., 2010). Children in following studies could benefit from additional previous exposure to the robot and more control over the robot (requiring the child to continue to press the switch in order to complete the robot's action). In addition it would be of great importance to conduct more studies that would allow children's exploration of robot mediated manipulation at young ages as well as children with disabilities' exploration of both robot and direct manipulation, recognizing the value in their own movement repertoire to determine the best ways in which robots can facilitate their cognitive and perceptual development.

The fourth and final paper (chapter 5 in this document) presents the results of the study conducted with typically developing children and the performance of child with a severe physical disability who participated in the task. Several differences emerged in the performance of typically developing 2 year olds between a robot-augmented version of the task and the typical reaching version. The robot version of the task increased the children's motivation in the task. The robot decreased the motor demands of the task while increasing the cognitive complexity. The complexity of the robot-mediated task was reflected in the initial learning difficulties that children had as indexed by the number of trials required to achieve criterion for reversal in the A-not-B task. Children were found to attribute agency and animacy characteristics to the robot, which may have caused them to perform more successfully in the second trial after each reversal. Event related waveforms revealed different cognitive processes between conditions that may be related to these differing expectations of children about robot performance. Also, waveforms were found to differ and this could be related to quantitative and qualitative differences in the underlying cognitive processes implicated in each version of the task. Although no differences were found in the proportion of correct responses in the post-reversal, an emerging pattern in the robot condition was found. In the robot condition, younger children displayed fewer errors, on average, when compared to their performance in the reaching version. The situation was reversed for the older children. Because sample size was small, no further analysis was performed but this pattern should be explored as this could indicate another difference with the typical manipulation version of the task (i.e. no differences in performance in the post reversal trials of this task has been found in children in this age range (Diamond, 1997)). This pattern could support a cognitive capacity account of perseveration (Berger, 2004; Berger, 2010). In this case, children with disabilities could benefit from the decreased motor demand of the task and focus their attention on the more central aspects of the task (Kahneman, 1973). In fact, studies that have looked into object search skills of children with physical disabilities support this account.

Riviere and Lecuyer (2002; 2003) explored the cognitive skills of children with spinal muscular atrophy Type II (SMA), a genetic disorder that causes severe motor impairments. Performance of 29 month-old children with SMA in a 3 location object search task was found to be similar to that of typically developing children (Riviere & Lecuyer, 2002; 2003). Typically developing children's successful performance in the task increased when the time between the object being hidden and the opportunity to find it increased. Riviere and Lecuyer (2003) concluded that the differences elicited by reaction time suggest that their perseveration could result from a motor-impulsive tendency to reach for objects and an inability to inhibit this motor behavior. Based on their studies with children with motor impairments, Riviere and Lecuyer (2002) suggest that further research is needed in order to explore whether children with motor impairments may in fact use pathways other than the ones used by typically developing children.

Further steps for this research include the study of robot-mediated manipulation by children with severe physical disabilities in the performance of cognitive tasks typically related with previous sensory-motor experience. Exploring the performance of children with disabilities when given access to these tasks can further advance our understanding of the developmental pathways that children with disabilities employ to developing cognitive skills typically related with manipulation and the ways in which robots can provide opportunities to further advance those skills. In addition, the performance of children with disabilities (who lack typical motor experience) can provide insight into the role of motor experience in certain cognitive skills such as the nature perseverative errors on the A-not-B task.

The comparison of direct manipulation and robot augmentative manipulation in similar tasks constitutes the first step in understanding the cognitive and perceptual demands of robot augmentative manipulation systems for children. Using both behavioural data and neuroimaging data provides a broader understanding of the potential differences between direct and augmented manipulation. Further exploration of neurophysiological data is required in order to determine the underlying functional components of robot augmented manipulation. Such exploration should include other neurophysiological methods such as EEG power and coherence.

The findings of this study provide a foundation for adaptation of tasks for augmentative manipulation and identification of robots that can better assist children in performing manipulative tasks. Robots decrease the motor demand but their characteristics need to make them accessible in terms of cognitive complexity, perhaps more intuitive from a user's perspective, especially for young children. The implications of agency and animacy attribution to the robot, as well as increased motivation in the robot mediated task, can serve as guiding principles to design studies that explore the learning opportunities afforded by robots as they provide scaffolding for children with disabilities.

The results of this study provide a foundation to identify and adapt the characteristics of robots and control interfaces that can better assist children in their manipulative behaviours. Several characteristics that robots designed for children should have are reported in the literature (an easy to learn operational system (Howell, Hay, & Rakocy, 1989); a natural interaction with the user in which decreased technical competence is required (Michaud et al., 2003)) but their achievement is limited by our current understanding of the complexity and cognitive demand of the robot use. Also, the use of commercially available robots has been identified as a strategy to overcome costs and dissemination of robot use by children with disabilities. Further knowledge about robot systems as augmentative manipulation and their developmental implications (as provided by this study) are needed to address the limitations of the commercially available devices and lay the developmental guidelines for further advances in the design of robotic systems for children (Cook et al., 2010).

References

1. Acredolo, L. (1990). Individual Differences in Infant Spatial Displacement. In J. Colombo & J. Fagen, Individual differenecs in Infancy: Reliability, Stability, Prediction (pp. 321- 340). New Jersey: Erlbaum.
2. Acredolo, L. (1985) Coordinating perspectives on infant spatial orientation. In: Cohen R. (Ed.) The development of spatial cognition. LEA, Hillsdale, NJ, pp. 115- 140.
3. Adams, K., Cook, A. (2013) Access to hands-on mathematics measurement activities using robots controlled via speech generating devices: three case studies. Disability and Rehabilitation: Assistive Technology, Early Online, pp. 1-13.
4. Adolph, K. E. & Robinson, S. R. (2013). The road to walking: What learning to walk tells us about development. In P. Zelazo (Ed.) Oxford handbook of developmental psychology, Volume 1, 403-443. NY: Oxford University Press.
5. Affolter, F. (2004) From action to interaction as primary root for development", in Movement and Action in Learning and development: Clinical implications for pervasive developmental disorders, I. Stockman, San Diego: Elsevier, pp. 169-199.
6. Altschuler, EL., Vankov, A., Hubbard, EM., Roberts, E., Ramachandran, VS., Pineda, JA., (2000) Mu wave blocking by observer of movement and its possible use as a tool to study theory of other minds. Poster Session Presented at the 30th Annual Meeting of the Society for Neuroscience; New Orleans: LA.
7. Amoroso, R. & Amoroso, P. (2003). The Fundamental Limit and Origin of Complexity in Biological Systems: A New Model for the Origin of Life. Computing Anticipatory Systems: CASYS'03 (pp. 144-159). Belgium: AIP Conference Proceedings.
8. Anwar, F., McLaughlin, D., Panesar, B. (2012) Biltareal Brachial Plexus Injury. J Coll Physicians Surg Pak, Vol. 22, pp. 176- 178
9. Aylward, G. (1994). Practitioner's guide to developmental and psychological testing. New York: Plenum Publishing Corporation.
10. Baird, A., Kagan, J., Gaudette, T., Walz, K., Hershlag, N. & Boast, D. (2002). Frontal Lobe Activation during Object Permanence: Data from Near- Infrared spectroscopy. Neuroimage, 16, 1120-1126.
11. Barca, L., Pezzulo, G., Castelli, E. (2010) Egocentric and allocentric spatial references in children with cerebral palsy. Proceedings of the 2010 Annual Meeting of the Cognitive Science Society (COGSCI), Portland, August 11-14.
12. Barnes, C., Mercer, G. (2004) Theorising and researching disability from a social model perspective. In: Barnes, C. & Mercer, G. (Eds), Implementing the Social Model of Disability:Theory and Research. Leeds: The Disability Press, pp. 1- 17.

13. Bates, E. (1979) The biology of symbols: Some concluding thoughts in The emergence of symbols: Cognition and communication in infancy, E. Bates, L. Benigni, I. Bretherton, L. Camaioni & V. Volterra, Eds, New York: Academic Press, pp. 315–370.
14. Bell, M. A. (2001). Brain Electrical Activity Associated with Cognitive Processing. Infancy, 2(3), 311-330.
15. Bell, M. A., & Adams, S. E. (1999). Comparable performance on looking and reaching versions of the A-not-B task at 8 months of age.Infant Behavior and Development, vol. 22, pp. 221–235.
16. Bell, A.J., & Sejnowski, T.J. (1995) An information maximisation approach to blind separation and blind deconvolution, Neural Computation, vol 7, no. 6, 1129-1159.
17. Bell, M. A. & Fox, N. (1992). The Relations Between Fronatl Brain Electrical Activity and Cognitive Development during Infancy. Child Development, 63, 1142-1163.
18. Bell, M. A., & Fox, N. A. (1994). Brain development over the first year of life: Relations between EEG frequency and coherence and cognitive and affective behaviors. In: G. Dawson & K. Fischer (Eds.), Human behavior and the developing brain, pp. 314–345. New York: Guilford.
19. Bell, M. & Fox, N. (1997). Individual Differences in Object Permanence at 8 Months: Locomotor Experience and Brain Electrical Activity. Dev Psychobiol, 31(4), 287-297.
20. Berger, S. E. (2001). Accounting for infant perseveration beyond the manual search task. Behavioral and Brain Sciences, vol. 24,no. 1 ,pp. 34- 35.
21. Berger, S. (2004) Demands on finite cognitive capacity cause infants' perseverative errors. Infancy, vol 5., No. 2, pp. 217- 238.
22. Berger, S. (2010). Locomotor Expertise Predicts Infant's Perseverative Errors. Developmental Psychology, 46(2), 326-336.
23. Bertenthal,B.I. & Campos, J.J. (1987) New directions in the study of early experience, Child Development, vol 58, pp. 560-567.
24. Berthental, B.I., Campos, J.J, Kermoain, R. (1994) An epigenetic perspective on the development of self-produced locomotion and its consequences. Current directions in psychological science, Vol. 2, pp. 140-145.
25. *Bertenthal, B. I. & Clifton, R. K. (1998) Perception and action. In D. Kuhn, and R. Siegler (Eds.), Cognition* and language, Vol. 2. In: W. Damon (Editor-in-Chief), Handbook of child psychology, 5th edition . New York: pp. 51-102.
26. Besio, S. (2004). Using assistive technologies to facilitate play by children with motor impairments: A methodological proposal. Technology and Disability, 16, 119-130.

