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SPECIAL ISSUE

Babies driving robots: self-generated mobility in very young infants

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Abstract Self-generated mobility via locomotion is a key for the cognitive, social and motor development of young infants. For certain children with special needs, self-generated mobility is only attained via assistive technology such as a power wheelchair. Up until recently, infants under 24 months of age were not considered candidates for training in power mobility. Recent work in our labs and others suggest that younger infants can utilize their reaching and grasping ability to learn power mobility. This interdisciplinary study combines our previous work in motor development and learning in infants with special needs, and the application of robot technology for rehabilitation to determine whether young infants without structured training, would drive a mobile robot, and if so, to determine how their driving would change over multiple sessions. The two infants that were seen for the most sessions were the focus of this pilot study. Both infants increased their total session time, percentage of session time spent driving, and total path length. These results suggest that, without training, young infants will independently move themselves using a mobile robot. These results provide the foundation for training studies to advance the self-generated mobility in young infants with special needs. Our future studies will explore the multiple training and technology combinations to reduce the barriers to exploration via self-generated mobility, and advance the general development of infants with special needs.

1 Introduction

Exploration of the world is one key to the rapid, significant advancement in cognitive, perceptual and motor abilities characteristic of early infancy. Two categories of skills provide the vehicle for physical exploration. The first to emerge is the ability to independently explore the local environment through reaching and grasping. The second is the ability to independently explore distant environments through locomotion. The aim of this study was to test whether infants would use their ability to reach and grasp to achieve self-generated locomotion via a mobile robot before they could independently locomote via crawling or walking.

Over the first 8 months of postnatal life, typically developing infants gain the ability to reach for and grasp objects within their local environment. Such local exploration has been associated with rapid advances in social [18,19], cognitive [5,15,34,35], perceptual [14,17], and motor development [13,21]. Exploration of the world by infants this age ultimately becomes limited by their inability to independently travel over distances. Consequently, these infants spend most of their time sitting and exploring the local environment that is within reach. For further exploration, caregivers must bring objects or playmates to them, or vice versa.

Over the next 8 months, this barrier to the exploration and manipulation of distant environments is overcome as infants gain self-generated mobility via various forms of locomotion such as creeping, crawling, cruising, and walking. Locomotion, like reaching and grasping, has often been considered a

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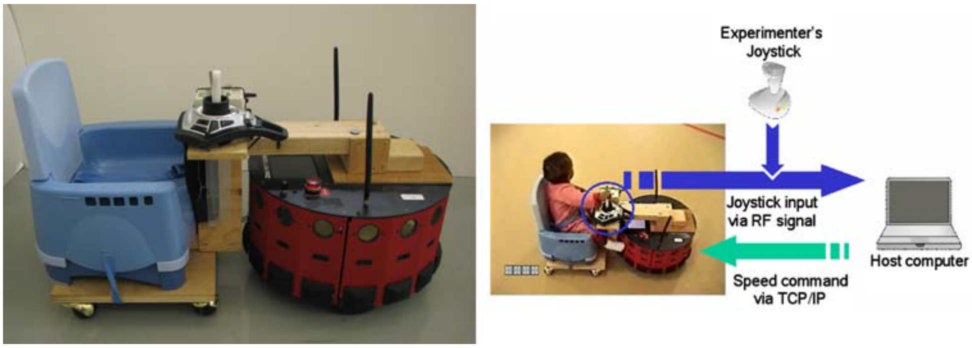


Fig. 1 Mobile robot with cart, seat and joystick (*left*); and the information flow into the mobile robot from host computer, and flow out of the robot joystick (*right*)

purely motor milestone, albeit a major one. In reality, infants must acquire a range of cognitive, perceptual as well as motor competencies for even the basic locomotor forms such as crawling to emerge. In turn, independent mobility has been linked with rapid advances in social, language, cognitive, perceptual and motor development (reviewed in [4,12]).

Our previous work has centered on motor development and learning in early infancy [6–9,25,26,28], and on rehabilitation application of mobile robot technology [22,23,29,31]. How would non-locomoting young infants react if offered the opportunity to use their reaching and grasping skills, which they have only used to explore their local environment, to gain distant exploration by driving a mobile robot? Would infants require extensive training to be motivated to even reach for and grasp the joystick? Would they tolerate being in a foreign apparatus in an open space, or simply cry and seek a caregiver? Would they sit quietly and visually explore the robot, or would they grasp and move the joystick, and enjoy the ride? What if they were offered multiple sessions to interact with the robot? Would they become increasingly bored of the once novel situation, or become increasingly intolerant of being strapped into a seat, or would they increase their tolerance, drive further and with more complicated patterns?

The specific purpose of this pilot study was to determine if young infants, without structured training, would drive a mobile robot, and if so, to determine how their driving would change over multiple sessions (Fig. 1). We predicted infants would increase their tolerance for the mobile robot, and move the robot for longer periods of time. We also predicted that the path would become more complicated as infants explored the robot's mobility, and that older infants would do better than younger infants. We did not believe that any infant would show signs of purposefully driving the robot to specific locations or to avoiding physical barriers in the open space, which require higher level skills such as associating specific movement of the joystick with that of the robot, and intention and motivation for avoiding obstacles.

Support for our hypotheses came from three separate but interrelated fields of study. First, the most direct support comes from a group of 9-month old trained to move a mobile cart forward ([4]; see also [1–3]). In this study, infants preferentially chose to pull a joystick that caused forward cart movement over one that did not cause cart movement. Prior to this study, there was little empirical data on the ability of children to drive a mobile apparatus in the first years of life, and no significant data on children under 20 months of age [10,11,33]. Second, there are more recent examples of infants with physical impairments learning to drive power wheelchairs with training when they were as young as 20 months old [27]. Lastly, infants are opportunistic explorers. That is, they display a significant drive for exploration using any and all current abilities. For example, we have shown that young infants offered toys within reaching distance will use their leg control to successfully reach many weeks before they gained the arm control to reach with their hands [20]. The information gained by this opportunistic exploration leads to new, more complex understandings about the world. The importance of this current study is that we predicted infants would not simply reach for and grasp a novel object (i.e. robot joystick), but would continue to move the joystick such that the mobile robot traveled throughout the open space. Moreover, infants seen across multiple sessions would not grow bored with the simply joystick, but would increasingly *use* the joystick as a means to move the robot to distant locations.

