UREAP Report

Examining Brain Function and Behaviour in Infants During Naturalistic Play: a fNIRS Study

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Undergraduate Research Experience Award Program

Summary

My Undergrad Research Experience Award Program (UREAP) has provided me with a great opportunity to develop research skills throughout the summer. My study focused on designing a protocol for investigating the development of motor skills in the infant brain, specifically within the prefrontal (pre-motor), motor, and parietal lobe. The project included a review of the literature and training on functional near-infrared spectroscopy (fNIRS) to build a sound protocol for neuroimaging infants while completing motor tasks. With minimal previous infant motor studies undergoing fNIRS, my study's protocol was further developed through trial and error. Specifically, infant protocols are hard to structure and we needed to allow a degree of flexibility for this population. A large focus of this summer was participant recruitment. For this I designed posters, leaflets, researched online platforms, and media advertisements. Additionally, I went in-person to visit local childcare, healthcare, and child activity centres. I then trained on the Jane App for participant recruitment, a user-friendly practice management software that allows participants to schedule time slots and get information and forms for our study in a confidential way. As part of the Baby Brain and Behaviour team, I wrote information about our study, our purpose, and developed a video introducing the researchers, the lab, and the experiment. During my UREAP I also learned valuable skills in data processing with software programs used to collect and process fNIRS and behavioural data. Specifically, I coded video data taken from 5 infants that we tested and identified behavioural markers that would be used to match with the brain activity collected by the fNIRS. My research activities conducted this summer have aided in me securing a position in the Psychology Honours program, where I can continue to test more participants with a sound experimental design and protocol and will also learn to analyze the data.

Background

The first two years of life is a critical stage in an infant's brain and nervous system development (Bornstein, 2014; Köster et al., 2020; Lloyd-Fox, Blasi, & Elwell, 2010). Studies on infant development commonly focus on two key periods, around birth and 12 months, indicating a key interest in the brain at birth and accumulated brain development at the first year (Azhari et al., 2020). Between 3 to 4 months, infants seem to have separate processes for visual information proprioceptive information (Corbetta et al., 2014; Corbetta 2021). When the fundamental skill of reaching for objects emerges at around 3-5 months of age, visual and motor areas begin to intersect (Corbetta et al., 2014; Corbetta 2021), and through trial and error, infants increasingly make contact while reaching for objects, forming a process known as reinforcement learning (Sutton & Barto, 2018). This goal-directed movement is due to functional and structural alterations within the brain that develops uncontrolled movement into goal-directed behaviours (Agyeman et al., 2023). However, the developmental changes that occur during this time have been difficult to measure, particularly, using neuroimaging methods like functional magnetic resonance imaging. Therefore, attempts at characterizing healthy brain-behaviour development involves several, some contradicting, theories that are difficult to test (e.g., Corbetta, 2021; Köster et al., 2020; McGraw, 1943; Nagai et al., 2019).

Developmental Theories

There are many developmental theories that attempt to explain the process of neurodevelopment in infants as they mature, yet the neural basis to this process is unknown (Nishiyori et al., 2016; Agyeman, 2023). The dynamic systems approach suggests that motor and cognitive development appears as dynamic changes within a complex system, emerging from interactions between infants and their environment (Gottlieb, Wahlsten, & Lickliter, 1998; Nagai, 2019). Additionally, the maturation of motor skills is not solely based on cortical development, rather the development and integration of perceptual, cognitive, affective, skeletal, and neuromuscular systems (Thelen, kelso, & Skala, 1987).

Neural maturationist theorists in the mid 1900's viewed motor development as a predetermined blueprint encoded by an individual's genes (Gesell & Amatruda, 1947). Motor skill acquisition develops through increased cortical control and receives no contribution from environmental interactions (Gesell & Amatruda, 1947). McGraw (1935) tested this theory with a set of infant twins that displayed a similar base level of controlled movements. One infant was given typical infant care, while the other was subjected to training sessions geared towards particular motor skills (e.g. climbing). McGraw (1935) found that training one child led to a higher level of motor skill development compared to the child who received normal care, suggesting that while a set neural framework exists, environmental learning can further enhance motor skills.

In contrast, the neuronal group selection theory (NGST) provides a comprehensive framework that integrates elements of both nature and nurture in explaining motor development. The NGST posits that motor development is neither exclusively governed by genetically predetermined neural circuits nor by environmental factors alone (Edelman, 1989; Sporns & Edelman, 1993). Instead, it is the result of a dynamic interplay between genetic information and environmental experiences (Edelman, 1989; Sporns & Edelman, 1993). The theory thus suggests that development begins with groups of interconnected neurons (Edelman, 1989; Sporns & Edelman, 1993) that are shaped by evolutionary processes and further refined through experience and behaviour, with synaptic connections being strengthened or weakened based on sensory input and activity (Sporns & Edelman, 1993).

