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Multimodal Perception in the Control of Infant Reaching

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Six-month-old infants were presented with sounding objects under 3 conditions of illumination: in full vision, in the dark with target location specified by a glowing and sounding object, and in the dark with location specified by sound alone. Reaching behavior was videotaped with an infrared camera, and hand movement was measured by infrared-emitting diodes on the hand that were tracked by a motion analysis system. No differences were found in reaching behavior for objects in the light and glowing objects in the dark. Reaches for sounding objects in the dark had higher speeds, shorter durations, and more errors compared to the other 2 conditions. These findings indicate that vision of the hand did not appear to affect infants' reaching in this situation, whereas vision of the target did.

Reaching is one of the earliest expressions of a goal-oriented action that integrates different sensorimotor systems. Numerous studies have documented the early propensity of infants to bring the hands into contact with visible objects in the environment. This propensity has been extensively used as a behavioral paradigm for the study of early cognitive (Corbetta & Mounoud, 1990), perceptual (Yonas & Granrud, 1985), and motor development (von Hofsten, 1991). The development of reaching in early infancy has often been studied in the context of emerging eye–hand coordination. According to the traditional view of infant reaching, infants use vision to guide the hand toward the target when they first begin to reach around the age of 4 months (Piaget, 1952; White, Castle, & Held, 1964). At older ages infants use vision to calibrate their hand shape to the size of the object (von Hofsten & Ronnqvist, 1988), to orient their hand appropriately for vertical or horizontal bars (Lockman, Ashmead, & Bushnell, 1984), and to engage differentially with either one hand or two hands when reaching for a small or large object, respectively (Clifton, Rochat, Litovsky, & Perris, 1991). All of these acts require planning of motor behavior in order to anticipate haptic consequences, with sight of the target's physical properties being a necessary part of this process.

On the other hand, recent work has shown that normally developing, sighted infants can reach successfully without vision. Perris and Clifton (1988) reported that 6- to 7-month-olds reached accurately in the dark for a sounding object presented randomly from five different locations. Stack, Muir, Sherriff, and Roman (1989) presented glowing and sounding objects in the dark to infants across a wide age span, 2 to 7 months. By 4 months of age infants contacted the glowing object (painted with luminous paint) on about 90% of trials. Reaching for sounding objects was less accurate and less frequent than for glowing objects, but by 7 months infants reached for sounding objects quite accurately. Clifton, Muir, Ashmead, and Clarkson (1993) tested infants longitudinally on a weekly basis beginning around 8 weeks of age in a reaching task in the light and the dark, and continued until infants were reaching proficiently. The onset of reaching was observed to be similar in the two conditions. Around 12 weeks of age infants began touching the objects in both light and dark and by around 16 weeks the first grasps were observed in both conditions. The similarity of reaching behavior, regardless of the hand's visibility, was both striking and unexpected.

These observations of accurate reaching in the dark raise questions regarding the traditional view of the role of vision in reaching. The variety of perceptual contexts in which infant reaching has been observed points to control of this action by multiple modalities. In the dark, the trajectory of the reach must be planned on the basis of proprioceptive information, integrated with either auditory information from a sounding object or visual information from a glowing object. There is no vision of the limb, and thus there cannot be visual guidance of the hand toward the object. Observations of reaching in the dark demonstrate that during the earliest stage of successful reaching, infants of 4–6 months of age integrate visual and auditory information with proprioceptive information from the arm(s) and hand(s). However, beyond this general conclusion, many questions remain about how the different modalities cooperate to control the motor action itself. The ease with which infants contact glowing objects in the dark suggests that sight of the target (but not sight of the hand) may be the significant factor in the reach. That is, as long as the target can be visualized, the infant will be able to direct the reach. The extent to which reaches in the dark and light resemble

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each other is unknown. No fine-grained measures of the motor action have been attempted in the studies of reaching in the dark cited previously. Although we know that infants are fairly accurate in terms of the end point of their reaches in the dark, we have little quantitative information about how the hand arrives at its destination.

The motor act of prehension has been divided into at least two phases, transport and grasping. In describing these components in human adults, Jeannerod (1984) found that transportation (or the reaching component) was little affected by presence or absence of visual feedback from the moving limb. The general trajectory toward the target had a similar speed profile regardless of vision of the limb (sight of the target was available to the subjects), and was characterized by the hand reaching peak speed around 40% of the way through the reach, followed by lower speed preceding contact with the object. However, the low-speed phase at the end of the movement was longer when visual feedback was available. Jeannerod suggested that when vision was available, subjects slowed their approach just prior to contact in order to allow more time for visuomotor feedback. Without sight of the limb, he reasoned that there was less need to slow down. The continued presence of the low-speed phase just before contact under conditions of no visual feedback led Jeannerod to conclude that the speed profile of the transportation component was controlled by "central patterning of prehension" independent of visual control (1984, p. 253). In a recent review of the adult literature, Elliott (1990) concluded that continuous visual feedback of the limb is unnecessary for accurate movements because the main role of vision is to provide updated information about the target's position. The influence of vision on infants' reaching may or may not conform to the adult pattern because of their more immature musculature and lack of experience in controlling limb movements. The purpose of this study was to compare hand movements under varied visual conditions with emphasis on the transportation component of the reach.

In this study infants' reaching movements were compared in the light and in the dark when the object was either glowing or sounding. We presented infants between 26–28 weeks of age with three conditions: (a) a colorful rattle toy in the light; (b) the same rattle in the dark but with a glowing object held immediately in front of the rattle; and (c) the same rattle in the dark without the glowing object. Thus, the same sound and same object were present in all three conditions, with visibility varied from full vision of the object and surround, to vision of only a glowing object, and no vision at all. The empirical questions guiding the study pertained to hand movement during the approach phase of the reach, specifically whether duration, speed, and trajectory of hand movements were similar in the light and in the dark, and whether the hand decelerated just before contact in anticipation of grasping the object. Comparison between the light condition and glowing object condition allowed evaluation of the effect of loss of sight of the hand and the surround while the target was still visible. Comparison between the two conditions in the dark allowed evaluation of the infant's ability to locate the object when the exact position of the target was uncertain. Although sound can specify the object's presence and its general location, the borders of the object, its orientation, and shape remain unspecified; uncertainty about these properties of the object and its location could lead to a different reaching strategy from the one used when the object can be seen.

