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Movement planning reflects skill level and age changes in toddlers

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Abstract

Kinematic measures of children's reaching were found to reflect stable differences in skill level for planning for future actions. Thirty-five toddlers (18–21 months) were engaged in building block towers (precise task) and in placing blocks into an open container (imprecise task). Sixteen children were re-tested on the same tasks a year later. Longer deceleration as the hand approached the block for pickup was found in the tower task compared to the imprecise task, indicating planning for the second movement. More skillful toddlers who could build high towers had a longer deceleration phase when placing blocks on the tower than toddlers who built low towers. Kinematic differences between the groups remained a year later when all children could build high towers.

Task demands affect the kinematics of reaching for objects in adults (Marteniuk, MacKenzie, Jeannerod, Athenes, & Dugas, 1987). Reaching slows when the hand approaches an object that will subsequently be picked up and used in a precise way compared to an imprecise way. When young adults were asked to grasp a disk (4 cm in diameter) and then to either fit it into a small well (4.1 cm in diameter) or throw the same disk inside a box (20 cm × 40 cm ×15 cm), the approach movement to pick up the disk during the fitting task was slower, with a longer duration and a longer time spent in the deceleration phase, compared to the throwing task (Marteniuk et al., 1987).

Similar findings have been observed in the healthy elderly (Weir, MacDonald, Mallat, Leavitt, & Roy, 1998) and to some extent in healthy 10.5-month-old infants (Claxton, Keen, & McCarty., 2003). Active healthy elderly slowed the approach phase of their reaching for the object and spent a longer duration in deceleration while completing the fitting task, compared to the throwing task. For infants only two measures, peak speed and average speed, distinguished between the tasks. Like adults, infants reached to pick up a ball more slowly if they were going to fit it into a plastic tube as opposed to subsequently throwing it. Claxton et al. (2003) interpreted their findings as evidence of motor planning for an

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upcoming task. These studies demonstrate that task demands of the subsequent action affect the kinematics of reaching for objects over a wide age range. Slowness in the approach kinematics has been assumed to reflect the person's intention to engage in a future precision action. This is striking because there was no obvious need to vary the approach with regard to the subsequent movement because the object was the same for both actions.

As would be expected, reaching kinematics differed during the action of completing a precision task, as well as during the approach phase. When young adults were asked to point at a target using their tip of index finger compared to using any part of their hand, reaching was characterized by lower peak velocity and a longer deceleration phase (Wu, Lin, Lin, Chang, & Chen, 2005). Bryden and Roy (1999) asked adults to place a peg into a hole. They varied the diameter of the peg while keeping the peg hole the same so that sometimes it fit snuggly and sometimes loosely in order to examine the effect of precision on reaching kinematics. Bryden and Roy also did the reverse: varying the peg hole but keeping the peg the same size. As expected, when the precision requirement increased with either manipulation, kinematic patterns during the action had longer movement time, lower peak velocity, and a longer deceleration phase. Thus, precision demands appear to exert a similar effect on both the approach phase and the manipulation phase.

To our knowledge, no study has examined whether task demands affect reaching kinematics in toddlers. Because toddlers have more reaching experience and better motor control than infants under a year of age, their reaching kinematics should more closely resemble those of adults. We specifically chose tower-building as the precision task in this study as it is an activity most of the toddlers enjoy and it requires precision when placing one block on the top of another. Age-related norms of children's ability to construct towers are well established in many standardized assessment tools, such as the Bayley Scale of Infant Development (Bayley, 1969), or the Gesell Developmental Observation (Gesell and Amatruda, 1954). Toddlers of the same age have different levels of performance in tower-building. For example, in the Bayley Scale, on average, the 13.8-month-olds (with a range of 10 to 19 months) can build a 2-level cube tower, 16.7-month-olds (with a range of 13 to 21 months) can build a 3-level cube tower, and 23-month-olds (with a range of 17 to 30 months) can build a 6-level cube tower. We know of no study that has reported whether there are any differences in reaching kinematics between the skilled and the less-skilled tower building toddlers, but one would predict that more skilled children would show more mature patterns of movement.

The adult learning literature describes how different skill levels affect the kinematics of movements in adults (Gentiner, 1983; Larochelle, 1983). The coordination patterns between skilled and less-skilled performers were distinguishable in adults (Gentiner, 1983; Larochelle, 1983; Temprado, Della-Grasta, Farrell, & Laurent, 1997). It is difficult to make predictions for young children based on adult performance, but we can hypothesize that differences in the skill with which toddlers can build block towers will be reflected in their reaching kinematics for the precision task. On the other hand, when engaged in imprecise tasks with those same blocks, movement kinematics would not be expected to differ with skill level.

In this study we examined how task demands, skill level, and object size affect the reaching kinematics of a group of typically developing toddlers. Tower-building, which required precision, was compared with a "clean up" task of putting blocks into a large container. In Study 1 we tested within the ages of 18 to 21 months indicated by the Gesell and Bayley Scale norms to encompass a range of ability in tower building. We hypothesized that all toddlers would 1) slow down their reaching to pick up and move blocks when building a block tower compared with the imprecise task, and 2) have different reaching kinematics when manipulating large and small blocks because it is harder to build a tower with small blocks. Furthermore, in order to examine the control strategies of toddlers who were better at the precise task, we compared high- and low-tower builders 1) when building towers and placing blocks in a container, and 2) when placing blocks low in the tower versus high in the tower when more care was required. We hypothesized that toddlers who could build a high tower would slow down more in the precision task but not differ on the imprecise task. We also hypothesized that their reaching kinematics would adapt to task difficulty, slowing still further as they placed the final blocks on a tall tower. Finally, in Study 2 we brought back a subset of children a year later to see how their developing motor skills affected reaching kinematics while performing those same tasks. The continuity of skill level in high-tower and low-tower children was also assessed. Because all children could build a tall tower at the older age, the question was whether any initial kinematic differences would remain.