Modern day theorists suggest that motor skills are acquired through action, perception, intrinsic motivation, and interactions with the environment (Corbetta, 2021; Köster et al., 2020; Nagai et al., 2019; Nishiyori et al., 2015). When looking at the development of motor skills in reaching and stepping, Nishiyori et al (2015) based their theory on the developmental systems approach (Gottlieb, Wahlsten, & Lickliter, 1998) and TNGS (Edelman, 1989; Sporns & Edelman, 1993). The result of this study contributed to their predictions that as infants explore initial movements, they begin to acquire goal-directed movements through repetition and trial and error (Nishiyori et al., 2015). During this process, specific brain regions and neural networks display a large range of activation (Nishiyori et al., 2015). However, after practice and further development of motor skills, the regions and networks begin to show a decrease in disbursed activation and increase in focal areas of activity (Nishiyori et al., 2015).

Köster et al (2020) theorizes that neural maturation during the development of motor skills are learned through a process of predictive processing. The framework of predictive processing posits that effective interactions with the surrounding environment is dependent on one’s capacity to refine predictions about how its actions will influence proprioceptive experiences (Helmholtz, 1867; Köster et al., 2020). Additionally, this process can also be based on predictions of social and physical behaviours of the external world (Schubotz, 2015). However, Köster et al. (2020) argue that intrinsic motivation and curiosity play a significant role in driving predictive processing during motor skill development. The natural curious and explorative nature of infants drives infants to interact with their environment and each failed attempt gives information of their surroundings (Köster et al., 2020). Through these novel experiences, infants can adjust their predictive models resulting in an increase in refined behaviours (Köster et al., 2020).

Like Köster and colleagues (2020) theory, Nagai et al (2019) propose that predictive learning of sensory information is a key feature in cognitive maturation. By using an internal model of the world, humans can predict the behaviour of their surroundings and intentionally manage bodily movements (Nagai et al., 2019). However, the ability to update a predictor based on previous sensory signals and executing an action based on a prediction are the two mechanisms that leads the development of motor skills.

Numerous theories attempt to explain the development of refined motor skills in infants, often offering conflicting perspectives (e.g., Köster et al., 2020; McGraw, 1935; Nagai et al., 2019). This inconsistency highlights the need for further research in this area. Despite modern theories emphasizing the role of perception, action, interaction, and predictive learning in motor skill acquisition (Corbetta, 2021; Köster et al., 2020; Nagai et al., 2019), the neural mechanisms underlying these processes remain largely unknown. Therefore, further research is needed to explore the learning process behind goal-directed movements and the neural correlates that contribute to motor skill maturation.

Regions of interest

Given previous findings, my study will focus on certain regions of interest (ROI) consisting of the prefrontal (pre-motor) cortex, motor cortex, and parietal cortex, each of our ROIs play a distinct yet interconnected role in the process of reaching and grasping. The pre-motor cortex (pMC) is particularly involved in the planning and preparation of motor actions. For example, this region is responsible for the anticipatory adjustments and mediations necessary to shape the hand according to the properties of an object (Tunik, Houk, & Grafton., 2009). The pMC integrates sensory information with motor commands, facilitating the selection and initiation of appropriate motor actions (Buch et al. 2006; Wenderoth et al., 2004). Moreover, this area is active during the observation of actions, which suggests its involvement in action understanding and motor learning processes (Cattaneo et al., 2009; Rizzolatti et al., 1996).

The motor cortex is primarily responsible for the execution of voluntary movements, including those required for reaching and grasping (Cattaneo et al., 2009; Nishiyori et al., 2016). This region is crucial for controlling fine motor skills and coordinating muscle activity (Nishiyori et al., 2016). Neurons in the motor cortex have been found to encode many aspects of movements such as direction, velocity, length, movement adjustments (Georgopoulos et al., 1982; Morgan & Schwartz, 1999), and muscle synergy (Holdefer & Miller, 2002). In addition, the motor cortex receives sensory input from the thalamus, which plays an important role in voluntary and skilled movements (Asanuma & Mackel, 1989).

