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Infants' emerging ability to represent occluded object motion

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Abstract

The emerging ability to represent an oscillating moving object over occlusions was studied in 7–21-week-old infants. The object moved at 0.25 Hz and was either occluded at the center of the trajectory (for 0.3 s) or at one turning point (for 0.7 s). Each trial lasted for 20 s. Both eye and head movements were measured. By using two kinds of motion, sinusoidal (varying velocity) and triangular (constant velocity), infants' ability to take velocity change into account when predicting the reappearance of the moving object was tested. Over the age period studied, performance at the central occluder progressed from almost total ignorance of what happened to consistent predictive behavior. From around 12 weeks of age, infants began to form representations of the moving object that persisted over temporary occlusions. At around 5 months of age these representations began to incorporate the dynamics of the represented motion. Strong learning effects were obtained over single trials, but there was no evidence of retention between trials. The individual differences were profound.

Keywords: Infant; Object representation; Visual tracking; Occluder

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1. Introduction

The fact that objects go in and out of view as they and/or the perceiver move poses a basic problem to the perceptuo-cognitive system. In order to identify objects across occlusions, their spatio-temporal continuity must be preserved over the occlusion

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intervals. Uninterrupted actions on objects that move temporarily out of view, such as tracking them and reaching for them, are even more demanding. In addition, to preserve spatio-temporal continuity, anticipation of the time and position of reappearance is required as well as an appreciation of the velocity and direction of motion at that moment. In order to solve the identity and anticipation problems and preserve spatio-temporal continuity over temporary occlusions, the representations of moving objects must persist over such events. The present research asks when and how such persisting representations emerge in development.

The question of infants' emerging representations has recently been subject to much attention (see e.g. Carey & Xu, 2001; Johnson et al., 2003; Meltzoff & Moore, 1998; Munakata, 2001; Spelke & von Hofsten, 2001). In summary, the research shows that different tasks put different demands on the representational system and give different results. The youngest age at which infants can recover a hidden object is about 8–9 months (Piaget, 1954), but preferential looking studies may grant even 3-month-olds the ability to understand the continued existence of occluded objects.

A set of studies have used violation-of-expectancy looking time to displays where the spatio-temporal continuity has been violated as an indicator of persisting object representations. Moore, Borton, and Darby (1978) either changed the features of the moving object while it was occluded, violated the time relations between disappearance–reappearance, or introduced a slit in the screen where the occluded object was or wasn't seen as it passed. Nine-month-old infants responded to all three violations while the 5-month-olds did not respond to the split-screen violation. They were not bothered whether the object was seen in the slit or not. Baillargeon and associates (Aguiar & Baillargeon, 1999; Baillargeon & deVos, 1991; Baillargeon & Graber, 1987) habituated infants to a tall and a short rabbit moving behind a solid screen. This screen was then replaced by one with a gap in the top. The tall rabbit should have appeared in the gap but did not. Five-and-a-half-, 3.5-, and 2.5-month-old infants looked longer at the tall rabbit event suggesting that infants had detected a discrepancy between the expected and the actual event in that display. Spelke, Kestenbaum, Simons, and Wein (1995) used the slit screen situation to test whether 4-month-old infants could generalize according to number. They habituated infants to an event where an object moved behind a split occluder and either appeared in the opening or not. If it appeared in the opening the infants should expect one object to be involved and if it did not they should expect two objects. The test display involving either one or two objects supported this hypothesis. After habituation to a display where one object was expected to be involved, the infants had a relative preference to look at a test display with two objects and vice versa.

Although Baillargeon and associates (Aguiar & Baillargeon, 1999; Baillargeon & deVos, 1991; Baillargeon & Graber, 1987) and Carey and Xu (2001) suggested that these results give evidence of early object permanence, Meltzoff and Moore (1998) argued that all these effects could be explained in terms of discrepancies from expectation based on representational persistence and identity, "object permanence is not necessary" (p. 203).

