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Contents lists available at ScienceDirect

Infant Behavior and Development



Visual information and object size in infant reaching

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ARTICLE INFO

Article history:

Received 28 August 2009

Received in revised form 10 February 2010

Accepted 16 July 2010

Keywords:

Infant
Reaching
Vision
Grasp

ABSTRACT

It has been suggested that the onset of successful reaching in infants is mediated by the onset of an ability to use sight of the hand to make corrective reaches. However, removing vision of the hand in infants younger than 6 months has not been shown to have an effect on reaching onset or kinematics. We investigated the use of vision of the hand by testing 6-, 9-, and 12-month-old infants reaching for objects in the light and in the dark. We found that infants reached faster in the dark at 6 months, and faster in the light at 1 year. Parallel effects were observed in the movement times. Consistent effects of altering target object size on average speed were seen at 12 months. The data support the hypothesis that vision is used by older infants around 6 months-of-age, and that reach and grasp planning differentiate with object size at about 9 and 12 months-of-age. At younger ages reaches are corrected on the basis of proprioceptive information and sight of the target object.

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Adult reachers normally make corrections when reaching for objects (Carlton, 1981; Goodale, Pelisson, & Prablanc, 1986). These corrections are based on visual estimates of the target's location and proprioceptively- and visually-based estimates of the hand's position (Bays & Wolpert, 2007). Vision tends to dominate these estimates of hand position, but proprioception becomes important when the hand is moving and when the distance to the target is the most important task constraint (van Beers, Wolpert, & Haggard, 2002).

The role of vision and proprioception in the development of infant reaching is still not well understood. Piaget (1952) argued that very young infants could not correct their reaching movements using visual information because of the lack of integration of the visual, proprioceptive, and action schemas. Visual information could trigger or elicit reaching in these young infants, but only with continued experience and development could proprioceptive and visual error information be used to generate corrective arm movements.

Bushnell (1985) reviewed the literature on the use of vision in reaching and described three phases in its development. In the initial phase, reaching movements were assumed to be visually elicited and were programmed using a primitive mapping between vision and proprioception. These early movements were generally unsuccessful and were described as largely ballistic and uncorrected (these movements are sometimes called "pre-reaches"). A second phase of development was proposed to begin when infants became able to correct their ongoing reaches using the visual error between the target and the hand. This achievement was said to occur at about 4 months-of-age.

Bushnell (1985) proposed a third developmental phase where there was a decreasing reliance on visual feedback of the hand. Bushnell suggested that with practice the infant's initial command to the arm became more appropriate and corrections became decreasingly necessary. This last phase began at about 8 months-of-age and was an important cognitive

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event because the reduced attentional demands of reaching freed up capacity that could be used to attend to other important aspects of the situation.

An alternative account of the development of reaching is the hypothesis that improvement in reaching was the result of general improvements in the use of perceptual information and in the ability to make finer, more reliable movements. In this account, infants used visual and proprioceptive information to modulate reaching from early in development. This general idea is consistent with the dynamic systems approach of Thelen et al. (1993) and with von Hofsten (1993), neither of whom argued for a qualitative shift in the way vision was used by the infant in the first year of life. Gibson and Pick (2000) discussed how reaching gradually becomes more skillful, better controlled, and more differentiated and how the development of reaching ability is reciprocal with the development of perception.

If Bushnell (1985) is correct and the critical advance at 4 months-of-age is the ability of the infant to incorporate sight of the hand in generating on-line corrections, then removal of sight of the hand at around 4 months-of-age should affect the kinematics of reaching. Comparisons of reaches when sight of the hand was available with reaches where sight of the hand was prevented should show differences in the speed, duration, or smoothness of reaching. Of course, this manipulation does not speak to the question of whether vision of the hand is important in the infant's developing of a mapping of space, but only to the question of whether sight of the hand is important for the on-line guidance of reaching in the middle of the first year of life.

Previous studies have not been able to find an effect of removal of sight of the hand and surround on the kinematics of reaching when infants were less than 6 months-of-age. Clifton, Muir, Ashmead, and Clarkson (1993) longitudinally tested infants from 2 to 5.5 months-of-age reaching for objects in normal illumination and for glowing objects in the dark and found no differences in the ages of first contact and first grasp, nor did infants differ in the proportion of contacts and grasps of the object. Clifton, Rochat, Robin, and Berthier (1994) and McCall, Robin, Berthier, and Clifton (1994) tested 3- to 6-month-olds using a motion analysis system and did not find any differences in the kinematics of reaches in the light and in a glowing-object condition. Also, Robin, Berthier, and Clifton (1996) did not find differences in 5- and 7-month-olds reaching for a glowing moving object in the light and the dark.

These results showing a lack of effect of removing vision of the hand and surround around the time of onset of successful reaching are not consistent with the suggestion that the critical event that allows for successful reaching at 4 months-of-age is the onset of the infant's ability to use vision of the hand for on-line control of reaching movements. This lack of effect of removing vision of the hand and surround does not imply that no corrections are made at this age. Although one would expect that vision of the hand would provide valuable information about the position of the hand at any one time, the infant might be able to correct their reaches using proprioception of the arm. In fact, van Beers et al. (2002) showed that adults weigh proprioception from the arm high relative to vision of the hand in generating corrections during reaching movements. Clifton et al. (1994) showed that 6-month-olds reaching for objects in the light and for glowing objects in the dark showed appropriately timed decelerations before contact with target objects.

While removal of vision of the hand and surround has no measurable effect on reaching at less than 6 months-of-age, removal of other visual information does affect the kinematics of reaching around 6 months-of-age. Clifton et al. (1994) showed that 6-month-old infants move faster and more directly when reaching for an invisible sounding object in the dark and McCarty and Ashmead (1999) showed that 5- to 9- month-old infants reach with short reach durations and with fewer movement units when reaching for an object that has been darkened during the reach. These two studies would seemingly be consistent with the spirit but not the timing of Bushnell's (1985) hypothesis in showing faster, less controlled reaching in the dark. However, besides involving older infants these visual manipulations involve either removing vision entirely or involve turning off the illumination of the room while a reach is in progress and thus likely involve more than removing vision of the hand from the cues the infant might use.

There are no data addressing how infants 6–12 months-of-age react when only vision of the hand is prevented, but studies with 15-month-old infants and adults found that removal of vision of the hand and surround slows reaching. Carrico and Berthier (2008) tested 15-month-olds reaching in the light and dark for glowing objects and found that infants reach more indirectly, with more movement units, and with longer movement times in the dark than in the light. These results are similar to those found with adults when reaching in a similar situation (Berthier, Clifton, Gullapalli, McCall, & Robin, 1996; Churchill, Hopkins, Rönqvist, & Vogt, 2000; Fukui & Inui, 2006; Hopkins, Churchill, Vogt, & Rönqvist, 2004; Schettino, Adamovich, & Poizner, 2003).