The parietal lobe is an integral part of processing spatial and sensory information (Wenderoth et al., 2004), allowing for guided movements during reaching and grasping. The posterior parietal cortex (PPC) is particularly involved in transforming sensory inputs into motor commands, enabling accurate hand movements towards an object (Andersen & Cui, 2009). Additionally, this region integrates visual and proprioceptive information, which is crucial for maintaining an accurate perception of the spatial relationship between the hand and the object (Andersen & Cui, 2009). An individual area of the PPC called Area 5 has a major role in spatial information for the limbs and arm reaching (Kalaska et al., 1997). The parietal lobe also has been found to be active during movement observations, specifically within the inferior parietal lobule (IPL) (Fogassi et al., 2005). Neurons within the IPL encode distinct movements, and they release while observing other movements (Fogassi et al., 2005). Each region involved in movement has many networks and subnetworks to communicate and coordinate efforts to achieve movement goals (Wenderoth et al., 2004).

fNIRS

Over the past decade, there has been an increase in the number of studies using fNIRS (Azhari et al., 2020; Ichikawa et al., 2019; Nishiyori et al., 2016). fNIRS is a non-invasive neuroimaging technique that measures oxygenated (HbO2) and deoxygenated (HbR) hemoglobin chromophore changes in brain tissue following neuronal activity (Li et al., 2024; Lloyd-Fox, Blasi, & Elwell, 2010; Pinti et al., 2020). Though fMRI and fNIRS measure the same hemodynamic responses, fNIRS has the advantage of higher temporal resolution, portability, and low sensitivity to body movements, enabling infants to have a degree of natural movement (Lloyd-Fox, Blasi, & Elwell, 2010; Nishiyori et al., 2016; Pinti et al., 2020). fNIRS uses transmitters that produce near-infrared light at various wavelengths (ranging from 700-900). To reach and measure cortical brain tissue, the infrared light penetrates through the layers of the head (hair, skin, skull, cerebrospinal fluid). The light is then absorbed, attenuated, or scattered and is detected with receiving optodes. With the advantage of fNIRS allowing infants the freedom of movement during tasks, it is then a cost effective, convenient, and sensitive technique to measure and better characterize the functional brain-behaviour changes in infant development.

Further research is needed to make up for the limited time-on-task from infants which impacts the quantity of data and thus the reliability and validity of findings (Crista et al, 2013; Nishiyori et al, 2016). Notably, multiple studies have highlighted the need to directly correlate fNIRS activity with performance (Lloyd-Fox et al., 2015; Nishiyori, 2016; Nishiyori et al, 2016; de Oliveira et al., 2018). The main objective of our study is to address the knowledge gap by examining and correlating brain-behaviour in typically developing infants. Once an optimal protocol design is identified, prefrontal, motor, and parietal brain activity will be measured using fNIRS whilst babies engage in naturalistic movements and reaching and grasping. This study consists of a longitudinal design to examine the changes in brain maturation as infants develop. Given recent findings, we predict focused brain activity and increased connectivity with more maturation in each ROI. My secondary aim will be to share event (e.g., reach) fNIRS data in open access repositories to help aid future study's direction and protocol.

Methods

Participants

So far, a total 5 Infants were recruited between the ages of 6 to 13 m/o. Recruitment involved leaflets and posters in community areas, posters on different social media platforms (e.g., Facebook groups), and radio advertisements. Infants were also recruited by visiting local hospitals, daycares, early childhood education programs, and children's therapy centres. Parents filled a brief medical history for their child, but there are no restrictions on eligibility based on health. Each child completed at least one session but were invited to participate across 3 sessions, at 6 months, 9 months and 12 months. For each session completed, parents/guardians received a $40 gift card to Starbucks or Indigo. Prior to the study, parents/guardians are debriefed through written and oral information on the purpose and all procedures of the experiment. All participant's parent/guardian will give written consent prior to any experimental procedure. This study has been approved by the Thompson Rivers University's ethics committee.

Session Overview

Prior to beginning the experiment, it can be helpful to provide the child time to get acclimated to the environment and researchers present. During this period, we will give the child toys to begin interacting with while we describe to the parent the study's design, answer any questions, and ensure the informed consent sheets have been signed. It is important when going over the procedure to ensure the parent is comfortable with the process, as they can influence their child's contentment (Raschle et al., 2012). Once complete we will make two measurements on the infant's head, one between the inion and nasion and the other between the left and right pre-auricular points (Nishiyori et al., 2016). From those two measurements we can locate the Cz point of the head (Jasper 1958). With those measurements we gently apply the fNIRS cap into position, we secure and adjust the hair as needed. The order of our study's tasks is subjective to each participant. For example, infants can come in hungry and want to reach for snacks right away, but some may be playful. A very important aspect of this study and working with infants is that we can not be demanding, working with what is available and keeping the child happy is the main priority throughout the study. The child will then be placed into a special fit infant chair (seat 26 cm from the ground, backrest approximately reclined 15° from a vertical position) with a strap going around the waist and between the legs for stability. During the experiment, parents are asked to sit next to their child and help engage them in the tasks at hand. Each full session will last between 45 to 75 minutes, depending on the willingness and mood of the child.