GENERAL METHOD

Stimuli and Apparatus

The stimuli consisted of ten 2.5-inch wooden blocks, ten 1-inch wooden cubes from the Gesell Scale of Infant Development (Gesell & Amatruda, 1954), and two large open containers with sizes appropriate to block size (30 cm × 21.5 cm × 8.5 cm and 18 cm × 12 cm × 7 cm). Gesell cubes were used rather than Bayley Scale cubes because the former are wooden and the latter are plastic. Because the large blocks were wooden, the small blocks needed to be made of the same material for comparison. The containers were available to children for the imprecise task of placing or throwing blocks into them. [Note: block size did not systematically affect kinematics or behavior and will not be considered further.]

Hand movements were recorded at 100 Hz sampling rate using two linked banks of cameras from Phoenix System (Phoenix Co, Canada). The two camera banks were placed on either side of the child to record movements of each hand. The camera banks were positioned at a height of about 2 meters from the floor and 2 meters away from the child. Prior to data collection, the testing area was calibrated by moving a rod with two sensors supplied by the Phoenix Systems through out the testing area. The average root-mean-square error in the calibration was always less than 0.9 mm for each data collection session. One digital camera (Sony, DCR-TRV510) with a superimposed timer was placed 45 degrees from the horizontal plane of the toddlers' left hand side to record behavioral movements. The kinematic data from the Phoenix Systems and video recording were synchronized by time codes placed on both devices during data collection.

Procedure

After obtaining signed informed consent from the parents, toddlers were seated on the lap of their parents at a card table, with the surface around waist height of the toddlers. The experimenter was seated across the table to present the testing stimuli and encourage toddlers to engage in the activities. Two small infrared-emitting sensors (5 mm in diameter) embedded in a Velcro wrist band were placed around each of the toddler wrists to record kinematic data for the Phoenix Systems.

Two tasks (tower-building and placing blocks into an open container) and two block sizes (large and small) were presented. The testing sequence was counterbalanced between large and small blocks so that half of the toddlers were presented with large blocks first and the other half with small blocks first. The session always started with the imprecise task to reduce the possible frustration of not being able to build the block tower. At the beginning of each task, the experimenter demonstrated throwing the blocks or the tower-building movements one or two times to encourage toddlers' engagement. For the imprecise task, toddlers were encouraged to grasp a block placed at their right hand side and then place or throw it into the large container placed at their left hand side. For the tower-building task, toddlers were encouraged to grasp the block placed at their right hand side and to build a block tower at their left hand side as tall as possible. The experimenter always put the first block of the tower on the toddler's left-hand side to mark the tower location. The distance between the blocks to be picked up and the container or the tower was about 20 cm; however, the starting position of the toddler's hand was not constrained. Unlike adult studies in which starting position of the hand is specified, the unconstrained starting position of toddler reaches results in a variable distance between block and hand over trials and children. If the toddler refused to perform the imprecise task, the experimenter moved on to the tower task and later went back to the imprecise task in an attempt to get a sufficient number of usable reaches. Each condition was repeated at least 4 times or until the toddlers were no longer interested. (See Fig. 1 for photo of child engaged in the tower-building task.)

Data Reduction

Position data were converted into 3-dimensional coordinate data using Phoenix system software. All reaches were viewed and scored from the videotapes to determine the beginning and end of a reach. Two types of reaches were scored: the approach phase and the placement phase. The approach phase began with the first frame that the hand started to move towards the block and ended when the hand contacted the block. The placement phase started with the first frame that the block in hand started to be moved and ended at the first frame when fingers opened to release the block either into the container or on top of the block tower.

A primary observer scored all reaches from the videotape for the onset and end time of the approaching and the placement phases, as well as the tallest level of the tower each toddler could perform during the testing. These times demarcated the Phoenix data so that kinematic measures could be derived from each reach using MATLAB software (Mathworks, MA, USA). A second observer scored all 310 reaches in 4 toddlers to calculate reliability for onset time of the approach phase (94% agreement), end time of the approach phase (97% agreement), onset time of the placement phase (95% agreement) and end time of the placement phase (78% agreement). Whenever the scored time differed by more than 0.099 sec (3 frames), the primary and secondary observers met to obtain agreement on the final times used for analyses (N=9 for onset time of the approach phase, N=4 for end time of the approach phase, N=9 for onset time of the placement phase, and N=37 for end time of the placement phase).

Six kinematic measures were derived for the approach and placement phases separately, including movement time (MT, defined as time from onset to end time of each phase), straightness ratio (SR, defined as the total path length of the hand divided by the shortest distance between hand positions at the start and end frames of the reach), average speed of the reach (MEANV), amplitude of the peak velocity (PV), percentage of movement time to peak velocity (PPV, defined as the time between the start frame to the frame of peak velocity, divided by the movement time), speed at time of contact (for the approach phase) or release of the block (for the placement phase) (ENDV, defined as the speed at the end of the reach).

Toddlers' skill level of tower-building was determined by the tallest level of tower they built using the 1-in blocks from the Gesell Scale. According to the norms for this scale, the mean age of toddlers to build a 2-block tower is 12 months, the mean age to build a 3-block tower is 18 months, and the mean age of toddlers to build a 7-block tower is 24.0 months. (These norms are comparable to the Bayley Scale norms, which have a mean age of 13.8 months for 2-block towers, 16.7 months 3-block towers, and 23 months for a 6-block tower.) We therefore divided our toddlers into 3 skill levels: 1) high-tower builders who could build a 4-block or higher tower, 2) low-tower builders who could build a 2- or 3-block tower, and 3) no-tower builders who could not build any tower. The reliability for scoring the tallest level of tower between the primary and the second observers were 100%.

For high-tower builders we used the same criteria of determining toddlers' skill level of tower-building to determine difficulty of reaches. Reaches during the act of tower-building were categorized into difficult reaches (i.e. placing block 4 or higher) and easy reaches (i.e. placing block 2 or 3).