Based on previous observations (Clifton, Perris, & Bullinger, 1991; Perris & Clifton, 1988) and on the recent longitudinal study by Clifton et al. (1993), we expected the kinematics of infant reaching to have certain similarities under different perceptual conditions. Specifically, we expected the movement of the hand to display similar trajectories in light and dark; peak speed was expected to occur at similar times in the movement followed by a decelerative phase just before contact with the object. If Jeannerod's (1984) observations with adults hold for infants, reaches in the dark should be faster, reflected in shorter duration and higher velocities. If there were no differences among these measures across different illumination conditions, this would indicate that infants may not be using visual feedback to direct their reaching movements.

Method

Subjects

Ten full-term infants (6 boys and 4 girls; age range = 26–28 weeks, $M = 27$) were tested. An additional 8 infants were excluded from the study because of equipment failure ($n = 1$), refusal to reach in any condition ($n = 2$), or refusal to reach in one of the dark conditions ($n = 5$). Infants were recruited from published birth announcements in the Amherst, Massachusetts, area with an explanatory letter followed by a telephone call. All infants were in good health and had a normal course of development as verified by the parents on the day of the test.

Stimulus and Apparatus

The object presented in the light and dark conditions was a hand-held, multicolored rattle (17 cm × 5 cm). A wooden clothespin painted with glow-in-the-dark paint was held against the front of the object during the glowing condition. The glowing object did not illuminate the surround, so the hand could not be seen when it approached and grasped the object.

The infants were videotaped throughout the session at 33 frames/s with an infrared camera (Panasonic WV1800) that was placed to the right of the infant for a side view of the reaches. During the dark and glowing conditions, an infrared light placed on top of the video camera was the only light source.

In addition to the videotape, the reaches were recorded using a Watsmart motion analysis system (Northern Digital). This system consists of two infrared cameras that generate two-dimensional data from which three-dimensional coordinates can be calculated for any points within a precalibrated space. The Watsmart system estimated the positions of five infrared-emitting diodes (IREDs) at a sampling rate of 100 Hz. The IREDs were manually triggered to emit a signal for 10-s intervals, which allowed the cameras to record their instantaneous positions during this period. The precalibrated space was oriented with the x- and y-axes in the horizontal plane and z in the vertical plane. Two IREDs were taped on the back of the infant's right hand, one just proximal to the joint of the index finger and one on the ulnar surface just proximal to the joint of the little finger. Two IREDs were used in order to keep at least one in camera view if the infant rotated his or her hand during the reach. Infants of this age are not bothered by the IREDs and tend to ignore them once they are in place. One IRED was placed on the experimenter's hand that held the rattle, and two were placed 5 cm apart on an immobile stick attached to the chair the parent sat on in order to check for measurement error. Both Watsmart cameras were placed above and to the right of the infant.

Both the video camera and the Watsmart system were fed through a date-timer (For-A) and into a videocassette recorder (Panasonic Model 1950) and a video monitor (Sony Model 1271). The Watsmart system and the date-timer were triggered simultaneously in order to time-lock the IRED data with the video-recorded behavior for later scoring.

Procedure

Infants were seated on their mothers' laps in front of the experimenter who presented the objects. The mothers were asked to hold their infants firmly around the hips to support the infant and allow for free movement of the infant's arms. The mothers were asked to refrain from attempting to influence the infant in any way. A second experimenter was seated out of view to trigger the Watsmart system and to observe the infant on the video monitor. After the IREDs were applied to the infant's hand, the presenter indicated that the session could begin. Before each trial the presenter got the infant's attention while concealing the rattle and began the trial when the infant looked straight ahead and made eye contact. A trial consisted of the presenter signaling the other experimenter to trigger the Watsmart, then bringing the rattle into view and shaking it slightly. The rattle was presented at approximately 30° from the midline in the infant's right hemifield about shoulder height and at arm's length. Presenting the object in this hemifield encouraged right-handed reaching, which could be tracked with IREDs. The presenter held the rattle in this position, shaking it intermittently, until the infant successfully reached for and grasped it, or until the 10-s trial ended. Trials in the dark were the same as trials in the light except that the experimenter pressed a pedal switch to turn off the overhead light and turn on the infrared light before the trial began. The sounding object trials then proceeded exactly the same as the light trials, whereas the glowing object trials required the presenter to hold the luminescent clothespin against the rattle. Note that sound was present in all three conditions, but that sounding object trials offered only sound, with no vision available. Intertrial intervals lasted approximately 10 s.

Light, glowing, and sounding object trials were always presented in blocks of two trials per condition. The order of blocks was randomized across subjects. Each infant continued to receive blocks of trials in random order until he or she had completed 18 total trials (6 per condition), or until he or she became fussy. All infants had at least one reach in each condition.

Data Scoring

The trials were scored by viewing the Watsmart data in conjunction with the videotape. Each trial was first examined on the videotape to ascertain whether a reach was performed on that trial, and approximately where during the 10-s trial the reach occurred. A reach was defined as a forward motion of the arm toward the object that was not part of a turning motion or a torso rotation. Reaches that did not result in contact with the object were labeled *attempts*, whereas reaches that resulted in hand contact with the object were labeled *successful reaches*. The Watsmart data for successful reaches were then examined to determine whether the IREDs had remained within sight of the cameras for the duration of the reach. If a reach occurred, and the IREDs remained in sight of the Watsmart cameras for at least 90% of the duration of the reach, then the kinematic data were analyzed. Of the two IREDs on the reaching hand, only the one that was missing the least amount of data was used for further analysis. If neither IRED was missing any data, then the IRED that was used in the majority of the other trials for that subject was used. We did not score reaches made with the hand without IREDs, but only 1 infant even contacted the object with the contralateral hand, probably because this action required reaching across the body.