27. Billard, C., Gillet, P., Signoret, J.L., Uicaut, E., Bertrand, P., Fardeau, M., Barthez-Carpentier, M.A., & Santini, J.J. (1992). Cognitive functions in Duchenne muscular dystrophy: A reappraisal and comparison with spinal muscular atrophy.Neuromuscular Disorders ,vol. 2,pp. 371–378.
28. Blauw-Hospers, C., Hadders-Algra, M. (2005) A systematic review of the effects of early intervention on motor development. Developmental medicine and child neurology, Vol. 47, No. 6, pp. 421- 432.
29. Bobath, B. (1971). Motor Development, its effects on general development and application to the treatment of cerebral palsy. Physiotherapy, 526-532.
30. Bourgeois, K., Khawar, A., Neal, S.A., Lockman, J. (2005) Infant manual exploration of objects, surfaces and their interrelations. Infancy, Vol. 8, No. 3, pp. 233- 252.
31. Boyer, T.W., Pan, J.S., Berthental, B. (2011) Infants understanding of actions performed by mechanical devices. Cognition, Vol 121, pp. 1-11.
32. Bremner, J., Bryant, P. (1977) Place versus response as the basis of spatial errors made by young infants. Journal of experimental child psychology, Vo. 23, pp. 162-171.
33. Butler, C. (1986). Effects of powered mobility on self- initiated behaviors of very young children with locomotor disability. Developmental Medicine & Child Neurology, 28, 325-332.
34. Butler, C. (1988). High tech tots: Technology for mobility, manipulation, communication, and learning in early childhood. Infants and Young children, 1(2), 66-73.
35. Butler C. (1991). Augmentative Mobility: Why do it?, Physical Medicine and Rehabilitation Clinics of North America, vol. 2,pp. 147 – 161.
36. Butler, C. & Darrah, J. (2001) Effects of neurodevelopmental treatment (NDT) for cerebral palsy: An AACPDM evidence report. Developmental Medicine and child neurology, Vol. 43, No. 11, pp. 778- 790.
37. Buttelmann, D.,Carpenter, M., Call, J. & Tomasello, M. (2008) Rational Tool Use and Tool Choice in Human Infants and Great Apes, Child and Development, Vol 79, Issue 3, pp. 609 – 626.
38. Butterworth, G. (1975) Object identity in infancy: The Interaction of spatial location codes in determining search errors. Child Development, Vol. 46, pp. 866- 870.
39. Chen, Z., Sanchez, R., Campbell, T. (1997) From beyond to within their grasp: the rudiments of analogical problem solving. Developmental Psychology, Vo. 33, No. 5, pp. 790-801.
40. Chen, X., Ragonesi, C., Galloway, J. & Agrawal, S. (2011). Training Toddlers Seated on Mobile Robots to Drive Indoors Amidst Obstacles. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 19(3), 271-279.
41. Chu, D. (2011). Complexity: Against Systems. Theory in Biosciences, 130(3), 229-245.

42. Classon, E., Rudner, M., Johansson, M., Ronnberg, K. (2013) Early ERP signature of hearing impairment in visual rhyme judgment. Front. Psychol.
43. Clearfield, M., Diedrich, F., Smith, L. & Thelen, E. (2006). Young infants reach correctly in A-not-B tasks: On the development of stability and perseveration . Infant Behavior & Development , 29, 435-444.
44. Cohen, J. (1988). Statistical Power analysis for the behavioral sciences (2nd Ed.). New York: Academic Press.
45. Cohen, R. (1985) What's so special about spatial cognition?. In: Cohen, R. (Ed.) The Development of Spatial Cogintion. New Jersey: Lawrence Erlbaum Associates, Publishers.
46. Collimore, L.M. (2011) The effects of motor contsraints on infant search behaviour. (Doctoral dissertation). Retrieved from ProQuest Dissertations and Theses. (Accession Order No. NR77938)
47. Coluccini, M., Maini, E.S., Martelloni, C., Sqandurra, G., Cioni, G. (2007) Kinematic characterization of functional reach to grasp in normal and in motor disabled children. Gait and Posture, Vol. 25, No. 4, pp. 493-501.
48. Cook, A. & Cavalier, A. (1999). Young Children using assistive robotics for discovery and control. Teaching exceptional children, 31(5), 72-78.
49. Cook, A. & Polgar, J. M. (2008). Cook and Hussey's Assistive Technologies: Principles and Practices (3rd ed.). Philadelphia: Elsevier Inc.
50. Cook, A., Adams, K., Encarnação, P. & Alvarez, L. (2012) The role of assisted manipulation in cognitive development, Developmental Neurorehabilitation, vol 15, no. 2, pp. 136-148.
51. Cook, A., Adams, K., Harbottle, N. & Harbottle, C. (2007). Using Lego Robots to Estimate cognitive ability in children who have severe disabilities. RERC State of the Science Conference & Coleman Institute Annual Conference Broomfield, CO.
52. Cook, A., Adams, K., Volden, J., Harbottle, N. & Harbottle, C. (2010). Using Lego robots to estimate cognitive ability in children who have sever physical disabilities. Disability and Rehabilitation, 1-9.
53. Cook, A., Adams, K., Volden, J., Harbottle,N., Harbottle, C. (2011) Using Lego robots to estimate cognitive ability in children who have severe physical disabilities, Disability and Rehabilitation: Assistive Technology, Vol 6, Number 33, pp. 8–346.
54. Cook, A., Bentz, B., Harbottle, N., Lynch, C. & Miller, B. (2005). School- Based Use of Robotic Arm System by Children With Disabilities. IEEE Transactions on Neural Systems and Rehabilitation Engineering, 13(4), 452-460.
55. Cook, A., Encarnação, P. & Adams, K. (2010) Robots: assistive technologies for play, learning and cognitive development, Technology and Disability, vol 22, no. 3, pp. 127-145.

56. Cook, A., Howery, K., Gu, J. & Meng, M. (2000) Robot enhanced interaction and learning for children with profound physical disabilities. Technology and Disability, pp. 1–8.
57. Cook, A., Liu, K., Hoseit, P. (1990) Robotic arm use by very young children, Assistive Technology, Vol 2, pp. 51–57.
58. Cooley, M.J. (2010) AAC Use by young children at home, Perspectives on Augmentative and Alternative Communication, vol 19, pp. 5- 11, 2010.
59. Cope, S., Trombly, C. (1998) Grasping in children with and without cerebral palsy: a kinematic analysis. Scandinavian journal of occupational therapy, vol. 5, pp. 59-68.
60. Cuevas, K., Bell, MA. (2010) Developmental progression of looking and reaching performance on the A-not-B task. Developmental Psychology, Vol. 46, No. 5, pp. 1363- 1371
61. Cummings, M. & Bjork, E.L. (1981). The Search Behavior of 12 to 14 Month-old infants on a Five Choice Invisible Displacement Task. Infant Behavior and Developent, 4, 47-60.
62. Cutting, J.E.., (1981) Six tenets for event perception, Cognition, vol 10, pp. 71-78, 1981.
63. Dalenoort, G.J., De Vries, P.H. (2004) The essential role of binding for cognition in living systems. In: Schaub, H., Detje, F., Bruggemann, U. The logic of artificial life: Abstracting and synthesizing the principles of living systems. Proceedings of the 6th German Workshop on Artificial Life, April 14- 16, Germany: IOS Press.
64. Darrah, J. & Bartlett, D. (1995). Dynamic Systems theory and management of children with cerebral palsy: unresolved issues. Infants and Young Children, 52-59.
65. Darrah, J., Law, M.C., Pollock, N., Wilson, B., Russell, D., Walter, S.D., Rosenbaum, P., Galupp, B. (2011) Context Therapy: a new intervention approach for children with cerebral palsy. Developmental Medicine & Child Neurology, Vol. 53, No. 7, pp. 615-620.
66. Davis, L. (1995) Enforcing normalcy: disability, deafness and the body. London: Verso.
67. Davis, L.J. (2006) Constructing Normalcy: The bell curve, the novel, and the invention of the disabled body in the nineteenth century. In: Davis L.J. (Ed) The Disability Studies Reader, 2nd Edition, pp. 3-16Routledge: New York.
68. De Hann, M. (2002). Infant EEG and Event Related Potentials. Psychology Press.
69. Deitz, J., Swinth, Y.,White, Y. (2002) Powered mobility and pre-schoolers with complex developmental delays, Am J Occup Ther, vol 56, Number 1, pp. 86-96.
70. Diamond, A., Goldman-Rakic P.S. (1989) Comparison of human infants and rhesus monkeys on Piaget's AB task: Evidence for dependence on dorsolateral prefrontal cortex. Exp Brain Res. Vol 74, pp. 24- 40.

71. Diamond, A. (1990) The development and neural bases of memory functions as indexed by the AB and delayed response tasks in human infants and infant monkets. In: A. Diamond (Ed), The development and neural bases of higher cognitive functions (pp. 267- 317). New York: New York Academy of Sciences.
72. Diamond, A., Prevor, M., Callender, G. & Drun, D. (1997). Prefrontal cortex cognitive deficits in children treated early and continuously for PKU. Monographs of the Society for Research in Child Development, 62(4), 1-206.
73. Diamond, A., Prevor, M., Callender, G., & Drun, D. (1997). Prefrontal cortex cognitive deficits in children treated early and continuously for PKU. Monographs of the Society for Research in Child Development, 62(4), 1-206.
74. Diedrich, F. J., Thelen, E., Smith, L. B. & Corbetta, D. (2000). Motor memory is a factor in infant perseverative errors. Developmental Science, 479- 494.
75. Dimoka, A.; Banker, R. D.; Benbasat, I.; Davis, F. D.; Dennis, A. R.; Gefen, D.; Gupta, A.; Ischebeck, A.; Kenning, P.; Müller-Putz, G.; Pavlou, P. A.; Riedl, R.; vom Brocke, J.; Weber, B.(2012) On the Use of Neurophysiological Tools in IS Research: Developing a Research Agenda for NeuroIS. MIS Quarterly 3/2012, 679-702.
76. Dirks, T., Blauw- Hospers, C., Hulshof, L., & Hadders- Algra, M. (2011). Differences between the family centered program and traditional infants physical therapy. Physical Therapy, 91(9), 1303-1322.
77. Duffy, B. (2003) Antropomorphism and the social robot. Robotics and autonomous systems, vol. 42, pp. 177-190.
78. Dunn, N., Shields, N., Taylor, N., Dodd, K. (2007) A systemati review of the self- concept of children with cerebral palsy and perceptions of parents and teachers. Physical and Occupational Therapy in Pediatrics, Vol. 27, No. 3, pp. 55- 71.
79. Edelman, G. (1987). Neural Darwinism: The Nueronal Group Selection theory. New York: Basic Books Inc.
80. Evans, W. F., & Gratch, G. (1972). The stage IV error in Piaget‟s theory of object concept development: Difficulties in object conceptualization or spatial location.Child Development,vol. 43, pp. 682-688.
81. Esseily, R., Nadel, J., Fagard, J. (2010) Object retrieval through observational learning in 8- to 18 month old infants. Infant behavior & Development, Vol 33, pp. 695- 699
82. Fetter, L., Ellis, T. (2006) A Perception-Action Framework for Physical Therapy for Persons with Neurologic Dysfuntion: Use of Therapeutic Affordance and Unitless Ratio. JNPT, vol. 30(3), pp. 139-144.
83. Flanagan, J.R., Bowman, M.C. & Johansson, R.S. (2006) Control strategies in object manipulation tasks, Current opinion in Neurobiology, vol 16, pp. 650-659.

84. Forman, G. (1986). Observations of Young Children Solving Problems with computers and robots. Journal of Research in Childhood Education, 1 (2): 60-75.

85. Frey, S.H. (2007) What puts the how in where? Tool use and the divided visual streams hypothesis. Cortex, Vol. 43, pp. 368-375.

86. Friedman, B., Kahn, P.H. (1992) Human agency and responsible computing: Implications for computer system design. Journal of systems software, Vol. 17, pp. 7-14.

87. Furumasu, J., Guerette, P., & Tefft, D. (1996) The development of a powered wheelchair mobility program for young children. Technology and Disability, vol. 5 (1), 41 – 48

88. Galloway, J.C., Thelen, E. (2004) Infant behavior and development, Vol. 27, pp. 107-112.

89. Garland, K.J. and Noyes, J.M., (2004) CRT monitors: Do they interfere with learning? Behaviour & Information Technology ,vol. 23,pp. 43–52

90. Gelman, S.S., Gottfried, G.G. (1996) Children’s causal explanations of animate and inanimate motion. Child Development, Vol. 67, pp. 1970-1987.