In sum, removing vision of the hand and surround does not seem to affect the kinematics of infant reaching at the onset of true reaching at 4–4.5 months-of-age. However, starting at about 6 months-of-age removing gross visual information seems to increase reach speed, but later in infancy removing vision of the hand and surround decreases reach speed. The current paper seeks to determine what the effects are of removing vision of the hand and surround in infants between 6 and 12 months-of-age. In doing so we hope to develop a more complete understanding of how vision of the hand is used during infancy to control reaching. Because vision of the hand is primarily thought to be used as an error signal to correct movement, we tested infants reaching for large and small objects, both of which afforded single-handed grasp. It is conceivable that vision of the hand might be used to guide reaches when task difficulty is high and the target object is small, but that vision of the hand might be of minimal use in reaching for relatively large objects. To these ends, we tested 6-, 9-, and 12-month-old infants reaching for a 4 cm object that afforded a palmar grasp and a 1 cm object that afforded a precision grasp in both the light and in the dark.

1. Method

1.1. Participants

Twenty-three 6-month-olds (mean age 6 months, 4 days; ranging from 5 months, 21 days to 6 months, 18 days), 20 9-month-olds (mean age 9 months, 6 days; ranging from 8 months, 27 days to 9 months 27 days), and 13 12-month-olds (mean age 12 months, 12 days; ranging from 11 months, 21 days to 12 months 26 days) participated in this study. Two infants of each age group were also tested but failed to reach for the target object during experimental sessions. One 9-month-old's data were lost due to a technical failure. All infants were born full term. The current research was approved by the University of Massachusetts Institutional Review Board and written informed consent was obtained from the parents of the participants.

1.2. Stimuli and apparatus

All infants were tested with the room illuminated by a 60 W light bulb. This light was turned off before the presentation of the object on dark trials and remained off on dark trials until the object was grasped by the infant. Infants reached for a fluorescent plastic ball (4 cm in diameter) and for a 1 cm object. The 12-month-olds reached for a piece of Cheerio breakfast cereal (1 cm in diameter) and the 9- and 6-month-olds reached for a 1 cm loop of braided plastic cord that was made out of fluorescent plastic line. This 1 cm loop was part of a longer braided cord that could be safely held and mouthed by the infant without a risk of choking. During presentations only the 1 cm loop was visible to the infant as the remainder of the braided object was concealed in the presenter's hand. The fluorescent ball and plastic loop naturally glowed in the dark and the Cheerio was illuminated from within by placing it on a small flashlight bulb whose illumination was controlled by the presenter (see Carrico & Berthier, 2008, for details). All reaches were video taped by an infrared sensitive Sony digital video camera under infrared illumination to assess reaching in both the light and dark.

1.3. Procedure

Infants sat in their parent's lap throughout testing. The infants were loosely held by their parent around the hips in a manner that provided postural stability but allowed infants to reach smoothly and lean forward at will. The target objects were presented by a presenter who faced the infant. The presenter presented the target objects at a location that was at approximately 80% of the infant's arm's length. Targets were placed at just below shoulder height and in the infant's right manual field to encourage right-handed reaching. Reliability of target placement was maintained by the presenter placing the target relative to their own body frame of reference. For example, the presenter typically rapidly moved the object towards a position above their own leg after data collection was triggered for that trial.

Four types of trials were given in pseudorandom order. There were light and dark trials for both the large and small objects. Presentations were in blocks of four trials with each trial type being represented in each block. Two counterbalanced orders were used. Trials continued until the infant became tired or fussy, usually resulting in 10–20 trials per infant. Dark trials began with the room light being extinguished and the experimenter presenting the object in complete darkness. On these trials infants did not observe the object's location before the lights were extinguished. The trial continued for 12 s or until the infant grasped the object. The room lights were re-illuminated as soon as the infant picked up the object. Infants were allowed to hold, explore, or mouth the object for a short period before the beginning of the next trial.

1.4. Kinematic scoring

The first four trials of the session were not analyzed to allow for the infant to adjust to the situation. Digital video was digitized and deinterlaced into single fields to improve the clarity and temporal resolution for scoring. The time of reach onset was defined as the time when the hand first moved forward toward the target object. Contact time was defined as the time of the initial touch of the target object by the infant. Grasp time was defined as the time between contact with the object and closure of the grasp in preparation for the infant moving the target object.

Two observers scored a subset of the data in order to assess inter-observer reliability. The median signed difference between the observers for reach onset time was 0 ms and 75% of the unsigned differences between observers were less than 100 ms. For object contact times, the median signed difference in the scores was 20 ms with 75% of the unsigned differences being less than 90 ms. The intraclass correlation for the movement times computed from the start and contact times of the two observers was .84. The two observer's grasp times showed a median difference of 110 ms and an intraclass correlation between the grasp times of .87.

Because of the difficulty in scoring grasp prior to contact using traditional methods such as used by Carrico and Berthier (2008), we asked five independent observers to score grasp preshaping using a Likert scale. Observers were asked to score each grasp at the time of contact from one to five, where a score of five indicated precise matching of the grasp to the object's size, and score of one indicated no grasp preshaping. A score of one corresponded to a reach where the object was

first touched by the fingertips of an extended hand. The five scores were averaged across observers and entered as a single number for each trial.

A Northern Digital Optotrak motion analysis system was used to record the kinematics of hand movement. The system tracks the positions of infrared emitting diodes that can be placed on a participant. In this study, two of these markers were placed on the back of the infant's right hand and one was placed on the infant's shoulder. The positions of these markers were tracked at 100 Hz for the full 12 s length of the trial.

Data were processed using custom software. Each trial was first examined for gaps in the data record. Trials with gaps of greater than 300 ms were discarded. If the gap was 300 ms or less, the data were graphically displayed on a computer monitor. Cubic splining was then performed by software and an observer assessed whether the resulting data were smoothly interpolated. A lack of smoothness in any of the three dimensions resulted in the trial being discarded from further analysis. Data were then low-pass filtered at a frequency of 20 Hz with a Butterworth zero-phase, 5th-order filter. The temporal derivatives of motion were calculated by differencing the data. Speed of the hand at each instant was computed as the magnitude of the velocity vector. Jerk was defined as the rate of change of the acceleration of the hand and a reach that was constantly accelerating and decelerating would have high average jerk.

Once the time of the reach was scored, that segment of the motion analysis data was processed to obtain the average speed, peak speed, movement time, distance, jerk, and number of speed peaks of the reach. The average speed was the mean speed of the samples during the reach and the peak speed was the maximum of the speed samples during the reach. The movement time was the amount of time between the start of the reach and contact. The jerk of the reach was the average of the squared jerk of each time sample. The number of speed peaks was the number of maxima of at least 10 mm/s above the nearest valley in the hand-speed profile.