Reach onset was defined as the moment when the infant's arm began an uninterrupted approach toward the object, which was determined by viewing the infant's behavior on videotape. Then, using the date-timer code superimposed on the video, the scorer located this period in the Watsmart displacement data. All three axes (x, y, z) were used to determine the exact beginning of movement. The same procedure was used to determine the time of initial contact with the object. Once time of movement onset and time of initial contact were determined on the Watsmart data, the duration of the reach was obtained by subtracting one from the other. Distance traveled by the hand during the reach was the total path length from movement onset to contact.

The onset and contact times for all trials were scored by two observers. Because onset and contact times yielded continuous data, Pearson correlation coefficients were calculated between the two scorers. The correlation between the two scorers was .996 for reach onset time and .998 for time of initial contact. Observers had 93% agreement within 0.1 s in judging the moment of movement onset and 84% agreement in judging moment of contact, for an overall 89% agreement. Disagreements were settled by a third independent observer.

Kinematic Data Analysis

The data obtained from the Watsmart system are estimates of the true IRED position at the time of the sample. Because the noise in most signals extends to high frequencies and because differentiation produces values proportional to input frequency, numerical differentiation can result in poor estimates of IRED speed. We therefore used two independent methods to obtain accurate estimates of the positions and speeds of the hand IREDs. The first method involved use of a standard frequency-domain approach. Fast Fourier transformation of sample data showed that the spectral density decreased steadily as frequency increased until about 20 Hz when the power leveled off or increased. Because 20 Hz is approximately where one might expect the highest frequencies to be present in the signal, we low-pass filtered the data at 20 Hz using a second-order Butterworth symmetrical filter.

However, low-pass filtering at 20 Hz resulted in discontinuous and distorted speed and position profiles. These results suggested that the signal extends up to about 20 Hz but that the noise extends below 20 Hz. In an attempt to compute better estimates of hand position and speed, we used the dynamic programming method of Busby and Trujillo (1985). This algorithm is different from the standard frequency-domain approach and has the advantage of increased accuracy, with the cost of increased computation. We found the Busby and Trujillo method gave smooth speed and position profiles while only marginally reducing peak speed. The Busby and Trujillo method gave estimates for average speed that were 90% of the value of the frequency-domain algorithm. Because the Busby and Trujillo algorithm gave speed profiles that were usable with only a slight underestimation of peak or average speed, we used the Busby and Trujillo algorithm. The Busby and Trujillo algorithm only requires that a smoothing parameter, analogous to the pass frequency of a filter, be set by the experimenter. We used the criteria suggested by Busby and Trujillo for selecting B and used $B = 1 \times 10^{-9}$.

Adequacy of the filtering procedure was assessed by examining data obtained from the stationary IREDs. Trials were selected from five different sessions for analysis. On each trial a difference vector was computed between sequential samples of the raw data and from sequential estimates of IRED position calculated by the Busby and Trujillo (1985) algorithm. The mean magnitudes of the difference vectors in the sequence of raw data were approximately 4–7 mm (SDs ≅ 4 mm). The mean magnitudes from the filtered data were approximately 0.15–0.30 mm (SDs ≅ 0.20 mm). The IREDs in the raw data also appeared to "jump" around in that the angles between successive difference vectors averaged about 120°. On the other hand, the filtered data provided smooth position estimates because the angles between successive difference vectors changed slowly, with angles averaging about 15°. It is not clear if the small residual movement of the IRED in the filtered data is artifactual or if the "stationary" IRED was actually slightly moving due to the building vibration.

The number of peaks in the speed profile was determined automatically by a computer program. The program first examined the speed profile to determine the points in the time series where the $\text{Sign}(x_t - x_{t-1}) \neq \text{Sign}(x_{t+1} - x_t)$. This provided a list of candidate peaks. However, some of the candidate peaks fulfilled the criteria because they were plateaus or minima and not true peaks. Final determination of whether the candidate peak was a true peak rested on whether the speed profile increased a criterion amount (10 mm/s) prior to the peak and decreased a criterion amount (10 mm/s) after the peak. This algorithm is somewhat arbitrary, but it led to good classification of the peaks as judged by visual inspection.

We computed the peak and average speed of the hand for each reach. The average speed was calculated as the mean magnitude of the velocity vectors (speed) during the reach. Peak speed was defined as the highest speed attained during the reach. Possible deceleration prior to contact with the object was assessed by analyzing the 15 data points (0.15 s) immediately before contact. Most reaches took between 0.5 s and 1.0 s to complete and the final 0.15 s captured the final phase of the reach.

A measure of the straightness of the reach was computed by calculating the deviation of the reach from a direct trajectory. A straight line was calculated from movement onset to contact, and distance of the hand from this line was computed at each time step. For each reach the average deviation and the peak deviation from this shortest path were computed. A second measure of reach straightness was the ratio of the hand path length over the straight-line distance from the starting to ending points of the reach. If the reach was perfectly straight, this ratio would equal 1.

Results

Infants were more likely to reach in the light than in the dark, a pattern that has been reported in previous studies of reaching in the dark (Clifton, Perris, & Bullinger, 1991; Perris & Clifton, 1988). A total of 78 trials were presented in the light condition, 65 in the glowing condition, and 63 in the sounding condition. Virtually all light trials elicited a reach (90%), and contact with the object was made on 100% of the trials when a reach occurred. Infants made very few unsuccessful reaches in the light (only 3% of contact trials had unsuccessful attempts before contacts were made). Although the proportion of trials on which reaches occurred was smaller in the dark (74% for glowing objects and 71% for sounding objects), contact was likely when reaching did occur (96% and 89% of the trials with reaches had contacts for glowing and sounding object trials, respectively). Nevertheless, reaching was much less accurate in the dark, particularly for the sounding object. Contacts with the sounding object were preceded about half the time by an unsuccessful attempt (18/40 = 45%), with an additional 4 trials in which an attempt was not followed by a contact. Contacts with the glowing object were preceded by attempts on 15% (7/46) of trials, with two additional attempts not followed by successful contact.