91. Gesell, A. (1928). Infancy and Human Growth. New York: Macmillan.

92. Gibson, J. (1979). The ecological approach to visual perception . Boston: Houghton Mifflin Company.

93. Gibson, E. J., Riccio, G., Schmuckler, M. A., Stoffregen, T. A., Rosenberg, D., & Taormina, J. (1987). Detection of the traversability of surfaces by crawling and walking infants. Journal of Experimental Psychology: Human Perception and Performance,vol. 13, pp. 533- 544

94. Gibson, J. (1999) The ecological approach to visual perception, Boston: Houghton Mifflin Company.

95. Gibson, J. & Gibson, E. (1955). Perceptual learning: Differentiation or enrichment? Psychological Review, 62, 32- 41.

96. Gibson, B., Teachman, G. (2012) Critical approaches in physical therapy research: investigating the symbolic value of walking. Physiotherapy theory and practice, Vol. 28, No. 6, pp. 474-484.

97. Gindis, B. (1995). The Social/ Cultural Implication of Disability: Vygotsky's Paradigm for Special Education. Educational Psychologist, 30(2), 77-81.

98. Gindis, B. (2003). Remediation Thorugh Education: Sociocultural Theory and Children with Special Needs. In K. e. al, Vygotsky's Educational Theory in Cultural Context (pp. 200-225). Cambridge: Cambridge University Press.

99. Greenfield, P. (1991) Language, tools and brain: The ontogeny and phylogeny of hierarchically organized sequential behavior, Behavioral and Brain Sciences, Vol. 14, Issue 04, pp. 531- 551.

100. Greif, M.L., Needham, A. (2011) The development of human tool use early in life. In: McCormack, T., Hoerl, C., Butterfill, S.,Tool use and causal cognition. New York: Oxford University Press.

101. Goldenberg, E.P. (1979) Special technology for special children. Baltimore: University Park Press.

102. Goldstein, H. (2012) Francis Galton, measurement, psychometrics and social progress. Assessment in Education: Principles, Policy & Practice, vol. 19, No. 2, pp. 147-158.

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

104. Hadders- Algra, M. (2008). The Neuronal Group Selection Theory: a framework to understand typical and atypical development. In L. Ramenghi, P. Evrard, & E. Mercuri. Montrougue: Editions Jhon Liberty Eurotext.

105. Handy, T. (2005) Interpreting event related potentials. In: Handy, T. (Ed.) Event- Related Potentials: A method Handbook. Cambridge, MA: MIT Press.

106. Handy, T. (2005) Basic Principles of ERP Quantification. In: Handy, T. (Ed.) Event- Related Potentials: A method Handbook. Cambridge, MA: MIT Press.

107. Haywood, K. & Getchell, N. (2009) Life Span Motor Development (5th ed.), Illinois: Human Kinetics.

108. Held, R.,Hein, A. (1963). Movement-produced stimulation in the development of visually guided behavior. Jouranal of Comparative and Physiological Psychology, vol. 56(5),pp. 872-876.

109. Herbert, M. (2003). Typical and Atypical Development: From Conception to Adolescence. Malden: BPS Blackwell.

110. Heriza, C. (1991). Motor development: Traditional and Contemporary theories. Foundation for Physical Therapy. Contemporary Management of Motor control Problems: Proceedings of the II STEP Conference (pp. 99- 126). Alexandria: American Physical Therapy Association.

111. Higginbotham, D. J. (1995) The use of non-disabled subjects in AAC research: Confessions of a research infidel. Augmentative and Alternative Communication, vol. 11,pp. 2--5.

112. Higginbotham, J., & Bedrosian, J. (1995) Subject selection in AAC research: Decision points. Augmentative and Alternative Communication, vol. 11,pp. 11–13.

113. Howell, R., Hay, K. (1989) Softwarebased access and control of robotic manipulators for severely physically disabled students. Journal of Artificial Intelligence in Education 1(1), pp. 53–72

114. Howell, R., Hay, K., Rakocy, L. (1989) Hardware and softawre considerations in the design of a prototype educational robot manipulator. RESNA Annual Conference, New Orleans, Louisiana.

115. Howle, J. (2002). Neuro- Developmental Treatment approach: Theoretical foundations and principles of clinical practice. Laguna Beach: Neuro- Developmental Treatment Association.

116. Humphreys, G. (2001)Objects, affordances... action!, The Psychologist, vol 14, pp. 408- 412

117. IBM Corp (2011). IBM SPSS Statistics for Windows, Version 20.0. Armonk, NY: IBM Corp. International SMA Consortium. (1999). 1998 Meeting Report. Neuromsucular Disorders, 272- 278.

118. Isabelle, S., Bessey, F., Dragas, K.L. & Blease, P. (2002) Assistive Technology for Children with Disabilities, Occupational Therapy in Health Care, Vol. 16, Number 4, pp. 29- 51.

119. International Organization for Standardization (2012) ISO 8373 Automation systems and integration, Subcommittee SC 2, Robots and robotic devices., Geneva, Switzerland: ISO/IEC.

120. James, A. (1995). On being a child: The self, the group and the category. In A. P. Cohen, & N. Rapport (Eds.), Questions of consciousness (pp. 60-76). London: Routledge.

121. Jasper, H.H. (1958) The ten-twenty electrode system of the International Federation. Electroenceph. Clin. Neurophysiol, vol. 10,pp. 371-375.

122. Jennings, K. & MacTurk, R. (1995). The motivational characteristics of infants and children physical and sensory impairments. In R. MacTurk & G. Morgan, Mastery Motivation: Origins, Conceptualization and Applications (pp. 201- 220). New Jersey: Ablex Pusblishing Corporation.

123. Jennings, K., Stagg, V., Connors, R. & Ross, S. (1995). Social networks of mothers of physically handicapped and nonhandicapped preschoolers: Group differences and relations to mother- child interaction. Jorunal of Applied Developmental Psychology, 193-209.

124. Jensen, G., Gwyer, J., Shepard, K., Hack, L. (2000) Expert Practice in Physical Therapy, Physical Therapy, Vol 80., No. 1, pp. 28- 43.

125. Johnson, S.C., Booth, K., O'Hearn, K. (2001) Inferring the goeals of a nonhuman agent. Cognitive development, Vol. 16, No. 1, pp. 637-656.

126. Johnson-Frey, S. (2004). The neural bases of complex tool use in humans. Trends in Cognitive Sciences, 8(2), 71-78.

127. Jones, M.A., McEwen, I.R., Hansen, L. (2003) Use of power mobility for a young child with spinal muscular atrophy. Physical Therapy, Vol. 83, pp. 253-262.

128. Judge, S., Floyd, K. & Wood- Fields, C. (2010). Creating a Technology- Rich learning enviorment for infants and toddlers with disabilities. Infants & Young Children, 23(2), 84-92.

129. Kaatiala, J., Yrttiaho, S., Forssman, L. (2013) A graphical user interface for infant ERP analysis. Behavioral Research; Early online,pp. 1-13.

130. Kahneman, D. (1973) Attention and effort. Upper Saddle River, NJ: Prentice Hall.

131. Kahrs, B.A., Jung, W.P, Lockman, J.J. (2013) When Does Tool Use Become Distinctively Human? Hammering in Young Children. Child Development, Early online, pp. 1- 12. DOI: 10.1111/cdev.12179

132. Karasik, L., Adolph, K.E., Tamis-LeMonda, C.C., Zuckerman, A. (2011) Carry on: Spontaneous object carrying in 13-month-old crawling and walking infants. Developmental Psychology, Vol. 48, No. 2, pp. 389-397.
133. Kamm, K., Thelen, E., Jensen, J.L. (1990) A dynamical systems approach to motor development, Physical Therapy, Vol. 70, No. 12, pp. 763- 775.
134. Keen, K. (2011) The Development of Problem Solving in Young Children: A Critical Cognitive Skill, Annual Review of Psychology, Vol 62, 1-21, 2011.
135. Keenan, T. & Evans, S. (2009). An Introduction to Child Development. Los Angeles: SAGE Publications Ltd.
136. Kermoian, R. (1998). Locomotor experience facilitates psychological functioning: implications for assistive mobility for young children. In B. Gray, L. Quatrano & M. Lieberman, dESIGNING AND USING ASSITIVE TECHNOLOGY. Baltimore: Paul H Brookes.
137. Kermoian, R. & Campos, J. (1988). Locomotor Experience: A Facilitator of Spatial Cognitive Development. Child Development, 908- 917.
138. Kirst-Ashamn, K.K., Hull, G.H. (2009) Understanding the generalist practice (5th edition). Belmon, CA: Brooks Cole
139. Khalil, H. (2002). Nonlinear systems. Prentice Hall.
140. Kohler, W. (1956). The mentaliy of apes. London: Routledge.
141. Kronreif, G., Kornfeld, M., Prazak, S., Furst, M. (2007) Robot assistance in playful environment- user trials and results, Proceedings of the IEEE International Conference on Robotics and Automation, April 10- 14, 2007, Rome, Italy.
142. Lackner, J.R. & Dizio, P. (1994) Rapid adaptations to coriolis force perturbations of arm trajectory. Journal of Neurophysiology, Vol. 72, pp. 299- 313.
143. Landsman, G.H. (2009) Reconstructing motherhood and disability in the age of "perfect" babies. Routledge: New York.
144. Larkin D, Summers J. (2004) Implications of movement difficulties for social interaction, physical activity, play and sports. In: Dewey D, Tupper DE, eds. Developmental motor disorders: a neuropsychological perspective. New York, NY: The Guilford Press; pp. 443-460.
145. Law, M., Darrah, J., Pollock, N., Rpsenbaum, P., Russell, D., Walter, S.D., Petrenchik, T., Wilson, B., Wright, V. (2007) Focus on function- a randomized controlled trail comparing two rehabilitation interventions for young children with cerebral palsy. BMC Pediatrics, Vol. 7, No. 31.