2 Methods

2.1 Participants

Seven infants from 7 to 15 months of age participated in this study after their parents or guardians provided informed consent as approved by the University of Delaware IRB. Infants were recruited from the Early Learning Center (ELC), University of Delaware, Newark, DE. The ELC is a childcare center serving infants through school age children including those with special needs. This paper focuses on the two infants (Elijah and Jackson) that participated in most sessions (Fig. 2). Elijah was a typically developing infant who began the study when he was 7 months old. He was able to reach, grasp, roll and sit independently for short amounts of time,

Fig. 2 **a** Video screen captures from Elijah's session; **b** video screen captures from Jackson's session

but was not yet crawling, pulling to stand or walking. Jackson was an infant diagnosed with Downs Syndrome who began the study when he was 14 months old. He was able to reach, grasp, roll and sit independently, and was able to crawl for short distances, but was not pulling to stand or walking.

2.2 Procedures

All data collections were performed within a standardized environment at the same time of day within the ELC. Experimenters transported all equipment twice weekly to the ELC

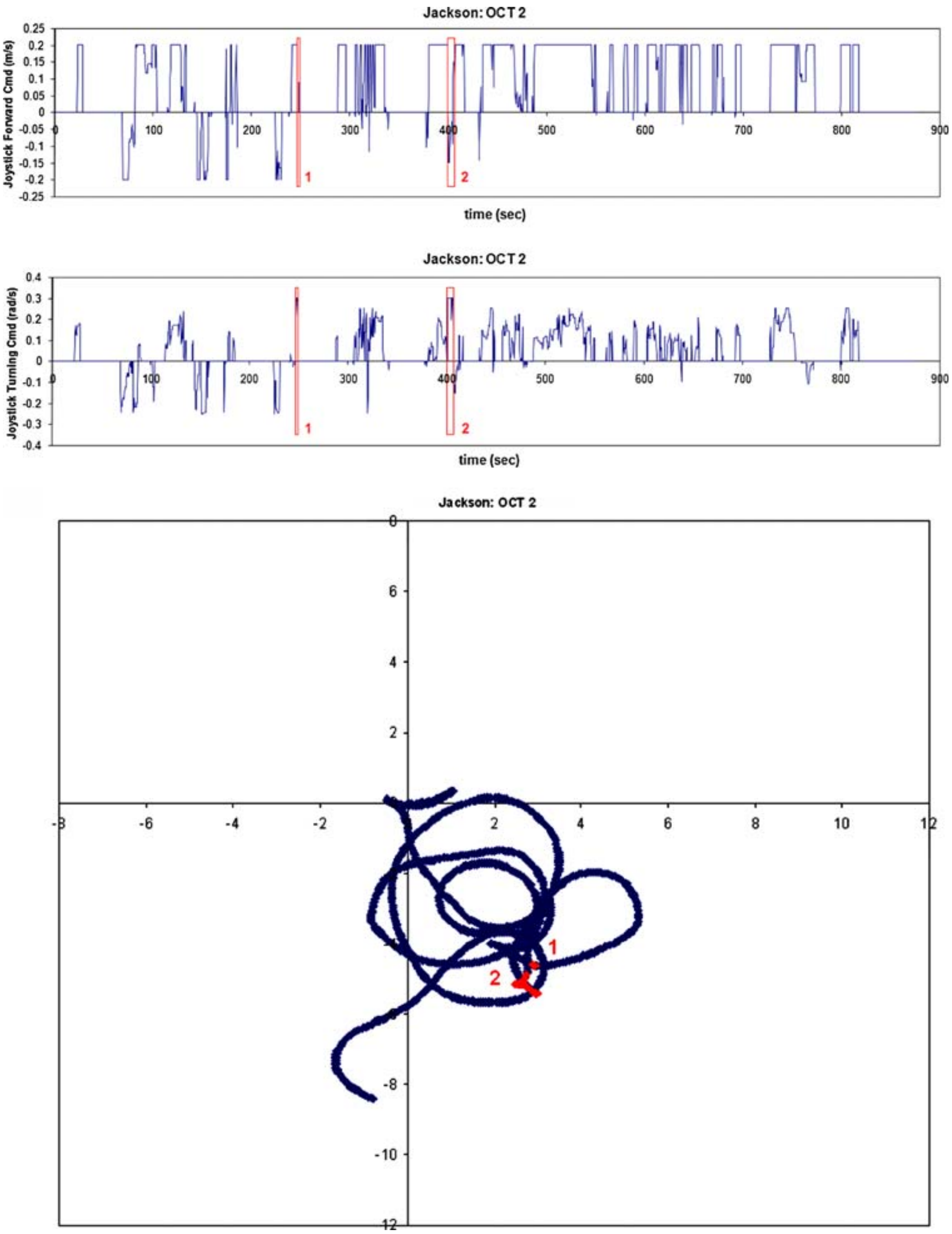
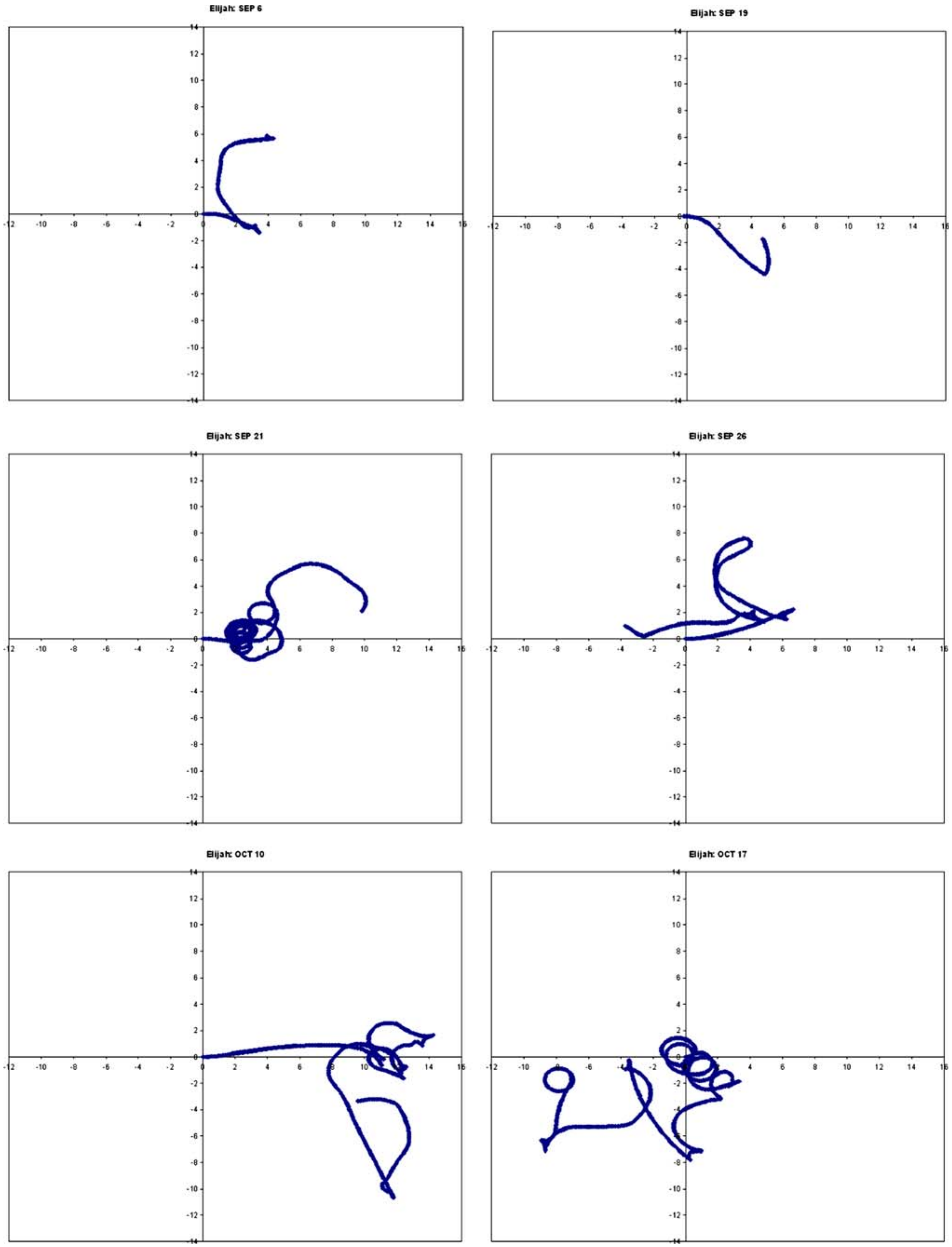