1.5. Statistical analysis

Because different infants contributed differing numbers of reaches, mixed-effects regression models were used to analyze the data. The statistical calculations were performed using the lme4 package of R (Bates, Maechler, & Dai, 2008; Pinheiro & Bates, 2000). This program computes restricted maximum likelihood estimates of the fixed effects regression coefficients and the variance-covariance matrix of the random effects. Unlike traditional analysis of variance, this procedure is robust in unbalanced designs. The coefficients of the model coded age (6, 9, and 12 months), viewing condition (light vs. dark), and target size (large vs. small). The age effect was coded as a continuous variable with a single coefficient and centered on 9 months. The decision to continuously code age was made after analyses with continuous and categorical coding were found to be substantially identical. Continuous coding of age requires fewer terms in the regression equation and is the more parsimonious model. Because all of the other effects have two levels, all the main and interaction effects in the regression model are contained in single coefficients. Significance tests of those coefficients correspond to testing the main and interaction effect of an ANOVA model. An alpha of .05 was used in all tests.

We entered the distance of the reach (defined as the straight line distance from the hand's position at the start of the reach to the position at contact with the target) as a covariate to control for differences in reach distance that occur both within and between ages. Because the participants in this study were infants, it was not possible to control reach distance experimentally. Reach distance is known to linearly scale with measures of reaching kinematics in children and if distance is not controlled, statistically significant differences in these other kinematic variables could be due to differences in reach distance (e.g., Claxton, Keen, & McCarty, 2003). Thus, the means displayed in the figures are adjusted for reach distance and the differences between means in conditions and age reflect change in the dependent variable due to change in the independent variable. For example, the difference between reach speed in the light and in the dark is the effect of the changing viewing condition controlling for reach distance.

Because of the difficulties in calculating the degrees-of-freedom of error terms in mixed-effects models (Baayen, Davidson, & Bates, 2008), *p*-values for effects were determined by Markov chain Monte Carlo methods using the languageR package of R (Baayen, 2008). We note that because of the Monte Carlo simulations, *p*-values show minor variability from simulation run to simulation run. We present the estimates of the regression coefficients from the model, standard errors of those coefficients, and the *p*-values for significant effects in this paper. An accessible reference discussing these methods is Baayen et al. (2008).

The data were log-transformed before analysis because initial plotting of the dependent variables indicated pronounced positive skewing of the distributions. When warranted by our initial overall model, follow-up models were estimated limited to a particular age (with viewing condition and object size as factors) or to a particular viewing condition (with age and object size as factors).

2. Results

Table 1 shows the average number of trials that each infant contributed to the analysis. Infants were given about 15–20 trials on average and on average, infants contributed reaches with unobscured marker data on about 8–11 trials, with slightly more usable data on light trials, with about 2.5 trials per infant, than on dark trials, with about 2.1 trials per infant. The relative contributions by viewing condition and size did not vary with age, but the 9-month-olds appeared to contribute slightly more trials per infant than did the 6- and 12-month-olds.

Table 1

Average number of reaches contributed by participants by condition and age.

Age	Light small	Light large	Dark small	Dark large	Total
6 Months	2.3	2.3	1.4	2.0	8.1
9 Months	3.2	3.0	2.6	2.4	11.1
12 Months	2.1	2.4	2.4	1.9	8.8
Average	2.5	2.6	2.1	2.1	9.3

2.1. Measures of reach speed

Fig. 1 shows the adjusted average speed of reaching as a function of age, viewing condition, and size of target object with the reach distance covariate held constant. Two trends are suggested by the figure. First, infants appeared to reach slower with age, faster in the dark than in the light at 6 months, and faster in the light than in the dark at 12 months. This impression was confirmed by the statistically significant effects for age ($b = -.05$, $SE = .02$, $p < .0003$) and for viewing condition by age ($b = -.08$, $SE = .02$, $p < .0001$). Second, there appeared to be consistently slower reaching for the small object in the light relative to the large object at all ages, but mixed effects of object size for reaches in the dark. The overall statistics supported this second impression with significant effects for target size and target size by viewing condition ($b = .08$, $SE = .04$, $p < .04$, $b = -.16$, $SE = .07$, $p < .03$).

Because of the interaction with age in the overall analysis of average reach speed, we separately analyzed the data at each age. Reaching was significantly faster in the dark at 6 months ($b = .22$, $SE = .06$, $p < .002$), but faster in the light at 12 months ($b = -.19$, $SE = .07$, $p < .007$). At 9 months a significant viewing condition by target size effect was observed ($b = -.25$, $SE = .11$, $p < .03$) indicating faster reaching in the light for the large object compared to the other conditions. A marginally significant target size effect was found at 12 months-of-age ($b = .12$, $SE = .06$, $p = .063$) indicating faster overall reaching for the large object. No other effects were significant in the follow-up analyses.

Similar to the analysis of average speed, peak speed showed significantly slower reaching with age ($b = -.04$, $SE = .01$, $p < .001$) and a viewing condition by age effect ($b = -.05$, $SE = .02$, $p < .002$). Follow-up analyses at each age showed only faster reaching in the dark at 6 months ($b = .17$, $SE = .06$, $p < .008$). The weaker effects for the peak speed analyses compared to the average speed analyses probably result from the increased variability of the peak speed data relative to the average speed

