2001

The role of vision in infants' precision reaching.

Renee L. Johnson
University of Massachusetts Amherst

THE ROLE OF VISION IN INFANTS' PRECISION REACHING

A Thesis Presented

by

RENEE L. JOHNSON

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE

May 2001

Psychology

THE ROLE OF VISION IN INFANTS' PRECISION REACHING

A Thesis Presented

by

RENEE L. JOHNSON

Approved as to style and content by:

Neil E. Berthier, Chair

Rachel K. Clifton, Member

Andrew H. Fagg, Member

Melinda Novak, Department Head
Psychology Department

DEDICATION

This work is dedicated to

C. Donald Johnson

Anna Marie Johnson

Otis Virgo

Evelyn Virgo

The strength of their love has been among the greatest blessings in my life.

DEDICATION

This work is dedicated to

C. Donald Johnson

Anna Marie Johnson

Otis Virgo

Evelyn Virgo

The strength of their love has been among the greatest blessings in my life.

ACKNOWLEDGEMENTS

I would like to thank my advisor, Neil Berthier, for his guidance during this process. He has been extraordinarily generous with his time and energy, and if I have succeeded in producing a worthwhile study, it is in large part due to his strengths as a scientist and a mentor. I would also like to thank my committee members, Rachel Clifton and Andrew Fagg, for their valuable suggestions and insights on this project.

Graduate school is often an arduous experience, but it would be infinitely more difficult without the support of other students. Their understanding and constant encouragement have eased the stresses of graduate school, and their friendships have enriched my life. I would especially like to thank Laura O'Sullivan, who has shared in each frustration and success along the way with empathy and quiet good humor. I am truly grateful for such friends.

I would like to express my deepest gratitude to my family, whose unwavering faith in my abilities continually inspires me to greater achievements. Their unfailing love and support has been the stable foundation from which I draw the strength to meet new challenges. Finally, I would like to thank Anthony Carrico. He has supported me through a sometimes circuitous career route with inexhaustible encouragement and dedication, and his steadfast love is my greatest daily joy.

TABLE OF CONTENTS

APPENDICES

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

A. Vision and Reaching in Infancy

Developmentalists have traditionally held that vision plays a crucial role in the development and guidance of infants' reaches. Piaget (1952) proposed that early reaches are visually guided, and infants use sight of the limb to coordinate mappings of visual and manual space. According to this view, reaching will not occur unless the infant sees both the hand and the target object in the same field of view. Once the hand and target object are in the same field of view, the infant closes the physical distance between the hand and the target by reducing the visual distance between them.

Support for this position came primarily from Piaget's (1952) observations of his own children, and White, Castle, and Held's (1964) longitudinal study of the development of prehension. At various points from 3 to 6 months–of–age, each of Piaget's children was observed engaging in alternate glances between their hands and a desired object while reaching. Similarly, White et al. reported that between 2 and 4 months–of–age, many infant reaches were characterized by brief alternating looks between the hand and the target object. Piaget concluded that, at this early stage of reaching, "the simultaneous viewing of hands and object is therefore still necessary for prehension" (p. 113). According to Piaget, such simultaneous viewing is required for infants to coordinate visual and motor schemas; only after these schemas have been coordinated are infants capable of reaching without visual guidance.

In her 1985 review of the literature, Bushnell charts the development of visually guided reaching over the first year of infancy. The development of reaching is described as comprising three distinct phases, with different kinematic characteristics and dependence on visual guidance. Initial "prereaching" movements are ballistic, and do not make use of visual cues of the hand to guide or correct movements. Rather, they are preprogrammed, uncorrected movements to the target, based on a rough mapping between visual and proprioceptive spaces.

Bushnell proposes that infants progress to the second stage of reaching development at around four months–of–age. Reaches in this stage are no longer ballistic, and exhibit corrective movements. These reaches also differ from earlier prereaching movements because they are visually guided in the classic Piagetian sense. Corrective movements are generated as the infant visually monitors the approach of the hand to the target. According to Bushnell, this period from four to eight months–of–age is a time of intense reaching practice, during which visual guidance is of great importance. As the infant becomes proficient at reaching, the mapping between visual and proprioceptive space is precisely coordinated. After this point, infants enter the third stage, of visually elicited reaching.

In Bushnell's third stage, infants become capable of reaching without active visual guidance, and can instead rely on the coordinated mapping between visual and proprioceptive space established in the previous stage. Reaches may still exhibit corrective movements, but they are generated by feedback from proprioception, rather than vision, of the hand. During this stage, proprioception can provide sufficient feedback to accurately guide infant reaches in most situations. However, Bushnell proposes that infants may rely on vision to guide their hand when faced with especially challenging tasks.

Recent work suggests that vision of the hand plays a less central role in the active guidance of reaching than earlier studies (Piaget, 1952; Bushnell, 1985) have proposed. A longitudinal study by Clifton, Muir, Ashmead, and Clarkson (1993) manipulated the amount of visual information infants had about a target object and their hand while reaching. Infants were tested repeatedly from 6 to 25 weeks–of–age reaching for glowing or sounding objects in the light and dark. When reaching in the light, infants have visual information about both hand and target available. In the dark, a glowing object provides visual information about the target but not the hand, while a sounding object provides no visual information at all.

If early reaching is indeed strictly visually guided, reaching should occur developmentally earlier in the light, where vision of the hand is available, and appear in the dark only after the infant has had enough experience reaching to coordinate the mappings between visúal and manual space. However, Clifton et al. (1993) found that infants contacted objects in the light and dark at about the same age, and concluded that simultaneous sight of the hand and target is not necessary for early reaching. Proprioception combined with vision of the target object appear to provide sufficient information to guide infants' reaches. Indeed, infants can perform relatively complex reaches successfully without sight of the hand. Robin, Berthier, and Clifton (1996) found that 5 and 7.5 month–olds were able to anticipate the trajectory of a glowing moving object in darkness and make contact with the same frequency as reaching for a moving object in the light.

Clifton, Rochat, Robin, and Berthier (1994) examined infant reaches in greater detail to determine if the amount of visual information affected the kinematics of the reach. In a procedure similar to that of Clifton et al. (1993), 6 month–old infants were encouraged to reach for glowing or sounding objects in the light or dark. Kinematic measures for each reach included duration, average and peak velocity, path length, and deviation from a straight path. Although reaches in the light were somewhat more accurate, no kinematic differences were found between successful reaches (where contact with the object was made) in light or glowing conditions. This is a further indication that sight of the hand is not necessary for the active guidance of early reaching.

Sight of the object, in contrast, does appear to be important for infant reaching; Clifton et al. (1994) found kinematic differences between reaching where the object was visible (an object in the light or a glowing object in the dark) and where the object was not visible (a sounding object in the dark). Reaches for the sounding object were faster, shorter in duration, and less accurate than reaches where the object was visible. These differences may be explained by the fact that auditory cues in this study provided far less information about the object than visual cues. Visual cues provide information about the size, shape, orientation, and precise location of an object, while sound cues can only localize the object more generally.

In sum, infants do not appear to require sight of their hand in order to contact and grasp an object. Proprioception and sight of the target object are sufficient to guide infants through a successful reach. Furthermore, removing sight of the target disturbs reach kinematics, but these kinematics remain wholly unchanged by loss of visual information about the hand. While infants may utilize visual information about their hand when it is available, it is not fundamentally necessary for the execution of a normal, successful reach.

B. Vision and Reaching in Adulthood

Though visual guidance may not be necessary for the development of infant reaching, studies suggest it plays a larger role in mature reaching. Jeannerod (1981) has proposed that the types of information vision can provide about an object fall into two categories: intrinsic and extrinsic. Objects can be described by features inherent to them, such as size, shape, weight and texture – their intrinsic properties. They can also be described by attributes such as location and orientation, which can vary without changing intrinsic properties of the object; these are extrinsic properties.

Vision provides information not only about an object's intrinsic and extrinsic properties, but also the location, orientation, and shape of the hand as it approaches the object during a reach. Adults have been shown to be quite sensitive to the loss of this visual feedback during reaching. Carleton (1981b) found reduced accuracy in aiming movements with a stylus when vision of the stylus was unavailable during the reach. According to Carleton, visual feedback about the stylus' position relative to the target seems to be most important during the later portion of the movement: movement times increased and accuracy decreased if visual feedback was removed during the last 25% of an aiming movement, but were unchanged by earlier removal of visual feedback about the position of the stylus (Carleton, 1981a). When visual feedback about the moving hand is unavailable, accuracy is further reduced by removing vision of the target (Prablanc, Pelisson, and Goodale, 1986).