Tasks

Reaching and grasping

I will be investigating motor skills during two specific behaviours, naturalistic play and reaching and grasping. For the reaching and grasping tasks, there are three conditions: baseline, reach and grasp, and observation. During the baseline condition, participants will view a children's sensory video (Hey Bear Sensory, 2019) for a minimum of a 10s period between the reach and observation conditions. This baseline condition will serve as a baseline for the hemodynamic responses of the following tasks. During the reach and grasp condition, children will be encouraged to reach for small snacks (cheerios and yogurt dots) for a minimum of one minute. The observation condition consists of the participant observing videos of other infants reaching and grasping for a minimum of one minute.

Table 1.

The experimental design will be in the following order, participants will complete three rounds of tasks

Reach & Grasp Experiment				
	Baseline	**Reach & grasp**	**Baseline**	**Observation**
Observation 1	~10s	~1min	~30s	~1min
Observation 2				
Observation 3				

Free Play

The free play task consists of three conditions: Baseline, free play, and observation. The baseline will remain the same as the prior tasks. During the free play condition, children will be encouraged to play freely with small toys, stuffed animals, and balls for a minimum of one minute. All toys used are around 5" (L) x 5" (W) x 5" (H). For the observation condition participants will view a video of an infant engaging in free play for a minimum period of one minute.

Table 2.

Infants will engage in three rounds of free play tasks

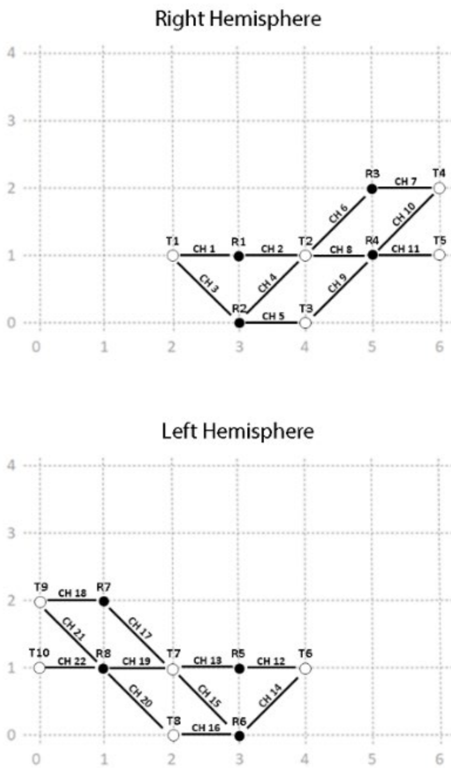
Free Play Experiment				
	Baseline	**Free Play**	**Baseline**	**Observation**
Observation 1	~10s	~1min	~30s	~1min
Observation 2				
Observation 3				

fNIRS Data Acquisition

Infants will be seated in an infant chair and fitted with a specialized Brite ergonomic cap with integrated wireless fNIRS optodes (Artinis, Medical Systems, The Netherlands). The light emitting optodes will cover bilateral pre-motor, motor, and parietal areas of the brain (22 channels) (see figure 3). The fNIRS system operates at two wavelengths, 760 and 850 nm, sampled at a rate of 25 Hz. The Optodes were placed 3cm apart, however one short separation channel (SSCH) was placed on the left hemisphere over the motor cortex. These SSCH are 1.5 cm apart and help reduce "noise," movement artifacts and physiological noise. Afterwards we will ensure that the infant can tolerate the cap and adjust the optodes as needed. Once complete I will begin with a cue that will mark the start of fNIRS and behavioural data collection. The cue is set by E-prime 3.0 (Psychology Software Tools, PA, USA), which is presented on a laptop (Dell Latitude 3410, 14" HD, 1920 x 1200 resolution) and sets off an auditory cue and inserts a time sync within the fNIRS data. During the experiment, the infant will have close contact with the parent/caregiver to help induce a high level of comfort. Between the reaching and free play tasks, the fNIRS system is recalibrated (Autobrite) and each optode signal is checked.

Figure 1.