Fig. 3 The infant joystick forward and turning commands throughout one session (blue trace in upper and middle graphs). The numbered *red traces* in the upper and middle graphs are the command data from the experimenter joystick. The numbered marks on robot path (lower graph) correspond to the numbered experimenter joystick activations in the upper and middle time series

for a 6-week period. Experimenters attempted to test all consented infants on each visit. All infants were not seen on all visits, however, due to the infant's sleep schedule, feeding schedule, willingness to leave the classroom and ELC attendance.

Infants were carried by a research assistant or teacher to the indoor gymnasium (46 m × 15 m), and placed into the mobile robot. The mobile robot was located in a standard starting position (x, y 0,0 in Figs. 3, 4 and 5). The joystick was pointed to and touched by an experimenter or teacher, and infants were verbally encouraged to touch the joystick. No standardized training was provided, and infants were not shown that the mobile robot could move. Thus, to move the mobile robot, infants had to independently reach for, grasp and move the joystick.

Although infants were free to behave in a range of ways, infants performed primarily one of three behaviors during a session. They cried, quietly explored the mobile robot but did not drive, or drove the mobile robot. Interestingly, behaviors did not differ significantly across sessions for individual infants. That is, if an infant cried or drove the first session, he or she tended to cry or drive for other sessions as well. Infants that cried for more than 2 min were removed, comforted and returned to their classroom. If infants cried during more than 2 visits, they were excluded from the study. Infants who did not engage the joystick after 5 min were given



Elijah: SEP 6

Elijah: SEP 19

Elijah: SEP 21

Elijah: SEP 26

Elijah: OCT 10

Elijah: OCT 17

Fig. 4 The actual mobile robot path continuously over time during six sessions for Elijah. Note that one session is not shown for space