Reach kinematics are also affected by reducing visual feedback about the target and moving arm. Berthier, Clifton, Gullapalli, McCall, and Robin (1996) presented adults with cylinders of varying size in three viewing conditions: full light, glowing in the dark, or in full darkness with the location of the object specified by sound. Differences in average and peak speed, peak grasp aperture, symmetry of hand–speed profile, and other kinematic measures occurred as a function of viewing condition. As visual information was reduced, resulting reaches were slower and longer in duration. Peak hand speed occurred earlier in the reach as visual feedback was reduced, reflected in increasingly asymmetrical hand–speed profiles. Reduced visual feedback also resulted in lower peak speeds during the transport phase of the reach, and an extended, slower grasp phase. Reaches showed an interaction between viewing condition and object size: peak grip apertures increased as visual feedback decreased. Subjects reached with larger, more conservative grip apertures as the position and size of the object became less certain. Other studies have found similar effects of reduced visual feedback on reaching. Jakobson and Goodale (1991) removed visual feedback about the hand and target by turning off overhead lights at the beginning of the grasp phase, and found that reduced visual feedback led to earlier and larger peak grip apertures. Blocking vision of the limb during reaching by use of a mirror apparatus caused similar kinematic changes, resulting in longer duration reaches and larger peak grip apertures (Gentilucci, Toni, Chieffi, & Pavesi, 1994).

Researchers have interpreted such studies as evidence that adult reaching depends to some degree on visual feedback about the target object and moving hand, and that reaches are altered by removal of this information. Connolly and Goodale (1999), however, suggest that it is not possible to determine whether the kinematic changes seen in the Berthier et al. (1996) and Jakobson and Goodale (1991) studies reflected the loss of visual feedback about the moving hand or the surrounding environment. Differences in ambient light levels between conditions left environmental visual cues available in full vision conditions, and unavailable in reduced vision conditions. Accordingly, Connolly and Goodale conducted a study which removed visual feedback of the moving hand while maintaining constant lighting levels across conditions. Subjects' view of their hand during the reach was occluded by a screen, which left the target visible throughout the reach. Reaches with reduced visual feedback were longer in duration than reaches with full visual feedback. However, in contrast to earlier findings, peak grip aperture did not occur earlier in the reach (as a percentage of movement time) with reduced visual feedback, and its magnitude was unchanged.

The relative contributions of visual information about the environment and hand were clarified in a study by Churchill, Hopkins, Ronnqvist, and Vogt (2000). Three conditions of progressively reduced visual information were used, in order to compare the effects of removing visual feedback of the environment and hand independently: vision of both hand and environment, of hand only, and of neither. In all conditions the target was visible throughout the trial. Churchill et al. (2000) found that removing environmental cues contributed to differences seen in movement time, peak speed, peak grip aperture, and relative time to peak aperture. Movement time increased as visual information was progressively reduced, with environmental and hand cues contributing to these increases. Peak speed was reduced without vision of the environment, but did not reduce further when vision of the hand was removed. Peak grip aperture increased and occurred earlier in the reach (percent of movement time) with both removal of environmental and hand cues.

Overall, the evidence shows that adults make use of visual information about the environment, the moving hand and arm, and the target object for the on–line control of reaching, and reaching and grasping patterns are altered when these sources of feedback become unavailable.

C. Vision and Reaching in Childhood

Although few studies have investigated visual control of reaching during childhood, it seems likely that reduced visual feedback may have similar effects on children's reaches as those seen in adults. Brown, Sepehr, Ettlinger, and Skreczek (1986) had children from 1.5 to 8 years–of–age reach to a small LED with different levels of visual information available. Children reached either in a lighted room, a darkened room with the LED still visible, or a darkened room with the LED extinguished shortly after the start of the trial. These conditions offer, respectively, full information about hand and target, information about the target only, and little information about either. As in adult studies, reaches were longer in duration when only the target was visible than when both hand and target were visible. Interestingly, the shortest duration reaches were those in complete darkness, suggesting a ballistic–type reach similar to those found by Clifton et al. (1994) for sounding objects. In general, reaches declined in accuracy as visual information decreased. However, when the target was visible (in light or darkness), slower movements increased accuracy.

D. The Role of Precision

While adults and infants are both capable of reaching without visual feedback about the hand, research shows that loss of that visual feedback alters the kinematics of adult reaches while leaving those of infants unchanged. It is possible these divergent results may be at least partially explained by the different levels of precision required in experimental tasks for infants and adults. Infant tasks involved little precision, as infants were presented only with relatively large objects and could contact them with any type of grasp. Adult tasks demanded far greater precision, requiring subjects to grasp very small objects with a pincer grip or point at small lights with a stylus or index finger. Adults were quite accurate when reaching for these small targets without sight of the hand, but their reaches were typically much slower than those where the hand was visible. Proprioception and sight of the target provide sufficient information for adults to succeed at these tasks, but that accuracy seems to come at the expense of speed (Fitts, 1954).

Studies which manipulate object size show alterations of reach kinematics as a function of task precision. Berthier et al. (1996) manipulated task precision by requiring adults to use a pincer grip to reach for objects from 4 – 49 mm in diameter, in conditions of varying visual feedback. Reducing the target object size correspondingly increases the precision requirements of the reaching task, and was found to alter reach kinematics. Adult reaches were slower and longer in duration as object size decreased. Peak speed occurred earlier in the reach for smaller objects, as the hand began slowing earlier in the reach in preparation for grasp. Peak grip aperture also occurred earlier in the reach as object size decreased, a finding replicated by Conolly and Goodale (1999). It is clear that smaller objects place higher precision demands on reaching, and adult reach kinematics correspondingly reflect these demands.

As we have seen, current research indicates that removing vision of the hand does not alter young infants' reaches during low precision tasks. Clifton et al. (1994) proposed that vision of the hand may become more important over development, as infants' reaches require greater precision. However, few studies have explored the role of visual guidance in precision reaching tasks with infants. Butterworth, Farnsworth, and Esposito (1998) investigated the relationship between viewing condition and grip selection in 9– to 13 month–old infants. Infants reached for small cubes (.5 and 2 cm diameter) in either full light, or full darkness with the location of the cube specified by sound. Three categories of grip were defined: precise (contact at thumb tip and index fingertip), imprecise (contact at thumb and the proximal joints of the index finger), and power (contact with the palm and proximal joints of the fingers). In the light, infants differentially chose grips based on object size, grasping the larger cube with significantly more power than precise grips, and grasping the smaller cube with a mixture of power and precise grips. In the dark, use of the precision grip declined but was not replaced by the power grip. Butterworth and colleagues conclude that precision grips require visual guidance for their selection and/or guidance, while power grips do not require such visual guidance.

While this study suggests that infants' performance on precision tasks may indeed be susceptible to disturbance from loss of visual feedback, it is difficult to draw any strong conclusions about the results. Because infants reached only in full light or complete darkness, it is not possible to determine if loss of visual information about the hand or the target caused the alterations seen in grasp preferences. In addition, sound cues alone may not be sufficient to enable accurate localization of such a small object. This ambiguity would contribute to the reduced accuracy in darkness, and may have dampened infants' motivation for the task. Indeed, infants reached far less frequently on dark trials than in the light, and this decrease was most notable for the smaller cube; infants contacted the small cube on only 21% of dark trials (compared to 75% of light trials). In addition, power grips for the smaller cube in the dark declined just as precise grips did, suggesting that loss of visual feedback for the smaller cube disrupted all grip types regardless of precision level. Nevertheless, these results are suggestive of a relation between the level of infants' reliance on visual feedback and the precision requirements of a task. It is this relation which the current study sought to investigate.

E. The Current Study

The current study sought to further investigate the role of vision in guiding reaching during later infancy. As Clifton et al. (1994) found, proprioception and sight of a target object appear to be sufficient to guide younger infants' reaches. Six–month–old infants can successfully contact a glowing object in darkness without sight of their hand or arm, and their reaches are kinematically identical to reaches made in the light where vision of the hand and arm is available. In contrast, it appears that adults rely far more heavily on vision to guide reaching, as loss of sight of the hand and limb markedly alters adult reaches (Berthier et al., 1996).

While these results appear to be in conflict, they may actually reflect the different levels of precision required in studies with infants and adults. Infants reached for large objects, obtainable by an imprecise reach; any type of grasp was acceptable.

Proprioception and sight of the target may have provided sufficient information to guide these reaches. Adults, in contrast, reached for very small objects, obtainable only by precise reach and grasp. It may be that vision of the hand becomes most useful during precision tasks. Loss of that visual information would be likely to alter precise reaches (as in the adult studies) but not imprecise reaches (as in the infant studies).