Study 1

Participants

Thirty-nine toddlers aged between 18 to 21 months of age participated in this study. Three were excluded from analysis because of fussiness and refusing to wear the sensors placed on the hands, and 1 was excluded because of disinterest in the block activities, leaving 35 toddlers (19 males, 16 females; mean age = 19.7 months, SD = 1.2 months). The sample was composed of 35 Caucasian, middle class children. The parents were first contacted by an informational letter describing the study, which was followed by a telephone call to see if they were interested in participating. Each toddler received a T-shirt with the lab logo and a certificate at the end of the testing as our appreciation of participation. All parents or legal guardians of the toddlers signed the informed consents in accordance with the policies of Institutional Review Board of the University of Massachusetts prior to testing.

Results

Four children in this study did not build a tower in the small block condition, so their data were excluded from the data analyses, leaving 31 children who provided complete data for reaches in both phases of both tasks. Of those, 15 were in the low-tower group (2- or 3-block tower) and 16 were in the high-tower group (4-block tower or higher).

In preliminary analyses, comparisons of the initial distance of the approach and the placement phase revealed a difference between the imprecise and tower tasks. For the approach phase, toddlers' reaches started significantly farther away from the block to be picked up in the imprecise tasks ($F(1,22)=13.22$, $p=.001$). The mean distance was 195 mm (SE = 7 mm) for the imprecise task and 161 mm (SE = 5 mm) for the tower task. For the placement phase, toddlers' reaches also started significantly farther away from the final release point in the imprecise tasks ($F(1,27)=25.32$, $p<.001$). The mean distance was 198 mm (SE = 6 mm) for the imprecise task and 166 mm (SE = 4 mm) for the tower task. Although the experimenter controlled the distance between the blocks and the container or tower, it was impossible to control the starting position and movements of the toddlers' hands. Because the distance the hand traveled could affect kinematic measures, such as MT and PV, we statistically controlled for initial distance as a covariate using mixed regression models to test the differences between tasks, skill level, and block sizes on each kinematic measure using the SAS program version 8.0 (SAS Institute Inc., 2005).

We also examined gender differences for each kinematic measure during approach and placement phases. None of the kinematic measures revealed statistical differences between male and female toddlers (all $p>.05$).

As noted above, the testing session in this study always started with the imprecise task, but 9 of the 31 children who built at least a 2-block tower started with the tower task because they initially refused the imprecise task. An analysis of variance was done with order as a main effect. There were no differences in the approach and placement phases for these 9 toddlers who performed the tower task first compared to others who performed the imprecise task first.

In the analyses comparing skill level of groups, only reaches for the approach and placement of blocks 2 and 3 were used because the low-tower group, by definition, did not contribute reaches beyond this level. The average number of reaches per child during the approach phase was 6.23 (SD=5.43) for the tower task and 10.09 (SD=7.62) for the imprecise task. The average number of reaches per child during the placement phase was 10.49 (SD=6.53) for the tower task and 13.20 (SD=8.09) for the imprecise task. Reaches to blocks placed higher in the stack were analyzed separately for the high-tower group. The data for each kinematic measure were analyzed with a mixed regression model of Task (2) × Block size (2) × Skill level (2), with initial distance between hand and object as a covariate for the approach phase data. A similar analysis was performed for the placement phase data, with initial distance between hand and tower/container as the covariate. Table 1 gives the adjusted means and standard errors for all kinematic measures for both phases of both tasks.

Task requirements and kinematic differences

As expected, the degree to which precise movement was required in the task changed the topography of the reach during both the approach and the placement phase. When toddlers approached a block with the intention of later placing it on a tower, peak velocity was reached earlier in the movement, followed by a long deceleration that ended in picking up the block (PPV = .42 for tower and .50 for throwing). Statistically this was expressed as a main effect of task in the PPV measure ($F(1,22) = 4.31$, $p < .05$, Cohen's $f = 0.33$). A lower PPV value indicates that the hand spent a longer portion of the reach in slowing its approach to grasp the block. The approach in the tower task also had a shorter movement time than the throwing task ($F(1,22) = 7.30$, $p < .01$, Cohen's $f = 0.45$; average MT for tower task was 0.97 sec and for throwing was 1.16 sec). The finding for movement time was unique in that it is the only measure significant in the opposite direction to that predicted. There is no ready explanation for this, and as reported below in the placement phase movement time was significant in the expected direction, with the tower task having a longer placement movement.

Once the block was grasped, the movement to place it on a tower was greatly slowed compared to a throwing movement into the container. Several velocity measures reflected this difference: tower building had a lower average velocity ($F(1,27) = 86.24$, $p < .0001$, Cohen's $f = 1.66$), a lower peak velocity ($F(1,27) = 11.89$, $p<.002$, Cohen's $f = 0.59$), a lower contact or end velocity ($F(1,27) = 53.32$, $p<.0001$, Cohen's $f = 1.30$), and as in the approach phase peak velocity was reached earlier in the movement ($F(1,27) = 83.41$, $p<.0001$, Cohen's $f = 1.63$ for PPV). Duration of movement was also longer for tower building ($F(1,27) = 74.07$, $p < .001$, Cohen's $f = 1.54$), as would be expected from the slower velocity measures. Figure 2a displays the group averages for velocity measures, MEANV, PV, and ENDV, showing the consistent slowing of the hand when engaged in a precision task. Figure 3 shows the velocity profile for a single trial from a child on each task, illustrating how the PPV measure varied with the task. This child's hand reached peak velocity earlier, allowing more time for small corrective movements when placing a block on the top of the tower compared to throwing a block into the container.