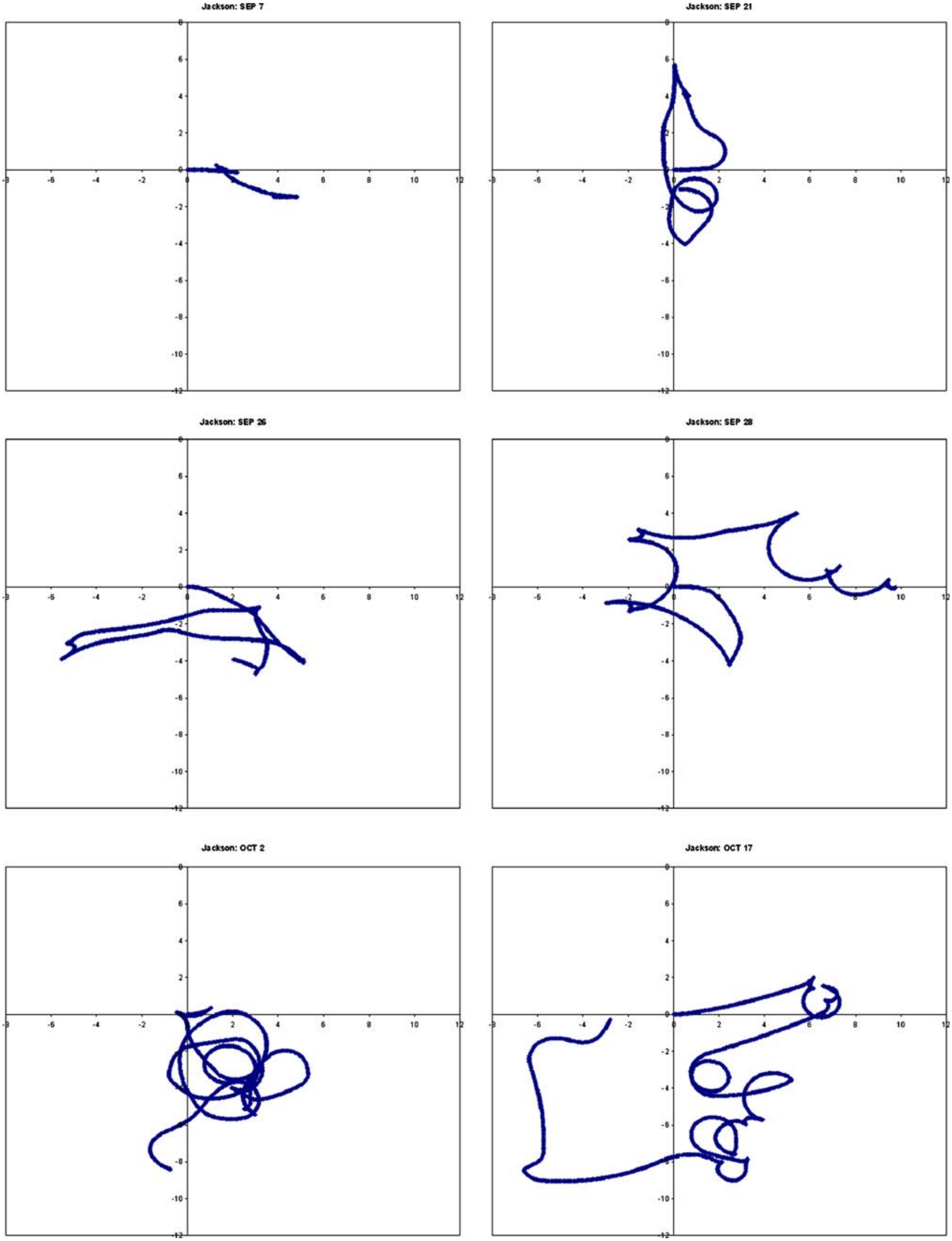


Fig. 5 The actual mobile robot path continuously over time during six sessions for Jackson

verbal praise for a good job, removed from the mobile robot, returned to their classroom and were tested on subsequent days. Infants who engaged the joystick were allowed to play with the robot for 20 min or until they showed signs of fatigue such as becoming fussy, holding arms out to be held or trying to get loose of the safety straps.

The open space (46 m × 15 m) contained a table for the collection computer, a few large colorful pieces of play equipment, and a stationary video camera set to capture a distant view of the entire driving space. In addition, one experimenter followed infants with a hand held video camera to capture close images of infants' body and robot. As expected, no infant attempted to turn the mobile robot around when approaching these barriers. Thus, whenever the mobile robot was within 30 cm of an object and headed directly for it, an experimenter used a 2nd joystick to turn the mobile robot 180°. The experimenter did not drive the mobile robot for any length nor interfere if the infant was driving alongside an object.

2.3 Mobile robot (Fig. 1)

The same mobile robot was used for all experiments. We built the mobile robot by fabricating and adding a wooden cart to the iRobot's Magellan Pro robot. The robot was equipped with an on-board computer and odometry. In odometry, sensed data of rotation of the robot's wheels were used to calculate the robot's position. The robot was also equipped with 16 IR and sonar sensors on the periphery of the body; however, these were not active in this study. A commercial infant seat (Safety 1st) was mounted on the cart that was firmly attached to the mobile robot. All parts were securely fixed using mechanical fasteners and the seat with safety harness secured the infant in a sitting position. The mobile robot is circular, 40.6 cm in diameter, 25.4 cm in height. The cart including the baby seat is approximately 41 cm × 38 cm in width by length. The robot moved using two differentially-driven wheels and a third caster wheel for balance. The cart had four caster wheels under the corners. In front of the infant seat, a wireless joystick (Logitech Freedom 2.4) was placed at chest level and within arm's length. To accommodate infant's small hands and low force generating ability, we modified the spring stiffness of the handle and removed the upper mechanical part of the handle. A separate joystick operated by an experimenter could override any command given to the robot in order to ensure the infants safety.

The joysticks communicated with a notebook computer (Centrino 2.0 GHz running Windows XP) by RF signal. The host program running on the notebook computer received joystick displacement inputs and resolved them into x, y-axis components. The forward speed and the turning speed of the robot are then set proportionally to the x, y displacement values of the joystick, respectively. Full pulling and pushing strokes of the baby's joystick in y-axis corresponded to 0.2 and -0.2 m/s of forward speed, respectively. Full strokes in left and right direction were interpreted as 14.3 and -14.3 deg/s turning speed of the robot, respectively. Speed commands were then sent to the robot through wireless TCP/IP connection. The on-board computer in the mobile robot collected commands, speeds, and position data every 0.3 sec. Figure 3 shows the onset and offset of joystick activations for both an infant and experimenter, and the corresponding mobile robot path throughout one session.

