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Spatial Cognition in Infants with Myelomeningocele: Transition from Immobility to Mobility

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Spatial Cognition in Infants with Myelomeningocele: Transition from Immobility to Mobility

by

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Spatial Cognition in Infants with Myelomeningocele:

Transition from Immobility to Mobility

Monica Rivera

Abstract

Previous studies with typically developing (TD) infants have shown that the onset of mobility facilitates advancement in specific spatial cognitive skills. The purpose of this investigation was to document spatial cognition in TD infants and infants with myelomeningocele (MMC), to determine the role of mobility experience in spatial cognitive development. A longitudinal study investigated changes in spatial cognitive performance in five infants with MMC as they progressed from immobility to mobility. Thirty TD eight to nine-month-old infants formed two equal crawling and non-crawling groups for comparison. The hypothesis was that significant differences would be seen in (1) visual control of posture (2) shape perception and (3) joint visual attention in both TD and MMC studies after the onset of mobility. The results showed the crawling TD group had significantly higher performance on all three spatial cognitive tasks compared to the non-crawling TD group. The MMC infants showed improvements on all three tasks after they transitioned to independent mobility, however, only the changes on the shape perception task were statistically significant. These results confirm previous TD studies and highlight the importance of mobility experience in spatial cognitive development. Furthermore, the results highlight the increased risk of spatial cognitive delay faced by the MMC infants because of their delayed onset of independent mobility.

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1. Introduction

The onset of independent mobility catalyzes developmental change across a broad range of psychological domains. Numerous studies have established that significant emotional, social, and cognitive advances occur after the initiation of crawling. Additionally, alternative forms of self-produced locomotion, such as those enabled by walking devices and powered apparatuses, have been shown to make a positive contribution to psychological development. [1-4] While the interaction between mobility and psychological transitions appears to cover a wide developmental spectrum, investigations have clearly defined specific processes that are responsive to the onset of locomotion. Although all the factors occurring in this process have not been fully clarified, investigators speculate that mobility facilitates attentional competencies which in turn promote a heightened awareness to relevant objects and events as an infant moves through space.[1, 5] In addition to increased environmental awareness, mobility alters social interactions, increasing the variety of caregiver-infant exchanges. For example, joyous outbursts of parental delight occur while crawling to outstretched arms or, in direct contrast, cries of fear and caution when the infant engages in hazardous play. Consequently infant mobility takes place within a rich environmental array which is embedded in social, emotional, and cognitive contexts.[6, 7] Therefore, an accurate description of the consequences of mobility is that it is a facilitator of skills and an organizer of psychological change across a spectrum of domains.[1]

The importance of mobility and its influence on psychological development has major implications for infants and children with movement disabilities. While some researchers and clinicians in the rehabilitation field have long advocated that delays in mobility lead to diminished cognitive capacities, there is limited evidence to support this notion. [8-10] In order to substantiate the relationship between mobility and psychological development, researchers have recently sought to determine whether providing powered mobility to young children will facilitate psychological change. Research has shown that seven month-old typically developing (TD) infants and infants with disability can move around proficiently using powered mobility; [11, 12] however, it has been a greater challenge to establish an association between mobility and psychological growth in these infants. Studies with infants and children using powered mobility have revealed a mixed pattern across the developmental spectrum, with minimal to modest growth in social and cognitive arenas.[13-16] One of the major drawbacks of these investigations is the use of broad based psychological measures of cognitive and social development, which lack the sensitivity to depict specific developmental transitions.[17] Given the complexities associated with investigating this interaction in the disability population, it is best to uncover the specific spheres that demonstrate sensitivity to locomotor onset in the TD population and from these findings implement definitive measures to verify mobility's influence in infants with motoric disability.

One area that has demonstrated responsiveness to the onset of locomotion is spatial cognition. Spatial cognition is an essential life skill; it encompasses the ability to perceive, store, and recall the location of items and places. A working definition of spatial cognition reveals a myriad of tasks and mental processes involving an individual's orientation in space, direction, and spatial relations between self and the environment.[18, 19] Activities such as moving from one location to another, recalling and retrieving everyday personal possessions, calibrating an object's length, depth, and height depicts some of its essential functions. Thus, independent mobility yields a dual effect in spatial dimensions; it expands a person's comprehension of the physical landscape, while promoting selective attention to location and spatial details of objects. In essence, locomotion widens and deepens an infant's spatial dimensions into far and near space, while providing critical information of spatial orientation and relationships to places and objects within the world. Specific spatial processes that have been associated with the onset of mobility are enhanced responsiveness to motion in the peripheral field of view, an increased understanding of an object's invariant characteristics, and an increased ability to locate objects in near and far space.

Mobility and Spatial Cognitive Development in Myelomeningocele

An ideal population in which to examine the interaction between mobility and psychological processes are infants with myelomeningocele (MMC). MMC is a neural tube defect involving incomplete closure of the posterior spine. The deficit occurs primarily in the lumbar and sacral region producing a spinal cord lesion with resultant lower extremity paraplegia. Additional neurological deficits include hydrocephalus, Arnold Chiari II malformation, and bowel and bladder involvement along with a range of orthopedic deformities.   While paraplegia results in motor skill delays, including the onset of mobility, most infants achieve self-propelled mobility.[20] In addition to the motor and cognitive deficits, MMC individuals have spatial-perceptual deficits. Although these deficiencies have been associated with hindbrain abnormalities commonly found in MMC, there is speculation that reductions in mobility and environmental experiences contribute to spatial-perceptual problems.[21] Infants with MMC provide an opportunity to investigate spatial-cognitive development, to determine if changes in performance are related to crawling experience or are influenced by other factors such as age and maturation.