Skill level differences in reaching kinematics

Once again, the point of reaching peak velocity in the movement (PPV) proved to be an extremely sensitive measure ($F(1,27)=5.28$, $p<.03$, Cohen's $f = 0.37$; mean PPV is .43 for the high-tower group and .50 for the low-tower group). The PPV measure is notable because when PV was reached early in the movement, this was followed by a lengthy deceleration as the hand approached the moment where the block was released. A long controlled deceleration reflects good control over the hand movement and would be expected in a skilled performer. Figure 4a shows velocity of a single reach for a high-tower child and a low-tower child when placing a block on a stack. Note the long deceleration limb as the hand approached the point of release for the high-tower child. Although end velocity and average velocity did not differ for high- versus low-tower children, the topography of the reach differed dramatically as shown in Figure 4. We expected to find, but did not, an interaction of skill level with task precision. That is, high-tower builders were expected to move more slowly than low-tower builders when building towers but not when placing blocks into a container, but the PPV difference is still evident when throwing (see Figure 4b). In summary, skill level differences were reliable only for the placement phase, and the earlier PPV is present in both tasks for the high-tower group.

The slowed-down approach toward the tower seems to be a necessary component of successfully placing blocks on a tall tower. We hypothesized that the kinematics of the movement toward the tower would change as the stack grew higher. An analysis was done on the kinematics of the high-tower group when they were placing blocks low in the tower (under 4 blocks) versus high in the tower (4 +). Contrary to our expectations, children did not change their strategy while building the tower. High-tower children showed greater deceleration when approaching the tower at all levels. Perhaps they represented the functional act of placing a block on the tower as a unit to be repeated, without regard for the changing level of the tower.

Study 2

The purpose of Study 2 was to assess the kinematics of reaching and manipulating blocks a year later in the same tasks that children were given at 18 to 21 months of age. The issue of greatest interest was whether the skill level differences apparent at the earlier age would persist a year later when all children could build tall towers. Earlier differences might be transitory if caution in placing blocks on the tower was produced because children whom we designated as high-tower got tested just at the point of learning to master a new skill. In other words, the difference between high- and low-tower children was due to catching some children while they were in the process of achieving new motor control in building block towers. On the other hand, if their kinematics at 18–21 months were indicative of some more general motor skill, the high-tower children would be expected to move with greater skill a year later. That is, if their greater skill at 18 months was a stable characteristic, then group differences would be expected to remain.

Participants

Seventeen of the 31 children who could build at least 2-level block towers in Study 1 returned to participate in Study 2. One of the 17 children who was diagnosed as having a developmental delay with recurrent seizure attacks was excluded from the final analysis, leaving 16 children (10 Males and 6 Females) aged 30 to 37 months (mean age = 33.98 Months, SD = 2.37 Months). Among the 16 children, 9 could build towers of 4 or more blocks in their first visit (high-tower group) and 7 could build towers of 2 or 3 blocks (low-tower group). All parents who still lived in the area were again contacted by an informational letter describing the study, which was followed by telephone call to see if they were interested in returning to the laboratory. Each child received a book and a certificate as tokens of our appreciation for their participation. All parents or legal guardians of the toddlers signed the informed consents in accordance with the policies of Institutional Review Board of the University of Massachusetts prior to testing.

Results

In preliminary analyses, comparisons of the initial distance of the approach and placement phase again revealed a difference between the imprecise and tower tasks. As in Study 1, for the approach phase children's reaches began significantly farther away from the block to be picked up in the imprecise tasks ($F(1,15) = 25.72$, $p<.0001$). The mean distance was 241 mm (SE = 9 mm) for the imprecise task and 188 mm (SE = 9 mm) for the tower task. For the placement phase, children's reaches also started significantly farther away from the final release point in the imprecise tasks ($F(1,15) = 5.00$, $p<.04$). The mean distance was 241 mm (SE = 9 mm) for the imprecise task and 212 mm (SE = 9 mm) for the tower task. Because the distance the hand traveled could affect kinematic measures, such as MT and PV, we statistically controlled for initial distance as a covariate using mixed regression models to test the differences between tasks, skill level, and block size on each kinematic measure using the SAS program version 8.0 (SAS Institute Inc., 2005).

Regardless of their skill level in Study 1, all of the children, now between 2.5 and 3.0 years of age, could build tall towers. The mean number of blocks in the stack for the high-tower group was 7.71 and for the low-tower group, 7.11. All reaches used to build towers were averaged and used to represent the tower task. The average number of reaches per child during the approach phase was 9.25 (SD=4.88) for the tower task and 28.88 (SD=9.07) for the imprecise task. The average number of reaches per child during the placement phase was 11.25 (SD=3.89) for the tower task and 29.56 (SD=10.96) for the imprecise task. The data for each kinematic measure were analyzed with a mixed regression model of Task (2) × Block size (2) × Skill level (2), with initial distance between hand and object as a covariate for the approach phase data. A similar analysis was performed for the placement phase data, with initial distance between hand and tower/container as the covariate. Table 2 gives the adjusted means and standard errors for all kinematic measures for both phases of both tasks.

Task and skill level differences a year later

No task differences emerged during the approach phase for these children. Once the block was grasped, however, the movement to place it on a tower was greatly slowed compared to throwing it into the container, similar to findings of Study 1. Several velocity measures reflected this difference: compared to the throwing task, tower building had a lower average velocity ($F(1,14) = 138.70$, $p<.0001$, Cohen's $f = 2.93$), a lower peak velocity ($F(1,14) = 40.98$, $p< .0001$, Cohen's $f = 1.58$), and a lower end velocity ($F(1,14) = 173.2$, $p<.0001$, Cohen's $f = 3.28$). Peak velocity was reached earlier in the movement ($F(1,14) = 369.38$, $p<.0001$, Cohen's $f = 4.80$). See Figure 2b for a display of these task differences. Duration of movement was also longer for tower building ($F(1,14) = 135.84$, $p<.0001$, Cohen's $f = 2.90$), as would be expected from the slower velocity measures.

