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Dynamic reaching in infants during binocular and monocular viewing

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Abstract

This study examined reaching in 6-, 8-, and 10-month-olds during binocular and monocular viewing in a dynamic reaching situation. Infants were rotated toward a flat vertical board and reached for objects at one of seven positions along a horizontal line at shoulder height. Hand selection, time to contact the object, and reaching accuracy were examined in both viewing conditions. Hand selection was strongly dependent on object location, not infants' age or whether one eye was covered. Monocular viewing and age did, however, affect time to object contact and contact errors: Infants showed longer contact times when one eye was covered, and 6-month-olds made more contact errors in the monocular condition. For right hand selection, contact times were longer when the covered right eye was leading during the chair rotation. For left hand selection, there were no differences in contact time due to whether the covered eye was leading during rotation.

Keywords

Reaching; monocular-binocular; infants; prospective control

Introduction

Planning and executing a reach is a dynamic activity. Infants need to position the body and plan arm movements relative to the positions of objects in visual space. These manual actions also need to be planned in the context of changes in body position, because the whole body is typically involved in reaching movements in everyday life (Land 2004). Each step in this process relies on planning and prediction to be successful. Thus, sensitivity to depth and distance information is critical.

When in development does binocular information become involved in the control of reaching? Binocular perception is not present at birth, and the ability to use binocular visual

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information for perceiving depth and distance does not appear until 10 to 16 weeks of age (Birch et al. 1982; Braddick 1996). Soon thereafter, infants begin to use binocular information to guide reaching (von Hofsten 1977).

When reaching for stationary objects, infants judge distance and object size more accurately in binocular than monocular viewing conditions (Granrud et al. 1984; Braddick et al. 1996). For example, when presented with a small reachable object and a large out-of-reach object, 5- and 7-month-olds reach for the closer, smaller object in binocular but not monocular viewing conditions (Granrud et al. 1984). From the infant's point of view, the visual angles to the objects are identical, and thus in the monocular condition, the objects appear to be equally reachable because of lack of additional distance information. Similarly, with one eye covered to remove binocular information, 7- to 9-month-olds reach less accurately (Braddick et al. 1996).

What is the role of binocular information for catching moving objects? Motion information improves peripheral vision (Finlay 1982), and therefore it is also conceivable that it improves monocular vision as a larger part of the visual field is in the periphery in this condition. Between 3 and 8 months of age, infants increasingly rely on binocular information to control the timing of interceptive arm movements (van Hof et al. 2006). Infants produced more reaching attempts for objects viewed binocularly than those viewed monocularly. Latency to initiate reaching and movement time increased in monocular conditions, and infants produced fewer reaching attempts. Thus, binocular viewing enhanced the spatial accuracy of the interceptive arm movements at all ages studied. Van Hof and colleagues (2006) conclude that attunement to binocular information is a key process in infants' adaptive control of goal-directed arm movements.

Lack of binocularity in early childhood impairs eye-hand coordination, especially in amblyopic children (Suttle et al. 2011). Two-year-olds with one eye removed and same-aged peers with one eye covered showed poor depth discrimination when the only available depth cue was motion parallax (Gonzalez et al. 1989). Children in both groups did not spontaneously move their heads - resulting in lack of motion parallax and poor reaching precision. However, when instructed to move their heads, children in both groups improved their reaching performance. Thus, it is possible that binocular information makes a difference primarily in situations where motion information is not available or is not generated from children's own movements.

Several studies show that adult reaching is largely uninfluenced by monocular viewing conditions (Coull et al. 2000; Heat et al. 2008). Monocular viewing leads to increased spatial variance, which in turn gives rise to longer movement durations (Loftus et al. 2004; Marotta et al. 1995).

Current Study

In the present study, we observed infant reaching under binocular and monocular viewing conditions in a dynamic situation in which infants' bodies rotated toward targets placed at varied locations across the horizontal reaching space. In the monocular condition, we covered one of the infants' eyes with a patch (which eye was patched was counterbalanced across subjects). The patch eliminated binocular information and obscured view of the "patched" side of the reaching space. Our aim was to test whether removing binocular information affects hand selection, time to object contact, and contact errors. In addition, we asked whether obscuring the view of the left or right side of visual space has deleterious effects in concert with removal of binocular information.

We created a dynamic reaching situation using a new pivot paradigm (described in Soska et al. 2013). Infants sat on their parents' lap in a swivel chair that rotated toward a flat vertical board on which small toys were placed at various positions along a horizontal line. An experimenter sat opposite the board and after the child retrieved the toy, the chair was rotated 180° back toward the experimenter. The chair was again rotated toward the board with a new toy placed in a different position. Infants found this game very enjoyable such that dozens of reaches were secured from each baby.

The pivot procedure created an experimental situation that is dynamic in a different way from what is typically used. In typical reaching experiments, infants are stationary and they reach for stationary or moving objects (von Hofsten 1979, 1983; van Hof et al. 2006; Fagard et al. 2009). In the present study, we moved the infant rather than the object. This manipulation created a rich source of vestibular and proprioceptive information in addition to the global visual flow created by the motion of the subject. This context differs from the reaching situation with a moving object and a stationary subject. The visual information defines the external position of the object in space and the vestibular and proprioceptive information specify the orientation of the body and the internal relations between body parts. Furthermore, in previous studies of infant reaching, objects were placed at infants' midline (e.g., Berthier and Keen 2006) or at locations near the left and right shoulders (e.g., Rönnqvist and Domelöf 2006; van Hof et al. 2002). In the present study, object placement varied across the horizontal reaching space. Infants were free to initiate reaching whenever they wanted - even before the chair had stopped rotating.