An investigation by Campos et al[22] with sacral MMC infants provides considerable insight into the development of spatial cognition skills. Seven MMC infants underwent two spatial cognitive assessments prior to and after the onset of crawling. The assessments involved a two position-hiding task and a test of joint visual attention (JVA), which shows the ability to follow another person's point and gaze gestures. The mean age of crawling onset was 10.75 months. Post mobility results showed significant increases in finding the object in the two position-hiding task along with a dramatic shift in looking toward the correct target in the point and gaze gesture task. Thus, in MMC infants demonstrating mobility delays there were distinct gains in performance after mobility onset, giving credence to the concept that crawling experience spurs transitions in spatial cognition.

The goal of this study is to extend the findings of the Campos et al investigation by examining MMC infants with lumbar and sacral deficits as they transition from immobility to self-produced crawling. The study will introduce two additional spatial cognitive processes previously linked to mobility, visual proprioception and shape perception. The study will include the JVA paradigm, to confirm if infants will show a delay in performance until the onset of mobility. The approach of investigating infants with mobility delays will provide a clear vantage point concerning mobility, as spatial cognitive skills are expected to remain relatively stable with immobility and advance with the onset of locomotion. Furthermore, infants with lumbar involvement show greater delays in the onset of mobility, thus producing stronger evidence that mobility experience is a factor in the development of spatial cognitive skills.

1.1 Background

Locomotor experience, visual proprioception, joint visual attention, and shape perception

This study focuses on three spatial-cognitive phenomena that are known to change markedly after the onset of independent mobility in typically developing infants: visual proprioception, joint visual attention, and shape perception. According to Gibson, active exploration and discovery are foundational for developmental advancement.[23] During the first stages of mobility, infants identify the necessary perceptual information (visual, haptic, auditory, and proprioceptive) critical for mobility sucess.[24] The interaction of motor activity and perceptual information or “perception-action coupling” describes the process of detecting and employing perceptual information to guide purposeful motor actions. To illustrate, as crawling emerges it permits access to objects, novel surfaces, distinct vantage points, and social exchanges. Infants perceive information (slopes, contours, caregiver’s gestures) critical for crawling proficiency while continuing to attend to significant information in the environment. More importantly, mobility does not occur as an isolated event, but in a vast array of experiential contexts. Thus the act of mobility involves discovery and integration of perceptual information that takes place within diverse cognitive, emotional, and social situations.[25, 26] This discovery in such a diversity of contexts provides the basis from which to expect important changes in psychological function.

As infants' gain mobility experience, specific alterations emerge in the perception of visual information. Visual information consists of rays of light reflecting off surfaces that project a geometrical pattern onto the retina. As an individual moves forward, this visual array becomes a dynamic flow of optic information or "optic flow." This process is eloquently described by Gibson as a "stream of visual information as one moves through space."[27] Optic flow is comprised of two distinct patterns: a radial pattern which occupies the central visual field and a lamellar pattern inhabiting the peripheral field when the observer looks in the direction of travel.[28] The radial pattern expands from a central point while the lamellar pattern delivers parallel streams in the periphery. Optic flow serves several essential functions: it provides a rich source of visual feedback regarding an individual's speed and direction of movement and is pivotal in postural maintenance.[27, 29] Individuals can recognize their own movement in space via optic flow in the peripheral and central field of view.

Optic flow can be controlled experimentally in a "moving room;" a three-wall enclosure with a set of independent moving patterned walls which create optic flow. Walls can be moved in a whole room (global) or sidewall (lamellar) configuration generating the illusion of self-movement and inducing a backward or forward postural sway depending upon the direction of wall movement.[30, 31] Investigations with infants reveal a developmental trajectory, in which postural sway to whole room movement occurs at 5-7 months and heightened responses to side wall movement occurs at 9 months.[32] While some researchers theorized that the transition in postural responses was due to maturational processes, Higgins et al [33] clearly demonstrated that the onset of mobility is associated with increased responsiveness to peripheral (lamellar) optic flow.

Another skill that is transformed after mobility onset is the understanding of the spatial layout; entailing a shift from an egocentric (body-referenced) orientation to an allocentric (environment-referenced) orientation. The transition expands the spatial world and organizes spatial relationships between self, object, and locations.[34] While this change is associated with maturational factors,[35, 36] others have argued that the skill is influenced by the onset of mobility, asserting that the allocentric scheme arises out of sheer necessity as infants require an environment-focused spatial reference system to keep track of objects and update their location in space.[37, 38] Investigations bear this out, revealing abrupt changes in spatial performance in the areas of manual search for hidden objects, spatial coding strategies, and memory retrieval after the onset of locomotion.[39-41]

Occurring alongside the transition to an allocentric orientation are changes in caregiver interaction, noted by the emergence of the caregiver referencing objects or events at distant locations.[42] For example, caregivers will point out objects at a distance and say, "Let's see what is over here" or with prohibitive statements such as "No, don't touch the plant." As crawling and far space communication becomes commonplace, the infant comprehends the caregiver's gestural cues of head turning, finger pointing, and eye direction to the relevant structures. The result is an evolution in infant social interaction involving the capacity to follow the caregiver's spatial referencing. This ability, also known as JVA and is best expressed by Butterworth's description, "looking where someone else is looking."[43] With ongoing experience, the infant grasps the verbal encounters and gestural cues of caregiver head, eye direction, and finger pointing. Research confirms the importance of locomotion in this transition, revealing an increase in following another individual's gestural and verbal directional declarations after locomotion onset, even, as noted earlier, in infants whose locomotor onset is delayed because of MMC.[42]