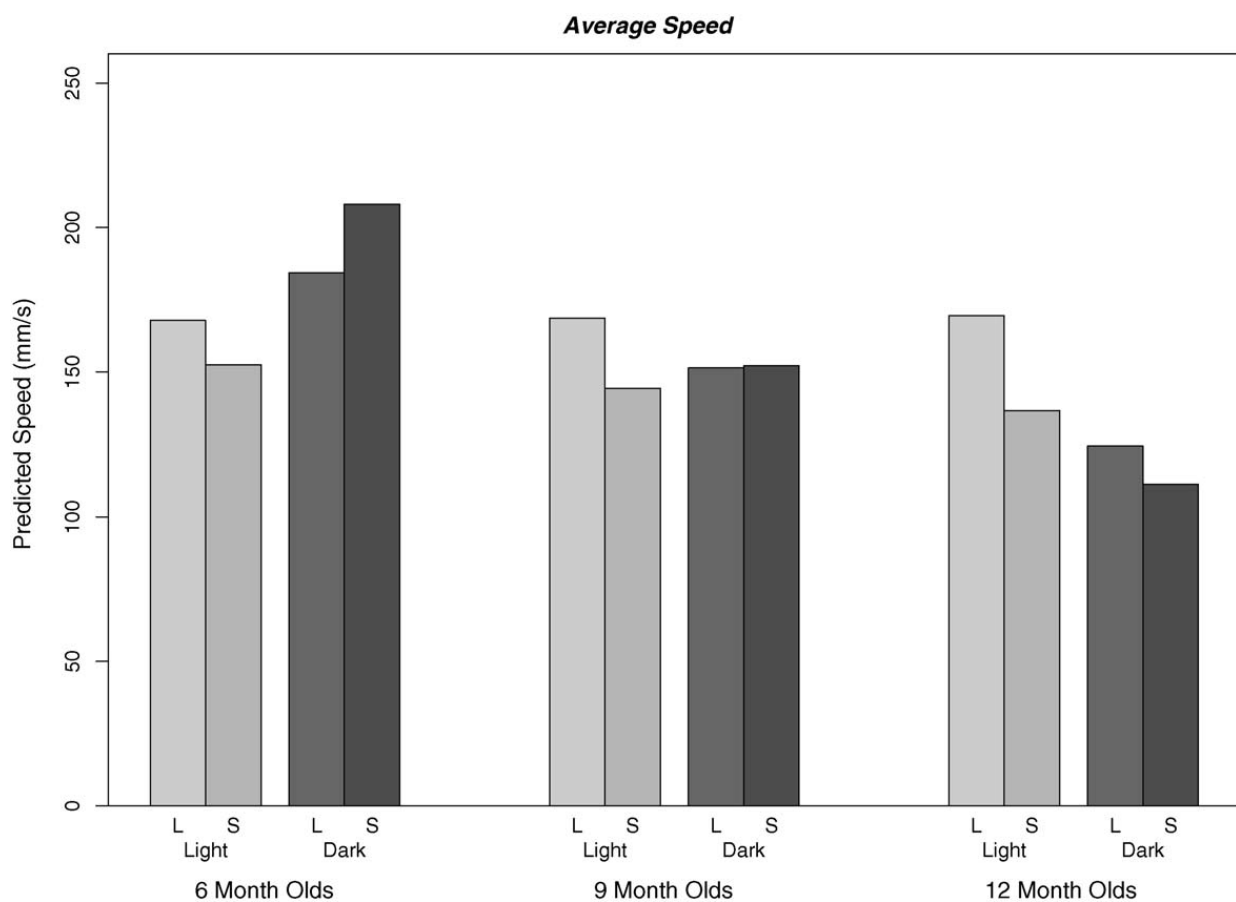


Fig. 1. The average speed of reaching as a function of the subjects age in the light and dark for the large and small object.

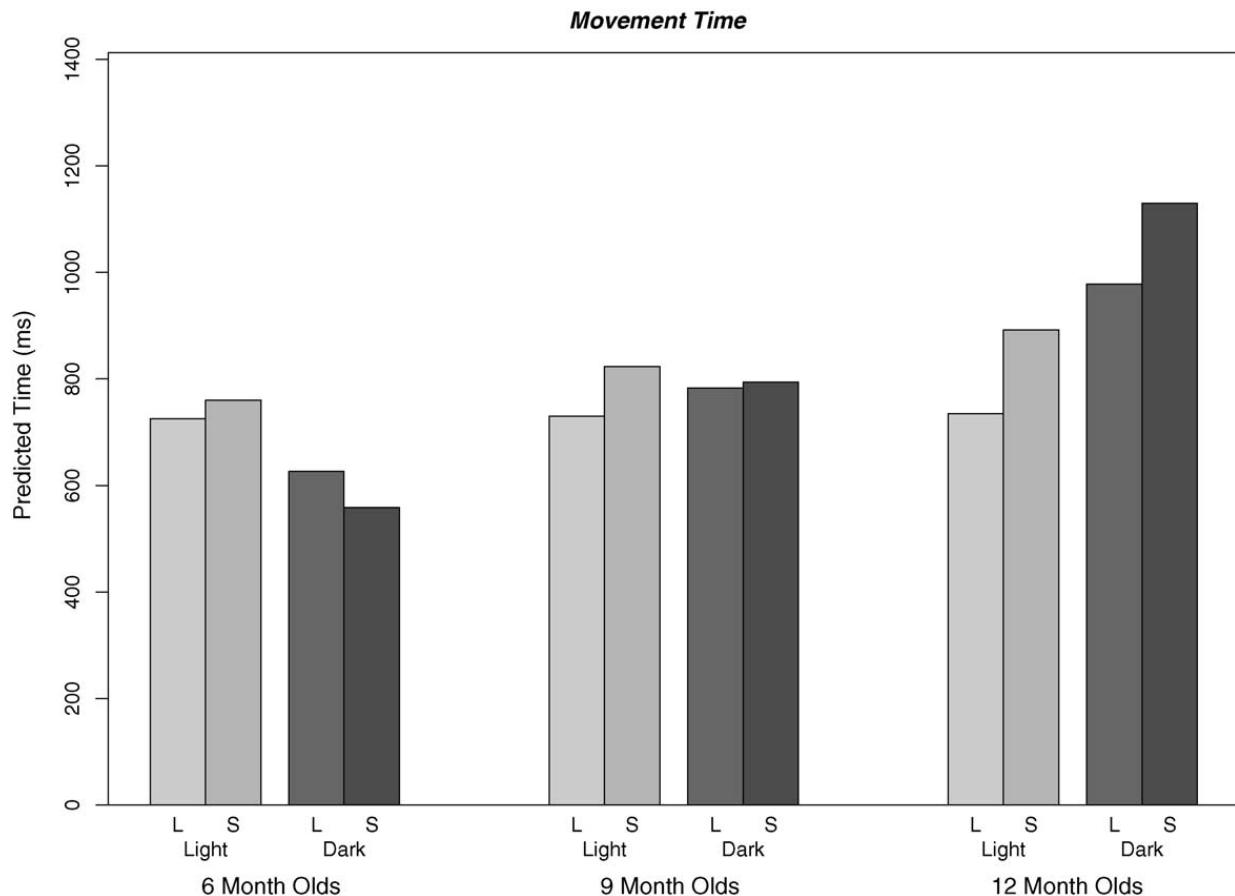


Fig. 2. The movement times of reaching as a function of the subjects age in the light and dark for the large and small object.

data. The peak speed data are based on a single sample from a reach, whereas the average speed data are based on the average value over an entire reach and thus are a more stable estimate of reach speed.

2.2. Measures of reach duration and smoothness

Fig. 2 shows the adjusted movement times for each condition. Overall, movement time increased with age ($b = .06$, $SE = .02$, $p < .0004$), but that increase depended on viewing condition (viewing condition by age effect, $b = .08$, $SE = .02$, $p < .0001$). Follow-up testing showed that movement times were shorter in the dark than the light at 6 months ($b = -.24$, $SE = .08$, $p < .002$) and longer in the dark at 12 months ($b = .16$, $SE = .07$, $p < .03$). These results mirror the reach speed analyses above in that movement times were relatively constant in the light, but increasing in the dark condition. Also like the speed analyses above, we observed a significant effect of target size only at 12 months where movement times were longer to the small target ($b = -.15$, $SE = .07$, $p < .03$).