The current study manipulated the level of precision required and the amount of visual information available in a reaching task. Infants reached for large objects which can be obtained with an imprecise grasp, and small objects which require a precise grasp. It was therefore important that infants in this study be adept at employing precision grasps. Infants develop a pincer grip between 9 and 12 months–of–age (Halverson, 1932), but as this skill may not be firmly established at these ages, infants may choose to abandon precision grips entirely when faced with a challenging reaching situation like reaching in the dark. In order to avoid this possibility, the current study recruited 15 month–olds, who should be sufficiently practiced at precision grasps to succeed at this task.

Both large and small objects were presented in full light, which provides visual information about both the infant's hand and the object, or glowing in the dark, which provides visual information about the target object only. If sight of the hand is important for the selection of precision grasps, or execution of reaches in a precision task, we may expect to see differences in grasp selection or kinematic measures when comparing reaches executed with sight of the hand and target to those performed with only sight of the target object.

CHAPTER II

METHOD

A. Participants

Twenty–two 15 month–old infants (thirteen females and nine males) participated in this study. Infants were recruited from Massachusetts state birth records, and contacted by an introductory letter and a follow–up phone call. Infants were given a small gift of appreciation for their participation. Only full term infants in good health on the day of testing were included in the final sample. Data from six infants were not included in the analyses for the following reasons: two infants provided insufficient reaching data, one infant was too old at the time of testing, and three infants were excluded due to experimenter error.

The remaining sixteen infants (ten females and six males) ranged in age from 459 to 482 days, with a mean age of 470 days. Each infant reached for both large and small objects, in light and dark, and reached on a minimum of three trials of each type.

B. Stimuli and Apparatus

Each infant was presented with both light and dark trials, during which they reached for one of two objects. During light trials the room was illuminated by a small 60 watt table lamp. All room lights were extinguished during dark trials. On test trials, infants were encouraged to reach for either a large or small object. The large object was a fluorescent rubber ball with a smiling face (4 cm in diameter) which glowed in the dark. The ball was presented to infants resting atop a cardboard cylinder (3 cm in diameter, 6 cm in length) which was concealed in the experimenter's hand. The small object was a Cheerio (1 cm in diameter), and was placed on a small light–emitting diode (LED) which protruded from the top of a battery operated, handheld flashlight. The top of this LED was painted black so that it emitted light only from the sides, illuminating the Cheerio from within on Dark trials.

Behavior was recorded by infrared video and a motion analysis system. An infrared video camera (Sony DCR–TRV510) was placed above and to the right of the infant, and was used to assess reach onset, contact with the object, and grip selection. The signal from this camera was fed through a date–time generator (For–A) and into a digital video deck (Sony DHR–1000) and a video monitor (Panasonic S1390).

Motion analysis was performed by a Northern Digital Optotrak system. Two infrared emitting diodes (IREDs) were placed on the back of the infant's right hand. Two banks of three infrared cameras each, placed above and to the right of the infant, estimated the location of the IREDs at 100 Hz throughout the 10 second trials. Data were low–pass filtered and differentiated as in Berthier et al. (1996). Gaps in the data had to be less than 330 ms in duration in order for a trial to be included in the analysis.

C. Procedure

Infants remained seated on a parent's lap throughout testing, across from an experimenter. Parents were instructed to hold their infants securely at the hips to allow for free arm movement. A second experimenter seated behind a curtain triggered the start of trials and observed infants on the video monitor.

Infants received four warm–up trials (one of each test trial type), followed by 16 test trials. Warm–up trials were intended to accustom the infant to the procedure and experimenter. Accordingly, they were similar, but more flexible, in procedure to test trials. Infants participated in four trial types: light room with big object (LB), light room with small object (LS), dark room with glowing big object (DB), and dark room with glowing small object (DS). Trial order was determined randomly, with the restriction that each trial type occurred once in each block of four trials. Infants received one of two test trial orders:

Order 1: DS, LS, DB, LB, LS, DB, LB, DS, LS, LB, DS, DB, LB, DS, LS, DB

Order 2: LB, DB, LS, DS, DB, LS, DS, LB, DB, DS, LB, LS, DS, LB, DB, LS

On Dark trials, the presenter first extinguished the lights by remote–control. Each trial (in Light or Dark) began with the presenting experimenter drawing the infant's attention to the object. The second experimenter then triggered the Optotrak to start all trials. The presenting experimenter held the object in front of the infant, at a comfortable reaching distance and slightly to the right of midline (to encourage right–handed reaching, since kinematic data could only be obtained for the right hand). Each trial continued until the infant contacted the object or the end of the 10 second trial was reached. The infant was allowed to hold and manipulate the object (infants usually ate the Cheerio) for a few seconds before the next trial was initiated. In order to obtain the most data possible, the session continued as long as the infant was engaged in the task, often continuing beyond 16 test trials. If the infant became fussy, the session was ended early.

D. Data Scoring and Analysis

Dependent measures assessed from the video data included time of reach onset, time of contact with the object, and grasp type. Reach onset was defined as the time at which the infant began a movement of the arm which was continuous and resulted in forward motion toward the object. Time of contact was scored as the first point at which the hand contacted the object. Both right and left handed reaches were scored if they resulted in a complete grasp of the object. Duration of the reach was then calculated from the onset and contact times.

Infant grips were divided into four categories based on the level of precision: Pincer, Precise, Imprecise, and Palmar. Pincer grips were defined as any two–fingered grasp of the object. Precise grips were defined as grasps with more than two fingers, which contact the object only beyond the first distal joint of the finger (i.e. at the fingertips). Imprecise grips were defined as grasps with more than two fingers, which contact the object at the proximal joints of the finger. Palmar grips were defined as grasps with more than two fingers which contact the object on the palm. The time of grasp was coded at the first point the grasp became stable on the object.

All video data were scored by a primary observer, with one–half of the data also scored by an independent observer to ensure inter–observer reliability. On trials where disagreement occurred, the primary observer's score was used. The observers agreed to within 150 ms (4 video frames) on eighty–four percent of trials for reach onset and contact. Observers chose the same grasp type for reaches on eighty–two percent of trials.

Kinematic measures computed from Optotrak data for each reach included average and peak speed, location of peak speed, path length and straightness, and measures of hand–speed profile symmetry.

CHAPTER III

RESULTS

Sixteen infants completed the task, completing between 13 and 27 test trials each, for a total of 294 trials. Of this total, 68 trials were Light–Big, 77 were Light–Small, 71 were Dark–Big, and 78 were Dark–Small. Infants were quite engaged in the task, reaching and contacting the object on 280 out of 294 test trials. Infants seemed to find all the trials motivating, and were equally likely to reach on all trial types. Reaching analyses are based on 65 reaches in the Light–Big condition, 76 reaches in the Light–Small condition, 67 reaches in the Dark–Big condition, and 72 reaches in the Dark–Small condition.

Initial analyses for all measures included sex as a factor, but as none of these analyses showed a significant effect of sex, the results below collapse across sex. All results are based on repeated measures 2 x 2 ANOVA (lighting condition x object size).

A. Grasp Data

We first analyzed how lighting condition and object size affected grasp type. Grasps for each reach were coded as one of four types: pincer, precise, imprecise, and palmar (see Method for descriptions). Figure 1 shows the grasp types employed by infants in each condition.