Locomotor onset transforms the spatial landscape and affords a new vantage point for observing objects from a variety of distances and angles. Mobile infants realize that an object's contours change with an adjusting viewpoint; however, the form, shape, and size of an object remain constant. Therefore, mobility provides experiences in "extracting" the essential features of objects, like shape and size. To test this hypothesis, Campos et al [44] investigated typically-developing locomotor and prelocomotor infants in an age held constant (7.5 months) design. Infants were exposed to six familiarization trials consisting of similar paired configurations of a rectangle, a cylinder, and a cube that were organized into the shape of a ship or a cross, with each trial displaying distinctions in color (yellow and red), orientation (upright and horizontal), and size (small and medium). Throughout all six trials, the same configuration (ship or cross) was displayed with variations in the other three distinctions. The seventh and eighth trials were "test" trials presenting the form of the previously observed shape paired with a new configuration, with both stimuli exhibiting a new size, color, and orientation. The results showed that crawling infants spent more time looking at the novel form compared to the familiar form, suggesting that they recognized the familiar form as one they had seen before even though its size, color, and orientation were different. In contrast, prelocomotor infants spent equal time observing the novel and familiar forms. The study concluded that locomotor skill contributes to the discernment of forms and shapes.

1.2 Study Aims

Therefore, the onset of mobility influences a wide spectrum of psychological domains with transitions occurring in distinct spatial-cognitive skills. Other developmentalists have recognized these diverse transactions and described mobility as a "psychological birth" and an infant's first real engagement with the world. [45] With this in mind, the primary hypothesis for this study is that infant spatial cognitive performance will improve significantly after the onset of mobility. The performance of the MMC infants as they transition from immobility to mobility will be compared with a cross sectional group of 8-9 month-old TD crawling and non-crawling infants who will undergo similar spatial cognitive testing. The first specific aim of the study is to confirm previous findings in the TD population, that there will be significant changes in the (1) visual control of posture (2) shape perception, and (3) joint visual attention after the onset of independent mobility. The second specific aim is to evaluate whether there are similar spatial cognitive changes from immobility to mobility in infants with MMC as they transition from immobility to self-produced crawling. We hypothesize that these skills will remain relatively stable during the period of immobility in the MMC infants and then demonstrate a marked advancement with locomotion.

2. Methods

MMC Subjects: The internal review board (IRB) at the University of California San Francisco (UCSF), University of California Berkeley (UCB), Children's Hospital Oakland (CHO), Kaiser Permanente Northern California and San Francisco and San Francisco State University (SFSU) approved the MMC study. Eight infants were recruited and enrolled from March to December 2011 from the following facilities: (1) Spina Bifida Clinic at UCSF Beniof Children's Hospital; (2) Spinal Defects Clinics at CHO; and (3) Genetics Clinic at Kaiser Permanente Oakland. The parents of two infants did not return after the first visit and another family did not return phone messages, leaving five infants for the study. Inclusion criteria were: (1) diagnosis of myelomeningocele or lipomyelomeningocele; (2) six months of age at time of recruitment; (3) prelocomotor skills upon initial testing; (4) lumbar lesion level or below; (5) controlled hydrocephalus; (6) upright sitting in a supported chair; and (7) 7.5 to 26 months of age. Exclusion criteria were (1) evidence of anoxic encephalopathy; (2) evidence of upper extremity weakness or spasticity in the upper extremities; (3) evidence of self-produced locomotor activity including artificial means (walker, mobility devices) at time of initial testing; (4) thoracic lesion level or above.

TD Subjects: The IRB at UCB approved this study. Infants were recruited from postcard mailings to cities surrounding the University of California, Berkeley. Inclusion criterion was eight to nine months of age. Exclusion criteria were: (1) premature birth (gestational age below 36 weeks) and (2) developmental disability. Infants were divided into two groups, crawling and non-crawling, by video tape analysis performed prior to the experimental testing. Infants were placed on an eight-foot mat (marked at one-foot intervals) with the caregivers located on the opposite end of the mat. Caregivers encouraged their infants to crawl by calling their name, using hand gestures and displaying toys/favorite objects. Infants were given two crawling trials. Infants in the crawling group demonstrated the following characteristics: (1) crawling six feet or more without stopping and (2) maintaining the quadruped position. Infants in the non-mobile group did not demonstrate any forward crawling behaviors during the two trials. The total number of infants numbered 30, with 15 infants in each group. See Table 1-2 for demographics of the TD participants. See Table 3 for demographics of the MMC participants.