2.4 Dependent measures

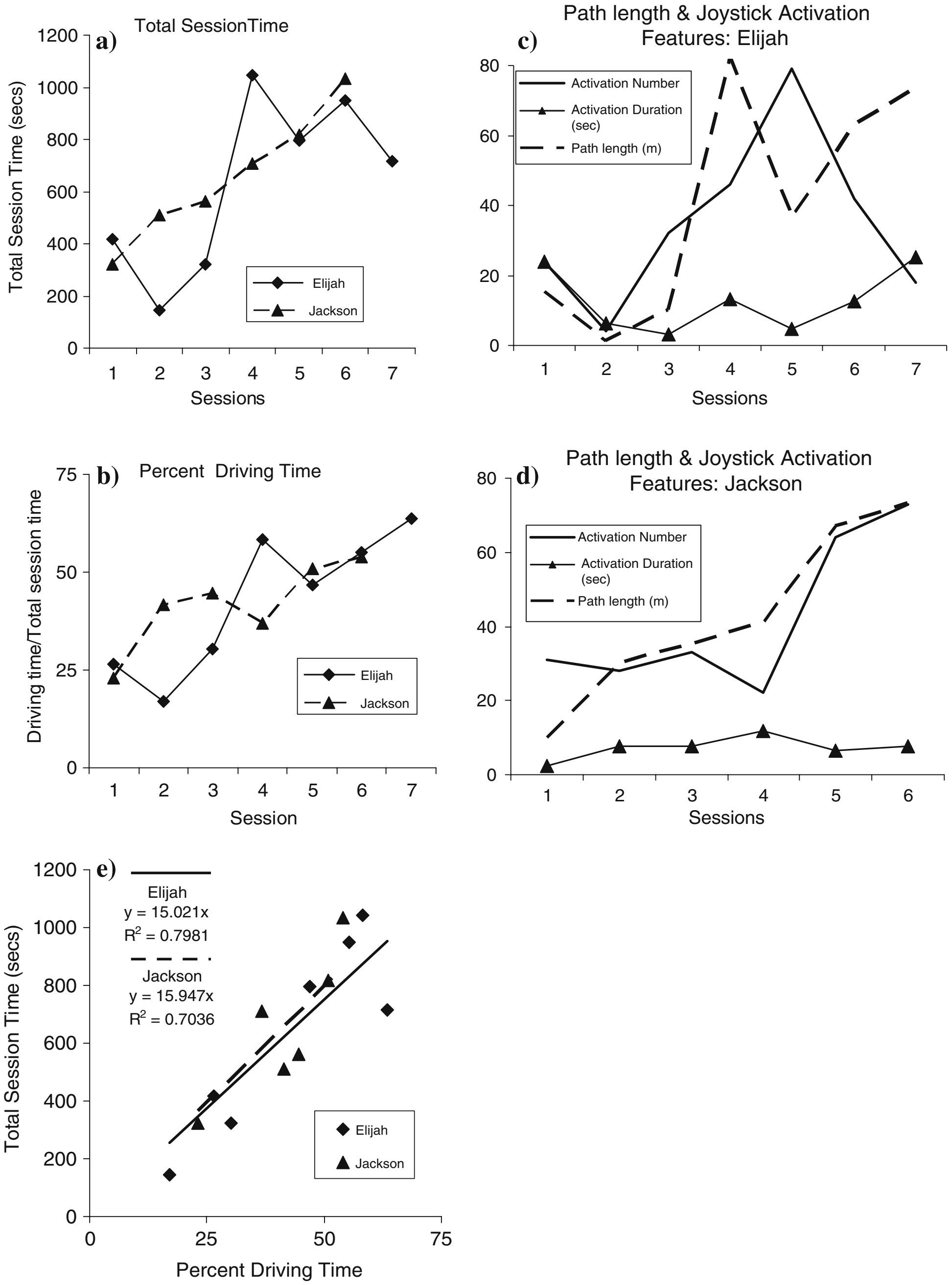
We obtained the following dependent measures: (1) total session time from start of session to the end of the last driving sequence; (2) percent of total session time spent driving: time robot was in motion/total session time; (3) total path length (m): distance traveled by the robot along the actual path from the start of the session to the end of the last driving sequence; (4) number and average duration of joystick activations. All information used for dependent measures were collected in real time from mobile robot.

3 Results

Elijah (*typically developing 7-month old*). This infant typically engaged the joystick with both hands and often with his mouth as well. While driving during initial sessions, Elijah was typically flexed forward over the joystick and looked at the walls, floor, objects and people as he passed primarily by moving his eyes. A preliminary review of the videotape of his sessions suggested that, qualitatively, he did not typically turn his head or trunk while driving, and maintained a neutral facial expression. By the last sessions, Elijah sat more upright, and contacted the joystick less with his mouth. He rarely altered his course throughout a session. That is, if he started driving in a circle or straight at the beginning of a session, he continued to drive that path until coming to a barrier from which an experimenter would turn the mobile robot. He would then resume a circle or straight path, and continue so until reaching another barrier. These features of the mobile robot's path can be seen in Fig. 4, which shows the path during six of the seven sessions analyzed for this infant.

1. Total session time (Fig. 6a): 147–416 s in the first three sessions (average 294 s) to 715–948 s during the last four sessions (average 819 s). This was a 170% increase in total session time.
2. Percent of total session time spent driving (Fig. 6b): 17–30% in the first three sessions (average 25%) to

Fig. 6 The Total Session Time (**a**), Percent of Driving Time (**b**), Path length and Joystick Activation Features (**d**) and the relationship between Total Session Time and Percent Driving Time (**e**). **a**, **b** and **e** display both infants data together. **c** and **d** present each infant's data separately. Note that Elijah has seven sessions, whereas Jackson has six sessions



47–64% during the last four sessions (average 55%). This was a 125% increase in the percent total session time spent driving. In absolute time spent driving, the increase was from an average of 74 s during the first three sessions to 451 s during the last four sessions.