Because infants were turned clockwise (CW) or counter-clockwise (CCW) toward the reaching apparatus, the time when the object came into view was affected by whether and which eye was patched, as well as the horizontal position of the object. Rotating the body on the side with a patched eye changes the opportunities for using visual information to plan the reach. Based on previous work, we expected that reaching under monocular conditions would be less precise and have longer latencies to object contact, especially in younger infants (van Hof et al. 2006; Braddick et al. 1996). We also expected that infants wearing the eye patch would be more likely to choose their reaching hand on the side that they could see better, that is, covering the right eye would make infants choose to reach more with the left hand. In addition, we asked whether covering one of the eyes would selectively impair time to contact the object and accuracy with the hand on the partly occluded side; that is, would covering the right and left eye impair reaching with the right and left hand, respectively, independent of object location? Finally we asked whether covering the right or left eye would selectively impair reaching toward the covered part of the visual field, independent of hand choice.

Method

Participants

In total, 72 infants participated: 29 6-month-olds (*M* age = 6.07 months; *range* = 5.8–6.5 months; 13 boys, 16 girls), 19 8-month-olds (*M* age = 8.33 months; *range* = 7.6 – 8.7 months; 10 boys, 9 girls), and 24 10-month-olds (*M* age= 9.96 months; *range* = 9.6 – 10.4 months; 15 boys, 9 girls). An additional 4 infants (3 8-month-olds and 1 10-month-old) were tested but not included in the final sample because they completed less than 15 reaching trials. The three age groups were chosen based on the varying degree of reaching experience at those ages. All infants were healthy and without any known visual problems and lived in a middle-sized Swedish city. The parents were given both oral and written information about the experiment upon arrival at the lab and signed a written consent form in accordance with the Helsinki Declaration. Families received a gift certificate for a local toy or bookstore as gratitude for their participation.

Materials and Procedure

Small toy targets were placed on an upright magnetic whiteboard (60 × 91 cm), which was clamped to a wooden table (65 cm high). The 15 toys used as reaching stimuli were approximately 5×5×4 cm in size and had magnets affixed to their backs that allowed for easy attachment to and removal from the magnetic board. They were placed on the board at seven positions varying from 0–28 cm to the left and right of midline in 9.3-cm increments. There were two experimenters: one experimenter sat opposite the board and administered the spinning procedure; the second experimenter placed the targets on the board at predetermined positions.

Infants sat in their parent's lap on an office swivel chair (with the wheels removed for stability) in front of the board. The chair was placed at the board's midline, and there was sufficient leg clearance beneath the table for the parent to swivel to and from the reaching apparatus. To ensure that infants could reach the objects at all positions, the height of the chair and distance to the board were carefully adjusted once parents positioned themselves. Parents were instructed to sit with their infants far out on their laps, provide postural support by holding their child's hips, and close their eyes before spinning around to face the board to limit their influence on infants' reaching. The second experimenter placed toys at infants' chest level, 9 to 12 cm perpendicular in distance from the center of the board. Thus, the distance to the outer positions was between 29.4 and 30.4 cm from the infants. A few warm-up trials were run before the start of the actual experiment to teach infants the spinning and reaching game and to ensure that they were able to reach the toy at the extreme positions.

At the start of each trial, the parent and infant faced away from the board toward the primary experimenter. The experimenter asked parents to close their eyes and then spun the chair 180° to a position straight in front of the board. The experimenter's attention was focused on the rotation of the chair to be able to stop it right at the midline.

The 180° spinning action took slightly longer than 2 s (90°/s). The rotation direction of the chair was alternated between trials to avoid influence on the infants' choice of hand. Infants were free to start reaching for the toys as soon as they began turning around. Infants were given approximately 10 s to reach for the toy before the chair was turned away. After each trial, the chair was spun away from the board, again facing the primary experimenter, who praised the infant and gently removed the objects from the infants' hands. The second experimenter was hiding behind a screen, and when the infant and parent had their backs to the magnetic board, she placed a new toy quietly at a predetermined position (according to a computer program that randomized target location across trials). Turn direction and object location were crossed in the task, such that infants were presented with objects on the right and left side of space while rotating both CW and CCW. She then hid behind the screen before the infant was again spun toward the board.

Every session started with the binocular condition. Then, infants were given a short break, and the experimenter put the eye patch (Master Aid's Ortopad) on one of the infant's eyes. Whether the patch was placed over the left or right eye was alternated between infants. After assuring that the infant could not see with the covered eye and was not disturbed by the patch, the monocular condition started, with the same procedure as the binocular condition.

Each of the binocular and monocular conditions consisted of four blocks, with seven trials in each block, giving each infant a maximum of 28 binocular and 28 monocular reaching trials. Infants had to complete at least 15 trials with binocular vision and 7 trials with the patch over one eye to be included in the final analysis. Sessions lasted approximately 20 minutes, including the short break between conditions.