Table 1*:* Demographics for typically developing crawling group (n=15)

Age	Sex	Mobility Onset (Months)	Weeks Crawling	Velocity (m/s)
8.54 ± 0.32	M=6 F=9	7.22 ±0.66	6.03 ± 2.10	0.2176 ± 0.062

Table 2: Demographics for typically developing infants non-crawling group (n=15**)**

Age	Sex	Mobility Onset (Months)	Weeks Crawling	Velocity (m/s)
8.40 ± 0.29	M=11 F= 4	0	0	0

Table 3: Demographics for Myelomeningocele participants (n=5)

Participants	SB02	SB03	SB05	SB06	SB07
Ethnicity	Latino	Other	Caucasian	African American	Latino
Sex	M	F	M	F	M
Lesion Level	L1	L4	L4	L4	L5
Age at study onset M=11.6 months	14	15	8.5	13	7.5
Age at crawling belly (Months) M=19.6 months	22	24	20	17	15
Age at crawling HK (Months)	23	0	0	0	16
AC Malformation	yes	yes	yes	yes	yes
Hydrocephalus	yes	yes	yes	yes	yes
VP Shunt	yes	yes	yes	yes	Yes

SB, Spina Bifida; AC, Arnold Chiari; VP, Ventriculoperitoneal.

Testing of MMC and TD participants took place at the Infant Studies Center at UCB, Institute of Human Development. MMC participants had up to six visits, returning to UCB at intervals of six to eight weeks. Each infant completed the study when he/she demonstrated independent forward crawling on hands and knees or had completed six visits. At the initial visit, caregivers completed three forms: (1) a development questionnaire; (2) caregiver survey and (3) a health intake form. At each subsequent visit, the developmental questionnaire was reviewed and a motor developmental examination was performed using the Alberta Infant Motor Scale (AIMS). Participants underwent three spatial cognitive assessments during each visit: Assessment 1: Testing for Visual Proprioception in a Moving Room; Assessment 2: Joint Attention Elicited by Point and Gaze; and Assessment 3: Extraction of Invariant Form from Varying Displays. The same test order was used each time to reduce error variance. The MMC participants were videotaped when crawling emerged.

The TD participants were tested one time at UCB. The caregivers filled out two forms: (1) a development questionnaire and (2) caregiver survey. The TD participants were videotaped to assess their crawling status and then underwent the three spatial cognitive assessments in the same order previously described for MMC participants.

Assessment 1: Testing for Visual Proprioception utilizing the Moving Room uncovers the effects of optic flow on infant sitting posture.[29, 30] The moving room is a three walled enclosure 1.2 x 1.2 x 2.1 m (H X W X L) designed for independent side wall and whole room movement. Blue fabric with white polka dots covers the ceiling and walls. Both side and front walls are attached to a potentiometer that computes the direction and distance of wall movement. The wall travels 35.5 cm over a two-second period. Four pressure transducers are located under each leg of the infant chair to measure shifts in the center of pressure that occur with postural movements. The cross-correlation between the changes in the infant's center of pressure and the changes in wall position is used to measure the infant's postural responsiveness to wall movement. See Figure 1 for the experimental set up of the moving room.

Figure 1: Moving Room experimental set-up

There were three forward and three backward trials for each of the two wall conditions: global (both sidewall and front wall) and peripheral (sidewall) movements, totaling 12 movement trials. The movement of the whole room presents global optic flow while the sidewall movement provides peripheral optic flow when the infant is looking forward. In addition, two pseudo-trials with no wall movement provide a baseline assessment. A camera records the infant's facial responses and position during the procedure to ensure that the infant is facing and looking forward.

Assessment 2: Joint Visual Attention Elicited by Point and Gaze assesses the ability to follow the point and gaze of the experimenter towards a target.[46] The experimental setting is a 140 X 95 cm space enclosed by two dark ceiling to floor curtains, which extend to two adjacent walls. A small section of the right facing curtain retracts 45 cm for recording of the experiment. Two floor projectors emit identical 46.5 X 62 cm scenes onto both walls. The scenes include four hybrid animals (depicting half mammal/half bird), 14 X 13 cm (length X height), projected to each corner of the screen.

The top images from the left and right projections are similar, while the lower figures depict different figures. Figure 2 show the experimental set-up of the paradigm.

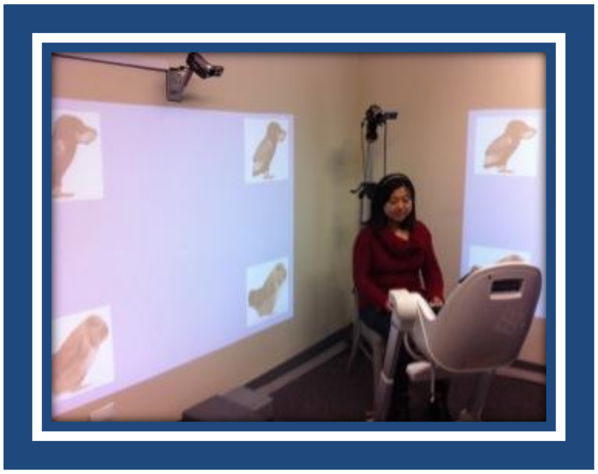

Figure 2: Joint Visual Attention experimental set-up

For the assessment, the infant sits in a high chair or in the caregiver's lap, with the examiner sitting directly in front of the infant at a distance of 46 cm. The height of the examiner's chair is adjusted so that the infant and the examiner are at eye level. The caregiver is instructed to sit behind the infant and not to interrupt the interaction between the infant and the examiner. Three cameras determine looking direction of the infant, one camera is located behind and above the experimenter, directed at the infant's face at a distance of 50 cm. Two cameras are located on the adjacent walls above the mid-point of the projected screen at a 45 angle from the infant's midline. One camera mounted at a far wall records the examiner's gesture. The vertical locations of the projected figures are 30 and 90 degrees respectively from the infant's midline. To initiate each trial the examiner establishes eye contact with the infant and turns her head to the appropriate target animal while pointing with the index finger across the body toward the target stating "[Baby's

Name, What's that?]. The experimenter holds the position for three seconds and places their head and hand to midline ending the procedure. For each trial, the experimenter gazes at each target two times in succession and then moves onto the next target. The experiment has 16 trials. There were four arrangements for the target order that were provided in random order.