146. Lew, A. R., Hopkins, B.,Owens, L. H., & Geer, M. (2007) Postural change effects on infants‟ AB task performance: Visual, postural, or spatial?. Journal of Experimental Child Psychology, vol. 97,pp. 1–13.
147. Light, J. (1989) Toward a definition of communicative competence for individuals using augmentative and alternative communication systems. AAC Augmentative and Alternative Communication, Vol 5, No. 2, pp. 137- 144. (doi:10.1080/07434618912331275126)
148. Lobo, M.A., Galloway, J.C., Savelsbergh, G.J.P. (2004) General and task related experiences affect early object interaction. Child Development, Vol. 75, No. 4, pp. 1268- 1281.
149. Lockman, J. (2000) A perception- action Perspective on Tool use development, Child Development, Vol 71, Issue 1, pp. 137- 144.
150. Lockman, J. J. (2005). Tool use: Developmental and evolutionary considerations. In V. Roux & B. Bril (Eds.) Stone Knapping: The necessary conditions for a uniquely hominid behaviour. McDonald Institute Monograph Series. (pp. 319-330). London: Cambridge.
151. Lockman, J.J. (2003) Object manipulation in context. In: Raeff, C., Benson, J. (Eds) Social and cognitive development in the context of individual, social and cultural processes, pp. 149- 167. Routledge: New York
152. Lockman, J.J. (2008) On tool use, perseveration and task dynamics. Infancy, Vol. 13, No. 3, pp. 279- 283.
153. Long, T. & Woodbridge, M. (2003). Integrating assistive technology into an outcome driven model of service delivery. Infants and Young children, 16(4), 272-283.
154. Longo, M. R., & Bertenthal, B. I. (2006). Common coding of observation and execution of action in 9-month-old infants. Infancy, 10, 43-60.
155. Lovarini, M., McCluskey, A. & Curtin, M. (2006). Editorial: Limited high-quality research on the effectiveness of assistive technology. Australian journal of Occupational Therapy, 53, 50.
156. Luck, S. (2005). An Introduction to Event Related Potentials and Thier Neural Origins. In S. Luck. Cambridge: MIT Press.
157. Luck S., Kappenman, E.(2012) The oxford handbook of event related potentials. Oxford Press: New York; 2012.
158. Luu, P., Jiang, Z., Poulsen, C., Mattson, C. (2011) Learning and the development of contexts for action. Front. Hum. Neurosci, Volume 5, pp. 1-12.
159. Luu, P., & Ferree, T. (2000) Determination of the Geodesic Sensor Nets' Average Electrode Positions and Their 10–10 International Equivalents. Eugene: Electrical Geodesics, Inc. [Technical Note].
160. Luwel, K., Siegler, R. & Verschaffel, L. (2008). A microgenetic study of insightful problem solving. Journal of experimental child psychology, 99, 210-232.

161. Makeig, S., Bell, A.J., Jung, T.P., Sejnowski, T.J. (1996) Independent Component Analysis of Electroencephalographic Data In: D. Touretzky, M. Mozer and M. Hasselmo (Eds). Advances in Neural Information Processing Systems, vol. 8,pp. 145-151.

162. Mandler, J.M. (1988) How to build a baby: On the development of an accessible representational system. Cognitive development, Vol. 3, pp. 113- 136.

163. Mangun, G.R. & Hillyard, S.A. (1991) Modulations of sensory-evoked brain potentials indicate changes in perceptual processing during visual-spatial priming. Journal of Experimental Psychology: Human perception and performance, vol. 17, no. 4,pp. 1057-1074.

164. Mankoff, J., Hayes, G. & Kasnitz, D. (2010). Disability studies as a socurce of critical inquiry for the field of assistive technology. ASSESTS' 10 Proceedings of the 12th International ACM SIGACCESS conference on Cumputers and accesibility. New York: ACM.

165. Maravita, A., Iriki, A. (2004) Tools for the body (schema). Trens in cognitive science, vol. 8, no. 2, pp. 79- 86.

166. Marcovitch, S. & Zelazo, P. D. (1999) The A-Not-B Error: Results from a Logistic Meta-Analysis. Child development, Vol. 70, No. 6, pp. 1297-1313.

167. Marcovitch, S. & Zelazo, P. D. & Schmuckler, M.A. (2002). The Effect of the number of A trials on performance on the A not B task. Infancy, 3(4), 519- 529.

168. Masaki, H., Wild-wall, N., Sangals, J., Sommer, W.(2004) The functional locus of the lateralized readiness potential. Psychophysiology,; vol 41, Issue 2, pp. 220-230.

169. Massey,C., & Gelman, R. (1988) Preschoolers' ability to decide whether pictured unfamiliar objects can move themselves. Developmental Psychology, vol. 24,pp. 307-317.

170. McCarty M.E., Clifton R.K. & Chollard R (1999) Problem solving in infancy: the emergence of an action plan, Developmental Psychology, vol 35, Issue 4, pp. 1091- 1101.

171. McCarty M.E., Clifton R.K. & Chollard R (2001) The beginnings of tool use by infants and toddlers Infancy, vol 2, Issue 2, pp. 233- 256.

172. McCarthy, J., Reid, K. (2002) The learning theory of Piaget and Inhelder. New York: Authors Choice Press.

173. McCormack, T., Hoerl, C., Butterfill, S. (2011) Tool use and causal cognition. New York: Oxford University Press.

174. McGraw, M. (1935). Growth: A study of Johny and Jimmy. New York: Appleton- Century- Crofts.

175. McKenzie, D.A. (1981) Statistics in Britain, 1865-1900. Princeton: Princeton University Press.

176. McKenzie, S.J., Getchell, N., Modlesky, C.M, Miller, F., Jaric, S. (2009) Using grasping tasks to evaluate hand force coordination in children with hemiplegic cerebral palsy. Archives of Physical Medicine and Rehabilitation, vol. 90, no. 8, pp. 1439-1442.
177. Meltzoff, A.N. (2005) Imitation and other minds: The "like me" hypothesis. In: S. Hurley & N. Chater (Eds.), Perspectives on imitation: From cognitive neuroscience to social science (pp. 55- 77). Cambridge: MIT Press.
178. Michaud, F., Duquette, A. & Nadeau, I. (2007). Characteristics of Moblie Robots used as tools for Pediatric Rehabilitation. Assistive Technologies, Special Issue on Intelligent System in Pediatric Rehabilitation, 19(1), 21-36.
179. Michotte, A. (1963) The perception of causality (Trans Miles, T.T. & Miles, E). New York: Basic Books.
180. Microsoft. Microsoft Excel. Redmond, Washington: Microsoft, 2003. Computer Software.
181. Millborne, D., Campbell, P. & Wilcox, M. (2004). Using Assistive Technologies with Infants and Toddlers: Evidence- Based Practice. Research Brief Tots n Tech Research Institute.
182. Miyahara, M., Reynders, K. (2003) Reflexes reflected. In: Savelsbergh, G., Davids, K., (Eds) Development of movement coordination in children (pp. 97-106). London: Routledge.
183. Moore, K.L.; Agur, A.M. (2007). Essential Clinical Anatomy (3rd ed.). Baltimore: Lippincott Williams & Wilkins. pp. 434–5. ISBN 978-0-7817-6274-8.
184. Morabia, A. (Ed.). (2004). A History of Epidemiologic Methods and Concepts. Boston, MA: Birkhäuser.
185. Morasch, K. & Bell, M. A. (2011). The role of Inhibitory Control in Behavioral and Psychological Expressions of Toddler Executive Function. Journal of Experimental Child Psychology, 593-606.
186. Mordkoff, J. T. & Gianaros, P. J.(2000) Detecting the onset of the lateralized readiness potential: A comparison of available methods and procedures. Psychophysiology,vol. 37, pp.347-360.
187. Munakata, Y. (1997) Perseverative reaching in infancy: The roles of hidden toys and motor history in the AB task. Infant behavior and development, Vol. 20, no. 3, pp. 405- 416.
188. Munakata, Y. (1998). Infant perseveration and implications for object permanence theories: A PDP model of the AB task. Developmental Science, 161-211.
189. Munakata, Y. (2001) Graded representations in behavioral dissociations. Trends in Cognitive Sciences, Vol 5, pp. 309- 315.
190. Munakata, Y. (2004). Computational cognitive neuroscience of early memory development. Developmental Review, 24, 133-153.

191. Nagamatsu, L., Munkacsy, M., Liu-Ambrose, T., Handy, T. (2013) Altered visual–spatial attention to task-irrelevant information is associated with falls risk in older adults. Neuropsychologia, vol. 51, pp. 3025–3032.

192. Nelson, C.A., & Bloom, F.E. (1997). Child development and neuroscience. Child Development,vol. 68,pp. 970-987.

193. Nelson, C. & Monk, C. (2001). The Use of Event Related Potentials in the study of cognitive development. In C. Nelson & M. Luciana, Hanbook of developmental Cognitive Neuroscience (pp. 125-135). Madison: Massachusetts Institute of Technology.

194. Newtson, D. (1973) Attribution and the unit of perception of ongoing behavior, Journal of Personality and Social Psychology, vol 28 , pp. 28-38, 1973.

195. Noland, J.S. (2008) Executive functioning demands of the object retrieval task for 8-month-old infants. Child Neuropsychology, vol. 14, No. 6, pp. 504-509.

196. Norman, D. (2002) The design of everyday things. New York: Basic Books

197. Nunez, P.L. (1981) Electric Fields of the brain: the neurophysics of EEG. New York: Oxfor University Press.

198. Ojose, B. (2008). Applying Piaget's Theory of Cognitive Development to Mathematics Instruction. The Mathematics Educator, 18(1), 26-30.

199. Okita, S.Y., Scwartz, D.L., (2006) Young children's understanding of animacy and entertainment robots.Journal of humanoid robotics, Vol. 3, No. 3, pp. 393- 412.

200. Oppenheim, R.W. (1981) Ontogenic adaptations and retrogressive processes in the development of the nervous system and behavior: A neuroembryological perspective. In: Connolly, K.J. & Prechtl, H.F.R. (Eds) Maturation and development: Biological and Psychological perspectives. Philadelphia: Lippincott, pp. 73-109.

201. Parker, S., Gibson,K. (1977) Object manipulation, tool use and sensoriomotor intelligence as feeding adaptations in cebus monkeys and great apes., Journal of Human Evolution, Vol 6, pp. 623–641, 1977.

202. Patterson, P. & Katz, J. (1992) "Design and evaluation of a sensory feedback system that provides grasping pressure in a myoelectric hand", Journal of Rehabilitation Research and Development, vol 29, number 1, pp. 1-8, 1992.

203. Paulus, M., Hunnius, S., Vissers, M., Bekkerig, H. (2011) Bridging the gap between the other and me: the functional role of motor resonance and action effects in infants' imitation. Developmental science, vol. 14, no. 4, pp. 901-910.

204. Pepping, G.J. & Li, F.X. (2005) Effects of Response Task on Reaction Time and the Detection of Affordances, Motor Control, vol 9, pp.129-143.

205. Piaget, J. (1950). The Psychology of Intelligence. London: Taylor and Francis.

206. Piaget, J. (1954) The construction of reality in the child. Great Britain: Routledhe.

207. Piaget, J. & Inhelder, B. (1969). The Psychology of the child. New York: Basic Books.

208. Picton, T., Bentin, S., Berg, P., Donchin, E., Hillyard, S., Jhonson, R., et al. (2000). Guidelines for using human event related potentials to study cognition: Recording standards and publication criteria. Psychophsyiology, 37, 127-152.

209. Picton, T. W., & Taylor, M. J. (2007). Electrophysiological evaluation of human brain development. Developmental Neuropsychology, Vol. 31, no. 3,pp. 249–278

210. Picton, T., Octavio, L. & Scherg. (1995). The recording and analysis of event related potentials. In F. Boller & J. Grafman, Handbook of Nueropsychology (pp. 3- 73). Elsevier.

211. Poletz, L., Encarnacao, P., Adams, K., Cook, A. (2010) Robot skills and cognitive performance of preschool children, Technology and Disability, vol 22, pp.117–126.

212. Polovina, S., Polovina, T., Polovina, A., & Polovina- Proloscic, T. (2010). Intensive Rehabilitation in children with cerebral palsy: our view on the neuronal group selection theory. Coll Antropol, 3, 981-988.

213. Press, C., Bird, G., Flach, R., Heyes, C. (2005) Robotic movement elicits automatic imitation. Cognitive Brain Research, vol. 23, pp. 632-640.

214. Riviere, J. & Lecuyer, R. (2003) "The C- not- B error: a comparative study", Cognitive Development, vol 18, pp. 285- 297.