The groups based on skill level as determined by their tower building during the earlier visit, still had kinematic differences when building towers. Although both groups built equally tall towers in this second visit, the hand movements of the high-tower group were faster. They had a shorter movement time between grasping the block and placing it on the stack, but no group difference when throwing blocks into the container (see Figure 5). Statistically this was shown by a task × group interaction for MT ($F(1,14) = 7.44$, $p<.02$, Cohen's $f = 0.63$). In addition the high-tower group reached peak velocity later in the reach, leaving less time for the hand to decelerate as the block was released from the fingers ($F(1,14) = 6.91$, $p<.02$, Cohen's $f = 0.61$). This resulted in a higher EndV for this group ($F(1,14) = 4.41$, $p<.05$, Cohen's $f = 0.46$). Being able to accomplish a precision task at a higher speed reflects greater mastery in motor control for this group. In Table 3 we list all reliable differences between high-and low-tower groups. The table also lists the PPV for the earlier test session because it is of interest to compare the absolute numbers for this important measure across ages.

Continuity within each child was tested by correlating their kinematic measures at the younger age with those same measures at the older age. All significant correlations were specific to the throwing task. MEANV was significant (r=.501 and .603 for approach and placement phases, respectively), and peak velocity was reliable for placement (r = .53). Movement time and straightness ratio of the approach phase had significant correlations (r=. 56 and .58 for MT and SR, respectively). MEANV, MT, and SR during approach were the same three variables that showed consistent improvement over age (see next section and Table 4), and these correlations suggest that the maturing arm/hand control between 2 and 3 years of age has stability within individual children. Developmental change in reaching kinematics between 20 and 30 months of age

Because the same children were tested about a year apart, developmental changes in reaching kinematics could be compared. Between the second and third years of life manual skill is advancing rapidly, shown by children’s mastery of fine motor control over fingers and arms to perform precision movements. In order to make comparisons between the first and second sessions, the initial distance the hand traveled during the approach and placement phases had to be taken into account. This distance was shorter when the children were younger, as would be expected because greater arm length and hand size would extend the length of reaches at the older age. For the approach phase, the mean distance traveled was 183.22 mm (SD = 38.17 mm) at the younger age and 195.06 mm (SD = 55.84 mm) when children were retested. Because the distance the hand traveled could affect kinematic measures, we statistically controlled for initial distance as a covariate using mixed regression models to test the age differences for each kinematic measure using the SAS program version 8.0 (SAS Institute, 2005).

To test for change in movement kinematics between the second and third year of life an ANOVA on Age × Task × Group was performed for approach and placement phases. When children’s hands approached a block, the older children had a shorter movement duration (MT: $F(1,14) = 49.51$, $p<.0001$, Cohen’s $f = 1.74$), reaches were straighter (SR: $F(1,14) = 14.06$, $p < .01$, Cohen’s $f = 0.90$), and had a higher average velocity (MEANV: $F(1,14) = 37.52$, $p<.0001$, Cohen’s $f = 1.51$). Once the block was grasped, the older children again took less time to place a block on top of the tower or throw it into a container (MT: $F(1,14) = 5.58$, $p<.04$, Cohen’s $f = 0.54$), they had straighter movements toward the target (SR: $F(1,14) = 7.86$, $p<.02$, Cohen’s $f = 0.65$), and a longer deceleration phase at the end of the reach (PPV: $F(1,14) = 6.97$, $p<.02$, Cohen’s $f = 0.61$). See Table 4 for adjusted means and standard errors for these kinematic measures at both ages. In general, as children approached 3 years of age their reaches were faster and more efficient in grasping and manipulating the blocks.

GENERAL DISCUSSION

Building a tower of blocks is a typical activity of children around 18–24 months of age. It reflects their ability to form a goal and pursue it by repeatedly executing sequential actions. The ability to link perceptual information (in our case shape and size of blocks, height of tower) with the proper motor actions suggests that an over-arching goal governed the entire sequence. We examined the kinematics of the approach phase to grasp a block and then the movement to place the block on the tower. Both phases were compared to a more casual task of picking up blocks to put them into a large open container. The approach phase kinematics were expected to differ if children were thinking ahead to their goal after they grasped the block, whereas the kinematics of placement were assumed to reflect the care with which children positioned the block for release (Johnson-Frey, McCarty, & Keen, 2004). This two-stage task of first grasping then manipulating the blocks offers a means of assessing how far ahead intentional actions are planned. Johnson-Frey, McCarty, & Keen (2004) had adults reach for a block and subsequently lift and hold it, or transport it to a new location. When adults were anticipating a transport movement, the initial reach-to-grasp duration was affected. The authors concluded that the approach phase was not planned in isolation, but was represented in the complete action sequence, including future movements once the block was in hand. Our data show that toddlers' reach-to-grasp actions also indicate planning of the entire sequence, rather than executing movements in isolation.

For the approach phase we found that toddlers reached for blocks differently depending on the task they intended to subsequently perform. In adults this difference shows up for many kinematic measures, such as total movement time, average speed, peak speed, and when peak speed is reached (Johnson-Frey, et al., 2004; Marteniuk et al., 1987), but only timing of peak speed and movement time were reliable for toddlers. It was expected that average and peak speed would be lower for the precision task as this was found for infants (Claxton, et al., 2003) as well as for adults. Adults and infants had highly similar tasks: pick up an object and either fit it into a tight hole or throw it into a container. Toddlers may not have viewed the tower building versus "clean up" tasks as differing very much in precision compared to the previous "fit it or throw it" tasks. Future studies with toddlers should test them on tasks more similar to what adults did. Nevertheless, as predicted from the adult data, peak speed was reached earlier in the approach for tower building. This task difference suggests that toddlers are beginning to plan sequential stages of the action from the very beginning of movement. Although there is no obvious need for the hand to slow in its approach to pick up the block, the intention to subsequently perform a precision task appears to affect hand speed in the first stage of this two-stage action. We conclude that for this age PPV is a more sensitive measure of the added care used when approaching blocks to be used in building a tower.