Two digital cameras recorded the infants' manual actions. One camera, suspended above the whiteboard (at 65 cm distance), recorded the actions from an overhead view. A second camera, presented a side view from the right of the board (at 130 cm distance). The side view camera had a wide-angle lens and presented a full view of infants' bodies. Using a Macintosh computer (Quad core Intel Xeon) and a video software program (Evological Evocam 3.6.2), the two camera views were mixed together online onto a single synchronized video frame for later offline coding of the reaching behaviors. Figure 1 shows the experimental setup from the two camera views.

Data Coding

The videos were coded offline using computerized video coding software (www.openshapa.org). A primary coder scored hand selection, time to contact the object, and contact errors. Hand selection was defined as the first hand that made contact with the target—right, left, bimanual (both hands contacted the object within 0.5 s of each other), or no reach attempt. A contact error was scored when the infant misjudged the position of the object on the board and hit the board first with the same hand used to contact the target. Contact time was the time from when the chair stopped rotating at midline to the first contact with the object was made. Because infants were allowed to reach freely for the toy, even before the chair stopped rotating, contact time could be scored as either positive (contact with the toy was made after the chair stopped at midline) or negative (contact with the toy was made before the chair stopped at midline).

A second coder scored 25% of each infant's trials for the binocular condition and 50% of trials for the monocular condition to ensure inter-rater reliability. Inter-rater reliability for hand selection was $\kappa = .988$ ($p < .001$), for contact error $\kappa = .895$ ($p < .001$), and the correlation coefficient between raters for the contact time measure was $r = .998$. Disagreements were resolved through discussion.

Statistical Analyses

For statistical analyses, we considered hand selection as a binary variable—right or non-right (left-hand reaches plus bimanual reaches). Contact error was also treated as a binary variable. Generalized linear models (GLIM) with a logit link (e.g., Olsson 2002) were used for these analyses. Since each child was exposed to multiple experimental conditions, mixed logistic models were warranted (Littell et al. 2006). We used GLIM instead of traditional analyses of variance because each infant's useable trials were not distributed evenly across object positions, which can be accounted for with the mixed model approach. Moreover, since each infant was exposed to several trials in multiple conditions, performance on trials coming from one individual infant was likely to be more correlated with each other as compared to trial performance coming from another infant. Furthermore, ANOVAs do not allow use of binary outcome measures.

In the analyses on hand selection and contact error, the child was included as a random effect. In addition, each combination of condition and block was also set as a random effect. The fixed effects included condition, object position, age group, and rotation direction, along with all interactions. Post-hoc pairwise comparisons of least squares means were adjusted for multiplicity using Tukey's method. The Glimmix procedure in the SAS (2008) package was used for the analyses.

Contact time was analyzed as a continuous variable using a mixed model approach (Mixed procedure in the SAS 2008 package). Subject and condition/block combinations were treated as random effects; condition, object position, age group, rotation direction, and all two-way interactions were used as fixed effects.

In the present study, we could not reliably determine the initiation of each reach, since the chair was often rotating during that time and the arm could have been passively extending. Therefore, we measured, instead, how contact with the object was timed relative to the end of the chair rotation (sometimes occurring before rotation ended).

Because infants were free to reach for the objects at their own will, this resulted in some of the trials being quite long. Since these long latencies were due to inattention or fussiness, a 10-second contact time cut-off was applied. This cut-off resulted in loss of 2.7% of trials that ended with a reach.

Results

General

The pivot paradigm worked well. Infants were interested in the task and attempted to reach on 95% of trials presented to them. Infants included in the final sample received on the average 35.4 trials in the whole experiment (M = 22.7 trials in the binocular condition and M = 12.7 trials in the monocular condition).

The infants reached on 95% of the binocular trials. Out of the trials in the binocular condition where the infants made contact with the object, on average 53.0% (*SD* = 16.2%) were right hand reaches. Corresponding values for left hand reaches were *M* = 43.9% (*SD* = 16.2%). Bimanual reaches were rare, 3.1% on average (*SD* = 5.5%).

The infants reached on 91% of the monocular trials. The distributions of right and left hand reaches in the monocular condition were similar to those in the binocular condition: 54.9% (*SD* = 16.7%) were right hand reaches, 42.9% (*SD* = 16.5%) were left hand reaches, and 2.3% (*SD* = 6.2%) were bimanual reaches. Table 1 shows the proportions of right, left, and bimanual reaches, contact errors, and time to object contact distributed over the two conditions.

Figure 2A shows the distribution of hand selection across reaching space for all ages in the binocular condition. The graph also displays the relation between hand selection and object position. The further to the right the object was positioned, the greater the proportion of right hand reaches. Figure 2B shows a corresponding distribution for the monocular condition.

The exclusion criteria described in the *Methods* section resulted in 48 infants being analyzed for the monocular condition (24 6-month-olds, 14 8-month-olds and 10 10-month-olds). The high attrition rate for the older infants was due to the fact that 58% of the 10-month-olds refused to wear the patch. However, those who accepted the patch rarely tried to rip it off. Twenty-five of the infants analyzed in the monocular condition wore the patch on their right eye and 23 on their left eye. Thirteen 6-month-olds wore a patch on the right eye and 11 6-month-olds wore a patch on the left eye. The corresponding figures for the 8-month-olds were 7 on the right eye and 7 on the left; for the 10-month-olds, 5 wore the patch on their right eye and 5 on the left.