Kinematic analyses of the data were concentrated on reaches that ended in contact with the object in order to compare guidance of the hand under different illumination conditions. In order for a trial to be included in our analyses, the IREDs had to be visible to the cameras for 90% of the reach because speed could not be calculated without these data points. Table 1 summarizes the distribution of trials and the reason for exclusion across all conditions. A total of 56 reaches was analyzed for the light condition, 35 for the glowing object condition, and 30 for the sounding object condition. All infants contributed at least one reach to each condition except for 1 infant who did not give an acceptable reach in the dark. When an infant reached on more than one trial within a condition, those trials were averaged so that each infant contributed the same amount of data to the statistical analyses.

Summary data for all kinematic measures are given in Table 2. Reaches in the dark for the sounding object were of shorter duration than reaches for the glowing object or for the object in the light. Statistically, this difference was supported by a main effect of condition, $F(2, 16) = 7.36$, $p < .005$, with follow-up paired Bonferroni t tests showing that reaching movements for the sounding object were of marginally significantly shorter duration than reaches for the glowing object, $t(8) = 2.84$, $p < .10$, and significantly shorter duration than for the object in the light, $t(8) = 4.67$, $p < .05$. Duration of reaches in the latter two conditions did not statistically differ from one another. This pattern of results suggests that infants modified their reaching behavior on the basis of whether the object was visible, rather than on whether their hand was visible.

Table 1
Distribution of Eliminated and Analyzed Trials in Each of the Experimental Conditions

Trial description	Light	Glowing	Sounding	Total
Total trials presented	78	65	63	206
No reach	8	19	20	47
Obscured IRED	7	10	11	28
Experimenter error	7	1	2	10
Trials included in analysis	56	35	30	121

Note. IRED = infrared-emitting diodes.

Table 2
Kinematic Summary for Reaches in Light, Glowing, and Dark

Measure	Condition (*M*)			Statistics	
	Light	Glowing	Sounding	$F(2, 16)$	p
Duration of reach (ms)	1,039	1,119	562	7.36	.005
Distance between hand position at movement onset to hand position at contact (mm)	160.5	158.8	133.0	1.51	.252
Maximum deviation from straight line (mm)	61.0	71.9	50.6	1.06	.370
Average deviation from straight line (mm)	29.7	35.0	26.2	0.96	.404
Ratio of path length over distance	1.799	2.047	2.405	0.51	.530
Path length of hand movement during reach (mm)	264.6	293.0	224.3	1.27	.308
Average velocity (mm/s)	283.1	274.6	423.1	6.61	.008
Peak velocity (mm/s)	565.4	578.9	707.1	1.69	.215
Number of peaks	2.9	3.3	1.9	6.89[a]	.032

Note. ms = millisecond(s); mm = millimeter(s).
[a] Friedman nonparametric analysis of variance.

In considering why reaches for the sounding object in the dark took less time, at least three possible reasons come to mind. One is that the infant's hand was closer to the object on the dark trials, and thus had a shorter distance to travel. A second possibility is that reaches for the sounding object followed a straighter trajectory, thus decreasing the total path length. A third possibility is that the hand moved more quickly when the object was not visible. The distance explanation stems from a problem not easily controlled in studies of infant reaching, because infants' unconstrained hands may begin a reach from any number of positions. Studies of adult reaching typically control for this by having subjects keep their hands on a starting location until a signal is given, but no one has yet figured out how to achieve a comparable situation with infants. Having the parent or the experimenter hold the infant's hand until the trial starts appears to lower the probability that the infant will reach (Hood & Willatts, 1986; Perris & Clifton, 1991). The best hope is that the variation in hand positions at the start of reaches will be spread out randomly over all trials and not have a reliable bias in any one condition. We measured the distance between the infants' hand positions at the start of each reach and the end of each reach at contact to see if the object was closer to the hand in some conditions. The mean distances were 161 mm, 159 mm, and 133 mm for the light, glowing, and sounding object conditions, respectively. These differences were not reliable (see Table 2).

The possibility that infants may have followed a straighter path when reaching for the sounding object was assessed in two ways. A straight-line trajectory was determined between movement onset position and point of contact position, then deviations of the hand's path from this line were calculated. The maximum deviations and the average deviations for each condition are displayed in Table 2; analyses of variance (ANOVAs) found no reliable difference among conditions for either of these measures.

Curvature was also estimated by dividing the path length by the distance from the starting to ending hand positions. If the path of the hand were perfectly straight, this ratio would equal 1.0. The degree to which the ratio was greater than 1.0 would indicate increasing hand path curvature. Table 2 shows the mean values for this measure for each of the experimental conditions. The values did not differ significantly across conditions, further evidence that the hand paths were comparably curved in the light, glowing, and sounding conditions. Finally, the total distance, or path length, that the hand moved during the reach was analyzed. An ANOVA indicated that conditions did not differ in path length. Thus, neither path length nor straightness differed for reaches made under widely varying conditions of illumination.

Another explanation for infants' shorter duration reaches for the sounding object is that their hands moved more quickly in this condition. Two measures of speed were taken: average speed of hand movement throughout the reach, and peak speed. Average speed was found to be 283 mm/s and 275 mm/s in the light and glowing object conditions, respectively, with the sounding object reaches considerably faster at 423 mm/s. This difference was reliable; the condition main effect was significant, $F(2, 16) = 6.61$, $p < .008$, and follow-up Bonferroni t tests revealed that speed of the reach for the sounding object was marginally significantly faster than for the glowing object, $t(8) = 2.72$, $p < .10$, and significantly faster than for the object in the light, $t(8) = 3.04$, $p < .05$.