In the placement phase toddlers exhibited numerous kinematic differences between the two tasks. When building a tower, all three measures of velocity (peak, average, and contact velocity) reflected slowing of the hand throughout the movement as blocks were lifted and added to the stack, compared to being lifted and released into an open container. Thus children appeared to hold their goal in mind when performing sequential actions involving several items, and exhibited lower velocity when engaged in a precision task just as adults do (Berthier, Clifton, Gullapalli, McCall, & Robin, 1996; Bryden & Roy, 1999; Johnson-Frey, et al., 2004; Wu et al., 2005).

The timing of peak velocity proved to be more sensitive to task demands and to skill level differences than other kinematic measures for this age group. Why should this be so? Presumably the point at which peak speed is reached, or PPV, reflects how control demands are exercised during the movement. The beginning of a movement is primarily devoted to transporting the limb while the later parts are controlling the final approach and securing an appropriate grasp in the approach phase and release in the placement phase. The later parts are more dependent on visual feedback for adjusting the details of the movement. In infants' reaching, movements are produced in a series of sub movements (movement units), each with a distinct acceleration and deceleration phase (von Hofsten, 1979, 1991). As infants come to master reaching, the largest unit will be situated at the beginning of the movement with one or several smaller units following toward the end. The large unit at the beginning is devoted to the transport while the smaller units are devoted to the grasp or release. At the end of the movement, the object and the reaching hand are simultaneously visible and control can therefore be quite precise. If precision demands are high, peak speed will occur earlier to allow time for precise control. On the other hand if precision demands are low, peak speed will occur later because the movement before peak speed is reached is focused on transport with less need for slowed-down movement.

As noted above, peak speed was reached earlier in the precise task and the hand noticeably slowed for the final approach. While all children displayed this pattern it was amplified in children who were more skilled at tower building. The high-tower group reached peak speed earlier than the less skilled group when they were initially learning to build a tower. Although their approach to pick up the blocks did not differ, the high-tower children had a more exaggerated deceleration as they placed blocks on the stack. We interpreted this to mean that these children employed the same strategy that adults do when engaged in a precision task, namely, reach peak speed early in the movement in order to slow down before reaching the point where greatest control is needed. For adults, this pattern is shown when picking up a very small object (Berthier et al., 1996), or placing an object into a tight-fitting space (Marteniuk et al., 1987). In this study this same pattern appeared in highly skilled children, suggesting that they realized that placing a block on a tower required care in keeping the entire stack balanced.

Unexpectedly, toddlers who were more skilled also showed this pattern of reaching peak velocity early when releasing blocks into the container when there was no need for extra care. Children of this age who can construct high block towers have probably achieved this skill recently, according to the Bayley norms. We propose that in performing this new skill the care and attention it required spilled over into the imprecise task which involved the very same blocks (Bushnell & Boudreau, 2000). We suggest that children who have recently acquired the ability to construct tall towers adopted similar movement characteristics for manipulating the blocks in any task. The fact that the same blocks were used in both tasks may have facilitated this tendency. As children become older, building block towers is less challenging and their manipulation kinematics would be expected to differ with task difficulty. When re-tested a year later, the high-tower group still had kinematic differences from the low-tower group when building a tower, but not when placing blocks into an open container.

As toddlers, the high-tower children moved more slowly than low-tower children as they placed blocks on a tower, but a year later they moved more quickly. This change appears to reflect an evolution in skill of tower building. When first learning to successfully balance several blocks in a tower, going slowly is associated with better success. Once mastery is achieved, these children show their superior motor control by going faster, just as highly skilled drivers or skiers can go faster than those with less skill. The fact that throwing velocity did not differ for the groups is evidence that the high-tower children do not move faster in general, but only in the precision task. It would be interesting to have tested other precision tasks because we do not know if their skill was specific to tower building or was characteristic of their approach to precision tasks in general.

We expected that greater maturity in manual skills would be evident in many kinematic measures when a subset of children from the original study was brought back a year later. The same pattern of task differences prevailed at both ages: average velocity, peak velocity, and velocity at contact were lower when building a tower than when throwing blocks into a container, and peak velocity was reached earlier in the movement. Within this similar velocity profile, age differences emerged. Reaches at the older age had a faster average velocity as the hand approached the object, and movements had straighter trajectories and shorter durations for both approach and placement phases. Moving faster and straighter toward one's goal in both phases of movement is exactly the expected result of greater motor maturity, and would be predicted from others' findings (Contreras-Vidal, 2006; Olivier & Bard, 2000). Konczak and Dichgans (1997) found similar changes in a longitudinal sample of children tested between 5 months and 3 years of age. The task in Konczak & Dichgans (1997) was a simple reach for an object held within the child's reach at his/her shoulder height; there was no placement phase in this study. They reported progressive straightening of the path, and increasing peak velocity, with reaches approaching the stereotypic adult pattern of arm kinematics by the third year of life. Of special interest is their finding that timing of peak velocity moves earlier in the reach, just as in our data, with greater maturity. Task difficulty was not manipulated in this study, but Carrico and Berthier (2008) did test 15-month-olds in the approach phase of reaching for big and small objects. The small object required a pincer grip. Their results mirror ours in several ways. The approach for pickup of the smaller object (a Cheerio) had slower average speed, longer movement time, and peak velocity was reached earlier in the movement, compared to the approach for the larger object (rubber ball).

The change in kinematic measures over age allows us to distinguish two factors included in the development of a skill. The first is about mastering precision requirements, an important aspect of which is allocating relatively more time to visual control of the final part of the movement. When the children in the low-tower group had mastered building a high block tower a year later, they showed very early PPV, the signature measure for extended time at the end of the reach. A second factor included in skill development is making the action more efficient. This includes shorter movement duration, straighter trajectories, and higher average velocity which all children showed when retested a year later. Most striking in the high-tower children a year later, PPV moved later in the reach so that the hand was moving faster when placing blocks on the stack. This higher velocity when performing a precision task reflects greater efficiency for this group.