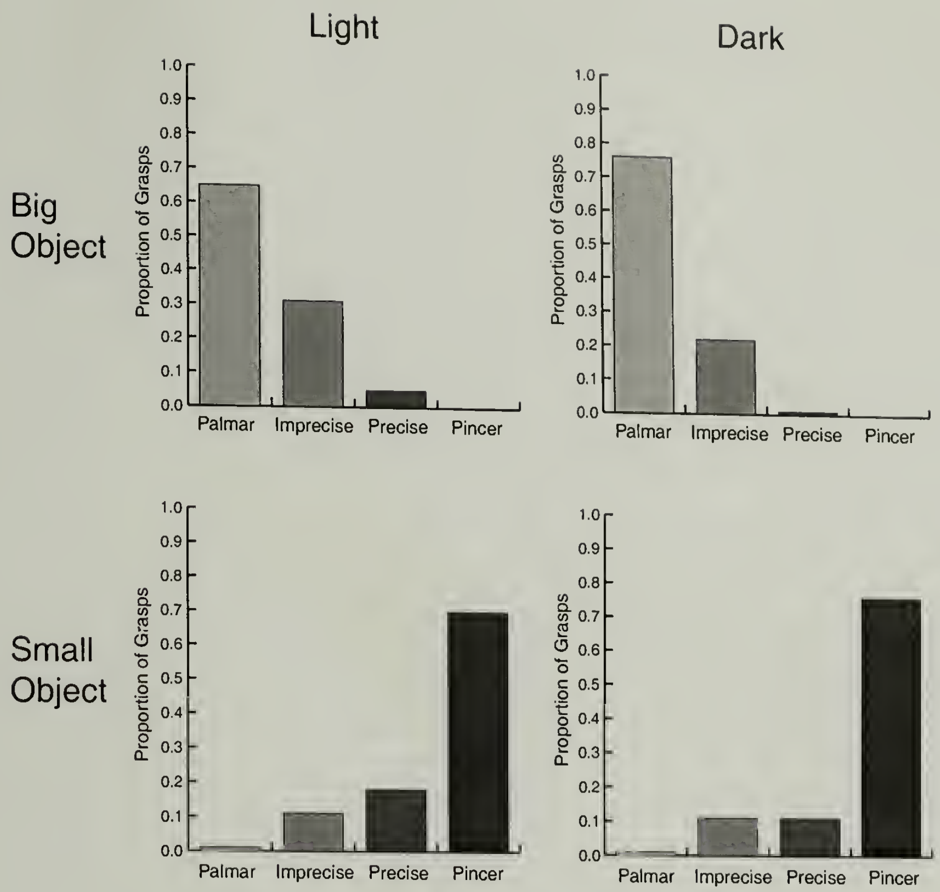

Figure 1. Proportions of grasp types on each trial type.

The large object overwhelmingly elicited imprecise and palmar grasps (128 out of 132 reaches), and the small object overwhelmingly elicited pincer and precise grasps (130 out of 148 reaches). Though the relation between object size and the grasps elicited was strong, it was not obligatory. Infants occasionally used precise grasps on the large object, and imprecise or palmar grasps on the small object.

Reaches were assigned precision scores based on grasp type, in increasing order of precision (palmar = 1, imprecise = 2, precise = 3, pincer = 4). Each infant was then given an average precision score for each trial type. Across all infants, the average precision score was 1.42 for the Light–Big condition, 1.39 for the Dark–Big condition, 3.59 for the Light–Small condition, and 3.65 for the Dark–Small condition. An effect of object size on precision score was found [$F(1,15) = 421.4$, $p < 0.0001$], with the small object (mean = 3.62) eliciting significantly higher–precision grasps than the large object (mean = 1.41). The effects of lighting condition and the interaction between lighting condition and object size were not significant ($p > .65$).

B. Kinematic Data

While grasp data and movement time could be scored entirely from videotape, all other kinematic measures required that the Optotrak camera have an unobstructed view of the IREDs (trials with gaps of less than 330 ms were accepted). To be included in the kinematic analyses, infants had to contribute at least one complete trial of each type. Of the sixteen infants included in the study, eleven contributed sufficient kinematic data, providing a total of 142 trials for analysis (9 to 20 trials per infant). Of these, 31 trials were Light–Big, 36 were Light–Small, 35 were Dark–Big, and 40 were Dark–Small. Data were averaged within trial type, such that each infant provided four scores for every measure, one for each trial type.

We investigated the speed, duration, and directness of each reach. Speed was assessed by computing the overall average speed, as well as the maximum speed during the reach (peak speed). As a measure of duration we computed the time between the movement onset and contact. Lastly, we assessed the directness of the reach by computing the straight–line distance between the points of reach onset and contact, then dividing the distance the hand traveled (path length) by this straight–line distance. A result of 1.0 would be a perfectly straight reach, with increasing values reflecting reaches than were less direct.

We assessed the general shape of the speed profile in three ways: calculating the number of peaks, time of the peak speed, and symmetry of the reach. The number of peaks in a reach was assessed by first computing the difference in speed between successive points along the profile. A peak was defined as a point where the speed was higher than the neighboring points, and more than 3 mm/sec greater than the preceding valley. Several values were tested for this criterion, and we found that 3 mm/sec was most successful at excluding small bumps in the speed profile, while capturing significant peaks. Time of peak speed was assessed both absolutely, in milliseconds, and relatively, as a percentage of total movement time.

Symmetry of the speed profile was assessed by computing a symmetry measure. First, we filtered the speed profile with a 5th order low–pass Butterworth filter (fig. 2a). The cut–off frequency was 1.25 Hz and was selected empirically because it led to a filtered speed profile emphasizing overall shape.

After smoothing, a program examined each data file to determine the point in time at which the peak of the speed profile occurred. We then used a procedure similar to Berthier et al. (1996) that calculated a symmetry measure for the speed profile. Briefly, the first half of the speed profile was reflected about the peak time, and the difference between the original speed profile (after the speed peak) and the reflected speed profile was computed at each point (fig. 2b). These differences were summed, then normalized by dividing the sum by the peak speed. This symmetry measure would be zero if the speed profile was perfectly symmetrical, negative if the profile was skewed to the right, and positive if the profile was skewed to the left.

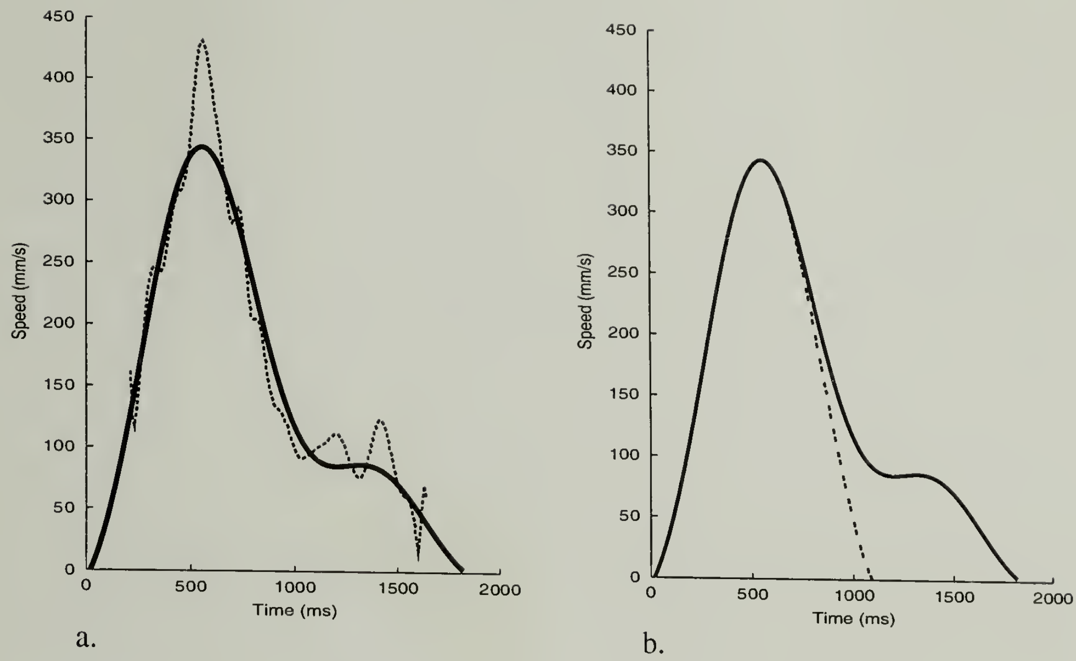

Figure 2. Filtering speed profiles and calculating symmetry. a.) Speed profile before (thin line) and after (thick, smooth line) filtering. b.) Calculating symmetry: the first half of the profile is reflected about the peak time (thin dotted line) to calculate symmetry.

Table 1. Mean Kinematic Measures by Trial Type

Measure	LB	LS	DB	DS
Speed				
Movement time (ms) * ‡	714	979	944	1348
Average speed (mm/s) ‡	189	165	189	130
Peak speed (mm/s)	390	387	421	366
Shape				
Peak speed location (ms)	446	412	312	439
Peak speed location (% of MT) * ‡	54.9	41.4	38.5	30.8
Symmetry * ‡	0.71	3	3.2	4.4
Straightness				
Number of speed peaks * ‡	2.5	3.8	3.4	5.3
Path length (mm)	171	187	190	185
Distance (mm)	130	130	130	121
Straightness *	1.3	1.5	1.7	1.7

Note: L = Light, D = Dark, B = Big object, S = Small object.
* denotes significant effect of Lighting Condition
‡ denotes significant effect of Object Size

Mean scores for all dependent measures are summarized in Table 1. There were no effects of lighting condition or object size on the distance between onset of movement and contact, indicating that the object was held at a constant distance from infants during all trial types. In addition, no significant interactions between lighting condition and object size were found on any measure. Representative speed profiles from each trial type are shown in Figure 3.