3. Total path length (Fig. 6c):1–15 m in the first three sessions (average 9 m) to 37–74 m in the last four sessions (average 58 m). This was a 547% increase in the total path length.
4. Number of joystick activations (Fig. 6c): 4–32 activations in the first three sessions (average 20) to 18–79 activations during the last four sessions (average 46). This was a 132% increase the number of joystick activations.
5. Average duration of joystick activations (Fig. 6c): 3–24 s in the first three sessions (average 11 s) to 5–25 s activations during the last four sessions (average 14 s). This was a 28% increase in the average duration of activations.
6. There was a linear relationship between the percent driving time and total session time ($R^2 = 0.8$, Fig. 6e). That is, the longer the session time the greater the percent of that time that was spent driving.

Jackson (*14-month old diagnosed with Downs Syndrome*). In comparison to Elijah, this infant typically engaged the joystick with one hand and rarely with his mouth. A preliminary review of the videotape of his sessions suggested that, while driving, Jackson sat upright and activated the joystick while turning his head and trunk to look at passing walls, floor, objects and people. He also altered his path several times a session such that a session's path contained but straight segments and circles. Jackson also smiled and laughed while driving. These features of the mobile robot's path can be seen in Fig. 5, which shows the path during the six sessions analyzed for this infant.

1. Total session time (Fig. 6a): 322–560 s in the first three sessions (average 464 s) to 709–1,033 s during the last three sessions (average 853 s). This was a 80% increase in total session time.
2. Percent of total session time spent driving (Fig. 6b): 23–45% in the first three sessions (average 36%) to 37–54% during the last three sessions (average 47%). This was a 30% increase in the percent total session time spent driving. In absolute time spent driving, the increase was from an average of 167 s during the first three sessions to 401 s during the last three sessions.
3. Total path length (Fig. 6d):10–35 m in the first three sessions (average 25 m) to 41–73 m in the last three sessions (average 60 m). This was a 141% increase in the total path length.
4. Number of joystick activations (Fig. 6d): 31–33 activations in the first three sessions (average 31) to 22–73 activations during the last three sessions (average 53). This was a 73% increase the number of joystick activations.
5. Average duration of joystick activations (Fig. 6d): 2–8 s in the first three sessions (average 6 s) to 7–12 s activations during the last three sessions (average 9 s). This was a 49% increase in the average duration of activations.
6. There was a linear relationship between the percent driving time and total session time ($R^2 = 0.70$, Fig. 6e). That is, the longer then session time the greater the percent of that time that was spent driving.

Observations from other infants. Two clear observations were made from the other infants, many of whom were not seen for more than 2 sessions. The first was that older infants (12–15 months of age) were interested in exploring the mobile robot, but not the joystick. Specifically, these infants pushed, pulled, poked and banged on the mobile robot, and a few even explored the joystick. None of these infants, however, drove the mobile robot even for a short distance. The second observation was that some younger infant (4–9 months of age) cried immediately upon being placed into the seat. For these infants, there did not appear to be anything we could do to increase their tolerance.

4 Discussion

The two infants that were seen for multiple sessions displayed the opportunistic exploration that characterizes young infants. During the first session, both infants independently grasped and moved the joystick within minutes of being placed into the seat, and continued to move the mobile robot for many minutes over many meters of motion. As predicted, over multiple sessions, both increased their total session time, reflecting their ability to tolerate sitting in and moving the robot at least once each 5 min up to a maximum of a 20 min session (Fig. 6a). These infants increased their tolerance from 5 to 8 min on average over the first three sessions to 14 min on average over the last three sessions. Our data on their driving reveal that they did not simply produce the minimum joystick activations, but rather produced an unexpected level of joystick activity. Specifically, we did not anticipate that both infants would consistently increase the percent of session time spent driving throughout the study (Fig. 6b,e). By the last session, both infants were driving more than 50% of the time they were in the mobile robot, which was double their starting percentage and resulted in approximately 8 min of active driving time. This level of activity is important as our future studies will train young infants to accomplish tasks by driving to specific locations or around obstacles, which will require sustained periods of active problem solving. Learning experiments in which infants are involved in problem solving suggest that actively moving the mobile robot for 10–15 min or more will provide a baseline of activity from which infants can learn to associate joystick motion with mobile robot motion [25].

As expected, both infants drove for longer path lengths over sessions; however each did so with a different pattern. Path length increased abruptly on session 4 for Elijah, whereas path length gradually increased over each session for Jackson (Fig. 6c and d, respectively). Each infant also displayed a different manner by which they increased the path length over the last three sessions. Elijah increased path length by increasing the duration joystick activations while decreasing the number of activations, whereas Jackson increased path length by increasing the number of joystick activations. Such individualized changes are also a common feature of learning and development in infancy. Future training studies will need to allow for such individualized exploration. Indeed, the strongest example of training for complex self-generated mobility in young infants utilized significant opportunities for individualized discovery and problem solving and avoided highly structured practice or adult guidance [27].

Our results demonstrate that young infants will independently move themselves via a mobile robot. Our data do provide indirect evidence that infants were not simply focused on moving the joystick but were associating joystick activation with their motion. First, infants did not habituate to the joystick. It is well known that infants will decrease their responsiveness with repeated presentations of the same situation or task [32]. The joystick used in the current study was not colorful or particularly interesting compared to the toys these infants spent their days with in their classrooms and at home. Thus, we would predict that if they were focused solely on the joystick, their responsiveness would have decreased over time within a session and between sessions. In contrast, their joystick activations increased in number and/or duration resulting in increased driving time and path length.

For both of these infants, the mobile robot provided the first experiences of self-generated mobility over long distances. Elijah, as a typically developing infant, will begin to walk around 12 months of age. Jackson, however, has a diagnosis of Down Syndrome. Children with Down syndrome often have delays in attaining the major developmental milestones such a walking and speaking. Many also have mild to moderate cognitive impairments (National Down Syndrome Society). At 14 months, Jackson was not yet pulling to stand and thus was at risk for delays in walking. Interestingly, other infants Jackson's age explored the various components of the mobile robot, but did not drive. Thus, Jackson performed as a somewhat younger infant in the mobile robot, which probably was related to his somewhat lower cognitive and motor abilities at the time of testing.