In summary, kinematic measures of toddlers' performance yielded insight into how they approach and execute tasks varying in difficulty. In particular, the timing of peak speed in relation to the endpoint of the movement was sensitive to children's level of skill and to task demands. Reaching peak velocity earlier in the movement in demanding tasks gives rise to a longer period of deceleration and thus better visual control before the hand arrives at the moment of either contacting the block in the approach phase or releasing it in the placement phase. This pattern was evident at both ages when children reached for a block when the upcoming action required precision and balance. Not surprisingly, this same kinematic pattern was demonstrated during the actual placement of the block on the tower, compared to transferring it to a container. Finally, the sensitivity of this movement timing extended to differentiating among children of different skill levels, a difference that remained stable over one year between test sessions. By using two-stage tasks that involved sequential movements, we demonstrated that toddlers engaged in movement planning beyond the available perceptual information and incorporated the final goal of the entire sequence.

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Figure 1.
Photo of a child engaged in the tower-building task using small blocks. Note two small infrared-emitting sensors embedded in a Velcro wrist band were placed around each of the toddler's wrists.

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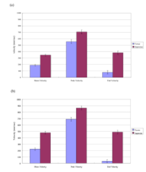

Figure 2.
Three velocity measures for the placement phase are displayed for the same children at 20 months in Study 1 (a) and a year later in Study 2 (b). Note the consistent slowing of the hand when engaged in a precision task.

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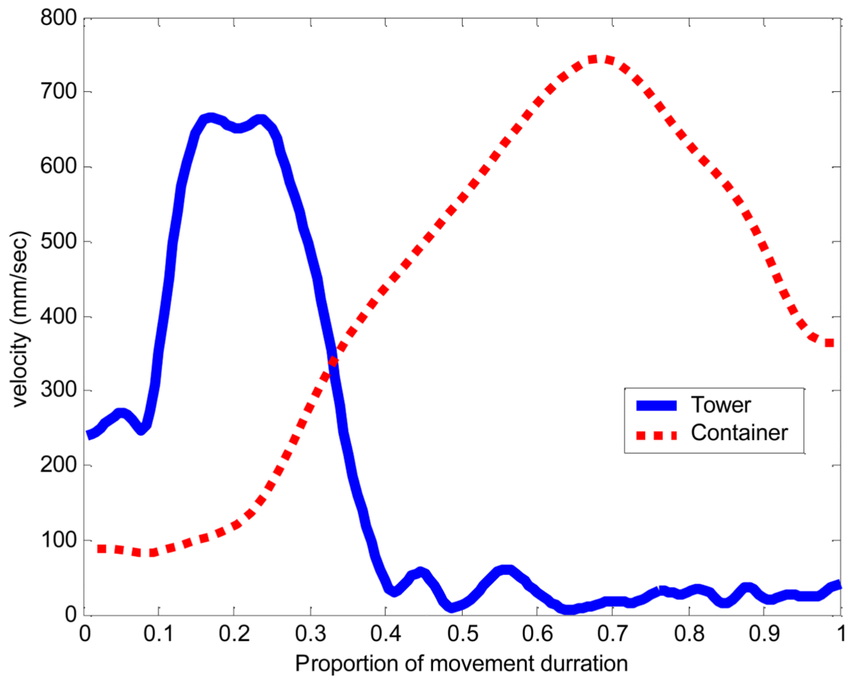

Figure 3.

The velocity profile on a single trial from the same child on each task. This child's hand reached peak velocity earlier when placing a block on the top of the tower compared to throwing a block into the container. Note: reaches were normalized to the movement time.