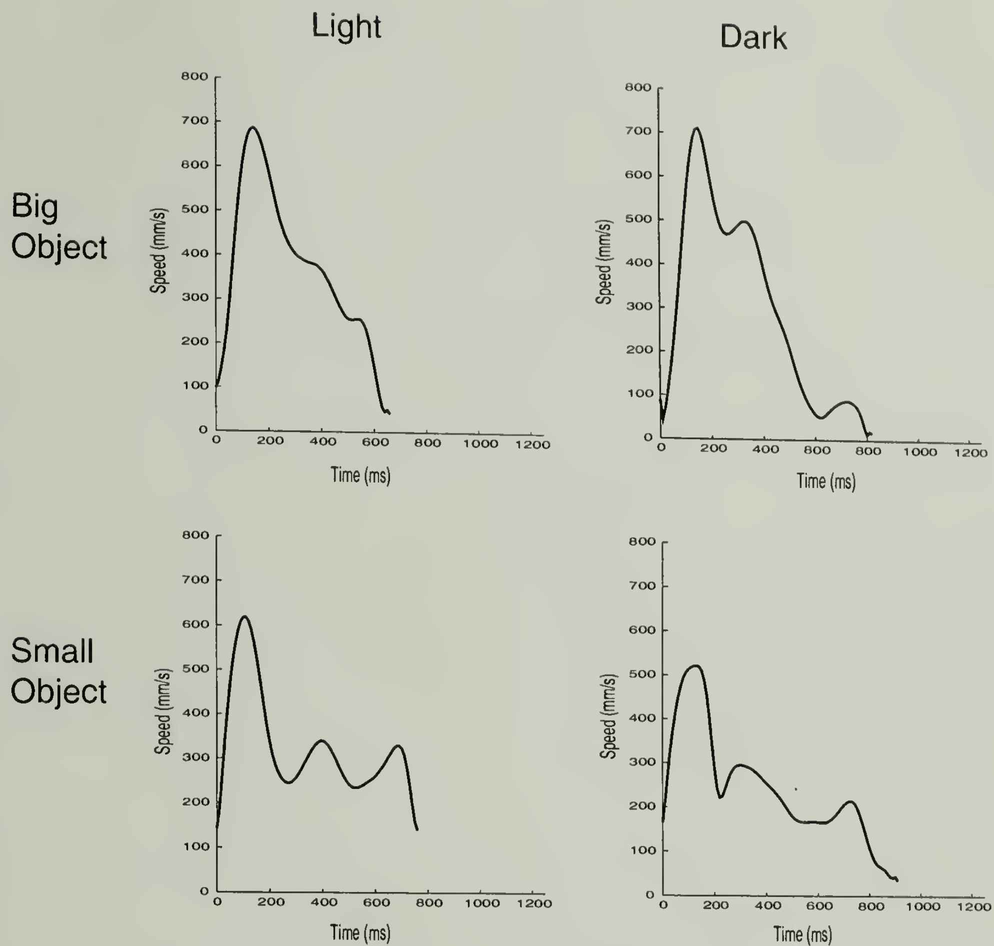

Figure 3. Representative speed profiles from a single infant.

1. Lighting Condition

Reaches in the dark were less straight, had more peaks, and were of longer duration than reaches in the light. In addition, reaches in the dark were less symmetrical, with peak speed occurring earlier in the reach, than reaches in the light. Reaches in the dark (mean = 1.7) were significantly less straight than reaches executed in the light (mean = 1.4, $F(1,10) = 6.6$, $p = .028$). Reaches in the dark had more movement peaks, with an average of 4.4 peaks, compared to an average of 3.2 peaks in the light. This effect of lighting condition was found to be significant [$F(1,10) = 7.0$, $p = .024$].

Movement times were also significantly longer in the dark (mean = 1,146 ms) than in the light (mean = 847 ms, [$F(1,15) = 32.7$, $p < .001$). Speed profiles of reaches in the dark were less symmetrical than of those in the light; the mean symmetry score in the dark was 3.81, compared to a mean score of 1.80 in the light; [$F(1,10) = 5.6$, $p = .039$].

Reaches in dark and light differ on many measures, but these differences occur primarily in the later portion of the reach, after peak speed is reached. Initially, reaches achieve the same peak speed (mean = 394 mm/sec in dark, 389 mm/sec in light), at the same time (mean = 375 ms in dark, 429 ms in light), without regard to lighting condition. After the peak speed, however, reaches are affected by changes in lighting. As a proportion of the reach, peak speed is achieved much earlier in the dark than in the light. Peak speed occurred at a mean of 34.7% of movement time in the dark, and significantly later in the light, at a mean 48.2% of movement time; [$F(1,10) = 11.0$, $p = .008$]. The locations of peak speed are closely related to the differences in symmetry noted above. Peak speed in the light occurred half-way through the reach, producing relatively symmetrical reaches. In contrast, peak speed in the dark was followed by a prolonged lower velocity phase, resulting in dramatically asymmetrical reaches. No differences were found in path length or average speed between light and dark trials.

2. Object Size

Reaches to the small object were slower, had more peaks, and were of longer duration than reaches to the large object. Reaches to the small object were also less symmetrical than reaches to the large object, with peak speed occurring earlier in the reach. Reaches to the small object were significantly slower than reaches to the large object, with an average speed of 159 mm/sec for the small object compared to 177 mm/sec for the large object; [F (1,10) = 9.3, p = .012]. Reaches to the small object had significantly more movement peaks, with an average of 4.6 peaks, compared to an average of 3.0 peaks to the large object; [F (1,10) = 24.4, p = .001]. Movement times were dramatically affected by changes in object size; the average movement time of reaches to the small object was 1,164 ms, while movement times of reaches to the large object were significantly shorter, at an average of 829 ms; [F (1,15) = 29.8, p < .001]. Speed profiles of reaches to the small object were less symmetrical than of those to the large object; the mean symmetry score for the small object was 3.64, compared to a mean score of 1.97 for the large object; [F (1,10) =7.3, p = .022].

As seen in the effects of lighting condition, reaches were sensitive to changes in object size only after peak speed was reached. The location of peak speed in milliseconds from reach onset did not differ between the large and small object, nor did its magnitude. However, the relative location of peak speed shifted within the reach for the different object sizes. Peak speed occurred at a mean of 36.1% of movement time for the small object, and significantly later for the large object, at a mean of 46.7% of movement time; [F (1,10) = 18.4, p = .002]. Again, this was reflected in markedly asymmetrical reaches to the small object, with an extended lower velocity phase following the time of peak speed. No differences were found in the path length or straightness of reaches to the large or small object.

CHAPTER IV

DISCUSSION

A. Grasp and Kinematic Effects

Infants chose their grasps based on object size, using precision grasps for the small object almost exclusively, and imprecise grasps for the large object. We might expect that as visual feedback is reduced, infants would become more conservative in their grasping strategies, reaching with less precise grasps, as Butterworth et al. (1998) reported. However, infants in the current study did not change their grasps according to lighting condition. Although infants adapted their grasps to the properties of the target object, they did not appear to modify these grasps when visual feedback of their hand became unavailable on dark trials. These results suggest that infants do not require vision of their hand to employ precision grasps.

Kinematic measures showed that infants' reaches were sensitive to changes in both lighting condition and object size, and these changes affected reaches in similar ways. Removing visual feedback of the hand or reducing object size resulted in reaches of longer duration, with more movement peaks. Reaches in the light, and those to the large object, were relatively symmetrical, with the peak speed occurring roughly half-way through the reach. In contrast, reaches in the dark and to the small object were markedly asymmetrical, reaching their peak speed at a much earlier percentage of movement time. These effects of lighting condition and object size occurred primarily in the later portions of the reach. The time of peak speed (in ms) was constant across all conditions. After peak speed, reaches in the dark and to the small object both exhibited extended lower velocity phases which were largely absent in reaches in the light and to the large object.

B. Precision Demands and Corrective Behavior

Previous research has shown that the importance of visual guidance during reaching changes from infancy to adulthood. Infants do not require sight of their hand early in the development of reaching (Clifton et al., 1993). Furthermore, infant reaches without visual feedback of the hand have been shown to be kinematically identical to reaches performed with full vision of the hand (Clifton et al., 1994). In contrast, mature reaching relies much more heavily on visual feedback for its control. Adult reaches without visual feedback of the hand's position are typically slower, longer in duration, and show an extended deceleration phase as the hand approaches the target (Berthier et al., 1996).