Due to the attrition of infants in the monocular condition, we compared the infants who contributed to both conditions and the ones who only did the binocular condition. This analysis was performed on binocular trials only. Mann-Whitney U statistics on the relevant variables showed that mean age was higher in the group who only performed the binocular condition ($Z = -2.94$, $p = .003$), which is explained by the fact that the attrition rate was greatest in the 10-month-old group. The infants who did both conditions also performed more binocular trials in total ($Z = -5.87$, $p < .001$) and performed reaches with shorter contact times ($Z = -2.36$, $p = .018$). There were no differences between the groups in the binocular condition concerning gender, hand selection, or number of contact errors.

The remaining analyses focused on the 48 infants who contributed data to both the binocular and monocular condition. First, we present omnibus analyses reflecting the study design. Significant differences between binocular and monocular conditions were followed by tests on only the monocular trials to examine the effects of which eye was patched, rotation direction of the chair, and object position.

Hand Selection

Table 2 shows least square mean values for all levels of the fixed effect variables in the generalized linear model examining proportions of right hand choice (i.e., hand selection).

The model revealed no significant effect of condition (*F* < 1.0); thus, it did not matter for hand selection whether infants reached for the object while looking with both eyes or only one eye. There was no interaction between condition and the object position on the board (*F* = 1.12), but the effect of condition on hand selection was dependent on direction of rotation (*F* (2) = 3.41, *p* = .034). The same model also showed a significant effect of object position on hand selection (*F* (6) = 46.14, *p* < .001). The further to the right the object was placed, the larger was the proportion of trials with right hand reaches. Rotation direction toward the board also affected hand selection (*F* (1) = 6.89, *p* = .009), such that right-hand use was larger when the chair was approaching the board in the CW direction, where the right hand was the leading hand, than CCW. There were no differences among the three age groups on hand selection (*F* < 1.0).

Contact Time

Table 3 shows least square mean values for all levels of the fixed effect variables in the mixed model examining average time to object contact. This model revealed a significant effect of condition (*F* (2) = 3.74, *p* = .026), with longer contact time in the monocular condition compared to the binocular one. There was also an effect of object position on average contact time (*F* (6) = 19.93, *p* < .0001), with longer contact times at the extreme end positions both to the right and left (±28 cm). In addition, there was an interaction between condition and object position (*F*= 3.32, *p* < .0001), such that during the monocular trials, time to object contact was longer at those positions on the patched side of reaching space. Contact times were also longer at the extreme end positions, independent of the positioning of the patch. No significant differences in contact times were found among the three age groups or between rotation directions of the chair (*Fs* < 1.0).

Given the significant effect of condition on contact time, follow-up analyses on only monocular trials were carried out to examine the effects of which eye was patched and effects of rotation direction of the chair on contact time. First, time to object contact was analyzed to examine whether there was a difference in timing between the hands on the patched as compared to the unpatched side. For a more detailed result, separate analyses were performed for reaching with the right and left hands, respectively.

A mixed model analysis examining the interaction between rotation direction and patched eye (left or right) with respect to contact time for right-hand reaching confirmed a significant interaction (*F* (1) = 5.85, *p* = .016). For right hand reaches, contact times were longer when the patched right eye was leading (turning CW). Table 4 shows least square mean contact time estimates (in s) for all levels of this analysis.

For left hand selection, the pattern looked different (see Table 4 for LSM contact time estimates). A mixed model examining the interaction between rotation direction and patched eye with respect to contact time for left hand selection showed no significant effect (*F* < 1.0). Thus, when infants reached with their left hand, there were no differences in contact time due to whether the unpatched eye was leading during chair rotation or not.

The omnibus analyses concerning time to object contact also revealed a significant effect of object position. Thus, we examined whether the time to object contact was larger when the patched eye was leading during the rotation of the chair, and the object was placed on the half of the board partly occluded by the patch. This follow-up analysis showed a tendency toward longer contact times when the patched eye was leading during the rotation and the object was placed on the covered half of the board, but it failed to reach significance (F (2) = 2.68, p= .070).

Reaching Accuracy

Table 5 shows least square mean values for all levels of the fixed effect variables in a generalized linear model examining frequency of contact errors. The model revealed a significant difference between conditions (F (2) = 4.35, p = .013). Infants committed more contact errors in the monocular than in the binocular condition. The same model showed that contact errors did not vary across object position or rotation direction of the chair (Fs < 1.6). The frequency of contact errors did, however, vary across the three age groups (F (2) = 27.99, p < .0001), with the 6-month-olds committing more mistakes compared to the 8- and 10-month-olds. There was no interaction between age and condition in this respect (p = 0.236).

Since the omnibus analysis for contact errors showed a significant result for condition, follow-up analyses on only monocular trials were carried out to examine the effects of which eye was patched and the object's placement on the board on the proportion of trials with contact errors. We first examined whether the infants would commit more contact errors with the hand on the same side as the patch (independent of the object's placement on the board). When the right eye was patched, the least square mean value for making a contact error with the right hand was .170 (*SE* = .048), and it was .171 (*SE* = .048) for making a contact error with the left hand. When the left eye was patched, the corresponding values for making a contact error with the right hand was .198 (*SE* = .056), and it was .185 (*SE* = .058) for making a contact error with the left hand. A GLIM confirmed no significant interaction between patched eye and hand choice with regards to frequency of contact errors with the ipsilateral hand (F < 1.0). No other interaction effects were found.