Peak speed was a less stable measure. Peak speed averaged over all conditions was 617 mm/s, with extremely high variability. The means for the separate conditions are displayed in Table 2. The position of peak speed within the trajectory was also highly variable, although on the average the highest speed was reached at 45% of the trajectory, which is similar to the position of adults' peak speed, which occurs around 40%. Again, the illumination conditions did not differ on this variable.

Reaches in the sounding condition had fewer speed peaks or movement units than reaches in the light or glowing conditions. Because of the categorical nature of number of peaks and its limited range, these differences were evaluated using nonparametric statistics. A Friedman ANOVA showed a main effect of condition ($\chi^2 = 6.89$, $p < .032$). Paired Wilcoxon signed-ranks tests showed that the sounding condition had significantly fewer speed peaks than the light condition ($z = 2.077$, $p < .038$), that the glowing and light conditions did not differ in the number of speed peaks

($z = .102, p < .92$), and that although the glowing condition had more speed peaks than the sounding condition, the two conditions were not statistically different ($z = 1.6, p < .11$).

The distributions of the dependent variables in the three experimental conditions were examined by means of scatterplots. Figure 1 shows the scatterplot for average speed and the number of speed peaks in the reach. Two aspects of the distributions are clear by inspection: First, the distributions for the light and glowing conditions overlap extensively throughout the entire range of the dependent variables. Second, although the variables for the sounding condition overlap the other conditions when fewer than four movement peaks are seen, there is only one reach in the sounding condition in the right two thirds of the plot. This figure was typical among the scatterplots in that any differences among the distributions were between the sounding condition versus the light and glowing conditions. In no plot did the distributions of the dependent variables differ between the light and glowing conditions.

In some ways cumulative frequency polygons capture the differences among conditions better than means and scatterplots. In Figure 2 we display cumulative frequency polygons for the three kinematic measures whose means were reliably different from one another. In all three measures—average speed, number of peaks, and duration—the sounding object condition stands out from the other two. For example, over 75% of reaches in the sounding object condition had durations of 0.6 s or less, whereas in the light and glowing conditions only 15–25% of reaches had durations this short. This pattern is seen in all three panels of Figure 2.

Plots of individual trials convey the same picture as the group data reported previously. Figure 3 presents one trial from each condition for a single infant. In all conditions reaches had multiple-speed peaks, with speeds averaging around 200–400 mm/s, and paths with slightly curved rather than straight trajectories. Vision of the hand appeared to have little effect on kinematic measures (compare Panels A–C for the light condition with Panels D–F for the glowing condition.) When neither the object nor the hand could be seen, there were fewer movement units, higher speed, and durations around 0.5 s rather than over 1.0 s (see Panels G–I for sounding object in Figure 3).

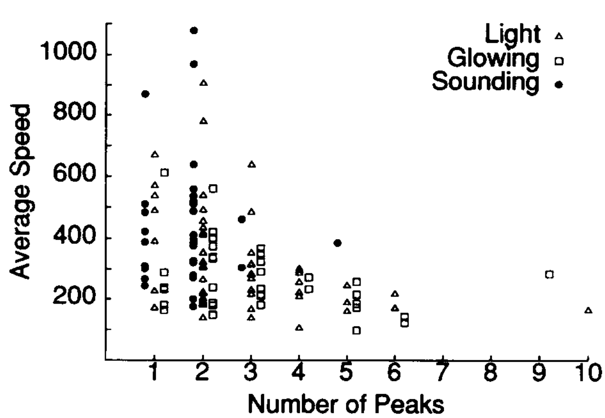

Figure 1. Scatterplot of average speed (in millimeters per second) as a function of number of peaks for the reaches in the three different conditions. The values for the three conditions are slightly offset in the figure to increase legibility.

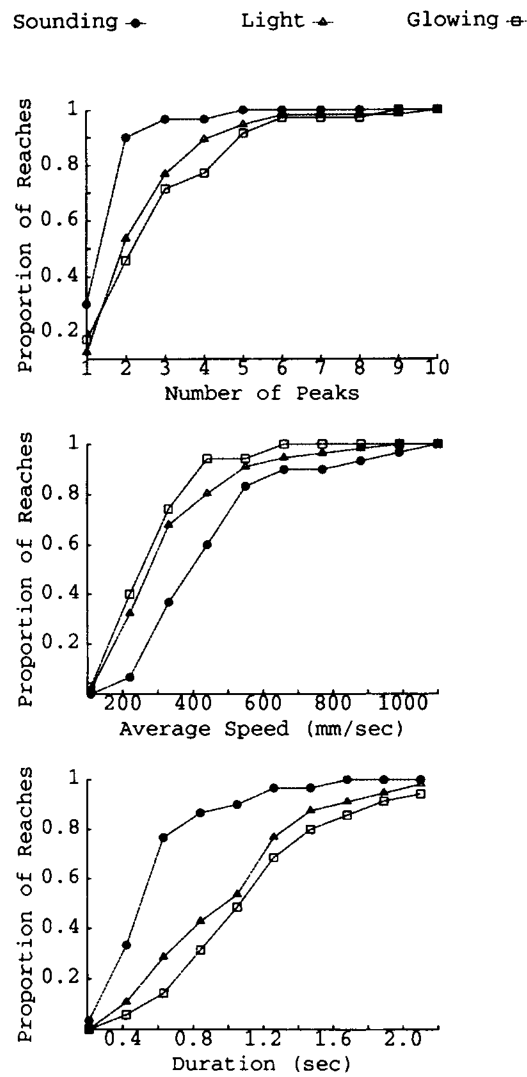

Figure 2. Cumulative frequency polygons for average speed of a reach, number of movement units in a reach, and the duration of a reach.