Right and left hemisphere optode array where white represents transmitting optodes and black represents transmitting optodes. The source-detector pairings make up 22 channels across the pre-motor, motor, and parietal lobe. A short separation channel in the left hemisphere has been placed on channel 17 (T7 & R7)



Channel	Receiver	Transmitter
1	R1	T1
2	R1	T2
3	R2	T1
4	R2	T2
5	R2	T3
6	R3	T2
7	R3	T4
8	R4	T2
9	R4	T3
10	R4	T4
11	R4	T5
12	R5	T6
13	R5	T7
14	R6	T6
15	R6	T7
16	R6	T8
17	R7	T7
18	R7	T9
19	R8	T7
20	R8	T8
21	R8	T9
22	R8	T10

Video Data Acquisition

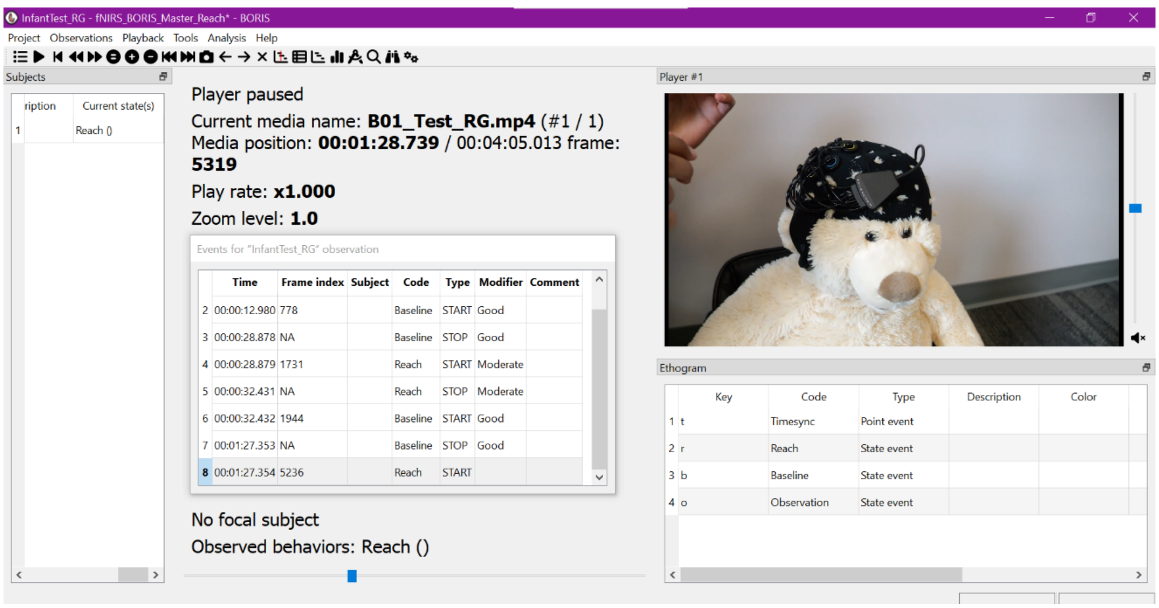
For behavioural data we use 2 digital cameras (Panasonic Lumix Gh6, Lens: Panasonic Leica DG Vario-Elmarit 12-60mm) sampled at 21 frames per second. The first camera will be positioned 3 ft in front of the infant and mounted to a stand approximately 75 cm tall, and the second camera set around 5 ft to the left of the infant and mounted to a stand around 68 cm tall. The cue from E-prime will be used to connect the behavioural data with fNIRS data.

Data Processing

Video data was analyzed through BORIS (Friard, 2024), a behavioural software program that is used for logging live observations. I have created an ethogram (see figure 5) to be able to code live events and rate the quality of movement, observation, and rest conditions. Each event was rated on the level of engagement of the participants, with good signifying high engagement and poor low engagement. Moderate was given when participants had momentary distractions.

Figure 2.

Inserting live observations in BORIS



The ethogram consists of five behaviours/events: time sync (t), baseline (b), reaching and grasping (r), free play, (f), and observation (o).

Figure 3.

Ethogram used to code live events in BORIS

Information | Ethogram | Subjects | Independent variables | Behaviors coding map | Converters

	Behavior type	Key	Code	Description	Color	Category	Modifiers	Exclusion	Modifiers coding
1	Point event	t	Timesync	Timesync	#0162ff				
2	State event	r	Reach	Reach	#dd0105		{"0": {"name": ...	Baseline,Observ...	
3	State event	o	Observation	Observation ...	#69e516		{"0": {"name": ...	Baseline,Reach,F...	
4	State event	f	Freeplay	Freeplay	#aaaaff		{"0": {"name": ...	Baseline,Reach,...	
5	State event	b	Baseline	Baseline (or rest ...	#01b6d6		{"0": {"name": ...	Reach,Observati...	