The smoothness of reaching was assessed by calculating the average squared jerk of reaches. **Fig. 3** shows that jerk generally decreased with age ($b = -.13$, $SE = .05$, $p < .001$) and that the effect of viewing condition was dependent on age (viewing condition by age effect, $b = -.15$, $SE = .05$, $p < .005$). Follow-up testing indicated a marginal effect of viewing condition at 6 months with higher jerk being observed in the dark ($b = .35$, $SE = .20$, $p < .09$) and a significant viewing condition effect at 12 months with higher jerk being observed in the light ($b = -.53$, $SE = .19$, $p < .009$).

The smoothness of reaching was also assessed by counting the number of peaks in the hand-speed profile of reaches (**Fig. 4**). The number of speed peaks showed a significant increase with age ($b = .07$, $SE = .04$, $p < .03$) and a viewing condition by age effect ($b = .08$, $SE = .04$, $p < .04$). The number of speed peaks was higher in the light than the dark at 6 months, but higher in the dark than in the light at 12 months. However, follow-up analyses showed no significant effects on the number of peaks at the individual ages. No significant effects were observed in the analysis of the straightness ratios of reaches.

2.3. Grasp

Fig. 5 shows the grasp preshaping scores for the conditions of this study. An overall mixed-effects model showed significantly increased preshaping with age ($b = .17$, $SE = .01$, $p < .0001$), increased preshaping for the large target relative to the small target ($b = .16$, $SE = .03$, $p < .0001$), and increased preshaping for objects viewed in the light compared to the dark

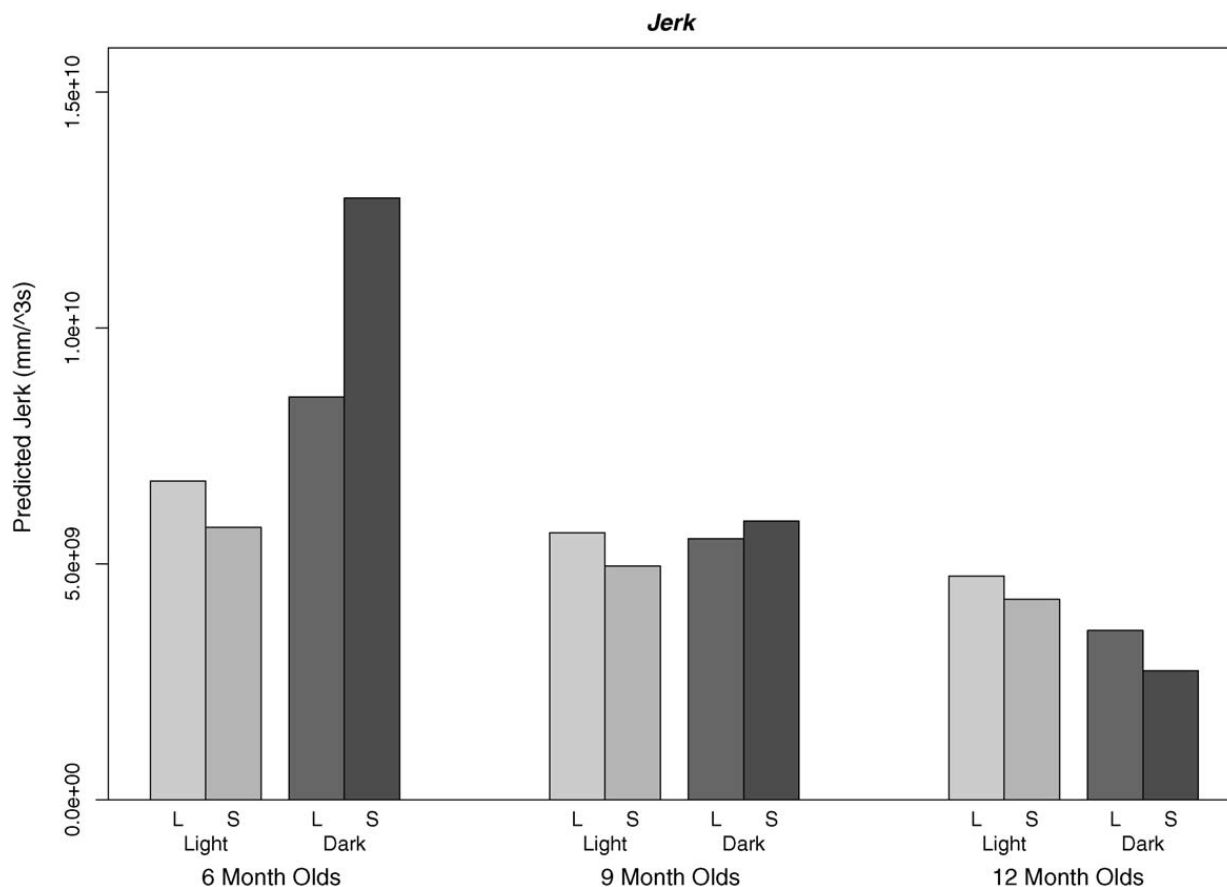


Fig. 3. The sum of squared jerk of reaching as a function of the subjects age in the light and dark for the large and small object.

($b = -.10$, $SE = .01$, $p < .0002$). Because the grip configuration required to match the large object was closer to the neutral hand configuration than the grip configuration to match the small object, the significant object size effect probably reflected the relative ease of matching the large object.

The amount of time from the initial contact of the hand with the target until the fingers attained a stable configuration suitable for grasping was calculated. Fig. 6 shows that these grasp times generally decreased with age and were much lower in the light. An overall mixed-effects model showed significant effects for age ($b = -.10$, $SE = .024$, $p < .0001$), viewing condition ($b = .55$, $SE = .07$, $p < .0001$), size ($b = -.17$, $SE = .07$, $p < .02$), and size by age ($b = -.07$, $SE = .03$, $p < .04$). Model fits of the data from the different ages showed viewing condition effects at each age with grasp times being longer in the dark ($b = .43$, $SE = .14$, $p < .002$, $b = .61$, $SE = .11$, $p < .0001$, $b = .55$, $SE = .15$, $p < .0002$, respectively) and a size effect at 12 months with grasp times being longer for the small object ($b = -.40$, $SE = .14$, $p < .04$).

Differences in grasp time might be due to difference in the configuration of the hand at the time of contact with the target object. Perhaps, grasp times are shorter in some conditions because the hand is better preshaped when initial contact is made in these conditions. In order to test this hypothesis we added grasp preshaping to our mixed-effect model predicting grasp times. The analysis confirmed that grasp preshaping did predict grasp time ($b = -.62$, $SE = .13$, $p < .0001$). In this model with preshaping entered as a covariate to control for grasp preconditioning, grasp times decreased with age ($b = -.06$, $SE = .02$, $p < .01$) and times were faster in the light than in the dark ($b = .49$, $SE = .07$, $p < .0001$). A significant age by target object size was also observed ($b = -.08$, $SE = .03$, $p < .009$). Follow-up modeling at each age showed significant viewing condition effects at each age ($b = .43$, $SE = .13$, $p < .0009$, $b = .56$, $SE = .13$, $p < .0001$, $b = .49$, $SE = .14$, $p < .0004$, respectively) indicating faster grasp times in the light, and a significant target size effect at 12 months ($b = -.39$, $SE = .13$, $p < .003$) indicating faster grasp times for the large object at a year of age.