To determine whether hand speed decreased in anticipation of grasp, we examined hand acceleration prior to contact. Figure 4A shows a theoretical, bell-shaped speed profile for a single movement unit during an infant's reach. The duration and amplitude of the profile is typical for a reach in the sounding condition. We found a good quantitative fit between individual movement units in infants and bell-shaped speed profiles in adults (Flash & Hogan, 1985). Figure 4B shows an acceleration profile for the movement in Figure 4A. Notice that as the hand decelerates and stops over the last 100 ms, the acceleration profile drops below zero and is concave upward at the end. Given the bell-

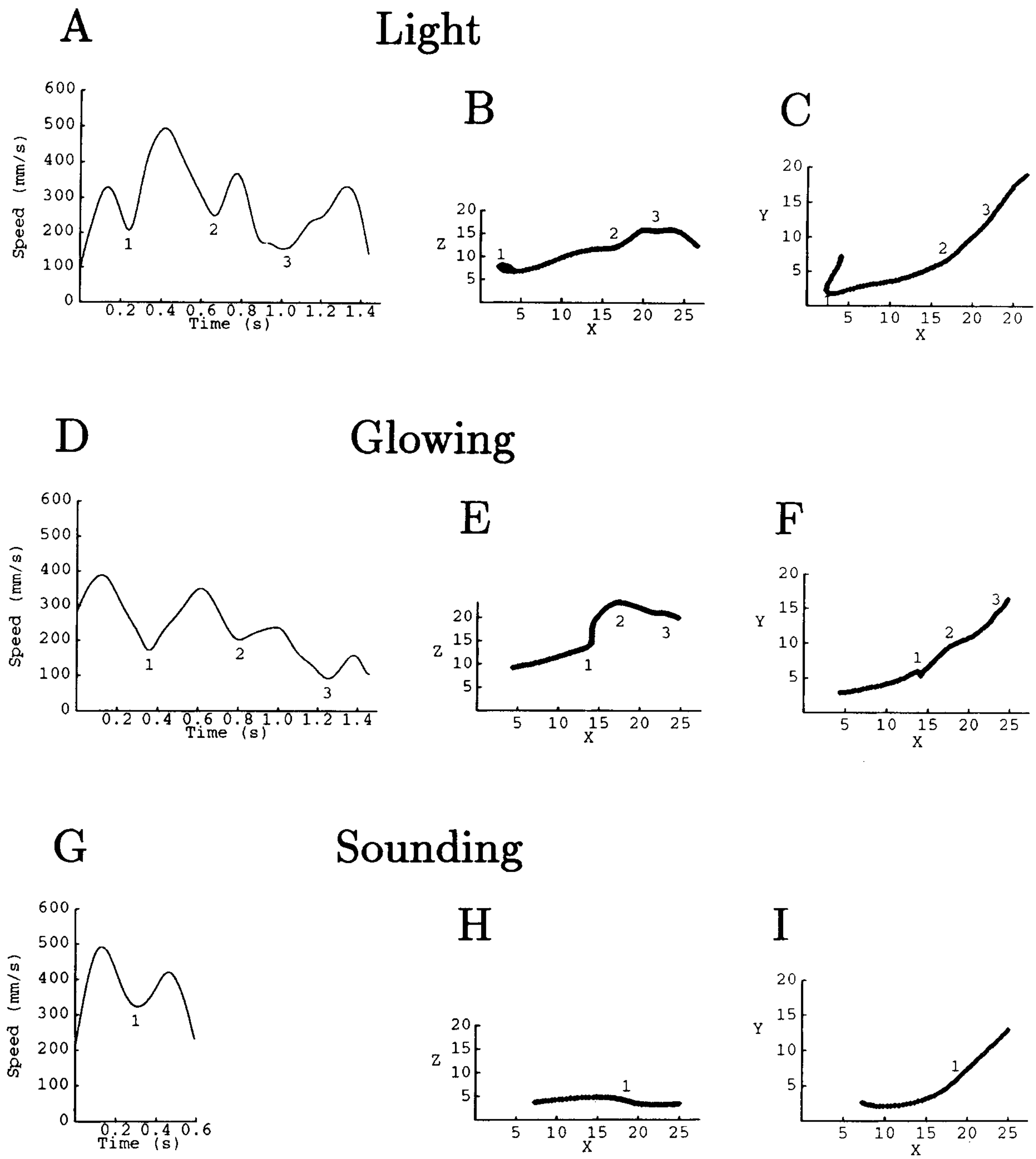

Figure 3. Representative reaches in the light (Panels A–C), glowing (Panels D–F), and sounding (Panels G–I) conditions. Panels A, D, and G show the speed of the hand as a function of time; Panels B, E, and H show side views, and Panels C, F, and I show top views of the hand's position during the reach. In the position plots the hand is moving from left to right and the scale of the axes are in centimeters. Movement in the *x* direction is movement away from the infant in the straight-ahead direction, movement in the *z* direction is up, and movement in the *y* direction is lateral movement. The numbers on the side and top view plots refer to the hand's position at minima, or speed valleys, in the associated speed plot.

shaped nature of the speed profiles in the current data, we expect that if the hand decelerates in anticipation of contact and grasp, the acceleration profile will be negative and concave upward just before contact.

Average accelerations for the three reaching conditions are shown in Figure 4C over the final phase of the reaches. Data are plotted with each reach contributing equally. Inspection of Figure 4C suggests that accelerations were neg-