215. Riviere, J. & Lecuyer, R. (2002). Spatial Cognition in Young children with spinal muscular atrophy. Developmental Neuropsychology, 2(3), 273-283.

216. Rochat, P. (1989) Object manipulation and exploration in 2- to 5- month- old infants. Developmental Psychology, Vol. 25, No. 6, pp. 871- 884.

217. Romski, M.A., Sevcik, R.A. (2005) Augmentative communication and early intervention: myths and realities. Infants & Young children, Vol. 18, No. 3, pp. 174-185.

218. Rose, L. T. & Fischer, K. W. (2009). Dynamic systems theory. In R. (Ed) Shweder, Chicago companion to the child. Chicago: University of Chicago Press.

219. Rosen, L., Arva, J., Furumasu, J., Harris, M., Lange, M., McCarthy, E. et al. (2009) RESNA Position on the application of power wheelchairs for pediatric users, Assistive Technology, vol 21, pp. 218-226.

220. Ruff,H., McCarton, C., Kurtzburg, D. & Vaughan, H. (1984) "Preterm infants' manipulative exploration of objects", Child Development, vol 55, pp. 1166-1173.

221. Ruffman, T., Slade, L., Sandino, J.C., Fletcher, A. (2005) Are A-not-B errors caused by a belief about object location? Child development, vol. 76, pp. 122-136.

222. Sayce, L. (2009) The route of cognitive conflict: A planning toolkit for teachers. Report prepared for the Reading Borough Council and the NCETM.

223. Schlosser, R. & Raghavendra, P. (2004). Evidence- Based Practice in Augmentative and Alternative Communication. Augmentative and Alternative Communication, 20(1), 1-21.

224. Shadmer, R., Mussa- Ivaldi, R.A. (1994) Adaptive representation of dynamics during learning of motor skills. Journal of neuroscience, Vol. 14, pp. 3208- 3224.

225. Sheridan, T., Verplank, W. (1978) Human and computer control for undersea teleoperators. MIT Man-Machine Systems Laboratory.

226. Schum, R. (2004) Psychological Assessment of Children with Additional Disabilities [STUDY]: Psychological Assessment of Children with Multiple Handicaps Who Have Hearing Loss. The Volta Review: available at: http://listeningandspokenlanguage.org/Document.aspx?id=465#sthash.UNYDvLkI.dpuf

227. Sebanz, N., Knoblich, G., Prinz, W., Wascher, E. (2006) Twin peaks: an ERP study of action planning and control in co-acting individuals.J Cogn Neurosci, vol. 18, no. 5, pp.859-70.

228. Smith, L. (2009) Dynamic Systems, senroiomotor processs and the origins of stability and flexibilty. In: Spencer, J. (Ed.) Toward a unified theory of development conncetionism and dynamic system theory re-consider. Oxford University Press:

229. Smith, L., Thelen, E., Titzer, R., McLin, D. (1999) Knowing in the context of acting: the task dynamics of the A-not-B error. Psychological Review, Vol. 106, No. 2, pp. 235- 260.

230. Smith, L. & Thelen, E. (2003). Development as a dynamic system. TRENDS in Cognitive Sciences, 7(8), 343- 348.

231. Sommerville, J.A., Woodward, A.L. (2005) Pulling out the intentional structure of action: The relation between action processing and action production in infancy. Cognition, vol. 95, pp. 1–30.

232. Sommerville, J.A., Woodward, A.L., Needham, A. (2005) Action experience alters 3-month-old infants' perception of others' actions. Cognition, vol. 96, pp. B1- B11.

233. Sommerville, J., Hildebrand, E. & Crane, C. (2008). Experience Matters: The Impact of Doing Versus Watching on Infants Subsequent Perception of Tool-Use Events. Developmental Psychology, Vol. 44, No. 5, 1249–1256.

234. Spencer, J., Clearfield, M., Corbetta, D., Ulrich, B., Buchanan, P. & Schoner, G. (2006). Moving toward a grand theory of development: In memory of Esther Thelen. Child Development, 77(6), 1521-1538.

235. Sporns, O. & Edelman, G. (1993). Solving Bernstein's Problem: A proposal for the Development of Coordinated Movement by Selection. Child Behavior, 960-981.

236.Sporns, O., Gally, J., Reeke, G. & Edelman, G. (1989). Reentrant signaling among simulated neuronal groups leads to coherency in their oscillatory activity. Proc. Nadl. Acad. Sci, 86, 7265-7269.

237.St Amant, R., Horton, T.E. (2008) "Revisiting the definition of animal tool use", Animal behavior, Vol 75, pp. 1199- 1208.

238.Stanger, C.A. & Cook, A.M. (1990). Using Robotics to Assist in Determining Cognitive Age of Very Young Children. International Conference of the IEEE Proceedings. 1911-1912.

239.Stifter, C.C., Spinrad, T.L, Braungart-Rieker, J.M (1999) Toward a developmental model of child compliance. The role of emotion regulation in infancy. Child development, vol. 70, pp. 21-32.

240. Tai, Y.F., Scherfler, D.J., Brooks, N., Sawamoto, N., Castiello, U. (2004) The human premotor cortex is mirror only for biological actions. Curr Biol, Vol. 14, pp. 117- 120.

241. Taylor, MJ., & Baldeweg, T. (2002) Application of EEG, ERP and intracranial recordings in investigation of cognitive functions in children. Developmental Science, vol. 5,no. 3, pp. 318-334.

242.Tefft, D., Guerette, P. & Furumasu, J. (1999). Cognitive predictors of young children's readiness for powered mobility. developmental Medicine & Child Neurology, 41, 665-670.

243.Tejima, N. (2000) "Rehabilitation robotics: a review", Advanced Robotics, Vol. 14, No. 7, pp. 551– 564.

244.Thatcher, R., Krause, P. & Hrybyk, M. (1986). Corticocortical association fibers and EEG coherence: A two compartmental model. EEG and Clinical Nuerophysiology, 123-143.

245.Thelen, E., Fisher, D. M., & Ridley-Johnson, R. (1984). The relationship between physical growth and a newborn reflex.Infant Behavior and Development, vol. 7,pp. 479–493.

246.Thelen, E. (1989). Self- Organization in developmental processes: can systems approaches work? In Gunner & Thelan, Systems and Development: The Minessota Symposia on Child Psychology (pp. 77-113). Minessota: Minessota Symposia on Child Psychology series.

247.Thelen, E. (1995). Motor development: a new synthesis. American Psychologist, 50(2), 79- 95.

248.Thelen, E. (2005). Dynamic Systems Theory and the Complexity of Change. Psychoanalytic Dialogues, 15(2), 255-283.

249.Thelen, E. & Adolph, K. (1992). Arnold L. Gesell: The Paradox of Nature and Nurture. Developmental Psychology, 28(3), 368- 380.

250.Thelen, E. (2000) Motor development as foundation and future of developmental psychology. International Journal of Behavioral Development, Vol. 24, No. 4, pp. 385-397.

251. Thelen, E. & Fisher, D. (1982). Newborn stepping: An explanation for a "disappearing" reflex. Developmental Psychology, 18(5), 760-775.

252. Thelen, E. & Smith, L. B. (1994). A dynamic systems approach to the development of cognition. Cambridge: MIT Press.

253. Thelen, E., Corbetta, D. & Spencer, J. (1996). The Development of Reaching During the First Year: The Role of Movement Speed. Journal of Experimental Psychology: Human Perception and Performance, 22, 1059- 1076.

254. Thelen, E., Schoner, G., Scheier, C. & Smith, L. (2001). The dynamics of embodiment: a field theory of infant perseverative reaching. Behavioral and Brain Sciences, 24, 1-86.

255. Thelen, E., Smith, L. (1996) A Dynamic Systems Approach to the Development of Cognition and Action. The MIT Press: Massachusetts.

256. Thierry, G. (2005). The Use of Event Related Potentials in the Study of Early cognitive development. Infant and child Development, 14, 85-94.

257. Touwen, B. C. L. (1976) Neurological development in infancy. Clinics in developmental medicine. London: Heinemann.

258. Tsai, C., Brass, M. (2007) Does the human motor system simulate Pinocchio's actions? Coacting with human hand versus a wooden hand in a dyadic interaction. Psychological Science, Vol. 18, pp. 1058-1062.

259. Valsiner, J. (2009). Thinking in Psychological Science: Ideas and their makers. New Jersey: Transaction Publishers.

260. Van Leeuwen, L., Smitsman, A., & Van Leeuwen, C. (1994) "Affordances, Perceptual Complexity, and the development of tool use", Journal of Experimental Psychology , vol 20 , numer 1,pp. 174-191.

261. Vauclair, J. (1984) Phylogenetic Approach to Object Manipulation in Human and Ape Infants, Human Development, Vol. 27, pp. 321-328.

262. Vereijken, B. (2010). The Complexity of Childhood Development: Variability in Perspective. Physical Therapy, 1850- 1859.

263. Vingerhoets, G., Vandamme, K. & Vercammen, A.(2009) Conceptual and Physical object qualities contribute differently to motor affordances, Brain and Cognition , vol, 69, pp. 481- 489.

264. Vygotsky, L. (1929) Vygotsky, L.S. (1929) The problem of the cultural development of the child, II. Journal of Genetic Psychology, 36, 414-434.

265. Vygotsky, L. (1978). Interaction between learning and development. In M. Gauvain & M. Cole, Readings on the development of children (pp. 29- 36). New York: W. H Freeman and company (Original work pusblihed in Vygotsky, L.S., Mind & Society. Cambridge, MA: Harvard University Press, 79-91)

266. Vygotsky, L. (1978). Mind in society: The development of higher psychological processes. Cambridge: Harvard University Press.

267. Vygotsky, L.S. (1986) Thought and Language. Cambridge, MA: MIT Press.

268. Vygotsly, L. (1993). The Collected works of L.S Vygotsky: The Fundamentals of defectology (Vol. 2). (R. Rieber, A. Carton, Eds., J. Knox & C. Stevens, Trans.) New York: Kluwer Academic/ Plenum Publishers (Original work published in 1931)

269. Wiart, L. & Darrah, J. (1999) Test-retest reliability of the energy expenditure index in adolescents with cerebral palsy, Developmental Medicine and Child Neurology, vol 41, pp. 716-718.

270. Wiart, L. & Darrah, J. (2002). Changing philosophical perspectives on the management of children with physical disabilities- their effect on the use of powered mobility. Disability and rehabilitation, 24(9), 492-498.

271. Wiart, L., Darrah, J., Hollis, V., Cook, A., May, L. (2004) Mothers' perceptions of their children's use of powered mobility. Physical and occupational therapy in pediatrics, vol 24 (4), pp. 3- 21.

272. Wiebe, S., Lukowski, A. & Bauer, P. (2010). Sequence Imitation and Reaching Measures of Executive Control: A Longitudinal Study Examination in the Second Year of Life. Developmental Neuropsychology, 35(5), 522-538.

273. Wolfe, C.D., Bell, .M.A. (2007) Brain reorganization from infancy to early childhood: Evidence from EEG power and coherence during working memory tasks. *Developmental Neuropsychology, 31*, 21-38.

274. Woodman, G.(2010) A brief introduction to the use of event-related potentials in studies of perception and attention. Attention, Perception & Psychophysics, vol. 72, no. 8, pp. 2031-2046.

275. Woodward, A.L. (2009) Infants' grasp of others' intentions. Current directions in psychological science, vol. 18, no. 53, pp. 53- 57.