Further, it was examined whether the infants committed more contact errors while reaching for objects that were placed on the side of the board partly occluded by the patch (independent of hand choice). To have sufficient power for this analysis, object locations from −28 to −9.33 cm were binned together to represent object placement on the left side of the board, and object locations from +9.33 to +28 cm were binned together to represent placement on the right side of the board. Objects at 0 cm were regarded as placed at the midline position.

For patching of the right eye, the least square mean value for making a contact error was .167 (*SE* = .069) for objects positioned on the left side of the board, .155 (*SE* = .082) for objects placed at midline, and .265 (*SE* = .084) for objects placed on the right. For patching of the left eye, the corresponding values were .171 (*SE* = .069) for objects placed on the left side, .136 (*SE* = .076) for objects placed at midline, and .345 (*SE* = .106) for placements on the right side. A GLIM confirmed no interaction between patched eye and the object's position on the board with regard to frequency of contact errors (F < 1.0). Thus, the infants did not make more contact errors when the object was placed on the side of the board that was partly occluded by the patch.

The same analysis, however, revealed a significant interaction effect between patched eye and rotation direction of the chair (F (1) = 4.12, p = .043). Infants committed more contact errors when the unpatched eye was leading during the rotation. When the right eye was leading and unpatched (chair rotating CW) the least square mean value was .219 (*SE* = .076); when the right eye was leading and patched it was .136 (*SE*= .054). When the left eye was leading and unpatched (chair rotating CCW), the least square mean value was .263 (*SE*= .075), and when the left eye was leading and patched it was .191 (*SE*= .065).

Discussion

The importance of binocular information for reaching in infants was evaluated in a dynamic reaching situation where binocularity was manipulated by patching either the left or the right eye. We asked how this situation would affect hand selection and the accuracy and timing of reaching.

Hand Selection

Object position was by far the most important factor determining hand selection for reaching. Although there were more right hand reaches overall, the frequency of reaches performed with the right or left hand was scaled to where the object was presented—independent of which eye was covered. This effect held for all ages tested. More reaches were performed with the right hand the further to the right the object was placed and vice versa. This scaling is illustrated in Figures 2A and 2B. This result expands on previous findings with objects in three locations (e.g., Rönnqvist and Domellöf 2006) and replicates findings from Soska and colleagues (2013) who placed objects in 15 locations.

In contrast to the strong effect of object position on hand selection, which eye was covered in the monocular condition did not influence infants’ hand selection. Thus, reachability but not visibility was an important factor in determining hand selection. It is possible that infants turned their heads in such a way as to compensate for the induced constraints on the visual field.

We found a greater frequency of right hand reaches when infants were turned toward the board in the CW direction. This finding could be explained by the fact that when turning toward the board in this direction, the object became available to the right arm first. It is interesting to compare this behavior to reaching where the object is moving laterally in front of a stationary infant. In cases like that, infants tend to reach with the hand that is contralateral to the approaching object, that is, with the hand that encounters the object last. In that case, one could argue that reaching with the contralateral hand gives the child more time to plan the action. Together, these findings suggest that infants are more predictive when they move toward a stationary object than when reaching for objects that move relative to infants’ stationary bodies.

Contact Time

Contact time was defined as the time between the end of chair rotation and infants' first contact with the object. Results from this measure show that reaches were to a great extent planned during the rotation of the chair. Contact was often made before the chair stopped or at a time after it stopped that was shorter than the time it takes to plan and execute a reach. von Hofsten et al. (1998) found that 6-month-olds required at least 300 ms to adjust their reaching to a moving object that suddenly changed direction and Berthier and Robin (1998) found that reaching adjustments to shifts in object position required 250–400 ms. The time it takes to execute a reach is more variable. Rönnqvist and Domellöf (2006) reported that a reach took, on average, around 1 s and von Hofsten (1983) found that reaching for a moving object took, on average, about 500 ms to execute; in no instance was the time shorter than 300 ms. Thus, a conservative estimate of the minimum time to program and execute a reach is about 600 ms (300 ms for programming and 300 ms for execution). In the present study, 22% of the reaches were completed within 600 ms of the touch and 38% were completed with 1 s.

Loftus and colleagues (2004) suggest that binocularity gives online information of the hand relative to the target, which might explain why binocular viewing conditions yielded faster reaches than monocular ones in the present study. They interpreted the longer times as the system's attempt to decrease the error at grasp. In adults, monocular viewing does not influence the transport phase of the reach, only the grasping action (Watt & Bradshaw 2000). In the present study, when examining the whole group of infants together, there was a difference in contact time between the binocular and monocular conditions, with longer contact times in the monocular condition.

Object position on the board also had a significant effect on the time to object contact. Contact times were longer when the object was placed at the extreme end positions, both to the right and left. It is probable that these longer contact times were due to the fact that it took longer for infants to discover the object.