To be clear, these results do not provide direct evidence that these infants were purposefully driving to specific locations. Our protocol for this study was designed to gather data for future studies involving training, and was not structured to formally quantify learning, memory or purposeful actions. What then explains the infants' actions if they were not focused on the joystick, but not yet purposefully driving to locations? We propose that mobile robot motion was reinforcing to joystick movement. That is, infants were rewarded for joystick motion with self-motion. A significant body of work, including our own work, has shown that even very young infants are able to associate body movement with motion in the environment, and remember this association for many days [30]. To formally test this requires having infants interact with a non active joystick (baseline condition), then an active joystick resulting in self-motion (acquisition condition), then a non active joystick (extinction condition). If infants associate joystick motion with self-motion, joystick activations during extinction should be greater than those during baseline. Moreover, memory is shown by comparing baseline levels on Day 1 with baseline levels of subsequent days. Such associative learning is a critical step in the development of purposeful behaviors. The next step would be to show that infants prefer to activate a joystick that results in self-motion. Campos and Anderson have reported that young infants (average age 9 months) displayed such preferential action [4]. Moreover, preliminary data from their follow-up training study suggest that 15 days of training were effective in advancing perception of the physical environment such as response to optic flow, and a wariness of heights (D. I. Anderson, personal communication). Although not the first to suggest the influence of locomotion on general development, Anderson and Campos have pioneered the experimental manipulation of locomotion [4,12]. Their primary focus is on how general development including perception and cognition is influenced by basic mobility in typically developing infants. Our team is focused on combining our previous work on training young infants, both typically developing and those with mobility impairments, with our work on mobile robotics technology to allow infants the ability to display increasingly complex self-generated mobility. Thus, complex mobility is the primary outcome with the advancement of general development an expected result of increased mobility, but not our primary focus. One important area of application of mobile robot technology is in the area of power mobility for infants and children with special needs.

4.1 Application of self-generated mobility

For certain children with special needs, self-generated mobility is only attained via assistive technology such as a power wheelchair [24]. Conventional wisdom from rehabilitation clinics (Campbell et al 2006) is that power mobility is most appropriate for children older than 20–24 months. There are very few clinical studies to support or refute this clinical view [16]. Moreover, a recent report showed significant effects of training with a 20-month old with spinal muscular atrophy [27], and provided direct evidence that power mobility can be a reality for younger children with special needs. This case study used a motor learning strategy for training a child who was unable to roll, crawl or walk. Training averaged 1.5 hrs per day for 6 weeks. At the end of training, the child displayed, for the first time, both basic and advanced wheelchair mobility. Moreover, her communication, social, cognitive, and self-care had not only continued to development, but was developing more rapidly than prior to mobility training. We believe that the 20 month barrier can be significantly lowered given the literature on young infants' learning and memory abilities, their drive for opportunistic exploration and the availability of robotic technology to help train these infants while making their mobility safe as they learn. Currently, there are no randomly controlled trials of the effects of early self-mobility in special needs populations, however the literature on the effect of self-generated mobility on typically developing infants and the above case study suggest that early self-mobility has the potential to advance the mobility and general development of very young infants.

Our future work will use mobile robot technology plus intensive training such that infants under 1 year with special needs have an ability to explore distant environments that is equal to or better than their typically developing peers. We propose that the combination of training and technology is not only sufficient for real world mobility across the natural environments explored by young children, but is in fact necessary for this the realization of the widespread use. For example, one non-intuitive drawback to intensive training is that infants become highly mobile without the necessary cognitive, perceptual and social abilities to safely negotiate the world. Two such safety concerns are hitting obstacles and not following adult directions. The conventional strategy for these is to simply not train infants for power mobility until they are 24 months of older, and can follow adult directions. We believe that this is both an unnecessary barrier given robotic technology, and more importantly short circuits the developmental processes that power mobility is designed to eliminate.

Obstacle negotiation. First, our mobile robot is equipped with both IR and sonar sensors designed for use in obstacle detection and then negotiation. Thus, with current technology, the mobile robot will reroute itself if an infant was headed for a barrier. With realistic technology modifications, infants should be allowed to drive not only in open spaces with static barriers, but in classrooms and gyms with their peers. This would allow exploration of both the physical space and social interaction with peers and adults, which is the primary focus of early mobility.

Adult direction. Even more troubling to parents and therapists is the prospect of a highly mobile infant without the necessary cognitive and social ability to follow directions. This is a significant barrier to not only outdoor use, but also to daily management in the community such as early education centers, daycares and the home. To us, this barrier is both unnecessary given the potential robotic technology and short circuits the developmental processes critical to future skills such as those required for mainstream education. Given the sensing and planning abilities of modern robots, we envision a scenario in which the mobile robot maintains a prescribed distance from an adult, can be called to that adult's position, and can follow an adult at a prescribed distance. Moreover, we believe that advances in technology will allow for a dynamic interaction between adult prescribed mobility and infants' self-generated mobility. This is important as typical mobility develops as an interaction with cognitive and social abilities both within the infant and between infant and caregiver, not in a sequence in which mobility waits for a safe level of adult direction. Thus, we would welcome the scene of an 18 month old with special needs using her mobile robot to 'run' from a parent who is calling her just as her typically developing peers would do. With robot technology, unlike with typically developing toddlers, the parent could stop the mobile robot, and ask the child to return to them. If the child did not drive to them, the parent could require the child's return by specifying the mobile robot come to within a prescribed distance. Our future studies will explore the multiple training and technology combinations to reduce the barriers to exploration via self-generated mobility, and advance the general development of infants with special needs.