Assessment 3: "Extraction of invariant form from varying displays" or Form Extraction examines the role of locomotor experience in discriminating various shapes across three dimensions: size, color, and orientation. The experiment is comprised of six training and two test trials. The configurations are comprised of three shapes: cube, rectangular block, and cylinder that form a cross or ship. Figure 3 provides a picture of the configurations. The two side-by-side training stimuli consist of these possible combinations: color (green, red, and yellow), sizes (5 cm, 9 cm, and 14 cm), and orientations (standing on end, standing at a 45 degree angle, and lying flat). Throughout the training trials, the stimuli were similar in configuration (cross or ship) while the dimensions of size, color, and orientation differed from the previous and subsequent trials. During the two test trials, one configuration was similar to the training trials, while the other stimulus was a novel shape. The test stimuli differed from the training stimuli in color and size: color is blue, and 11 cm in size.

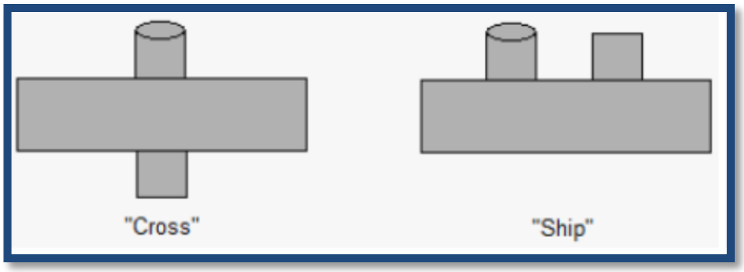

Figure 3: Extraction of Invariant Form configurations

The stimuli were secured to a 14 X 10 X 2 cm tray (width X length X depth) by two central equidistance screws. A 31cm X 31cm table includes an upright attachment 21 cm X 2 cm (height X width) containing an 18 X24 cm (width by length) aperture. Slated curtains hang from the top of the aperture and conceal the entire aperture. The aperture allows the tray with the stimuli to move from the experiment side through the aperture to the infant. A four cm round opening in the upright attachment permits a camera to record infant looking direction. An additional camera mounted above the infant records hand interaction with the stimuli. See Figure 4 for the experimental set-up of the extraction of invariant form.

Figure 4: Extraction of Invariant Form experimental set-up

The infant sits in a high chair or on the mother's lap at one side of the table. The experiment guides each of the eight trays from the experimenter side through the aperture to the infant side. Each training trial lasts 20 seconds, with a 10-second inter-trial interval. The two test trials are 10 seconds long, with a 10-second inter-trial interval.

2.1 Data Analysis

Six independent coders were blinded to the mobility status of the infant. Two coders were assigned to each of the paradigms and provided coding analysis across both the MMC and TD experiments. Inter-rater reliability was performed on the JVA and extraction of invariant form experiments. A kappa analysis was performed on the JVA variables of looking at the correct and incorrect targets and at the experimenter. Coding variables in the extraction of invariant form task were the amount of time the infants spent looking at the novel and the familiar form. A Kappa analysis was performed on the looking direction (novel and familiar) and an Intraclass Correlation (ICC) was conducted on the percentage of looking time.

TD study**:** To determine whether mobility promoted significant changes in spatial cognitive performance, a two by two analysis of variance (ANOVA) was performed in the Form Extraction paradigm involving two crawling factors (crawling and non-crawling) and two stimuli factors (novel and familiar), with repeated measures on the stimuli factor. To examine the effects of mobility in the JVA paradigm, a two way ANOVA was performed with two crawling factors (non-crawling and crawling) and two looking variables, looking at the correct target or experimenter. For the test of visual proprioception, a two-sample t-test was conducted comparing the cross-correlation results in the sidewall forward condition between the non-crawling and crawling groups. The level of significance was set at $p<0.05$. Excel 2010 performed the statistical analysis.

MMC study: To determine whether the onset of mobility produced significant changes in spatial cognitive performance, the data for each experiment were arranged into two categories: a non-mobile and a mobile phase. The non-mobile phase was comprised of the mean of the two sessions prior to the last visit and the mobile phase was the last visit to the infant center at UCB. A paired t- test was conducted in the test of visual proprioception comparing the non-mobile to mobile phases. The variables analyzed in the JVA and Form Extraction experiments were similar to the TD infants and data were analyzed with two-way repeated measures ANOVAs. The MMC study significance levels were set at $p<0.05$. Excel 2010 provided statistical analyses for the t-test and the two-way repeated measures ANOVA was analyzed using SPSS Statistics 20.

3. Results

Reliability Results Form Extraction: Inter-rater reliability for duration (time) was analyzed via the intraclass correlation coefficient (ICC) using a two-way mixed model, revealing ICC (3, 1) absolute=0.929. The reliability for infant looking direction revealed a strong agreement between raters, Kappa=0.972($p < 0.000$).

Reliability Results Joint Visual Attention: Inter-rater reliability for looking direction was analyzed by using Kappa statistics. The results revealed strong to moderate agreement for inter-rater reliability. Reliability analyses were performed in three directions: left and right: Kappa=0.887, up and down: Kappa=0.599, 45 degrees and 90 degrees: Kappa=0.649.