276. World Health Organization. (2005, 01 01). WHO. Retrieved 04 03, 2011, from Disability and rehabilitation WHO Action Plan: http://www.who.int/disabilities/publications/action_plan/en/index.html

277. Zelazo, P.D., Frye, D., Rapus, T. (1996) An age related dissociation between knowign rules and using them. Cognitive development, Vol. 11, pp. 37- 63.

278. Zidarov, D., Thomas, A., Poissant, L. (2013) Knowledge Translation in physical therapy: from theory to practice. Disability and Rehabilitation, Vol 35., No. 18, pp. 1571- 1577.

Appendices

Appendix A

Recruitment poster adult study

You are an adult that likes robots and technology?
You want to help improve research related experiences for children with disabilities?
Would you like to help us understand how using a robot changes a task?

Purpose:

We invite you to take part in a pilot study where we want to understand the implications of using a robot for grasping objects during different tasks. This pilot will inform our research on development of children with motor disabilities and the use of robots to provide them with meaningful opportunities to learn and explore!

What we would ask you to do:

- You will be asked to come to the EEG Lab of the department of Psychology, University of Alberta for 2 hours.
- You will use a robot controlled by switches to complete game-like tasks finding objects hidden under different containers!
- We will record your scalp electroencephalogram (EEG). In order to do this, we will place a net on your head that has all the electrodes attached to it. The experience of wearing the net resembles that of wearing a swimming cap!

Interested? Contact us!

Liliana Alvarez
Phone: (780) 492-5422
Email: lalvarez@ualberta.ca

Liliana Alvarez
Phone: (780) 492-5422
Email: lalvarez@ualberta.ca

Liliana Alvarez
Phone: (780) 492-5422
Email: lalvarez@ualberta.ca

Liliana Alvarez
Phone: (780) 492-5422
Email: lalvarez@ualberta.ca

Liliana Alvarez
Phone: (780) 492-5422
Email: lalvarez@ualberta.ca

Liliana Alvarez
Phone: (780) 492-5422
Email: lalvarez@ualberta.ca

Liliana Alvarez
Phone: (780) 492-5422
Email: lalvarez@ualberta.ca

Liliana Alvarez
Phone: (780) 492-5422
Email: lalvarez@ualberta.ca

Liliana Alvarez
Phone: (780) 492-5422
Email: lalvarez@ualberta.ca

Liliana Alvarez
Phone: (780) 492-5422
Email: lalvarez@ualberta.ca

Appendix B

Consent form adult study

UNIVERSITY OF
ALBERTA

Department of Speech Pathology and Audiology

2-70 Corbett Hall
Edmonton, Alberta, Canada T6G 2G4

www.uofaweb.ualberta.ca/rehabmed

Tel: 780.492.5990
Fax: 780.492.9333
Corbett Clinic: 780.492.5314
MSc-SLP Inquiries: 780.492.5088

Consent Form

Title of Project: ***Neural correlates of robot use for manipulation activities***

Principal Investigator: Liliana Alvarez, PhD Candidate,
Faculty of Rehabilitation Medicine, University of Alberta
Phone number: 780- 4925422

Co-Investigator(s): Albert M. Cook, PhD, Faculty of Rehabilitation Medicine, (Supervisor)
Kim Adams, Assistant Professor, Faculty of Rehabilitation Medicine, (Co- supervisor)
S. Wiebe, Department of Psychology
A. Singhal, Department of Psychology

To be completed by the research subject:

Do you understand that you have been asked to be in a research study?	Yes	No
Have you read and received a copy of the attached Information Sheet?	Yes	No
Do you understand the benefits and risks involved in taking part in this research study?	Yes	No
Have you had an opportunity to ask questions and discuss this study?	Yes	No
Do you understand that you are free to refuse to participate or to withdraw from the study at any time without giving a reason and without negative consequences?	Yes	No
Has the issue of confidentiality been explained to you? Do you understand who will have access to your data?	Yes	No
Do you consent to be videotaped for research purposes?	Yes	No
Do you consent to being videotaped for educational purposes? **If yes, you will be contacted before using videos for teaching or presentations.	Yes	No

This study was explained to me by: ____________________________

I agree to take part in this study.

____________________________ ________________
Signature of Participant Date

____
Printed Name

I believe that the person signing this form understands what is involved in the study and voluntarily agrees to participate.

_________________________________ _________________
Signature of Investigator or Designee Date

Appendix C

Information letter adult study

UNIVERSITY OF ALBERTA
Department of Speech Pathology and Audiology
2-70 Corbett Hall
Edmonton, Alberta, Canada T6G 2G4
www.uofaweb.ualberta.ca/rehabmed
Tel: 780.492.5990
Fax: 780.492.9333
Corbett Clinic: 780.492.5314
MSc-SLP Inquiries: 780.492.5088

Neural correlates of robot use for manipulation activities

Investigators:

Principal Investigator: L. Alvarez (PhD candidate, Faculty of Rehabilitation Medicine)

Co- investigators:
Supervisor: A. Cook (Department of Speech Pathology and Audiology, Faculty of Rehabilitation Medicine)
Co- supervisor: K. Adams (Faculty of Rehabilitation Medicine, Glenrose Rehabilitation Hospital)
S. Wiebe (Department of Psychology)
A. Singhal (Department of Psychology)

Purpose: You are being asked to participate in a pilot study, where we are interested in learning how infants with disabilities can develop their cognitive and perceptual skills. This study is part of the PhD thesis of the Principal Investigator as named above. Participation in this pilot study is completely voluntary. This information letter will provide you with some basic information about this study. If you have any questions or you wish to participate please don't hesitate to contact us.

Background: It is largely believed that children who can't move independently have cognitive delays as a result. However, some research shows that children with disabilities can develop the cognitive skills associated with movement. We want to explore how children develop these skills. To do that, we will study how children can use a robot to handle objects and demonstrate their cognitive skills. We first need to explore how the robot is perceived and how it changes the task.

First, this pilot study will be conducted with adults. Adults can reflect on the task and tell us what it's like to use the robot. Also, we will examine the electrical activity that occurs in the brain while doing the task. We will use the information from the pilot to improve the task and the process for phase two. In phase two, infants with and without disabilities will do the task and we will see if it is fun and easy for them, and examine the brain electrical patterns.

Procedures: You will be asked to complete come to the EEG Lab of the department of Psychology, University of Alberta. The session will last approximately 2 hours. You will complete two game-like tasks finding objects hidden under different containers. In one, you will find the objects using a robotic arm. The robotic arm is controlled by big switches that are easily pressed (see picture below).

In the other, you will repeat the tasks, this time using your hands. We will record your scalp electroencephalogram (EEG). The EEG records changes in the electrical signals from the brain. We will place a net on your head that has electrodes attached to it. Wearing the net feels like wearing a swimming cap. Before placing it, the net is immersed in water with baby shampoo and a special non-toxic solution. This allows the electrodes to become conductive. Drops of water from the electrodes may drip onto your face. We will provide a towel for you to wipe away the drops during the task. Wearing the cap will cause your hair to be slightly wet. We will provide a hair dryer after the session. We will try our best to assure you are comfortable at all times.

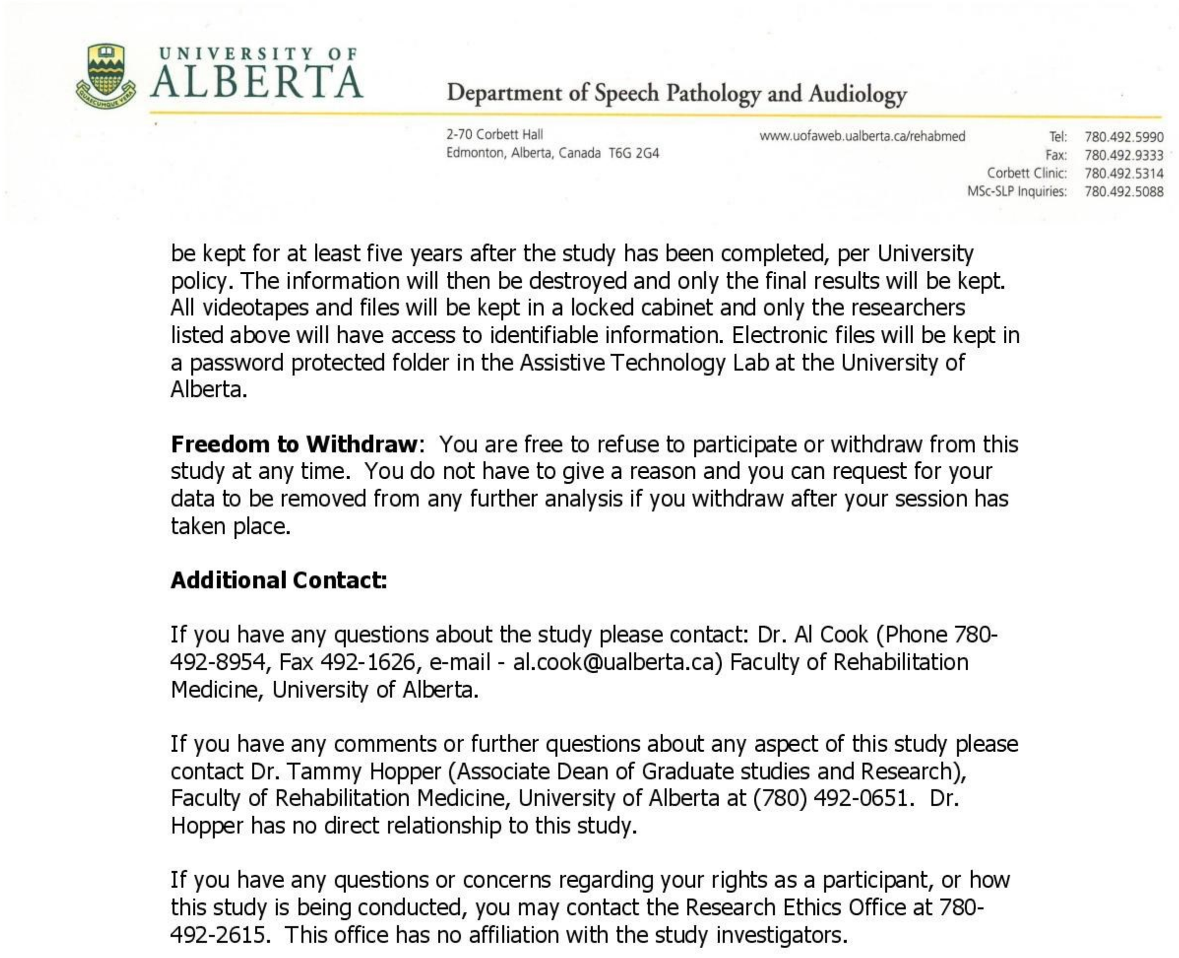
The EEG signals will be stored for later analysis. The sessions will be videotaped so we can correlate what you are doing in the task with the time of occurrence of the brain electrical activity.

Finally, we will ask you to tell us about your experience with the robot as a tool and the switches. We would like to know what you thought about the overall experience.

Benefits: The activities and the robot are a fun and interesting experience. Your participation allows us to move forward in our understanding of the use of robots. This pilot study will help us provide better experiences for children with disabilities. No other benefits for you are derived from participating in this study.