Adult reaches are similarly affected by reducing object size, becoming slower, less symmetrical, and longer in duration as object size decreases. These kinematic effects appear to reflect corrective movements in reaches which become necessary as tasks become more challenging. Reaching for a glowing object in the dark increases task difficulty in several ways. Localization of a visible target becomes more difficult when surrounding cues from the environment are not available (Connolly & Goodale, 1999; Churchill et al., 2000). In addition, adults must rely on proprioception to estimate the position of the hand relative to the target when visual feedback of the hand is unavailable. Both of these effects introduce some uncertainty about the position of the hand relative to the target during the reach, which increases the need for corrective movements. Similarly, reducing object size correspondingly increases the difficulty of a reaching task, requiring precise localization of the object and precision grasps. These increased task demands necessitate a greater reliance on on–line feedback control during the reach, which is accomplished by an increase in the use of corrective movements.

The current study shows that older infants also employ corrective movements in reaching, particularly when the reaching tasks are challenging. As reaching tasks become more difficult, either through loss of visual feedback or increased precision demands, infant reaches show more evidence of corrective movements. When visual feedback of the hand is unavailable, infants reach more conservatively, spending more time in a slow approach to the object than in the light. This slow approach results in the asymmetrical speed profiles of reaches in the dark. Reaches in the dark also follow less straight paths and have more peaks than in the light, suggesting that more corrective movements are necessary when infants reach without visual feedback about their hand. Infants also employ corrective movements in reaching when precision demands are high. Reaches to the small object were slower and had more speed peaks than reaches to the large object. They also had highly asymmetrical speed profiles, reflecting the dramatic slowing of the hand as it approached the object.

Infants in the current study were sensitive both to reduced visual feedback and increased precision demands while reaching. It is possible that any kinematic effects of reduced visual feedback may be more pronounced for reaches that require precision. If infants are using visual feedback to guide the hand, removing that feedback may affect reaches to a small object more than those to a larger target. Uncertainty about the hand's position in the dark might be more disruptive when the reach requires precise localization of a small target. It is, then, somewhat surprising that no significant interactions were found between lighting condition and object size in the current study. However, the data suggest there may be some added effects of removing visual feedback during precision reaches. The effect of object size on movement time in the light was only 265 ms, compared to 404 ms in the dark (with longer movement times to the small object). Similarly, the effect of object size on the number of peaks in the light was 1.3, compared to 1.9 in the dark (with more peaks to the small object). Given these observations, one must use caution in concluding, based on our statistical analyses, that there are no additional effects of reduced visual feedback on precision reaches.

C. Development of Visually Guided Reaching

Previous work has provided considerable information on the develompent of reaching in infancy. Even at birth, many aspects of infants' arm movements exhibit a surprising degree of organization and control. Newborns' arm movements show organized phases of acceleration and deceleration, and changes in the direction of arm movements generally occur at the speed valleys between these accelerations and decelerations (von Hofsten, 1993). In addition, newborns are capable of directing their arm movements toward visually fixated objects (von Hofsten, 1982; Ennouri & Bloch, 1996). By about 16 weeks–of–age, these early arm movements have matured into functional reaching, and infants become able to contact objects (Thelen, Corbetta, Kamm, Spencer, Schneider, & Zernicke, 1993; Berthier et al., 1999). These beginning reaches do not require vision of the hand, and are probably guided largely by proprioception (Clifton et al., 1993).

Over the next several months, motor control improves substantially, and infants' reaching skills continue to be refined. Reaches become more efficient through development, requiring fewer corrective movements and displaying greater organization, with the transport phase occurring more reliably at the beginning of the reach, and covering a greater percentage of the distance traversed (von Hofsten, 1991). Infants begin to shape their hand to an object's size in advance of contact, and become capable of precision grasps (von Hofsten & Ronqvist, 1988; Halverson, 1932). Visual feedback about the hand's position still does not appear to be necessary, even when infants are executing relatively demanding reaches, indicating that proprioception and vision of the target continues to provide sufficient feedback for successful reaches (Clifton et al., 1994; Robin et al., 1996).

The current results provide information about the role of visual guidance and precision demands in 15 month olds' reaching. Infants in the current study reached quite differently than younger infants, showing sensitivity to both reduced visual feedback and increased precision demands. While younger infants' reaches are kinematically identical with or without sight of the hand, older infants' reaches are dramatically affected by the loss of visual feedback about the hand's position. Clifton et al. (1994) have proposed that as infants acquire fine manual dexterity and precision grips, sight of the hand may become a more important source of information for the on–line control of reaching. Our results support this proposal, and suggest a developmental trend toward greater reliance on visual feedback during reaching.

Indeed, infants in the current study showed remarkably similar effects of reduced visual feedback when compared with adults. Infant reaches, like adult reaches, were longer in duration and less symmetrical, with peak time occurring earlier as a percentage of movement time, when visual feedback about the hand was unavailable. These similarities are striking when compared with the seeming unimportance of visual feedback of the hand during earlier infancy. One key difference between infants in the current study and adults, however, is the portion of the reach affected by changes in visual feedback. Berthier et al. (1996) found that changes in lighting condition affected both early and late portions of the reach, with lower average and peak speeds in the dark. In contrast, the current study indicates that, at 15 months–of–age, only the later portions of the transport phase are altered by changes in visual feedback, as average and peak speed did not differ in light and dark conditions.

Previous research on the effects of precision demands on infant reaching has suggested a relation between grip selection, object size, and lighting condition (Butterworth et al., 1998), with infants selecting grips based on object size, but largely abandoning precision grips in the dark. The current study found that grip selection was indeed strongly tied to object size, but was unaffected by changes in lighting condition. In contrast to the findings in Butterworth et al. (1998), infants in the current study used precision grasps in the same frequency in the light and dark. Methodological differences between the studies may explain these conflicting results. While the current study allowed infants vision of the glowing object on dark trials, Butterworth et al. (1998) presented sounding objects in full darkness. Sound may have provided insufficient information for infants to accurately localize small objects in the dark. Thus the reduction in precision grips in the dark may have been caused by infants' difficulty localizing the object, rather than an inability to perform precision grips without visual feedback of the hand. When infants can use visual information to localize an object, they do not appear to require sight of their hand in order to employ precision grasps.

Kinematic measures revealed that infant reaches are altered by increased precision demands, and these changes closely mirror the effects of increased precision on adult reaches. Both infant and adult reaches are slower, longer in duration, and less symmetrical as object size decreases. Peak speed occurs earlier (as a percentage of movement time) for both infant and adult reaches, as the hand slows during approach to the object.

Although there are many similarities between infant and adult reaches in the effects of increasing task difficulty (by reducing visual feedback or object size), infant reaches are nonetheless quite different than mature reaches. Adult reaches are generally composed of a single, smooth movement unit with only one speed peak, as shown in figure 4 (from Berthier et al., 1996). In contrast, an average infant reach from the current study had 3.8 speed peaks.

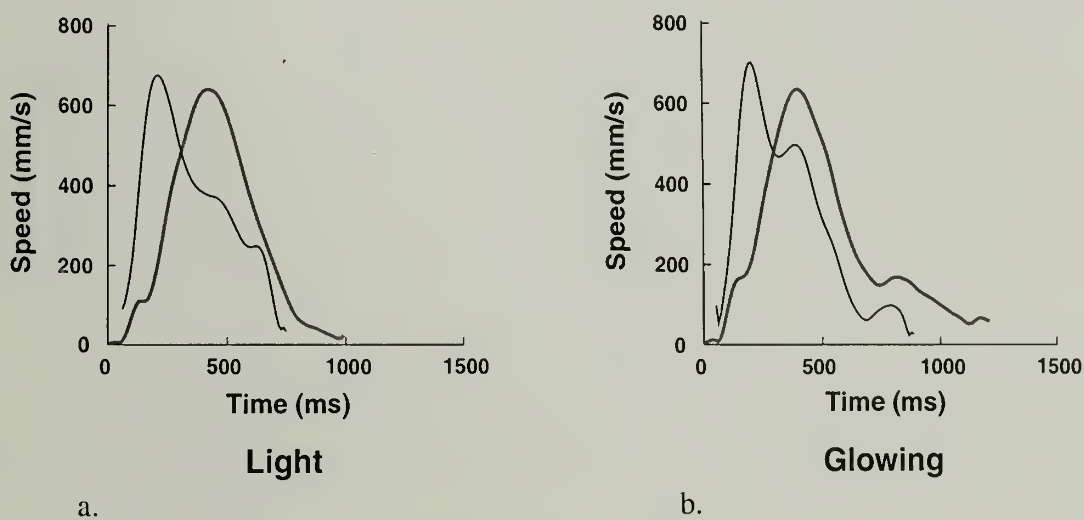

Figure 4a. A comparison of infant and adult reaches. a.) Infant (thin line) and adult (thick line) reaches in full lighting. b.) Infant and adult reaches to a glowing object in the dark. Adult reaches are from Berthier et al. (1996).