References

1. Anderson DI (2000) Can prelocomotor infants learn to control a powered mobility device? Paper presented at the International Society for the study of behavioral development Biennial conference, Beijing, China, July
2. Anderson DI, Campos JJ (2000) The ontogeny of postural responsiveness to peripheral optic flow: experimental manipulation of a developmental process. Paper presented at the Fifth Biennial motor control and human skill research workshop. Gold Coast, Australia, Januaray
3. Anderson DI, Campos JJ, Barbu-Roth MA, Uchiyama I (1999) Motor behavior and psychological function. Paper presented at the North American Society for the psychology of sport and physical activity. Clearwater Beach, FL, June
4. Anderson DI, Campos JJ, Anderson DE, Thomas TD, Witherington DC, Uchiyama I, Barbu-Roth MA (2001) The flip side of perception–action coupling: locomotor experience and ontogeny of visual-postural coupling. Human Movem Sci 20:461–487
5. Bensen JB, Uzgiris IC (1985) Effect of self-initiated locomotion on infant search activity. Develop Psychol 21:923–931
6. Bhat A, Galloway JC (2006) Toy-oriented changes during early arm movements: hand kinematics. Infant Behav Develop 29:358–372
7. Bhat A, Galloway JC (2008) Toy-oriented changes during early arm movements III: Constraints on Joint Kinematics. Infant Behav Develop (in press)
8. Bhat A, Heathcock J, Galloway JC (2005) Toy-oriented changes in hand and joint kinematics during early infancy: a cross-sectional study. Infant Behav Develop 28:445–465
9. Bhat A, Lee HM, Galloway JC (2007) Toy-oriented changes during early arm movements II: Joint kinematics. Infant Behavior and Development 30:307–324
10. Butler GA (1986) Effects of powered mobility on self-initiated behaviors of very young children with locomotor disability. Develop Med Child Neurol 28:325–332
11. Butler GA, Okamoto, McKay TM (1984) Motorized wheelchair driving by disabled children. Archi Phys Med Rehabili 65:95–97
12. Campos JJ, Anderson DI, Barbu-Roth MA, Hubbard WM, Hertenstein MJ, Witherington D (2000) Travel broadens the mind. Infancy 1:149–219
13. Corbetta D, Bojczyk KE (2002) Infants return to two-handed reaching when they are learning to walk. J Motor Behav 34(1):83–95
14. Corbetta D, Thelen E, Johnson K (2001) Motor constraints on the development of perception–action matching in infant reaching. Infant Behav Development 23:351–374
15. Diedrich FJ, Highlands T, Spahr K, Thelen E, Smith LB (2001) The role of target distinctiveness in infant perseverative reaching errors. J Exp Child Psychol 78:263–290

16. Dugan LM, Campbell PH, Wilcox MJ (2006) Making decisions about assistive technology with infants and toddlers. Top Early Child Spec Educat 26:25–32
17. Eppler MA (1995) Development of manipulatory skills and the deployment of attention. Infant Behav Develop 18:391–405
18. Fogel A, Dedo JY, McEwen I (1992) Effect of postural position and reaching on gaze during mother infant face-to-face interaction. Infant Behav Develop 15(2):231–244
19. Fogel A, Messsinger DS, Yale ME, Disckson KL, Hsu H (1999) Posture and gaze in early mother-infant communication: Synchronization of developmental trajectories. Develop Sci 2(3):325–332
20. Galloway JC, Thelen E (2003) Feet first: Object exploration in human infants. Infant Behav Develop 27(1):107–112
21. Goldfield E (1990) Transition from rocking to crawling: postural constraints on infant movement. Develop Psychol 25(6):913–919
22. Hao Y, Agrawal SK (2005) Formation planning and control of UGVs with trailers. Autonom Robots 19(3):257–270
23. Hao Y, Agrawal SK (2005) Planning and control of UGV formations in a dynamic environment: a practical framework with experiments. Robot Autonom Syst 51:101–110
24. Hays RM (1987) Childhood motor impairments: clinical overview and scope of the problem. In: Jaffe KM (eds) Childhood powered mobility: developmental, technical, and clinical perspectives. Proceedings of the RESNA first northwest regional conference. Rehabilitation Engineering and Assistive Technology Society of North America, Washington, DC, pp. 1–10
25. Heathcock J, Bhat A, Lobo M, Galloway JC (2004) Performance of infants born preterm and full-term in the mobile paradigm: learning and memory. Phys Ther 84:808–821
26. Heathcock J, Bhat A, Lobo M, Galloway JC (2005) The relative kicking frequency of infants born full-term and preterm during learning and short-term and long-term memory periods of the mobile paradigm. Phys Ther 85:8–18
27. Jones MA, McEwen IR, Hansen L (2003) Use of power mobility for a young child with spinal muscular atrophy. Phys Ther 83:253–262
28. Lobo MA, Galloway JC, Savelsbergh GJP (2004) The effects of specific and general practice on the development of reaching. Child Develop 75:1268–1281
29. Pathak K, Agrawal SK (2005) An integrated path-planning and control approach for nonholonomic unicycles using switched local potentials. IEEE Trans Robot 21(6):1201–1208
30. Rovee-Collier CK, Hayne H, Colombo M (2001) The development of implicit and explicit memory. Series B: Research in progress-experimental, descriptive, and clinical research in consciousness, Vol 24. John Benjamins, Philadelphia, 322 pp
31. Ryu J, Pathak K, Agrawal SK (2006) Control of a passive mobility assistive robot. ASME IMECE 2006, November 5–10, Chicago, IL, IMECE2006–14701
32. Schöner G, Thelen E (2006) Using dynamic field theory to rethink infant habituation. Psychol Rev 113:273–299
33. Tefft D, Guerette P, Furumasu J (1999) Cognitive predictors of young children's readiness for powered mobility. Develop Med Child Neurol 41:665–670
34. Thelen E, Schöner G, Scheier C, Smith LB (2001) The dynamics of embodiment: A field theory of infant perseverative reaching. Behav Brain Sci 24:1–34
35. Yan JH, Thomas JR, Downing JH (1998) Locomotion improves children's spatial search: a meta-analytic review. Percept Motor Skills 87:67