TD infant study: The t-test on the infant's postural responsiveness in the moving room (MR) compared the cross correlation of the center of pressures changes and wall movement (sidewall forward condition) in the crawling and non-crawling group. As found in previous studies, the crawling group ($M=0.59 \pm 0.18$) showed a significantly higher cross correlation than infants in the non-crawling group ($M= 0.45 \pm 0.16$), ($t(28)=-2.16$, $p=0.04$).

In the JVA experiment, the main effect of looking direction was significant, $F(1, 56) = 23.54$, $p < 0.0001$ while the effect of locomotor status was not significant, $F(1, 56) =3.76$, $p=0.06$. However, the interaction effect was significant, $F(1, 56) = 11.23$, $p=0.001$. Post-hoc analysis using Bonferroni adjusted alpha levels of 0.0250 per test (0.05/2) revealed significant findings. First, crawling infants spent significantly more time looking at the correct target than the non-crawling infants. Second, non-crawling infants spent significantly more time looking at the experimenter, while crawling infants were able to disengage from the experimenter and seek out the target. Table 4 provides the post-hoc analysis results.

Table 4: Post hoc results for Joint Visual Attention, typically developing infants

Assessment	Non-Mobile Mean	Mobile Mean	Independent t-test p< 0.025
Testing for JVA (percentage of correct looks)	M=14.16±10.15	M=21.25± 6.1	t(28)=-2.22,p=0.03
Testing for JVA (percentage of looks towards experimenter)	M=52.91±29.11	M=27.91±18.87	t(28)=2.79,p=0.009

In the final task, extraction of invariant form, the main effect for crawling was non-significant, F (1, 52) =2.66, p=0.11, nor was there a significant main effect of looking at shapes, F (1, 52) =0.04, p=0.84. However, the interaction effect was significant, F (1, 52) =7.96, p=0.006. Post-hoc analysis was performed (planned comparison) revealed significant findings revealing that within the crawling group, infants spent significantly higher looking percentage at the novel compared to the familiar shape. See Table 5 for results.

Table 5: Post-hoc results for Extraction of Invariant Form, TD group

Assessment	Mobile Mean Familiar	Mobile Mean Novel	Paired t-test $p < 0.05$
Testing for Form Extraction (percentage of looking time)	M=25.00 ± 8.6	M=35.29 ± 13.52	t (13)=2.45 p=0.002

MMC study: The results for the MMC infants conformed to expectations, though not all of the findings were statistically significant. The infants' postural responsiveness to the movement of the room in the sidewall forward condition showed a 0.11 increase in the cross correlation from the non-mobile phase (M=0.37 ± 0.17) to the mobile phase (M=0.48 ± 0.25), although the findings were not significant t(4) =-0.92, p=0.20. The JVA data were analyzed with a two way repeated measures ANOVA with two levels of looking (experimenter, correct looks) and two levels of mobility (mobile, non-mobile). The main effect of looking was not significant F (1, 4) =0.127, p=0.740, nor was the main effect of mobility, F (1, 4) = 0.820, p=0.416. There was no significant interaction, F (1, 4) = 2.26, p = 0.21. However, the MMC infants revealed a similar pattern to the TD infants. The correct looks increased 8.85% from the non-mobile phase (M=18.65 ± 9.5) to the mobile phase (M=27.50 ± 12.9). Additionally, there was a 19.41% decrease in gazing at the experimenter (M=35.65 ± 26.8) from the non-mobile phase to mobile phase (M=16.24 ± 8.3).

The extraction of invariant form data were analyzed with a two-way repeated measure ANOVA with two levels of mobility (mobile, non-mobile) and two levels of looking (novel, familiar) (see Figure 5). The main effect of mobility was not significant *F* (1, 3)=1.21, p=0.35 while the main effect of looking was significant, *F* (1,3) =99.03, p=0.002. The main effects were overshadowed by a significant interaction *F* (1,3)=41.26, p=0.008. In a planned comparison using a paired t-test, the mobile phase showed a significant increase of 32.11 percent in looking at the novel object (M=64.21 ± 20.9) compared to the non-mobile phase (M=32.11 ± 12.8) (t (3) =-2.42, p=0.04). Additionally, within the mobile phase, there was significantly greater looking at the novel object (M= 64.21 ± 20.9) compared to the familiar, (M=25.11 ± 13.87), (t(3)=2.48, p=0.04).