The follow-up analyses including only monocular trials showed that for reaches performed with the right hand, time to object contact differed depending on rotation direction of the chair and which eye was patched. In this case, the contact times were longer when the right eye was patched and leading during the turn. In contrast, when infants chose to reach with their left hand, there were no differences in contact time whether the patched eye was leading during the chair rotation or not. Thus, there seems to be a privileged connection between reaches performed with the right hand and visibility compared to reaches performed with the left hand. This coupling might be associated with the finding that the right hand has an advantage in early reaching over the left hand - with comparatively shorter contact times and more efficient planning, including fewer corrective changes (Morange-Majoux et al. 2000).

Reaching Accuracy

As hypothesized, infants committed more contact errors in the monocular condition. Further, the 6-month-olds committed more contact errors overall compared to the 8- and 10-month-olds. This result is reasonable since these infants have had less reaching experience. Van Hof and colleagues (2006) obtained a similar result for successful reaches to large objects: Fewer contact errors were made at 8 months than at 6 months. However, in the present study, no decrease in errors was found after 8 months of age.

Surprisingly, no effect of object position was observed on the number of contact errors. This result suggests that the infants did not have more difficulty planning reaches for objects far out in the periphery compared to objects placed at or around midline. Infants showed longer latencies to objects contact at the extreme end positions. Thus, these longer latencies could account for the fact that the number of contact errors committed at the extremes was not larger. In the analyses including only monocular trials, placing objects on the same side as the patch, did not produce an increase in the number of contact errors. As in the case with hand selection being unaffected by patching an eye, infants may have turned their heads to compensate for the induced visual constraint. However, the obtained interaction with turn direction suggests that they did not totally compensate. To examine this possibility further, it would be fruitful to use the paradigm of the present study in combination with a motion tracking system. In this way, the movements and velocities of both the infants’ heads and arms could be captured with millisecond accuracy.

One surprising result was that more errors were observed when the unpatched eye was leading during the rotation toward the board. When the unpatched eye views the board first, the object becomes visible earlier. As a result, infants may have produced earlier reaching movements while the chair was still in motion or had recently stopped. For this reason, their reaching movements may have been less precise. In support of this conclusion was the finding that when the covered right eye was leading the time to object contact was longer.

The fact that the binocular condition was always presented first might have led to a learning effect, where the infants became more efficient in their reaching after learning the game of rotating toward the board to obtain the object. However, this is not likely to have affected the results since the object was placed randomly in a new position for each trial and there was a warm up period. Also, the omnibus analyses show that the infants are slower and make more mistakes in the second (i.e., monocular) condition. This difference between conditions might, of course, be more pronounced if a counterbalanced design had been used.

Hand selection in the binocular condition

In the binocular condition, the infants reached for the objects more with their right hand than with their left hand (53.0% right hand reaches as compared to 43.9% left hand reaches). This bias of using the right hand at this age has been shown in other studies as well (Fagard & Lockman 2005; Rönnqvist & Domellöf 2006). In the binocular condition of the present study, the choice of hand was also similar to that in the study by Rönnqvist and Domellöf (2006), except for their higher frequency of bimanual reaching at 6 months of age (14.2 %). In the present study, the overall prevalence of bimanual reaches was only 3.1% on average. This difference cannot be explained by object size, as they were similar. The definition of a bimanual reach could, however, explain the difference between the studies. In the present study, a bimanual reach was defined as both hands contacting the object within 0.5 s; whereas, Rönnqvist and Domellöf (2006) required that the two hands begin their approaches within 0.5 s. Thus, in the latter study, the two hands could have begun their approaches close in time, ended up at the target further apart in time, but still be defined as a bimanual reach. In addition, in the present study, both hands had to contact the object, whereas in Rönnqvist and Domellöf (2006) both hands were only required to come within 5 cm of the object. During the age period studied, there is evidence that hand preference becomes established (Fagard 1998). In their study of reaching for stationary objects, Rönnqvist and Domellöf (2006) found fewer movement units and straighter trajectories for the right hand. They interpreted this result as a predisposed preference for right hand reaching. They concluded, however, as did Fagard and Marks (2000) and Newman and colleagues (2001) that the choice of hand for reaching and grasping is optimized to the reaching task. Fagard and colleagues (2009), for instance, found that when infants reach for objects that move across reaching space, they have a strong bias to use the hand contralateral to the direction from where the object arrives. If the object is stationary, the crossing of the midline is not the most rational strategy. Then it makes more sense to use the hand on the same side that the object is situated.

Benefits of the Dynamic Reaching Procedure

The idea with the dynamic reaching paradigm was to introduce a more natural reaching situation for the infants. When infants are reaching for objects in everyday life, the object is rarely placed right in front of them. It is much more common to turn around to reach for things that are placed at different distances and also at different positions across reaching space (Land 2004). However, the passive rotation of the trunk and head introduces a complex summation of visual and vestibular information as shown by Bresciani et al. (2005) and Bortolami et al. (2008). Further experiments are needed to evaluate reaching while being in motion, preferably in combination with a motion tracking system.

An important difference between patching the left versus the right eye appeared in the interaction with rotation direction. Performance was always driven by which eye was patched in combination with how the infant was rotated. This result indicates that the effect of patching on infant reaching is not simply about removing binocular information; reach planning is affected by obscuring parts of the visual field. The interaction between patching and turn direction neatly accounts for the overall condition effects, as these are always 2-way interactions. The pivoting paradigm was needed to show this effect.