Once complete, events are exported to excel where the event times are converted to match the fNIRS data. Then we can combine our behavioural observations with our fNIRS data within Oxysoft 4.0 (Artinis, Medical Systems, The Netherlands), which allows for me to insert the events manually. The fNIRS and behavioural data is then fully combined in Oxysoft and exported to the AnalyZIR software, which converts the data into the form of a snirf file for further analysis in MATLAB (MATLAB, 2021).

Data Analysis

A neural connectivity analysis will also be implemented to extract movement artifacts and physiological noise (Huppert, 2016). Then we will implement a general linear model (GLM) that will be used to find significant brain activity within specific channels for naturalistic play and reach conditions.

Future Directions

My UREAP has provided me with valuable research experience, this summer I got the opportunity to engage in the process of developing and designing my experiment. It can be rare for students to be so closely involved in the design of a study, so I consider myself quite lucky to get such a detailed learning experience that will help me with future research endeavors. As we continue to test participants and begin to analyze the data, we will be checking to ensure that our design is well thought out and note what changes we could improve upon in the future. I was also able to learn how to use data collection software and begin coding my first few participant's fNIRS and behavioural data. Working with the NIRS system has been an amazing experience, throughout the summer I was able to learn how to properly set up the NIRS cap, check for good signals of each transmitter and receiver, and to navigate Oxysoft for data collection.

Since this project is a longitudinal design, I plan to continue this research into my Honours Thesis, where I can continue recruitment, test more participants, and learn to analyze the data. Since beginning my studies, I quickly learned that my area of interest is brain and behaviour, and conducting research is my primary goal in the future. Once completing my bachelor's degree, I hope to continue into a master's degree in cognitive science. Working with a special population such as babies and carers is quite a unique opportunity that will help me in my future career. Learning complex techniques like fNIRS and behavioural coding will also be helpful given these techniques may be implemented in future research settings.

This research can provide further understanding of the brain-behaviour changes that occur in infant development. Our results will provide insight into how the brain re-organizes as a child builds motor skills by examining brain activity using fNIRS and correlating such activity with movements. The infants will produce repetitive movements such as reaching, touching, grasping, and kicking as with previous studies. However, unlike previous studies, our study will be able to identify brain activity over multiple areas of the brain as the infants produce and rehearse these movements. It is important to note that this study will also serve as time one (cross sectional) and continue as part of a longitudinal design, which are largely lacking in developmental neuroscience. Future research will benefit from the characterization of brain activity synced with behaviour for the identification of and to facilitate early interventions for atypical developmental trajectories.

References

Agyeman, K., McCarty, T., Multani, H., Mattingly, K., Koziar, K., Chu, J., Liu, C., Kokkoni, E., & Christopoulos, V. (2023). Task-based functional neuroimaging in infants: a systematic review. *Frontiers in neuroscience*, *17*, 1233990.

Andersen, R. A., & Cui, H. (2009). Intention, action planning, and decision making in parietal-frontal circuits. *Neuron*, *63*(5), 568-583. https://doi-org.ezproxy.tru.ca/10.1016/j.neuron.2009.08.028

Asanuma, H., & Mackel, R. (1989). Direct and Indirect Sensory Input Pathways to the Motor Cortex - Its Structure and Function in Relation to Learning of Motor-Skills. *Japanese Journal of Physiology*, *39*(1), 1–19. https://doi.org/10.2170/jjphysiol.39.1

Azhari, A., Truzzi, A., Neoh, M. J. Y., Balagtas, J. P. M., Tan, H. H., Goh, P. P., Ang, X. A., Setoh, P., Rigo, P., Bornstein, M. H., & Esposito, G. (2020). A decade of infant neuroimaging research: What have we learned and where are we going? *Infant Behavior and Development, 58*. https://doi.org/10.1016/j.infbeh.2019.101389

Bornstein, M. H. (2014). Human infancy… and the rest of the lifespan. Annual Review of Psychology. Annual Review of Psychology, *65*, 121–158. https://doi.org/10.1146/annurev-psych-120710-100359

Buch, E. R., Brasted, P. J., & Wise, S. P. (2006). Comparison of population activity in the dorsal premotor cortex and putamen during the learning of arbitrary visuomotor mappings. *Experimental Brain Research*, *169*(1), 69–84. https://doi.org/10.1007/s00221-005-0130-y