While both adult and infant reaches are less symmetrical as task difficulty increases, infant reaches are in general much less symmetrical than adult reaches. These differences reflect the larger role corrective movements play in infant reaching than in mature reaching. As infants develop better feedforward planning and on–line feedback control of reaching, these corrective movements become less common and more subtle.

Until recently, reaching has been characterized as requiring visual guidance in early infancy, with the role of visual guidance diminishing through development. Piaget (1952) proposed that simultaneous viewing of the hand and a target object is necessary during early reaching for infants to coordinate mappings of visual and manual space. As infants become proficient at reaching, the mapping between visual and proprioceptive space is precisely coordinated, resulting in a decline in the importance of visually guided reaching toward the end of the first year (Bushnell, 1985). However, more recent research indicates that the development of visually guided reaching follows a markedly different course, in which the importance of visual guidance increases, rather than decreases, over development. Infants' earliest reaches do not require visual guidance (Clifton et al., 1993), and are kinematically identical whether vision of the hand is available or not during reaching (Clifton et al., 1994). The current study reveals that, by 15 months–of–age, infants are using visual feedback to guide reaching, and their reaches are kinematically altered when vision of the hand is unavailable. Reaching continues to be visually guided through childhood (Brown et al., 1986), and into adulthood (Berthier et al., 1996).

It appears, then, that by 15 months–of–age, many developmental changes in the control of reaching have taken place. Infants are relying on visual feedback of the hand to control reaching, and infant and adult reaches show similar kinematic alterations from changes in visual feedback and precision demands. Future work is needed to investigate the appearance and development of visually guided reaching which occurs between 6– and 15 months–of–age. Although at 15 months–of–age infant reaching still exhibits important differences from adult reaching, infants seem to be well underway towards developing mature reaching patterns.

APPENDIX A

GRASP DATA

Table 2. Number of Reaches for Grasp and Kinematic Analyses

	Total # of Reaches				Reaches Used for Kinematic Analyses			
Subject	LB	LS	DB	DS	LB	LS	DB	DS
2	4	5	3	7	2	2	1	4
3	4	3	3	4	3	3	4	3
4	4	6	5	3	0	0	0	0
5	4	3	3	8	4	3	1	3
8	6	7	6	3	0	0	0	0
9	4	5	4	4	3	2	2	3
11	4	5	5	4	3	6	6	5
12	5	5	5	4	4	2	4	2
13	5	5	5	5	3	6	4	6
14	3	5	3	4	0	0	0	0
15	4	4	4	3	0	0	0	0
16	4	4	4	6	0	0	0	0
17	3	5	5	4	3	4	4	4
18	5	5	5	6	2	3	4	4
21	3	4	3	3	2	3	3	2
22	3	5	4	4	2	2	2	4
Total:	65	76	67	72	31	36	35	40

Note: L = Light, D = Dark, B = Big object, S = Small object

Table 3. Numbers of Each Grasp According to Trial Type.

	Palmar	Imprecise	Precise	Pincer	Total
Light-Big	42	20	3	0	65
Dark-Big	51	15	1	0	67
Light-Small	1	8	14	53	76
Dark-Small	1	8	8	55	72

Table 4. Average Movement Times and Precision Scores on Light–Big Trials.

Subject	MT	Precision	# Reaches	# Trials
2	0.68	1.25	4	5
3	0.61	1.25	4	4
4	0.70	1.25	4	4
5	0.91	2.25	4	4
8	0.75	1.17	6	7
9	0.68	1.00	4	4
11	0.68	1.25	4	5
12	0.71	1.00	5	5
13	0.69	2.00	5	5
14	0.62	1.00	3	3
15	0.62	1.25	4	4
16	0.78	1.25	4	4
17	0.80	2.00	3	4
18	0.86	1.40	5	5
21	0.59	1.33	3	3
22	0.75	2.00	3	3
			Total	Total
Mean =	0.71	1.42	65	69

Table 5. Average Movement Times and Precision Scores on Light–Small Trials.

Subject	MT	Precision	# Reaches	# Trials
2	0.92	3.60	5	6
3	1.10	4.00	3	3
4	0.76	3.67	6	6
5	1.27	3.34	3	3
8	0.92	3.29	7	7
9	0.72	3.00	5	5
11	0.74	3.80	5	5
12	1.06	3.00	5	5
13	1.15	3.80	5	5
14	0.78	3.80	5	5
15	0.67	4.00	4	4
16	1.01	3.50	4	4
17	1.19	3.40	5	5
18	1.07	3.40	5	5
21	1.32	4.00	4	4
22	0.99	3.80	5	5
			Total	Total
Mean =	0.98	3.59	76	77

Table 6. Average Movement Times and Precision Scores on Dark–Big Trials.

Subject	MT	Precision	# Reaches	# Trials
2	0.87	3.00	3	6
3	0.51	1.00	3	3
4	0.75	1.20	5	5
5	0.98	1.34	3	3
8	0.89	1.00	6	7
9	0.80	1.00	4	4
11	0.75	1.00	5	5
12	1.21	1.20	5	5
13	0.89	2.00	5	5
14	1.31	1.67	3	3
15	0.90	1.75	4	4
16	1.16	1.00	4	4
17	1.28	1.00	5	5
18	1.09	1.00	5	5
21	0.81	1.00	3	3
22	0.91	2.00	4	4
			Total	Total
Mean =	0.94	1.39	67	71

Table 7. Average Movement Times and Precision Scores on Dark–Small Trials.

Subject	MT	Precision	# Reaches	# Trials
2	1.20	3.43	7	7
3	1.26	4.00	4	4
4	1.56	3.67	3	3
5	2.04	3.38	8	8
8	2.15	3.33	3	6
9	0.96	3.50	4	4
11	0.56	3.75	4	4
12	1.61	4.00	4	4
13	1.25	3.80	5	5
14	1.43	2.75	4	5
15	1.08	4.00	3	3
16	1.00	3.83	6	8
17	1.20	3.50	4	4
18	1.55	3.50	6	6
21	1.35	4.00	3	3
22	1.37	4.00	4	4
			Total	Total
Mean =	1.35	3.65	72	78

APPENDIX B

KINEMATIC DATA

Table 8. Speed and Shape Measures for Light–Big Trials

Subject	Avg. Speed	Peak Speed	Peak Time (ms)	Peak Time (%)	Symmetry	# Reaches
2	164.00	321.00	330.00	0.45	1.50	2
3	174.67	424.33	263.33	0.41	0.91	3
5	196.00	406.00	247.50	0.26	4.70	4
9	282.33	518.33	393.33	0.58	0.76	3
11	219.33	455.67	420.00	0.58	0.73	3
12	168.25	311.25	750.00	1.01	-0.93	4
13	141.33	271.00	676.67	0.67	0.36	3
17	142.33	288.00	413.33	0.48	2.62	3
18	214.50	542.50	490.00	0.53	-1.96	2
21	124.50	255.50	490.00	0.53	-0.94	2
22	254.00	500.50	435.00	0.56	0.10	2
						Total:
Mean =	189.20	390.37	446.29	0.55	0.71	31

Table 9. Straightness Measures for Light–Big Trials

Subject	# of Peaks	Path Length	Distance	Straightness	# Reaches
2	2.50	137.75	110.00	1.23	2
3	2.00	130.65	119.67	1.10	3
5	3.00	210.79	147.00	1.43	4
9	1.67	233.97	169.00	1.39	3
11	1.67	183.61	157.33	1.16	3
12	3.00	153.50	115.25	1.30	4
13	3.67	147.88	120.00	1.29	3
17	3.33	140.39	94.67	1.55	3
18	2.00	225.06	171.50	1.28	2
21	2.50	104.04	76.00	1.34	2
22	2.50	211.88	152.00	1.39	2
					Total:
Mean =	2.53	170.86	130.22	1.32	31

Table 10. Speed and Shape Measures for Light–Small Trials

Subject	Avg. Speed	Peak Speed	Peak Time (ms)	Peak Time (%)	Symmetry	# Reaches
2	238.50	598.00	415.00	0.52	0.69	2
3	74.00	140.00	370.00	0.50	3.79	3
5	168.33	383.67	315.00	0.24	9.54	3
9	242.50	621.50	275.00	0.35	1.89	2
11	157.17	359.67	350.00	0.51	1.52	6
12	278.00	597.50	475.00	0.42	4.51	2
13	113.50	249.33	390.00	0.29	8.67	6
17	57.50	152.50	453.33	0.33	-3.33	4
18	219.67	523.00	410.00	0.39	5.04	3
21	110.67	294.67	380.00	0.38	3.11	3
22	157.00	335.00	695.00	0.64	-3.58	2
						Total:
Mean =	165.17	386.80	411.67	0.41	2.89	36