The dynamic reaching paradigm worked very well. It presented infants with more challenges (such as maintaining their own postural control), but the infants also perceived the rotation procedure as an exciting, social, turn-taking game. Therefore, many trials could be secured from each infant. In the binocular condition, every infant included in the final analysis contributed with more than two trials at each toy position. The described setup may easily be applied in studies of clinical groups.

Monocular vision in contrast to restriction of the visual field

What is the effect of patching on the visual field in a swivel situation? Is it just the effect of creating monocular vision (in relation to depth perception); or is it a manipulation of peripheral vision, or both? In the present paradigm, the analyses comparing turn direction and eye patched address this concern: The comparison of patched versus unpatched tells about the effect of removing binocular information. The interaction of eye patched with turn direction informs on removing part of the visual field. There were differences between conditions in contact time and contact errors. Yet, for both measures, the condition effect wass qualified by reliable interactions with patched eye and turn direction. There also is likely a link between contact time and errors, with longer contact times producing fewer errors - and the interaction with eye patched and turn direction echoes this effect in both directions.

However, to be able to answer these questions in a satisfactory way, we need to compare the patching condition with one where the peripheral vision is restricted. This could be created with peripheral blinders (similar to horses wearing side blinders), electronic shutters, or old-fashioned bonnets that obscure peripheral vision. To do this manipulation in a proper way it is also necessary to vary how far out in the periphery vision is occluded. This question is the next to be asked.

Conclusions

By using a dynamic reaching situation, we examined the role of binocular and monocular viewing for the control and development of reaching behaviors. It was found that which eye (left or right) was covered had no effect on infants' hand selection, but the position of the toy on the board did. Thus, reachability, but not visibility, was an important factor in determining hand selection. All age groups showed a larger proportion of right hand reaches the further to the right the object was positioned, independent of which eye was covered. Furthermore, time to object contact was longer in the monocular condition for all age groups. For right hand reaches, contact times were longer when the right eye was covered and leading during the chair rotation (CW). In contrast, when infants reached with their left hand, there were no differences in whether the covered eye was leading during the chair rotation or not (CCW). This coupling might, in fact, be the precursor to more established hand laterality in later development. Lastly, more contact errors were committed in the monocular condition, with the youngest infants committing more errors compared to the two older age groups.

Acknowledgments

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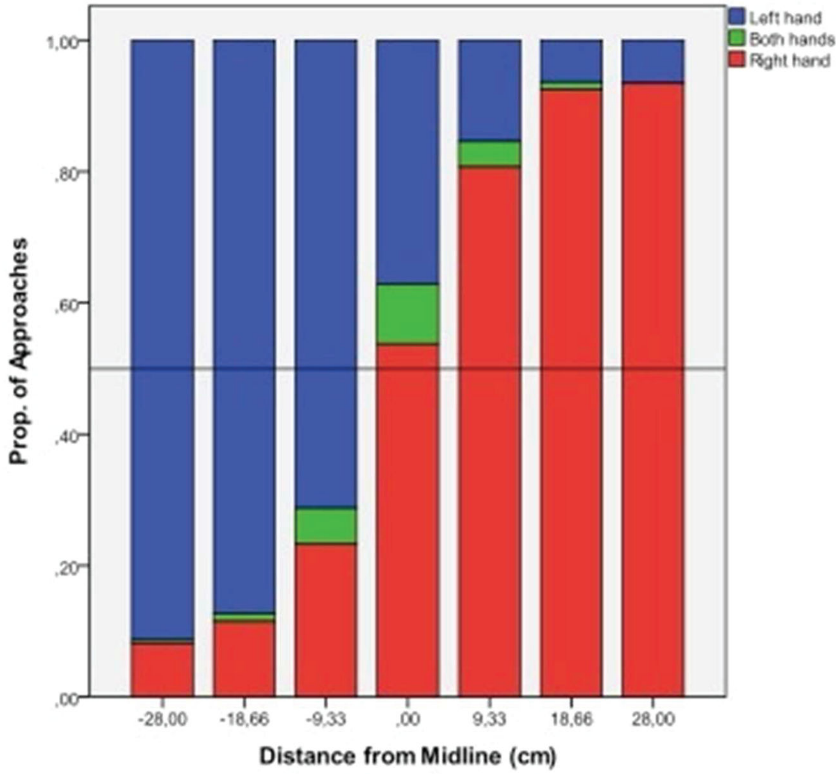
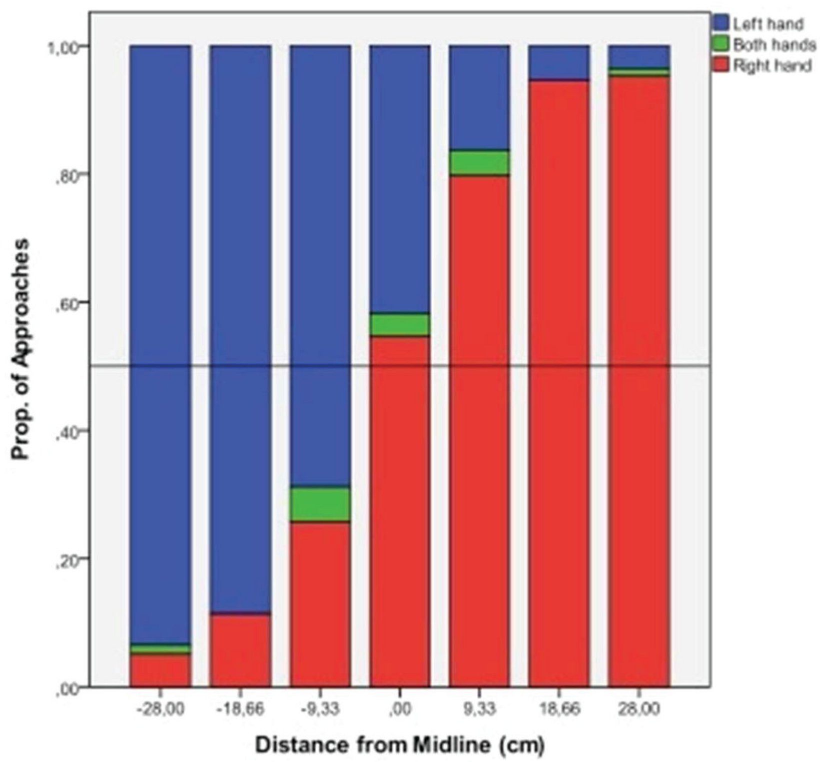
Figure 1.
Still photo from the experimental setup showing an infant grasping a target toy positioned 28 cm from midline. The upper side of the white board had markings of the pre-specified intervals where the toys were placed.