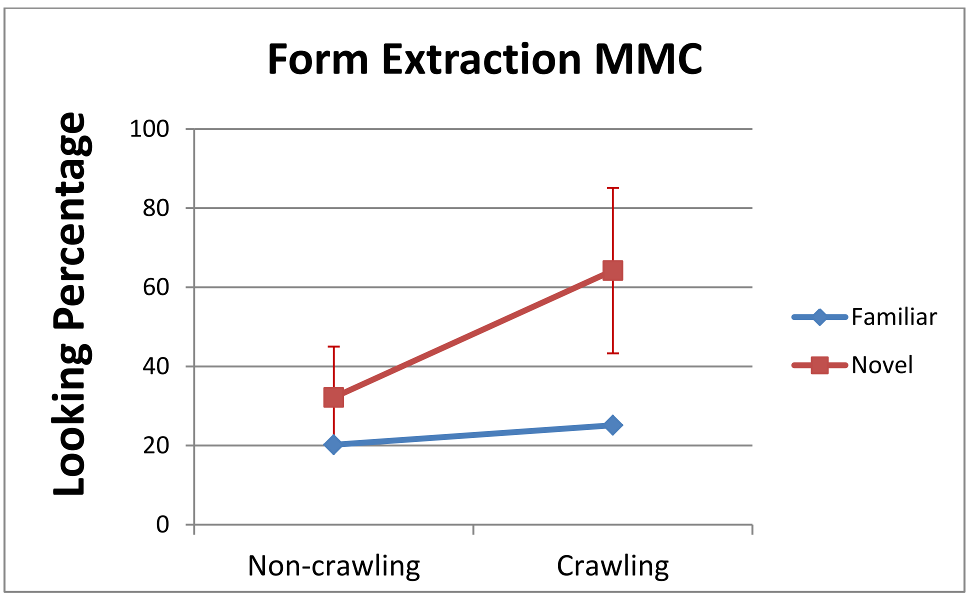

Figure 5: Results for extraction of invariant form experimenter: MMC group. Comparison of the non-crawling to crawling looking to the novel (paired t-test,p=0.04).

4. Discussion

The purposes of this study were to investigate the relationship between mobility and spatial cognition with MMC infants and to confirm whether typically developing crawling infants perform better than same-aged typically developing pre-crawling infants on three tasks that assess spatial cognition. The TD cross sectional results confirmed that crawling experience was associated with a significant advantage on the three spatial cognitive tasks. These findings are consistent with the results from previous spatial cognitive studies that have examined the effects of crawling experience.[33, 39, 40] In the form extraction task, the MMC infants showed significant increases from the non-mobile phase to the mobile phase in the percentage of looking time to the novel object. Furthermore, within the mobile phase, looking at the novel shape was significantly higher than the familiar shape. While the findings in the JVA and MR tasks were statistically weak in the MMC cohort, the results were positive and they support the premise that the acquisition of mobility enhances spatial-cognitive development. In spite of the weak findings in the MMC cohort, all together these findings strongly suggest that mobility plays a critical role in the development of infant spatial cognitive performance.

Some of the possible explanations for the lack of significant results in the MMC infants for the JVA and MR tasks are the small number of infants in the study (n=5), and the heterogeneity of the MMC population (spinal levels varying from Lumbar (L) one to L5. An additional explanation lies in the differences in the crawling characteristics amongst the MMC infants when compared to the TD crawling infants. There were distinct variations in crawling abilities in infants with higher lumbar involvement compared to the infant with a lower level of involvement (L5). The infants with higher lumbar levels (L1-L4) demonstrated belly crawling as their primary mode of crawling, but more noteworthy was how much effort was involved in their mode of locomotion: using upper limbs for forward progress with limited lower limb assistance, frequent stopping, and variability in head posture during crawling. While infants in the lower lumbar levels showed deviations in their patterns, the infant at the L5 level sustained a quadruped posture and was able to maintain an erect steady head posture while crawling six feet. In contrast, the TD crawling group displayed proficient abilities, demonstrating the ability to crawl at least six feet without stopping, maintain a quadruped posture, and demonstrating the ability to maintain an upright head posture. More importantly, the L5 infant's performance on the three spatial cognitive paradigms resembled the performance of the TD infants. Therefore, it could be postulated that the higher level lumbar infants' extra motoric effort, coupled with inconsistent head posture may reduce the ability to visually scan the environment while crawling, thus limiting the amount of attention that could be devoted to the environment.[44] This may indicate that infants require a specific level of crawling proficiency to advance spatial cognitive performance. For example, to increase visual proprioception in the periphery of the field of view, the infant may require steady forward mobility over certain distances while concurrently maintaining an erect head posture in order to differentiate radial and lamellar optic flow patterns. In other words, the quality and characteristics of crawling experience could be the critical components in order for infants to functionalize visual information for use in the control of posture and locomotion.

Each of the paradigms provides unique insight in the underlying process in spatial cognitive development. In spite of the late onset of mobility in the MMC group, the results revealed lower cross correlation measurements in the sidewall forward condition in the non-mobile phases while demonstrating an overall increase in postural responsiveness to the sidewall forward movement during the mobile phase. Mobility therefore produces a functional shift in visual proprioception capabilities, facilitating increased detection and utilization of peripheral optic flow. Similarly, in the TD study, the crawling group showed higher postural responsiveness to the sidewall forward condition compared to the non-crawling group, thus confirming the findings of previous studies showing mobility influences the infant's use of peripheral optic flow. These important findings in infants with MMC reveal that despite long delays in mobility onset, utilization of peripheral optic flow improves noticeably after the onset of SPL. The results of the MMC and TD infants, along with findings from an accelerated paradigm with 7-month-old TD infants[2], clearly illustrate that self-produced mobility and not maturation (age) appears to be the focal mechanism in the utilization of peripheral optic flow.

JVA reveals one of the earliest and most significant signs of social interaction, as its emergence signals an infant's ability to perceive another person's gaze and gesture to a third object.[46] In the JVA paradigm, infants respond in three ways: one is to remain gazing at the experimenter, another is to gaze at an incorrect target and another is to locate the correct target. Non-crawling infants in both the TD and MMC cohorts show reduced capabilities in perceiving the experimenter's gestures, by maintaining their attention on the experimenter. In contrast, mobile infants demonstrated the ability to follow the experimenter's intent by shifting their gaze to locate the object. Although it appears that mobility is a prime motor skill facilitating joint visual attention, other skills may be implicated. Wasserman [47] reported that children with or at high risk for motor disabilities were less likely to follow their parent's gaze and showed diminished interaction with objects. Arens et al [48] suggested that motor skills such as poor or later developing head control may lead to difficulty in shifting attention. These studies imply that joint visual attention is a complex entity, and involves the interaction of several domains: motor, environmental, and social.