Cattaneo, L., Caruana, F., Jezzini, A., & Rizzolatti, G. (2009). Representation of goal and movements without overt motor behavior in the human motor cortex: a transcranial magnetic stimulation study. *Journal of Neuroscience*, *29*(36), 11134-11138. https://doi.org/10.1523/JNEUROSCI.2605-09.2009

Corbetta, D. (2021). Perception, Action, and Intrinsic Motivation in Infants' Motor-Skill Development. *Current Directions in Psychological Science*, 30(5), 418-424. https://doi.org/10.1177/09637214211031939

Corbetta, D., Thurman, S. L., Wiener, R. F., Guan, Y., & Williams, J. L. (2014). Mapping the feel of the arm with the sight of the object: on the embodied origins of infant reaching. *Frontiers in Psychology, 5*. https://doi.org/10.3389/fpsyg.2014.00576

de Oliveira, S. R., Cabral de Paula Machado, A. C., de Paula, J. J., Paiva de Moraes, P. H., Silverio Nahin, M. J., Magalhaes, L. de C., Novi, S. L., Mesquita, R. C., de Miranda, D. M., & Ferrarez Bouzada, M. C. (2018). Association between hemodynamic activity and motor performance in six-month-old full-term and preterm infants: a functional near-infrared spectroscopy study. *Neurophotonics, 5*(1), 011016. *https://doi.org/10.1117/1.NPh.5.1.011016*

Edelman, G.M. (1989) *Neural Darwinism: The Theory of Neuronal Group Selection*. Oxford University Press.

Fogassi, L., Ferrari, P. F., Gesierich, B., Rozzi, S., Chersi, F., & Rizzolatti, G. (2005). Parietal lobe: from action organization to intention understanding. *Science 308*, 662–667. DOI: 10.1126/science.1106138

Friard, O. (2012-2024). *BORIS*. https://www.boris.unito.it/

Georgopoulos, A. P., Kalaska, J. F., Caminiti, R., & Massey, J. T. (1982). On the relations between the direction of two-dimensional arm movements and cell discharge in primate motor cortex. *Journal of Neuroscience 2,* 1527–1537. https://doi.org/10.1523/JNEUROSCI.02-11-01527.1982

Gesell, A., & Amatruda, C.S. (1947) *Developmental Diagnosis; Normal and Abnormal Child Development* (2nd ed.). Harper & Row.

Gottlieb, G., Wahlsten, D., & Lickliter, R. (1998). The significance of biology for human development: A developmental psychobiological systems view. In *Handbook of child psychology: Theoretical models of human development* (Vol. 1, pp. 233–273). John Wiley & Sons. https://doi.org/10.1002/9780470147658.chpsy0105

Helmholtz, H. V. (1867). Handbuch der physiologischen Optik [Manual of physiological optics]. Leopold Voss.

Hey Bear Sensory. (2019, July 14). *Hey Bear Sensory - Under the Sea - Relaxing animation - Sleep Video- Baby Sensory* [Video]. YouTube. https://www.youtube.com/watch?v=qCMZYEIlztY

Holdefer, R. N., & Miller, L. E. (2002). Primary motor cortical neurons encode functional muscle synergies. *Experimental Brain Research*, *146*(2), 233–243. https://doi.org/10.1007/s00221-002-1166-x

Huppert, T. J. (2016). Commentary on the statistical properties of noise and its implication on general linear models in functional near-infrared spectroscopy. *Neurophotonics, 3*(1), 010401. https://doi.org/10.1117/1.NPh.3.1.010401

Ichikawa, H., Nakato, E., Igarashi, Y., Okada, M., Kanazawa, S., Yamaguchi, M. K., & Kakigi, R. (2019). A longitudinal study of infant view-invariant face processing during the first 3–8 months of life. *NeuroImage, 186,* 817–824. https://doi.org/10.1016/j.neuroimage.2018.11.031

Jasper H (1958) The ten-twenty electrode system of the international federation. *Electroencephalography and Clinical Neurophysiology 10*:371–375

Kalaska, J. F., Scott, S. H., Cisek, P., & Sergio, L. E. (1997). Cortical control of reaching movements. *Current Opinion in Neurobiology, 7*(6), 849–859. https://doi.org/10.1016/S0959-4388(97)80146-8

Karim, H., Schmidt, B., Dart, D., Beluk, N., & Huppert, T. (2012). Functional near-infrared spectroscopy (fNIRS) of brain function during active balancing using a video game system. *Gait & Posture*, *35*(3), 367–372. https://doi.org/10.1016/j.gaitpost.2011.10.007