Risks: There are no anticipated risks derived from participating in this study. A large number of studies have used EEG recordings during different tasks without any risk to the participant. The robot has been previously used in research with infants as young as 8 months. No electronic or mechanical parts will come in contact with you. The researcher conducting the session will have a switch that can completely turn off the robot at any time.

Confidentiality: All the information you provide will be kept confidential. For data analysis purposes we will use a participant code and your name will not be used at any time. No identifiable information will be linked to your data. We may use the videotapes or data derived from our analysis of the results for teaching or research presentations, academic publications and reports if you agree to it. As part of the analysis we want to correlate the places where you look with what you do. For this reason, your face will be visible in the videos. We will not provide any identifiable information related to your video. We will only report group data and we will not identify any specific participants in any presentation or report. The information will



UNIVERSITY OF
ALBERTA
Department of Speech Pathology and Audiology
2-70 Corbett Hall
Edmonton, Alberta, Canada T6G 2G4
www.uofaweb.ualberta.ca/rehabmed
Tel: 780.492.5990
Fax: 780.492.9333
Corbett Clinic: 780.492.5314
MSc-SLP Inquiries: 780.492.5088

be kept for at least five years after the study has been completed, per University policy. The information will then be destroyed and only the final results will be kept. All videotapes and files will be kept in a locked cabinet and only the researchers listed above will have access to identifiable information. Electronic files will be kept in a password protected folder in the Assistive Technology Lab at the University of Alberta.

Freedom to Withdraw: You are free to refuse to participate or withdraw from this study at any time. You do not have to give a reason and you can request for your data to be removed from any further analysis if you withdraw after your session has taken place.

Additional Contact:

If you have any questions about the study please contact: Dr. Al Cook (Phone 780-492-8954, Fax 492-1626, e-mail - al.cook@ualberta.ca) Faculty of Rehabilitation Medicine, University of Alberta.

If you have any comments or further questions about any aspect of this study please contact Dr. Tammy Hopper (Associate Dean of Graduate studies and Research), Faculty of Rehabilitation Medicine, University of Alberta at (780) 492-0651. Dr. Hopper has no direct relationship to this study.

If you have any questions or concerns regarding your rights as a participant, or how this study is being conducted, you may contact the Research Ethics Office at 780-492-2615. This office has no affiliation with the study investigators.

Appendix D

Recruitment poster typically developing infants

Robot project for typically developing little kids! <(*_*)>

Why? We are studying how small infants with and without motor impairments learn about objects and the world around them. Also, we are exploring how can robots support this process!

What? Children will play a game of finding a toy under cups while using a robot. The kids will control the robot themselves using colorful big switches! They will wear a EEG cap during the game.

Who? We are looking for infants who:

- Have 18 to 30 months of age.
- Were born full term and weighted at least 6 pounds at birth.
- Have no diagnosis of any neurological disorder.

If you know anyone who meets this criteria and that would be interested in participating; or if you have any questions, please contact :

Liliana Alvarez
Phone: (780) 492-5422
Email:
alvarez@ualberta.ca

Liliana Alvarez
Phone: (780) 492-5422
Email:
alvarez@ualberta.ca

Liliana Alvarez
Phone: (780) 492-5422
Email:
alvarez@ualberta.ca

Liliana Alvarez
Phone: (780) 492-5422
Email:
alvarez@ualberta.ca

Liliana Alvarez
Phone: (780) 492-5422
Email:
alvarez@ualberta.ca

Liliana Alvarez
Phone: (780) 492-5422
Email:
alvarez@ualberta.ca

Liliana Alvarez
Phone: (780) 492-5422
Email:
alvarez@ualberta.ca

Liliana Alvarez
Phone: (780) 492-5422
Email:
alvarez@ualberta.ca

Liliana Alvarez
Phone: (780) 492-5422
Email:
alvarez@ualberta.ca

Appendix E

Recruitment poster children with disabilities

Robot project for little kids with motor impairments!

<(*_*)>

Why? We are studying how small infants with motor impairments learn about objects and the world around them. Also, we are exploring how can robots support this process!

What? Children will play a game of finding a toy under cups while using a robot. The kids will control the robot themselves using colorful big switches!

Who? We are looking for infants who:

- Have 18 to 30 months of age.
- Have restricted manipulation and/or locomotion.
- Have a congenital or early acquired motor disorder.
- Have a motor disorder with no known effect on cognitive skills

If you know anyone who meets this criteria and that would be interested in participating; or if you have any questions, please contact:

Liliana Alvarez
Phone: (780) 492-5422
Email:
alvarez@ualberta.ca

Liliana Alvarez
Phone: (780) 492-5422
Email:
alvarez@ualberta.ca

Liliana Alvarez
Phone: (780) 492-5422
Email:
alvarez@ualberta.ca

Liliana Alvarez
Phone: (780) 492-5422
Email:
alvarez@ualberta.ca

Liliana Alvarez
Phone: (780) 492-5422
Email:
alvarez@ualberta.ca

Liliana Alvarez
Phone: (780) 492-5422
Email:
alvarez@ualberta.ca

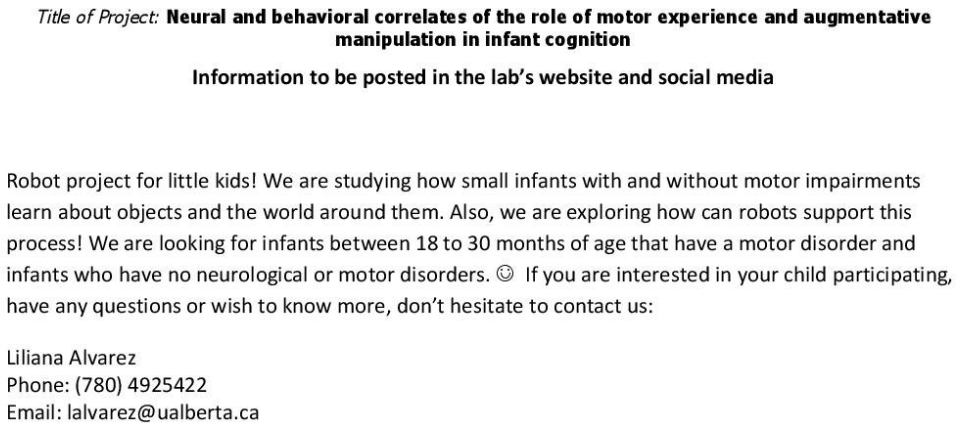
Liliana Alvarez
Phone: (780) 492-5422
Email:
alvarez@ualberta.ca

Liliana Alvarez
Phone: (780) 492-5422
Email:
alvarez@ualberta.ca

Liliana Alvarez
Phone: (780) 492-5422
Email:
alvarez@ualberta.ca

Appendix F

Social media recruitment information



Title of Project: **Neural and behavioral correlates of the role of motor experience and augmentative manipulation in infant cognition**

Information to be posted in the lab's website and social media

Robot project for little kids! We are studying how small infants with and without motor impairments learn about objects and the world around them. Also, we are exploring how can robots support this process! We are looking for infants between 18 to 30 months of age that have a motor disorder and infants who have no neurological or motor disorders. ☺ If you are interested in your child participating, have any questions or wish to know more, don't hesitate to contact us:

Liliana Alvarez
Phone: (780) 4925422
Email: lalvarez@ualberta.ca

Appendix G

Recruitment letter infant study

UNIVERSITY OF ALBERTA

Department of Speech Pathology and Audiology

2-70 Corbett Hall
Edmonton, Alberta, Canada T6G 2G4

www.uofaweb.ualberta.ca/rehabmed

Tel: 780.492.5990
Fax: 780.492.9333
Corbett Clinic: 780.492.5314
MSc-SLP Inquiries: 780.492.5088

Dear Parent/Guardian,

We are writing to let you know of a research study that we think your child may enjoy. We are studying how infants with motor impairments learn about the objects and the world around them. Also, we are exploring how robots can be used as a way to support this process. For this purpose we are looking for interested parents of typically developing infants and infants with motor impairments between 18 and 30 months of age. This study will be conducted at the ABCD Lab, located in P-206A Biological Sciences Building of the University of Alberta and the Electrophysiology Lab, located in P322 Biological Sciences Building. The parent or caregiver will be with the child at all times throughout the session. The session will last approximately 2 hours. If necessary, the parents and child will be requested to come in for a second session.

We have enclosed an information letter that provides with more information and a consent form. If you would like your child to participate, please contact me.

Liliana Alvarez
PhD candidate
Faculty of Rehabilitation Medicine
3-59 Corbett Hall
University of Alberta
Edmonton AB T6G 2G4
Phone: 780-494-5422
Email : lalvarez@ualberta.ca

You are under no obligation to participate.

Sincerely,

Liliana Alvarez, O.T, MSc.

Student's supervisor:
Al Cook
Department of Speech Pathology and Audiology
Faculty of Rehabilitation Medicine
3-79 Corbett Hall
University of Alberta
Edmonton AB T6G 2G4
Phone: 780-492-5422
Fax: (780) 492-9333

Appendix H

Information letter infant study

UNIVERSITY OF
ALBERTA

Department of Speech Pathology and Audiology

2-70 Corbett Hall
Edmonton, Alberta, Canada T6G 2G4

www.uofaweb.ualberta.ca/rehabmed

Tel: 780.492.5990
Fax: 780.492.9333
Corbett Clinic: 780.492.5314
MSc-SLP Inquiries: 780.492.5088

Neural and behavioral correlates of the role of motor experience and augmentative manipulation in infant cognition

Investigators:

Albert Cook (Department of Speech Pathology and Audiology, Faculty of Rehabilitation Medicine)
Liliana Alvarez (PhD candidate, Faculty of Rehabilitation Medicine)
Kim Adams (Faculty of Rehabilitation Medicine, Glenrose Rehabilitation Hospital)
Sandra Wiebe (Department of Psychology)

Purpose: We are interested in learning how infants with disabilities can develop their cognitive skills and learn about the world around them. This study is part of a PhD thesis. Participation in this study is completely voluntary. This letter will provide you with some basic information about this study. If you have any questions, you wish to learn more or you wish to participate please don't hesitate to contact us.

Background: It is largely believed that children who can't move independently have cognitive delays as a result. However, some research shows that children with disabilities can develop the cognitive skills associated with movement. We want to explore how infants with motor disabilities develop these skills and how can technology support them in his process. To do that, we will study how infants can use a robot to play a game of finding a toy in different hiding places on a table. We will also study how typically developing infants do it. This will allow us to see if the robot is easy to use and can in fact support the child.

Procedures: The session will last approximately 2 hours. He or she will be sitting on your lap at all times. The session will be videotaped for later analysis. Your child will be given several toys and you can help us identify his or her favorite. Your child will then play a game. The researcher will hide the toy under one of two plastic baby cups. Your child will be asked "where's the toy?" .The cups will be out of reach. A small robot (see below) will be placed next to the child and out of reach. Your child can easily make the robot move and uncover the cups by pressing either one of two colorful buttons (see below) placed in front of him. We can also place the buttons wherever the child is more comfortable pressing them.