The most intriguing of all the spatial cognitive paradigms is the extraction of invariant form. In both the TD and MMC infants, mobility enabled the infants to perceive the differences in form as revealed by the significant increase in looking time at the novel item. How does a functional motor activity formulate changes in the perception of three-dimensional form? An explanation is provided by Soska and colleagues,[49] who revealed that self-sitting is a skill that increases the ability of four to seven-month-old TD infants to perceive three-dimensional form. The rationale is that independent sitting frees the upper extremities for manual exploration of toys. The increase in physical skill coupled with exploration of objects results in developmental advancements in object perception. Similarly, in both the MMC and TD study, crawling allows for an increase in visual inspection of objects from differing vantage points, allowing a "complete" viewpoint of objects. Thus, the mobile infant has the capability for a 360-degree view of an object's form by means of their mobile capabilities.

The foundational premise in the interaction between mobility and spatial cognitive development is that mobility increases exploratory activities, providing distinctly new experiences, which in turn stimulate cognitive development.[23, 50] Mobility therefore provides a multitude of avenues for new perceptual learning, which in turn contributes to spatial cognition. For example, the non-mobile infant analyzes the spatial properties of objects in stationary postures with objects that are within reaching length. Furthermore, mobility facilitates a distinct range of skills, as infants must estimate distance and direction to travel to places and persons, couple movement and visual perception for postural maintenance and demonstrate ongoing selective vigilance to maneuver in the environment. Consequently, the growth of selective attention is required for spatial cognitive skills to flourish. Atkinson[5] proposes a similar line of thought, suggesting that the motor activities of manipulation and mobility underlie spatial attention. Initially, infants employ an attentional system mediated by observing single targets, followed by integration of visual eye hand coordination thereby establishing egocentric spatial relationships. When the infant initiates mobility, there is greater complexity in integrating visual eye hand coordination and an increased need for spatial attention in external space. During the course of mobility, the infant acts upon the environment as either a bodily movement or an eye movement towards the object or person of interest. Mobility places demands on the infant "selecting" or "perceiving" the critical elements in the environment. To accommodate for the increased attentional demands, vision is transformed by allocating attention to steer forward within the environment, selectively attending to the important variables in space and relegating visual attention in the periphery for management of postural stability.[51, 52]

While there is strong support for the interaction between mobility and psychological change, there are some caveats. First, mobility is not responsible for creation of the new phenomena; rather the psychological process is already present although in elementary form. Mobility elevates an already present entity to a higher functional capacity. Secondly, the skill may emerge via other psychological means, indicating other avenues of change. Thirdly, maturational factors play an important part in the developmental evolution.[1]

Therefore, the mobile infant must integrate, select, and perceive items and information to be successful in the world. Infants with mobility delays lack the diverse experiences arising from mobility thereby reducing attentional exploration and increasing the risk for impaired spatial cognitive skills. The cognitive-perceptual deficits in children with MMC are in the visual perception and attention realms. These deficits are strongly associated with brain abnormalities found in MMC. Research however is emerging that early and ongoing reductions in mobility contribute to the cognitive perceptual deficits in children with MMC. [21, 53, 54] This study sheds light on the influence of delayed mobility on spatial cognition in infants with MMC, providing evidence for mobility deficits having a negative effect on spatial cognitive and perceptual development.

Infant rehabilitation can benefit from the outcomes of this study, as implementing early mobility can truly serve the "whole child." Therefore, interventions with and without the use of mobility aids should be a high priority, as the outcomes of mobility advances other spheres such as joint attention and object perception. Moreover, as communication and perceptual skills are enhanced by self-produced mobility, rehabilitation professionals other than physical therapists should implement mobility within their interventional plans. Early intervention services have identified the "transdisciplinary model" as a best practice model, as it promotes shared responsibilities and collaboration among rehabilitation professionals. Mobility interventions could be a perfect vehicle for encouraging this model, as its outcomes influence speech and occupational therapy realms.

Limitations in the MMC study include the small number of MMC subjects, the heterogeneity of the MMC subjects, particularly with respect to the wide variation in motor and functional deficits, and the variability in the number of visits for testing. Future research should continue to investigate the relationship between motor acquisition and cognitive perceptual skills in other children with motor disabilities. The relationship between self-propelled and powered devices should be investigated to discover if there are advantages in spatial performance with specific types of mobility. For example, does the motoric ease of powered mobility provide an advantage for the perception of peripheral optic flow? More importantly, investigations must continue to explore infant development as an interaction of realms, rather than studying these domains in isolation. Thelen provides a foundation for this idea, stating that infant cognition depends upon motor and perceptual experiences, that these experiences are "inseparably linked," and together form the matrix from which reasoning, memory, emotion, and language are embedded.[55]

5. Conclusion

The onset of mobility promotes dynamic changes in an infant's psychological development. Promotion of early mobility via physical aids or powered means should be considered with all infants with motor disabilities to enrich environmental exploration and enhance spatial cognitive development. Future studies must study the specific effects of powered versus manual mobility in infants with disability to comprehend the effects of physical effort on spatial cognitive skills.

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