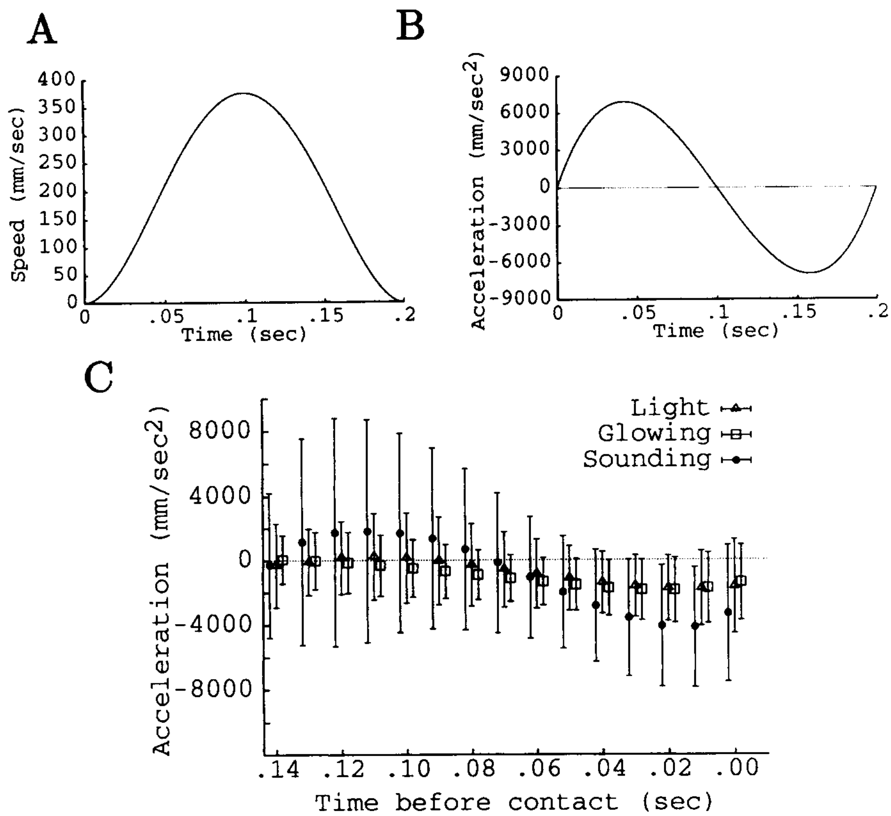

Figure 4. A. Minimum-jerk speed profile for a movement lasting 200 ms: This theoretical speed profile is similar in form and duration to a single infant movement unit. B. Acceleration profile for movement in A: During the deceleration phase of the movement unit, the acceleration profile is concave upward. C. Average acceleration of the infant's hand for the 140 ms prior to contact for the three conditions: Time .00 is the time of contact estimated from the videotapes, and the error bars show the standard deviations for each data point. The data are based on the reaches themselves and are not weighted so that each subject contributes equally. The values for the three conditions are slightly offset in the figure to increase legibility.

ative and concave upward over the last 100 ms, a result confirmed by trend analysis for each condition. Separate ANOVAs for each of the three conditions confirmed a significant quadratic trend in hand acceleration over the last 100 ms, $F(1, 56) = 13.7$, $F(1, 34) = 13.6$, and $F(1, 29) = 14.35$, $p < .001$, in the light, glowing, and sounding conditions, respectively. The magnitude of the concave upward function was larger for the sounding condition than for the light and glowing conditions, a result that is consistent with greater movement speeds in the sounding condition. Furthermore, the standard deviation of the accelerations is high until about 100 ms prior to contact. This reduction in variance in the decelerative phase indicates that hand speed was quite variable before the 100-ms point, but that over the final 100 ms of the reach, reaches showed consistent decelerations. Analysis of individual speed curves confirmed a consistent decrease in speed of the last 100 ms in 97% of the trials.

Finally, because there were so few differences in reaches in the light and dark, we determined whether reaches in the dark predominantly occurred on later trials. If so, this pattern would suggest that infants practiced reaching the light first, and then transferred this knowledge to reaching in the dark. Chi-square analysis of the distribution of reaches showed no support for this hypothesis. Tables of reach frequencies were prepared with reaches divided by viewing condition and whether the reach occurred early or late in the experimental session. When early reaches were defined as reaches that occurred on the first 6 trials and late reaches were defined as reaches on later trials, χ^2 (2, N = 121) = 0.32 ($p \leq .85$). If early reaches were defined as those on the first 12 trials, χ^2 (2, N = 121) = 0.09 ($p \leq .95$). These analyses indicate that infants distributed their reaches throughout the session similarly in the three conditions.

Discussion

Infants were presented with objects in three perceptual conditions that differed in the information available about the location of the target object and about the posture of the arm and hand. In the light condition infants had auditory information plus full vision of the object and surroundings as well as of the hand and arm; in the glowing condition, infants had auditory information plus vision of the object but did not have vision of the hand, the arm, or surroundings; and in the sounding condition, infants had no vision, with only auditory information about the position of the object. The results showed that reaching in the light and glowing conditions was remarkably similar even though the visible rattle in the light was larger than the luminous object held in front of it in the dark. However, reaching for sounding objects was substantially different than reaching for a visible target. Because of the nature of audition, information about the object's position and boundaries was necessarily less precise in the sounding condition than in the light or glowing conditions and may have contributed to this result.

Typical reaches in the light and glowing conditions consisted of three or four movement units with average speeds of about 280 mm/s, and durations of about 1.07 s. As can be seen in Figure 3, reaches in the light and dark were relatively straight. No significant differences for any measure were found between reaching in the light and glowing conditions. These measurements are fairly similar to those reported by von Hofsten (1991) for this age infant. At 28 weeks his 5 longitudinal infants averaged 2.8 movement units, with an average duration of 0.91 s, and fairly straight trajectories. The peak speed of the hand in the light condition was 565 mm/s, a value that is higher than von Hofsten's maximum speed of 426 mm/s, but this difference may be due to a smoothing procedure he used that reduced velocity. Generally, we found peak speed to be a less stable measure than average speed, probably because infant reaches have multiple peaks with great variation in where the highest peak is located. In contrast, adult reaches tend to be single-peaked, bell-shaped profiles with the peaks around 40% through the reach (Jeannerod, 1984).

The critical difference between reaching in fully illuminated conditions and in the dark for glowing objects is the lack of any visual information about the posture of the arm and location of the hand. In light of the generally held hypothesis that reaching is visually guided at this age, it is surprising that infants showed so little effect of loss of vision of the hand. If infants relied on vision of the hand to control the reach, there should have been dramatic differences in reaching between the light and glowing conditions. The fact that no such differences were found suggests that visual guidance of the hand is not critical at this age. This conclusion is supported by two additional studies that presented infants with a more difficult task than the stationary target used here. Robin and Clifton (1993) reported that infants were able to intercept a moving, glowing object in the dark that was within reach for only about 1 s during each movement past the infant. Ashmead, McCarty, Lucas, and Belvedere (1993) found that 9-month-olds corrected the hand's trajectory in the dark when a lighted toy shifted position in midreach.