3. Discussion

3.1. Summary

The dependent variables that assessed the transport phase of the reach all showed similar statistical effects. Average speed, peak speed, movement time, average jerk, and number of speed peaks all showed overall age and age by viewing condition effects. The signs of those effects differed between the measures, with average speed, peak speed, and movement jerk showing negative coefficients for both effects, and movement time and number of speed peaks showing positive coefficients

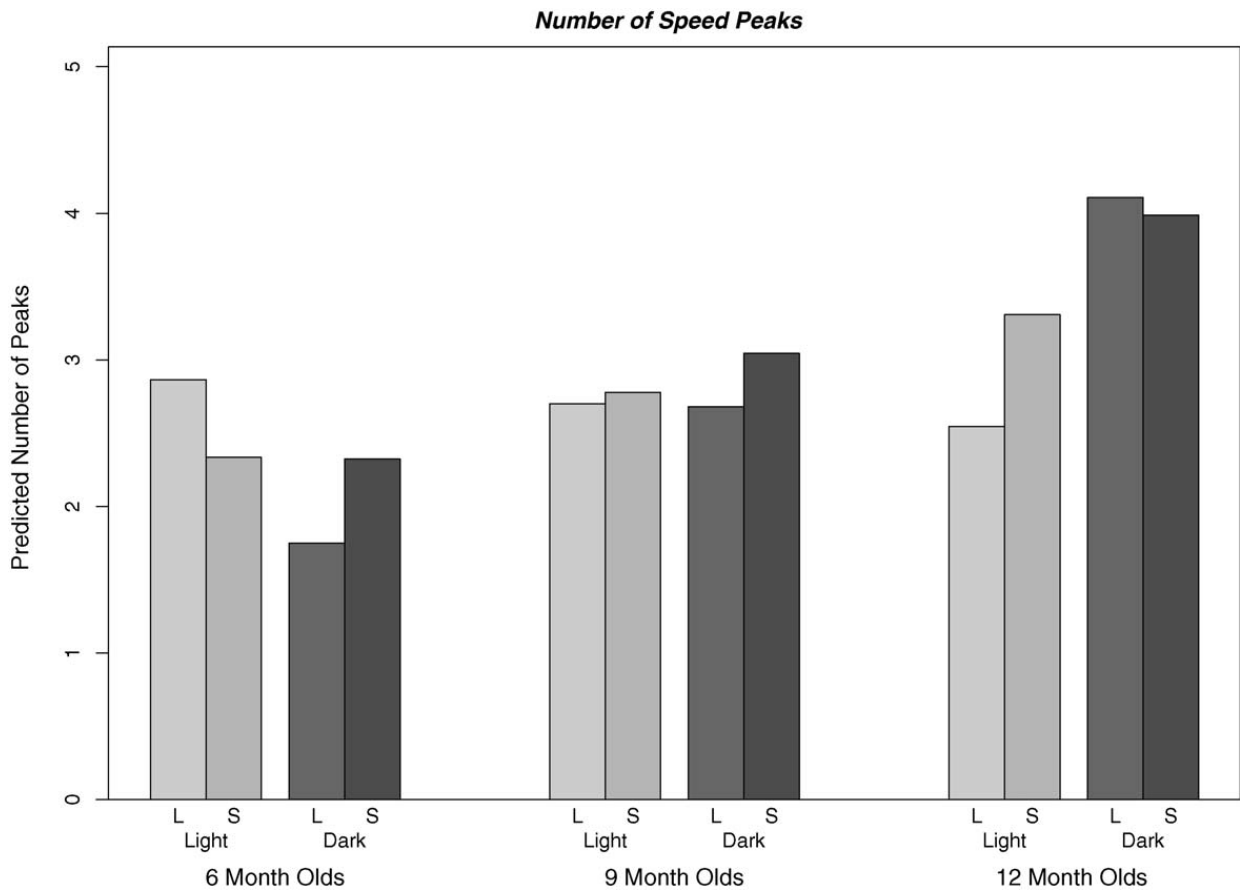


Fig. 4. The number of peaks in the speed profile as a function of the subjects age in the light and dark for the large and small object.

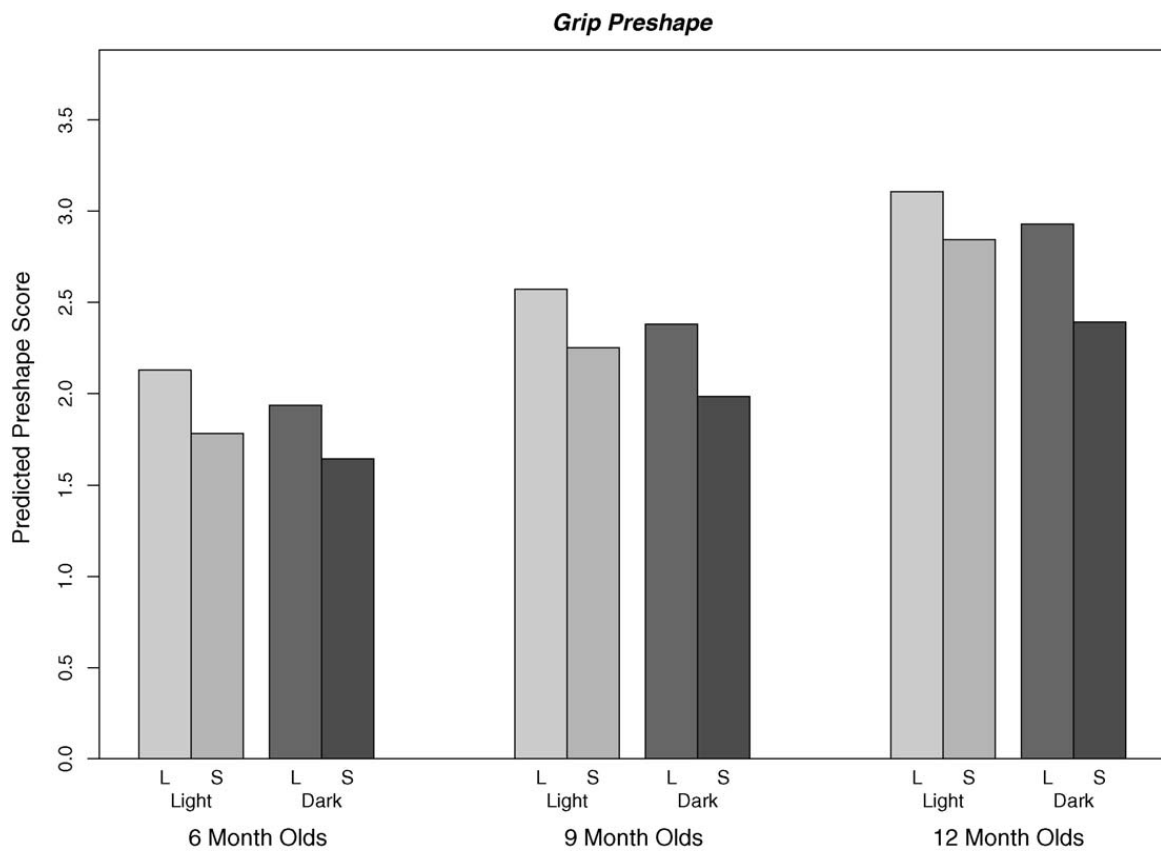


Fig. 5. Grasp preshaping at the time of contact as a function of the subjects age in the light and dark for the large and small object.