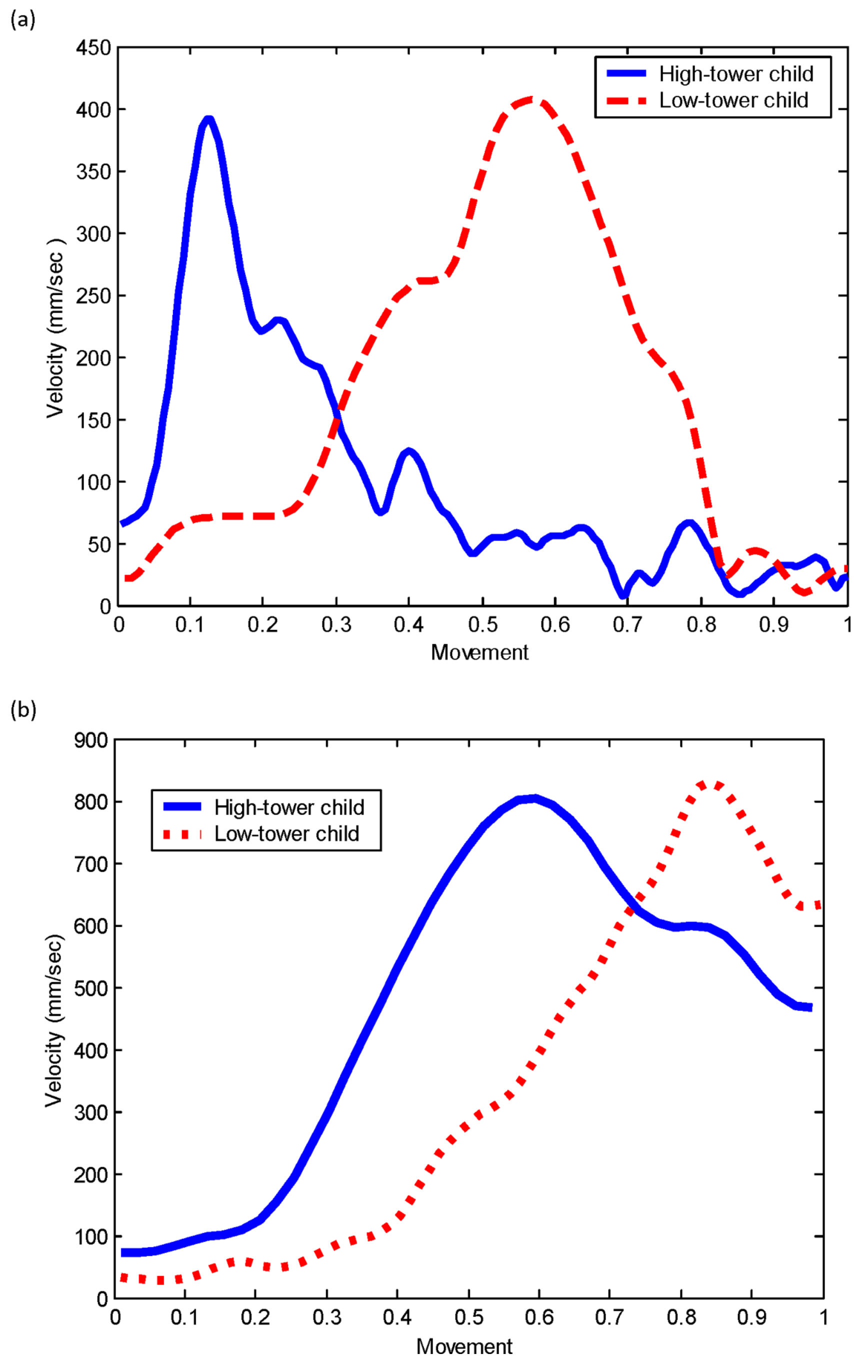

Figure 4.

The velocity profile on a single trial of the (a) tower-building task and (b) imprecise task from a high-tower child and a low-tower child. The hand of the high-tower child reached peak velocity earlier in both cases compared to the low-tower child. Note: reaches were normalized to the movement time.

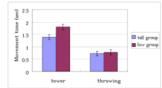

Figure 5.

Movement time (MT) in the high-tower group and the low-tower group in precise and imprecise tasks in Study 2.

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Table 1

Adjusted means and standard errors for all kinematic measures in the precise and the imprecise tasks in the approach phase and the placement phase in Study 1.

	Tower (Precise)	**Container (Imprecise)**
Approach Phase		
Movement time	0.97 (.05) sec	1.16 (.05) sec**
Straightness ratio	1.81 (.15)	1.98 (.15)
Average speed of the reach	319.84 (13.81) mm/sec	304.50 (13.80) mm/sec
Amplitude of peak velocity	684.91 (43.77) mm/sec	615.59 (43.75) mm/sec
Point of peak velocity	.42 (.02)	.50 (.02)*
End speed	210.12 (17.66) mm/sec	245.30 (17.64) mm/sec
Placement Phase		
Movement time	1.80 (.07) sec	1.02 (.07) sec**
Straightness ratio	1.67 (.08)	1.72 (.08)
Average speed of the reach	189.90 (12.18) mm/sec	347.63 (12.17) mm/sec**
Amplitude of peak velocity	556.31 (30.53) mm/sec	706.95 (30.50) mm/sec**
Point of peak velocity	.32 (.02)	.61 (.02)**
End speed	79.26 (28.56) mm/sec	383.85 (28.53) mm/sec**

* p<.05

** p<.01

Table 2

Adjusted means and standard errors for all kinematic measures in the precise and the imprecise tasks in the approach phase and the placement phase in Study 2.

	Tower (Precise)	Container (Imprecise)
Approach Phase		
Movement time	0.77 (.04) sec	0.73 (.04) sec
Straightness ratio	1.44 (.06)	1.43 (.06)
Average speed of the reach	431.30 (17.02) mm/sec	452.88 (16.83) mm/sec
Amplitude of peak velocity	787.14 (33.04) mm/sec	739.70 (32.64) mm/sec
Point of peak velocity	0.42 (.02)	0.46 (.02)
End speed	285.31 (25.83) mm/sec	346.74 (25.50) mm/sec
Placement Phase		
Movement time	1.59 (.07) sec	0.75 (.07) sec**
Straightness ratio	1.38 (.03)	1.36 (.03)
Average speed of the reach	221.03 (21.39) mm/sec	476.12 (21.28) mm/sec**
Amplitude of peak velocity	686.87 (30.61) mm/sec	861.40 (30.48) mm/sec**
Point of peak velocity	0.22 (.02)	0.62 (.02)**
End speed	32.10 (27.15) mm/sec	486.77 (26.95) mm/sec**

* $p<.05$

** $p<.01$

Table 3

Adjusted means and standard errors for significant kinematic differences between the high-tower group and the low-tower group in the placement phase of studies 1 and 2.

	High-tower group		**Low-tower group**	
	Tower	**Container**	**Tower**	**Container**
Study 1				
Placement Phase				
Point of peak velocity *	0.28 (0.03)	0.58 (0.03)	0.36 (0.03)	0.65 (0.03)
Study 2				
Placement Phase				
Movement time*	1.39 (0.09)	0.73 (0.10)	1.80 (0.11)	0.78 (0.11)
Point of peak velocity *	0.25 (0.02)	0.66 (0.02)	0.18 (0.03)	0.58 (0.03)
End speed*	52.57 (34.57)	554.62 (35.16)	11.63 (41.45)	418.93 (39.76)

*indicates a significant skill level difference p<.05

Table 4

Adjusted means and standard errors for significant kinematic differences averaged over tasks between children tested at 20 months (study 1) and re-tested at 34 months (study 2) in the approach and placement phases.

	Younger Age (Study 1)	**Older Age (Study 2)**
Approach Phase		
Movement time**	1.04 (.04) sec	0.70 (.04) sec
Straightness ratio**	1.74 (.06)	1.45 (.06)
Average speed of the reach **	328.38 (13.93) mm/sec	416.59 (13.90) mm/sec
Placement Phase		
Movement time*	1.32 (.06) sec	1.14 (.06) sec
Straightness ratio*	1.63 (.05)	1.44 (.05)
Point of peak velocity *	0.49 (.02)	0.43 (.02)

*indicates a significant age difference $p<.05$

**indicates a significant age difference $p<.001$