Köster, M., Kayhan, E., Langeloh, M., & Hoehl, S. (2020). Making sense of the world: Infant learning from a predictive processing perspective. *Perspectives on Psychological Science, 15*(3), 562–571. https://doi.org/10.1177/1745691619895071

Li, X., Jin, M., Zhang, N., Hongman, W., Fu, L., & Qi, Q. (2024). Neural correlates of fine motor grasping skills: Longitudinal insights into motor cortex activation using fNIRS. *Brain & Behavior*, *14*(1), 1–19. https://doi.org/10.1002/brb3.3383

Lloyd-Fox, S., Blasi, A., & Elwell, C. E. (2010). Illuminating the developing brain: The past, present and future of functional near infrared spectroscopy. *Neuroscience and Biobehavioral Reviews*, *34*(3), 269–284. https://doi.org/10.1016/j.neubiorev.2009.07.008

Lloyd-Fox, S., Wu, R., Richards, J. E., Elwell, C. E., & Johnson, M. H. (2015). Cortical Activation to Action Perception is Associated with Action Production Abilities in Young Infants. *CEREBRAL CORTEX*, *25*(2), 289–297. https://doi.org/10.1093/cercor/bht207

MATLAB. (2021). *version 9.11.0.1837725 (R2021b)*. Natick, Massachusetts: The MathWorks Inc.

McGraw M. (1935) *Growth: a study of Johnny and Jimmy.* D. Appleton – Century company.

McGraw, M. B. (1943). *The neuromuscular maturation of the human infant*. Columbia University Press.

Moran, D. W., & Schwartz, A. B. (1999). Motor cortical representation of speed and direction during reaching. *Journal of Neurophysiology, 82*, 2676–2692. https://doi.org/10.1152/jn.1999.82.5.2676

Nagai, Y. (2019). Predictive learning: its key role in early cognitive development. Philosophical Transactions: *Biological Sciences, 374*(1771), 1–13. https://doi.org/10.1098/rstb.2018.0007

Nishiyori, R. (2016). fNIRS: An Emergent Method to Document Functional Cortical Activity during Infant Movements. *FRONTIERS IN PSYCHOLOGY*, *7*. https://doi.org/10.3389/fpsyg.2016.00533

Nishiyori, R., Bisconti, S., Meehan, S. K., & Ulrich, B. D. (2016). Developmental changes in motor cortex activity as infants develop functional motor skills. *Developmental Psychobiology*, *58*(6), 773–783. https://doi.org/10.1002/dev.21418

Pinti, P., Tachtsidis, I., Hamilton, A., Hirsch, J., Aichelburg, C., Gilbert, S., & Burgess, P. W. (2020). The present and future use of functional near-infrared spectroscopy (fNIRS) for cognitive neuroscience. *Annals of the New York Academy of Sciences, 1464*(1), 5–29. https://doi.org/10.1111/nyas.13948

Raschle, N., Zuk, J., Ortiz, M. S., Sliva, D. D., Franceschi, A., Grant, P. E., Benasich, A. A., & Gaab, N. (2012). Pediatric neuroimaging in early childhood and infancy: challenges and practical guidelines. Annals of the New York Academy of Sciences, *1252*(1), 43–50. https://doi.org/10.1111/j.1749-6632.2012.06457.x

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

Schubotz, R. I. (2015). Prediction and expectation. In A. W. Toga (Ed.), *Brain mapping: An encyclopedic reference* (Vol. 3, pp. 295–302). Elsevier. https://doi.org/10.1016/B978-0-12-397025-1.00247-5

Sporns, O., & Edelman, G. M. (1993). Solving Bernstein's problem: a proposal for the development of coordinated movement by selection. *Child Development 64*(4) 960–81. https://doi.org/10.2307/1131321

Sutton, R. S., & Barto, A. G. (1998). *Reinforcement learning: An introduction*. Bradford Books.

Thelen, E., Skala, K. D., & Kelso, J. S. (1987). The dynamic nature of early coordination: Evidence from bilateral leg movements in young infants. *Developmental Psychology*, *23*(2), 179–186. https://doi.org/10.1037/0012-1649.23.2.179

Tunik, E., Houk, J. C., & Grafton, S. T. (2009). Basal ganglia contribution to the initiation of corrective submovements. *NeuroImage*, *47*(4), 1757–1766. https://doi.org/10.1016/j.neuroimage.2009.04.077

Wenderoth, N., Debaere, F., Sunaert, S., van Hecke, P., & Swinnen, S. P. (2004). Parieto-premotor Areas Mediate Directional Interference During Bimanual Movements. *Cerebral Cortex*, *14*(10), 1153–1163. https://doi.org/10.1093/cercor/bhh075