Table 11. Straightness Measures for Light–Small Trials

Subject	# of Peaks	Path Length	Distance	Straightness	# Reaches
2	3.00	216.15	171.50	1.26	2
3	3.33	76.20	65.67	1.16	3
5	6.33	252.80	181.00	1.40	3
9	2.50	219.05	133.00	1.65	2
11	2.50	146.95	108.33	1.40	6
12	3.50	338.38	187.50	1.81	2
13	5.00	158.60	126.00	1.39	6
17	6.25	86.01	64.00	1.63	4
18	2.67	252.57	169.00	1.49	3
21	3.67	122.69	84.67	1.44	3
22	3.50	190.67	143.50	1.71	2
					Total:
Mean =	3.84	187.28	130.38	1.49	36

Table 12. Speed and Shape Measures for Dark–Big Trials

Subject	Avg. Speed	Peak Speed	Peak Time (ms)	Peak Time (%)	Symmetry	# Reaches
2	244.00	476.00	530.00	0.84	0.64	1
3	222.50	488.00	215.00	0.38	0.95	4
5	184.00	411.00	240.00	0.24	5.18	1
9	218.50	479.50	190.00	0.24	2.62	2
11	211.50	481.17	288.33	0.34	4.14	6
12	186.25	429.25	347.50	0.33	3.86	4
13	208.75	581.75	230.00	0.29	4.09	4
17	78.50	234.25	340.00	0.37	1.53	4
18	128.50	254.75	215.00	0.23	6.84	4
21	132.33	251.00	483.33	0.56	1.52	3
22	260.00	542.00	349.17	0.40	4.18	2
						Total:
Mean =	188.62	420.79	311.67	0.38	3.23	35

Table 13. Straightness Measures for Dark–Big Trials

Subject	# of Peaks	Path Length	Distance	Straightness	# Reaches
2	1.00	193.43	183.00	1.06	1
3	1.75	149.57	127.75	1.19	4
5	3.00	207.81	115.00	1.81	1
9	3.00	198.79	150.50	1.34	2
11	4.00	203.58	97.67	3.70	6
12	5.25	257.38	133.00	2.08	4
13	5.75	262.36	148.25	2.07	4
17	3.50	86.49	71.25	1.22	4
18	4.00	141.44	99.75	1.47	4
21	3.33	129.85	100.33	1.29	3
22	3.00	258.81	207.00	1.31	2
					Total:
Mean =	3.42	189.95	130.32	1.68	35

Table 14. Speed and Shape Measures for Dark–Small Trials

Subject	Avg. Speed	Peak Speed	Peak Time (ms)	Peak Time (%)	Symmetry	# Reaches
2	149.50	341.75	317.50	0.38	2.52	4
3	107.00	378.33	283.33	0.22	4.37	3
5	152.00	494.67	353.33	0.23	6.09	3
9	130.00	360.67	400.00	0.22	3.22	3
11	188.40	493.20	310.00	0.43	0.69	5
12	130.00	270.50	1195.00	0.56	0.07	2
13	125.67	403.67	310.00	0.25	3.20	6
17	86.25	221.75	530.00	0.41	7.01	4
18	109.75	329.00	352.50	0.19	7.85	4
21	140.00	418.00	430.00	0.30	6.49	2
22	113.50	319.00	345.00	0.20	6.66	4
						Total:
Mean =	130.19	366.41	438.79	0.31	4.38	40

Table 15. Straightness Measures for Dark–Small Trials

Subject	# of Peaks	Path Length	Distance	Straightness	# Reaches
2	4.00	145.73	114.50	1.30	4
3	5.67	147.68	77.67	1.88	3
5	6.00	278.60	139.33	1.92	3
9	5.33	184.57	93.33	2.09	3
11	2.20	148.56	120.40	1.22	5
12	8.50	213.93	141.00	1.52	2
13	4.00	171.98	139.33	1.29	6
17	3.75	116.84	79.50	1.78	4
18	7.50	216.57	151.50	1.48	4
21	5.50	211.27	159.50	1.37	2
22	6.00	202.19	111.75	2.53	4
					Total:
Mean =	5.31	185.27	120.71	1.67	40

REFERENCES

Berthier, N. E., Clifton, R. K., Gullapalli, V., McCall, D. D., & Robin, D. J. (1996). Visual information and object size in the control of reaching. *Journal of Motor Behavior, 28*, 187–197.

Berthier, N. E., Clifton, R. K., McCall, D., & Robin, D. (1999). Proximodistal structure of early reaching in human infants. *Experimental Brain Research, 127*, 259–269.

Brown, J. V., Sepehr, M. M., Ettlinger, G., & Skreczek, W. (1986). The accuracy of aimed movements to visual targets during development: The role of visual information. *Journal of Experimental Child Psychology, 41*, 443–460.

Bushnell, E. (1985). The decline of visually guided reaching during infancy. *Infant Behavior and Development, 8*, 139–155.

Butterworth, G., Farnsworth, L. & Esposito, L. (1998, April). Reaching in the dark: Role of vision in selection of power and precision grips. Poster session presented at the International Conference on Infant Studies, Atlanta, GA.

Carlton, L. (1981a). Processing visual feedback information for movement control. *Journal of Experimental Psychology: Human Perception and Performance, 7*, 1019–1030.

Carlton, L. (1981b). Visual information: The control of aiming movements. *Quarterly Journal of Experimental Psychology. A, Human Experimental Psychology. 33A*, 87–93.

Churchill, A., Hopkins, B., Ronnqvist, L., & Vogt, S. (2000). Vision of the hand and environmental context in human prehension. *Experimental Brain Research, 134,* 81–89.

Clifton, R. K., Muir, D. W., Ashmead, D. H., & Clarkson, M. G. (1993). Is visually guided reaching in early infancy a myth? *Child Development, 64*, 1099–1110.

Clifton, R. K., Rochat, P., Robin, D. J., & Berthier, N. E. (1994). Multimodal perception in the control of infant reaching. *Journal of Experimental Psychology: Human Perception and Performance, 20*, 876–886.

Connolly, J. D., & Goodale, M. A. (1999). The role of visual feedback of hand position in the control of manual prehension. *Experimental Brain Research, 125*, 281–286.

Ennouri, K., & Bloch, H. (1996). Visual control of hand approach movements in newborns. *British Journal of Developmental Psychology, 14*, 327–338.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology, 47*, 381–391.

Gentilucci, M., Toni, I., Chieffi, S., & Pavesi, G. (1994). The role of proprioception in the control of prehension movements: A kinematic study in a peripherally deafferented patient and in normal subjects. *Experimental Brain Research, 99*, 483–500.

Halverson, H. M. (1932). A further study of grasping. *Journal of Genetic Psychology, 7*, 34–63.

Jakobson, L. S., & Goodale, M. A. (1991). Factors affecting higher–order movement planning: A kinematic analysis of human prehension. *Experimental Brain Research, 86*, 199–208.

Jeannerod, M. (1981). Intersegental coordination during reaching at natural visual objects. In J. Long & A. Baddeley (Eds.), *Attention and Performance IX*. Hillsdale: Erlbaum, 153–168.

Piaget, J. (1952). *The origins of intelligence in children.* New York: Norton.

Robin, D. J., Berthier, N. E., & Clifton, R. K. (1996). Infants' predictive reaching for moving objects in the dark. *Developmental Psychology, 32*, 824–835.

Thelen, E., Corbetta, D., Kamm, K., Spencer, J. P., Schneider, K., & Zernicke, R. F. (1993). The transition to reaching: Mapping intention and intrinsic dynamics. *Child Development, 64*, 1058–1098.

von Hofsten, C. (1982). Eye–hand coordination in the newborn. *Developmental Psychology, 18*, 450–461.

von Hofsten, C. (1991). Structuring of early reaching movements: A longitudinal study. *Journal of Motor Behavior, 23*, 280–292.

von Hofsten, C., & Ronnqvist, L. (1988). Preparation for grasping an object: A developmental study. *Journal of Experimental Psychology: Human Perception and Performance, 14*, 610–621.

von Hofsten, C., & Ronnqvist, L. (1993). Structuring of neonatal arm movements. *Child Development, 64*, 1046–1056.

White, B. L., Castle, P., & Held, R. (1964). Observations on the development of visually directed reaching. *Child Development, 35*, 349–364.