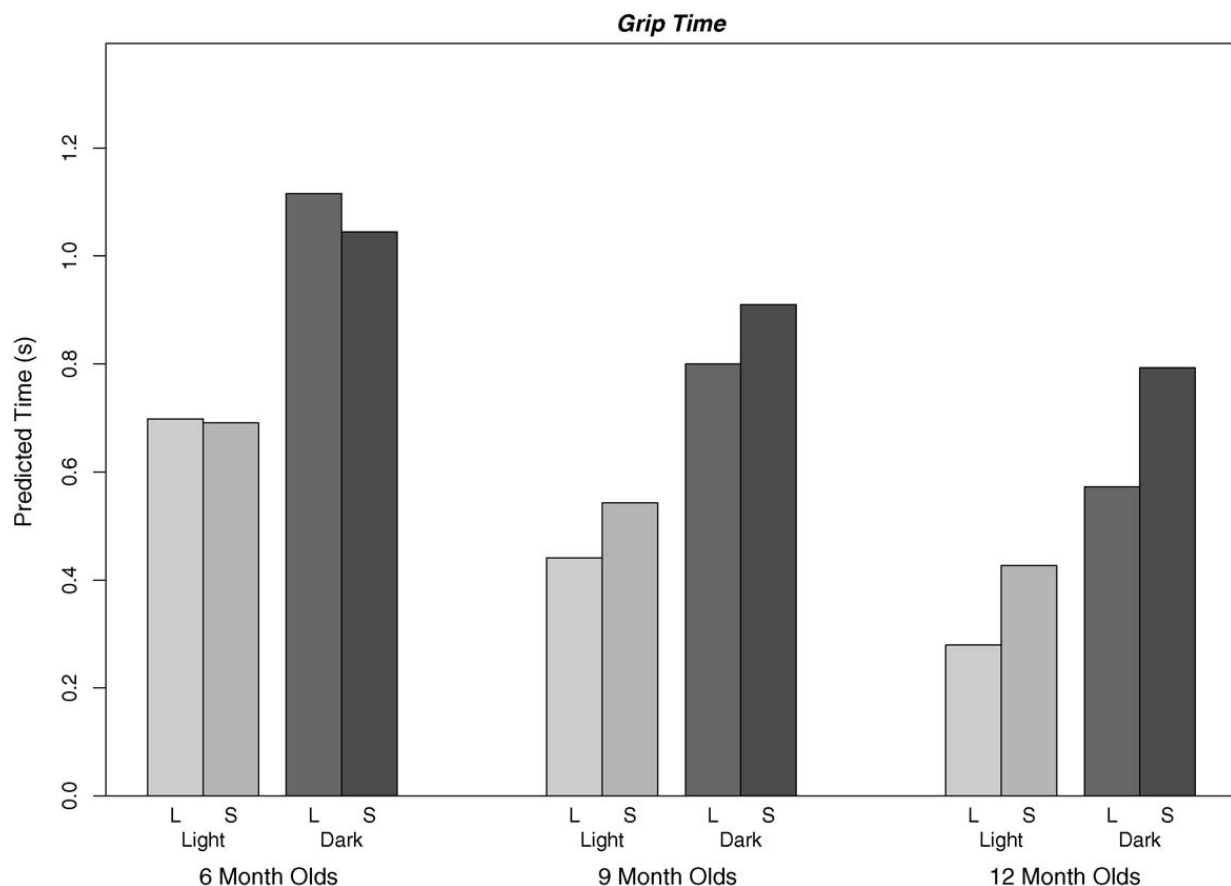


Fig. 6. The time to accomplish a grasp as a function of the subjects age in the light and dark for the large and small object.

for both effects. These associations among the dependent variables are similar to the correlations observed by Berthier and Keen (2006).

These statistical effects indicate that overall speed and jerk of reaching decreased with age and that movement time and number of speed peaks increased with age. However, these effects were qualified by viewing condition interactions. While follow-up testing at each age did not always result in a clear explanation for these age by viewing condition interactions, significant and marginally significant effects of viewing condition on average speed, peak speed, movement time, and jerk were generally observed at 6 and 12 months-of-age. Removing vision of the hand and surround at 6 months-of-age resulted in faster, shorter duration, and jerkier movements, but removing vision of the hand and surround at 12 months-of-age had the opposite effect of producing slower, longer duration, and less jerky reaches.

In considering the grasp phase of the reach, removing vision of the hand and surround had significant effects on grasp preshaping and on grasp time at all three ages. Infants were better at configuring the hand prior to contact and faster at completing the grasp when vision of the hand and surround was available. The effects of vision on grasp times were not solely due to more effective preshaping in the light because analyses of grasp times with preshaping statistically controlled showed highly significant effects of visual condition.

The current data are cross-sectional and do not allow for the investigation of individual developmental trajectories. Furthermore, while the design of the experiment was the same at the three ages, the functional task may have differed between ages from the infant's point of view. The data on grasp preshaping suggest that younger infants may have been attempting to transport the hand to the target and then execute a grasp, while older infants may have been attempting to execute an integrated reach and grasp with a significant closure of the grasp during transport. In the current experiment we are on much firmer ground when comparing within an age group than between age groups.

To summarize these complex results. First, younger infants showed much more limited preshaping of the grasp during transport than did older infants. Second, the effect of removal of vision of the hand and surround at 6 months was to speed up reaching whereas the effect of removal of vision at 12 months was to slow reaching. The faster reaching in the youngest infants was accompanied by more jerk, shorter movement times, and fewer peaks in the speed profile, and the slower reaching by 12-month-olds was accompanied less jerk, longer movement times, and more peaks in the speed profile. Third, the effects of target size on the transport phase kinematics were largely limited to the oldest infants. Lastly, removing vision of the hand and surround resulted in worse preshaping of the hand at the time of contact and longer grasp times at all ages tested.