How, then, are infants able to reach in the glowing condition? The problem facing the infant in learning to reach is not simply the learning of a map from proprioception to static arm postures in space (Thelen et al., 1993). Reaching is a dynamic problem that requires multimodal integration for successful solution. The information that is available in both the light and glowing conditions comes from vision of the object, somatosensory cues from the arm and trunk, and efference copy or information about the movement being executed on the basis of previous reaching experiences. Because infants reach similarly in both the light and glowing conditions, it seems likely that infants normally use all or some of this information as a basis for generating commands for movement.

Research from adults points to the importance of proprioception in the initiation and control of reaching. Ghez, Gordon, Ghilardi, Christakos, and Cooper (1990) examined multijoint reaching in normal adults and in adult patients with no proprioception of the arm. Normally, deafferented patients show fairly good reaching when they use vision of the hand to compensate for loss of limb proprioception. Ghez et al. tested the deafferented patients in reaching with and without sight of the hand and arm. They found that deafferented patients showed errors in both the initial guidance of the reach and in final position of the hand when reaching without sight of the hand. Analysis of limb dynamics suggested that errors in initial guidance of the hand were due to the deafferented patients being unable to compensate for the biomechanical properties of the arm at the starting posture without vision.

Ghez et al. (1990) suggested that adults use proprioceptive information to build and update an internal representation, or model, of the mechanical properties of the limb that can be used for planning and adjusting reaching. Their studies with deafferented patients emphasize the importance of proprioceptive information about the state of the limb in the control of movement. Because the results here show that reaching in the light and glowing conditions was similar, they support Ghez et al.'s suggestions and emphasize the relative importance of nonvisual information, such as proprioception, in controlling the hand during a reach for infants as well as adults. The results of this research reflect the fact that proprioception and somatosensory cues were unaltered across conditions. Nonvisual information is the common denominator among the variable visual conditions, and infants apparently used this information to control their reaching movements.

The differences between reaches for the sounding object and reaches for the visible target are revealing. First, it must be emphasized that reaching in the dark per se had almost no effect because no differences emerged between reaches in the glowing and lighted object conditions. But in contrast to the light and glowing conditions, a typical reach in the sounding conditions was much faster and had shorter duration. Reaches in the sounding condition had significantly fewer peaks than reaches in the light or glowing conditions. Looking simply at major characteristics of the hand movement, the reach for the unseen sounding object appeared more "mature" in that the movement was faster and had fewer movement units, which would be typical of older infants and adults. The price was paid in accuracy. There were more misses for the sounding object than when the target could be seen. On the other hand, infants appeared to localize the target within a specific area correctly because their hand markedly slowed in the final phase before contact. This finding rules out a characterization of reaches for the sounding object as high-speed swipes that occasionally hit the object as the hand passes through the general vicinity of the sound. If reaching in the dark consisted of mere swiping motions, consistent decelerations before contact would not be observed.

The high rate of inaccurate reaching in this study contrasts with the much lower rates reported in previous work (Clifton, Perris, et al., 1991; Perris & Clifton, 1988). Two factors may have contributed to less accuracy in this study: (a) the object was hand-held by the experimenter and may have been poorly placed and more difficult to reach on some trials; and (b) the sound was different and may have been more difficult to localize. Properties of sound such as bandwidth, peak frequencies, and transients affect ease of localization (Mills, 1972). Reaching for a sounding object is necessarily more difficult than when vision specifies the edges, shape, and orientation of the object. For this reason the sound's characteristics are critical in determining the subjects' accuracy in localizing the source. Regardless of possible difficulties in localizing the sound in this study, however, infants appeared to reach with control over their hand, exhibiting motor organization that was consistent over trials and over infants in this condition. For most kinematic measures, reaches for the sounding object were no different from reaches in the other conditions. When they did differ, their higher speed and shorter duration may have reflected a strategy in which feedback and correction during the approach was not possible because the target could not be seen. Older children (2–8 years) showed a similar pattern, reaching more quickly in total darkness for a object than when the object was glowing or presented in the light (Brown, Sepehr, Ettlinger, & Skreczek, 1986). Likewise, those children had more errors in total darkness even when movement time was taken out with an analysis of covariance.

Whereas we have emphasized the critical role that proprioception plays in infant reaching, we are not implying that vision is unimportant. Bushnell (1985) reviewed the literature and proposed that infants go through a period of visually guided reaching; then, after achieving a certain level of proficiency, they no longer need visual guidance and can reach without seeing their hands. Although this sequence was reasonable on the basis of the literature available at that time, it is no longer viable. Reaching in early infancy does not depend on visual guidance of the hand (Ashmead et al., 1993; Perris & Clifton, 1988; Stack et al., 1989). These results offer a much richer picture of reaching as a complex behavior controlled by many modalities. The infant makes use of vision of the target, of auditory information from the target, and proprioceptive information from sensory receptors in muscles and joints. Singularly unimportant at this early stage of life is sight of the reaching limb. During development reaching and grasping will become more precise and efficient as the infant learns to match aperture of thumb and index finger to size of object (von Hofsten & Ronnqvist, 1988), to pick up tiny objects (Halverson, 1932), and even later to insert small objects into small apertures, an item on the Bayley Scales of Infant Development at about 14 months (Bayley, 1969). When the infant is first learning to reach, visual guidance of the hand offers little aid because the early reaching and grasping are gross movements with little precision. By the time the infant is 9–12 months of age and older, vision of both the hand and object assumes a greater importance because grasping and handling of objects becomes more complicated and delicate. We propose that visual guidance of the hand is a late development rather than an early development, and that it continues to be critical for control of the hand in difficult manipulations throughout life.

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