We will repeat the game without the robot. We will keep track of where the child looks. During the games, we will record your child's scalp electroencephalogram (EEG). EEG is a completely non-invasive way of recoding small electrical changes from the brain. A net (see below) is placed on your child's head. The net will be worn by your child for up to 30 minutes out of the two hours. This net has small electrodes attached to it. The electrodes record the brain activity. They do not pass any current into the scalp. They do not put your child at risk. A researcher will measure the size of your child's head to find the correct sized of sensor net. The net will then be placed in warm water with baby shampoo and a special non-toxic solution. This allows the electrodes to become conductive. Next, the researcher will place the net on your child's head. She will adjust it so that it fits correctly and all sensors are reading properly. Wearing the net feels like wearing a swimming cap. Drops of water from the electrodes may drip onto your child's face from the net. We will provide a towel for you to wipe away the drops. We will also try our best to assure you and your child are comfortable at all times and that your child has as much fun as possible. You will remain in the room with your child throughout the session.

Picture: http://www.skidmore.edu

During the session, we will ask you to complete two short questionnaires. This will take 30 minutes (or less). The first one will ask you questions regarding the ways your child normally interacts with objects and toys. The other one will ask you questions regarding your child's general health conditions and developmental (age, any diagnosis or surgeries and developmental milestones).

All study activities will take place in the EEG Lab ABCD Lab, located in P-206A Biological Sciences Building of the University of Alberta and the Electrophysiology Lab, located in P322 Biological Sciences Building. At the end of the session, your child will receive a book or small toy.

All the procedures described above are only for research purposes. They will help us understand the role of manipulation in development. No diagnostic testing or information will be acquired or reported.

Benefits: The activities will be fun and the child will interact with colorful and sound-making toys. Your participation allows us to increase our understanding of how children with disabilities learn. We will also learn what can be done to support them. No other benefits for you are derived from participating in this study.

Risks: There are no expected risks derived from participating in this study. A large number of studies have used EEG recordings during different tasks without any risk. The robot has been used in research with infants as young as 8 months. No electronic or mechanical parts will come in contact with you or your child. During the session, the researcher will have a switch that can turn off the robot at any time.

Confidentiality: All the information you provide will be kept confidential. For data analysis purposes we will use a participant code and your name and the name of your child will not be used at any time. No identifiable information will be linked to your data. We may use the videotapes or data derived from our analysis of the results for teaching or research presentations, academic publications and reports if you agree to it. As part of the analysis we want to correlate the places where your child will look with what he/she does. For this reason, if you agree to letting us use the videos for teaching and research purposes, the child's face will be visible in the videos. We will not provide any identifiable information related to your video. We will only report group data and we will not identify any specific participants in any presentation or report. The information will be kept for at least five years after the study has been completed, per University policy. The information will then be destroyed and only the final results will be kept. All videotapes and files will be kept in a locked cabinet and only the researchers listed above will have access to identifiable information. Electronic files will be kept in a password protected folder in the Assistive Technology Lab at the University of Alberta.

Freedom to Withdraw: You are free to refuse to participate or withdraw from this study at any time. You do not have to give a reason and you can request for your child's data to be removed from any further analysis if you withdraw after your session has taken place.

Additional Contact:

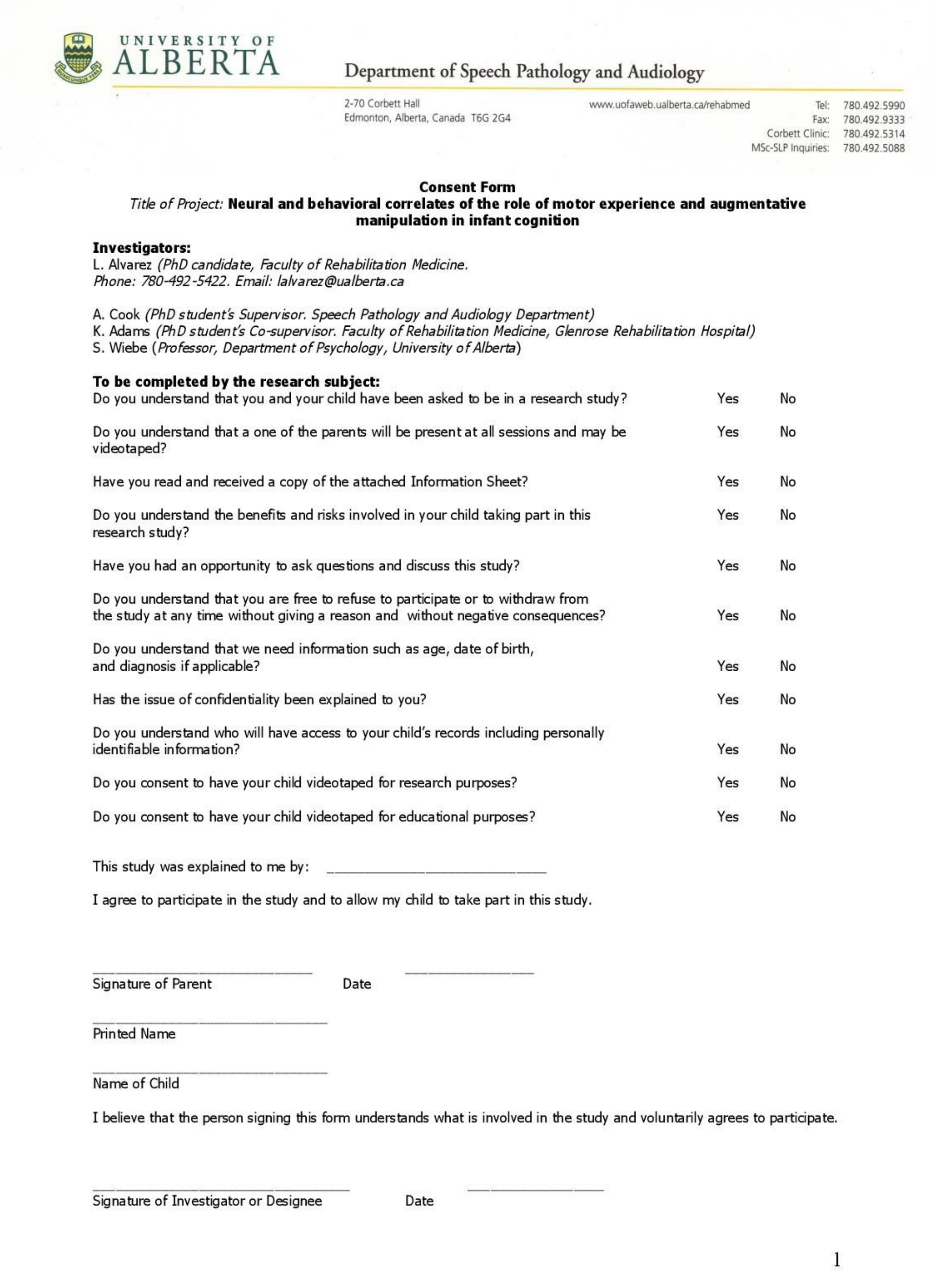
If you have any questions about the study please contact: Dr. Al Cook (Phone 780-492-8954, Fax 492-1626, e-mail - al.cook@ualberta.ca) Faculty of Rehabilitation Medicine, University of Alberta.

If you have any comments or further questions about any aspect of this study please contact Dr. Tammy Hopper (Associate Dean of Graduate studies and Research), Faculty of Rehabilitation Medicine, University of Alberta at (780) 492-0651. Dr. Hopper has no direct relationship to this study.

If you have any questions or concerns regarding your rights as a participant, or how this study is being conducted, you may contact the Research Ethics Office at 780-492-2615. This office has no affiliation with the study investigators.

Appendix I

Consent form infant study



UNIVERSITY OF
ALBERTA

Department of Speech Pathology and Audiology

2-70 Corbett Hall
Edmonton, Alberta, Canada T6G 2G4

www.uofaweb.ualberta.ca/rehabmed

Tel: 780.492.5990
Fax: 780.492.9333
Corbett Clinic: 780.492.5314
MSc-SLP Inquiries: 780.492.5088

Consent Form

Title of Project: **Neural and behavioral correlates of the role of motor experience and augmentative manipulation in infant cognition**

Investigators:
L. Alvarez *(PhD candidate, Faculty of Rehabilitation Medicine.*
Phone: 780-492-5422. Email: lalvarez@ualberta.ca

A. Cook *(PhD student's Supervisor. Speech Pathology and Audiology Department)*
K. Adams *(PhD student's Co-supervisor. Faculty of Rehabilitation Medicine, Glenrose Rehabilitation Hospital)*
S. Wiebe (*Professor, Department of Psychology, University of Alberta*)

To be completed by the research subject:

Do you understand that you and your child have been asked to be in a research study?	Yes	No
Do you understand that a one of the parents will be present at all sessions and may be videotaped?	Yes	No
Have you read and received a copy of the attached Information Sheet?	Yes	No
Do you understand the benefits and risks involved in your child taking part in this research study?	Yes	No
Have you had an opportunity to ask questions and discuss this study?	Yes	No
Do you understand that you are free to refuse to participate or to withdraw from the study at any time without giving a reason and without negative consequences?	Yes	No
Do you understand that we need information such as age, date of birth, and diagnosis if applicable?	Yes	No
Has the issue of confidentiality been explained to you?	Yes	No
Do you understand who will have access to your child's records including personally identifiable information?	Yes	No
Do you consent to have your child videotaped for research purposes?	Yes	No
Do you consent to have your child videotaped for educational purposes?	Yes	No

This study was explained to me by: ______________________________

I agree to participate in the study and to allow my child to take part in this study.

______________________________ Date ________________
Signature of Parent

____
Printed Name

____
Name of Child

I believe that the person signing this form understands what is involved in the study and voluntarily agrees to participate.

______________________________ Date ________________
Signature of Investigator or Designee

Appendix J

Technology exposure survey

UNIVERSITY OF ALBERTA
Department of Speech Pathology and Audiology
2-70 Corbett Hall
Edmonton, Alberta, Canada T6G 2G4
www.uofaweb.ualberta.ca/rehabmed
Tel: 780.492.5990
Fax: 780.492.9333
Corbett Clinic: 780.492.5314
MSc-SLP Inquiries: 780.492.5088

Questions for Parents or caregiver

Title of Project: **Neural and behavioral correlates of the role of motor experience and augmentative manipulation in infant cognition**

Investigators:

Albert Cook (Department of Speech Pathology and Audiology, Faculty of Rehabilitation Medicine)
Liliana Alvarez (PhD candidate, Faculty of Rehabilitation Medicine)
Kim Adams (Faculty of Rehabilitation Medicine, Glenrose Rehabilitation Hospital)
Sandra Wiebe (Department of Psychology)

Name of participant:	**Name of person providing the information:**
Age of participant:	**Relation to participant:**
Diagnosis (if applicable):	

Part 1
Does your child have experiences interacting with the following types of toys and devices?
How frequently does she/he plays with them?
How would you describe those interactions in terms of skill?

Type of Toy/ Device	Frequency of Use			Skill Level		
	Never	Seldom (weekly)	Often (daily)	Low (trial & error)	Medium	Proficient (task mastered)
Battery operated toys (e.g. Tickle me Elmo)						
Mobile Battery operated toys (e.g. walking pig toy)						
Battery operated toys with remote control (e.g. lego robots, remote control cars).						
Directional controls (e.g., joystick for toy car, video games, DVD arrows for games)						
Games on computers, tablets, or smart phones						

Part 2

How does your child communicate what she/he wants?

How would you describe your child's interactions with other adults?

How would you describe your child's interactions with other children?

How would you describe your child in one sentence?

Appendix K

Certificate for participants

Sammy the robot and the Assistive Technology Lab award this certificate to:

John Doe

A young scientist who helped researchers discover new exciting things about robots and children!

Thank you very much!