3.2. Effects of removing vision of the hand and surround

The observed reach slowing with removal of vision in the 12-month-olds is similar to the effects of removal of vision in 15-month-olds (Carrico & Berthier, 2008) and in adults (Berthier et al., 1996; Churchill et al., 2000). Given results showing the importance of visual feedback of the hand near the target in adults (e.g., Carlton, 1981), the dramatic slowing observed in reaching in the dark by adults is almost certainly due to a disruption of visual information about the hand's and target's location during the terminal phases of the reach. Consistent with the hypothesis that vision of the hand and surround play an important role in the terminal phases of the reach are our results showing that removal of vision has the effect of reducing the quality of hand preshaping and lengthening the grasp time for all three ages of our study. At 12 months and above, the loss of precision information provided by vision of the hand also results in infants slowing the transport of the hand.

In contrast, when vision was removed at 6 months, infants reached faster in the dark with increased jerk, changes that are likely due to poorer control of the hand during the transport phase. The current data are the first data to show kinematic changes in reaching in the dark for glowing objects for infants 6-months-old or younger. Previously, infants 6-months-old and younger showed no effect on reaching success or reach kinematics when reaching in the dark for glowing objects (Clifton et al., 1993, 1994; McCall et al., 1994; Robin et al., 1996). Other studies where changes were observed in reduced vision conditions at around 6 months-of-age were Clifton et al. (1994) who observed that 6-month-olds reached faster for invisible, sounding objects in the dark, McCarty and Ashmead (1999) who found that infants reached with shorter movement times for a rod that was darkened in mid-reach compared to reaches where the object remained visible, and Corbetta, Williams, and Snapp-Childs (2007) who found that reaching speeds were higher for infants showing simple fixation of an object compared to more thorough scanning of the target. In comparing the results of these studies it seems clear that infants around 6 months-of-age reach faster when the visual support for the reach is reduced.

There are two plausible reasons for the observed increased reaching speed by 6-month-olds in the dark. First, it could be that darkening the room causes 6-month-olds to switch their reaching style to a higher energy mode. This mode of reaching is still controlled in that infants make contact with the target and show hand decelerations in reduced vision when approaching the target (Clifton et al., 1994).

The explanation that 6-month-olds are more highly energized in reaching in the dark is not consistent with our data showing that removing vision of the hand and surround *increased* the speed of the approach phase, but *decreased* preshaping and speed of grasp at 6 months. One would expect an increase in motivation or energy would cause increases in the speed of both phases of the reach. This observation of a relative decoupling of transport and grasp at 6 months-of-age supports models of grasping where distinct systems control the two phases of reaching (e.g., Fagg & Arbib, 1998; Oztop, Bradley, & Arbib, 2004).

A second reason for the higher speeds in the dark at 6 months might be that the feedback control system involved in reaching works faster without the added burden of having to incorporate visual information into the control signal to the muscular system. This possibility was raised by Bushnell (1985) who suggested that the use of visual information to control reaching had a cost in increased visual attention. It could be that at young ages visual information of the hand and surround slows reaching because of the added computational burden, but that at older ages infants are more efficient processors of visual information so that the effect is one of increased reaching speed in the light. Our finding of better hand preshaping in the light in 6-month-olds suggests that vision of the hand and surround is used to improve accuracy of the reach and grasp.

A parsimonious model of the use of vision in the development of reaching would follow many of the hypotheses of Bushnell (1985). Early reaching would be either uncorrected (ballistic) or corrected using proprioception of the hand and vision of the target. Proprioception is a particularly powerful input as studies show that 5-month-olds reach for glowing, moving objects in the light and dark with indistinguishable kinematics (Robin et al., 1996). Starting at about 6 months-of-age, when data first shows that removing vision of the hand and surround has significant effects on the transport and grasp phase, infants start to use vision to guide their hand to the target and to preshape the hand. The incorporation of vision of the hand and surround into the control process requires effort and slows reaching when vision is available as compared to when vision of the hand and surround is not available. With development and practice, the use of vision of the hand and surround becomes more efficient so that at 9 months-of-age reaches are equally fast in full vision and in darkness, and at 12, 15, and older ages, reaches become faster in full illumination.

This proposed model differs from Bushnell's (1985) model in two significant ways. First, while Bushnell hypothesized that the onset of successful reaching at 4 or 4.5 months is the result of the infant being able to use vision of the hand to correct reaches, the proposed model suggests that vision of the hand only begins to be used after the onset of successful reaching at about 6 months. Second, Bushnell (1985) suggested that vision of the hand declines in importance at about a year of age, and the proposed model emphasizes the continued importance of vision of the hand and surround throughout later development.

3.3. Effects of changing object size

The effects of changing target object size were predominantly seen at 12 months-of-age. The viewing condition by target size effect on reach speed and movement time seemed largely due to faster reaching for the large object at 12 months. The effect for target object size on grasp time controlled for preshaping was only seen at 12 months-of-age and reflected faster grasp times for reaches for the large object.

The current results showing effects for target size being limited to late in the first year are consistent with other studies. Newell, Scully, McDonald, and Baillargeon (1989) showed that while infants differentiated grip configuration to object size as early as 4 months-of-age, they did so haptically after contact. Visually-based differentiation was only observed in infants approaching 8 months-of-age. von Hofsten and Rönnqvist (1988) showed that infants needed to be 9 months-of-age before a kinematic approach variable, maximum grip aperture, differentiated based on object size. Lastly, Rocha, Silva, and Tudella (2006) showed that object size had no effect on the average speed or the straightness of reaches at 6 months. All told, the literature and current data show that while there may be small effects of changing object size as early as 6 months-of-age, substantial and significant effects of object size on the approach and grasp of targets only appear after 8 or 9 months-of-age.

This age at which object size reliably affects the approach and grasping of objects corresponds with the shift from proximal to distal control of reaching (Fagard, 2000) and correlates with the time at which the corticospinal tract innervates the distal musculature of the hand to provide for multidigit grasping (Olivier, Edgley, Armand, & Lemon, 1997). There is strong evidence that this development is not simply maturational, but mediated by experience and exploration of the infant (Salimi, Friel, & Martin, 2008). Investigators have suggested that the severity of disabilities such as those observed in individuals with cerebral palsy might result from cerebral silence during this period of wiring of the corticospinal tract (e.g., Salimi et al., 2008).

It is remarkable that the time at which vision of the hand and surround becomes increasingly important is when one first observes effects of target size. It seems highly likely that differentiation of grasping first observed at 8 or 9 months-of-age is jointly dependent on increases in motor precision made possible by control of the distal musculature by the corticospinal tract and increased use of vision of the hand, fingers, and surround. Perhaps, in younger infants vision of the hand and surround, while potentially a rich source of precise information about the current location of the hand, fingers, and target, is of limited use because proprioception provides sufficient information to control movements to the extent that is possible when independent use of the fingers is absent.

Acknowledgement

This material is based upon work supported by the National Science Foundation under Grant Number BCS-0214260.

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