Left hand
Both hands
Right hand
1,00
,80
,60
,40
,20
,00
Prop. of Approaches
-28,00
-18,66
-9,33
,00
9,33
18,66
28,00
Distance from Midline (cm)


Left hand
Both hands
Right hand
1,00
,80
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Prop. of Approaches
-28,00
-18,66
-9,33
,00
9,33
18,66
28,00
Distance from Midline (cm)

Figure 2.

Figure 2A. Hand selection across reaching space in the binocular condition. Proportions of reaches made with the right, left or both hand(s) distributed over object positions.

Figure 2B. Hand selection across reaching space in the monocular condition. Proportions of reaches made with the right, left or both hand(s) distributed over object positions.

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Table 1

Proportions of trials with right hand, left hand, and bimanual reaches (hand selection), proportions of trials with contact error, and contact time (in s) for all trials in both conditions.

	Binocular trials (*N*=72[a])		Right eye patched (*N*=25[b])		Left eye patched (*N*=23[b])	
	M	***SD***	***M***	***SD***	***M***	***SD***
Hand selection						
Right hand reaches	.49	.16	.46	.15	.52	.15
Left hand reaches	.42	.16	.41	.18	.37	.21
Bimanual Reaches	.03	.05	.03	.07	.01	.03
Contact errors	.21	.21	.27	.23	.26	.22
Contact time	1.7	.79	1.9	.80	2.0	.86

Note.

[a]Minimum performance of 15 binocular trials.

[b]Minimum performance of 15 binocular trials, plus 7 monocular trials.

Table 2

Least square mean values for all levels of the fixed effect variables in the model, examining proportions of trials with right hand reaches (i.e. hand selection). Position −28cm is furthest to the left.

	M	SE
Condition		
Binocular	.51	.06
Right patched	.59	.09
Position		
−28 cm	.02	.01
−18.7 cm	.08	.03
−9.3 cm	.20	.05
0 cm	.54	.07
9.3 cm	.83	.04
18.7cm	.97	.01
28 cm	.97	.02
Age (months)		
6	.54	.09
8	.47	.09
10	.58	.11
Rotation direction		
CCW	.45	.06
CW	.61	.06

Table 3

Least square mean values for all levels of the fixed effect variables in the model examining average time (in s) to target contact. Position −28cm is furthest to the left.

	M	SE
Condition		
Binocular	1.60	.09
Right patched	1.86	.15
Left patched	1.96	.16
Position		
−28 cm	2.48	.17
−18.7 cm	1.52	.16
−9.3 cm	1.42	.15
0 cm	1.18	.15
9.3 cm	1.46	.15
18.7 cm	1.71	.15
28 cm	2.88	.16
Age (months)		
6	1.94	.12
8	1.78	.16
10	1.70	.19
Rotation direction		
CCW	1.84	.11
CW	1.77	.11

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Table 4

Least square mean time estimates (s) to object contact in the mixed model examining the interaction between rotation direction, patched eye, and hand selection with respect to contact time (in s). SE values shown in parentheses.

	Right hand		**Left hand**	
	Left eye	**Right eye**	**Left eye**	**Right eye**
CW	2.02 (.405)	2.10 (.386)	2.72 (.391)	1.29 (.385)
CCW	1.80 (.425)	1.20 (.401)	2.53 (.370)	1.40 (.375)

Table 5

Least square mean values for all levels of the fixed effect variables in the model examining proportions of trials with contact errors. Position −28cm is furthest to the left.

	M	SE
Condition		
Binocular	.10	.01
Right eye patched	.18	.04
Left eye patched	.16	.04
Position		
−28 cm	.14	.04
−18.7 cm	.08	.03
−9.3 cm	.18	.04
0 cm	.16	.04
9.3 cm	.16	.04
18.7 cm	17	.04
28 cm	.15	.04
Age (months)		
6	.45	.05
8	.07	.02
10	.07	.03
Rotation direction		
CCW	.13	.02
CW	.16	.03