Johnson et al. (2003) also used the violation-of-expectancy looking time procedure to investigate how infants perceive occlusion events. After habituation, the infants were either shown the object traveling through the same path without being occluded or were shown the object disappearing over the interval where it had been occluded before.

The rationale is that if infants perceive the continuous motion behind the occluder they will look longer at the test display where the object disappears into thin air. They found that this was the case for 6-month-old but not for 2-month-old infants. Four-month-olds displayed an intermediate pattern of performance, apparently perceiving the continuity of the trajectory of a moving object when it was occluded for a very short duration (67 ms), but showing no preference when the object was out of sight for a longer period (627 ms). Although these results indicate that object representations appear later than suggested by the studies cited above, the contrast between the two test conditions may have been somewhat attenuated by the fact that the object in the discontinuous condition actually disappeared and reappeared gradually in the same way as in the real occluder event, providing evidence of real occlusion (Gibson, Kaplan, Reynolds, & Wheeler, 1982).

Looking time experiments measure reactions to perceived discrepancies between the actual and the expected outcome of an occlusion event. Thus, any kind of change between habituation and test may be the elicitor of longer looking times. One should therefore be cautious when interpreting the results of such experiments, especially when inferring higher order processes (Haith, 1998; Hood, 2001). In addition, even when looking time experiments reflect infants' persistent representations, they do not demand the subjects to use the representations to organize actions on the reappearing object. Therefore, precise conception of how the object moves behind the occluder is not necessary. For instance, in a number of preferential looking experiments, infants' inferences failed to accord with inertia although reaching and tracking studies indicate that they do accord with inertia (Spelke, Katz, Purcell, Ehrlich, & Breinlinger, 1994; see also Spelke et al., 1995). The 6-month-old infants in one series of experiments viewed an object moving on a straight line as it disappeared behind an occluder, and then the occluder was removed to reveal the object at rest in various positions. Infants looked reliably longer at an outcome display that presented the object on the far side of a barrier, providing evidence that they represented object motion on a connected, unobstructed path. In contrast, infants looked equally at outcome displays that presented the object at a position on the line of its visible motion and at a position far removed from that line. The latter finding suggests that infants failed to extrapolate object motion on a linear path.

Infants' actions on moving objects reflect in a more precise way both how they perceive and conceive object motion. Action studies are admittedly conservative in the evaluation of infants' cognitive capabilities as infants may have a certain capability but not use it in organizing their actions. What do infants' actions then tell us about their abilities to perceive and represent object motion? Although neonates track visual motion (Bloch & Carchon, 1992; Dayton & Jones, 1964; Kremenitzer, Vaughan, Kurtzberg, & Dowling, 1979) it is only by around 2 months of age that the tracking becomes smooth and predictive (Aslin, 1981; von Hofsten & Rosander, 1996, 1997). When infants start to reach for objects by 4 months of age, they will catch moving objects by directing their reaches toward a future position where the object and the hand will meet (von Hofsten, 1980). These extrapolations of object motion are in accord with the principles of inertia. When the direction of a linearly moving object was abruptly perturbed at the endpoints of the trajectory, 3-month-old infants continued to move their gaze in the original direction for a quarter of a second before reversing their visual tracking and recovering the object. Five-month-olds showed some learning of the abrupt turn and their lag diminished (von Hofsten

& Rosander, 1997). Infants of the same age watching a linearly moving object disappearing behind an occluder had a strong tendency to turn to the opposite side of the occluder as if expecting the object to turn up there (Jonsson & von Hofsten, 2003; von Hofsten, Feng, & Spelke, 2000). This was the case irrespective of whether the object consistently turned up on the other side. However, infants also learnt to expect a different reappearance point over six trials for a motion trajectory that was systematically perturbed behind the occluder.

Reaching is less flexible than visual tracking. When the trajectory of a visible object was perturbed, 6-month-old infants continued to reach towards a position along the original trajectory (von Hofsten, Vishton, Spelke, Feng, & Rosander, 1998). When the same motion was perturbed behind an occluder, Spelke and von Hofsten (2001) found that 6-month-old infants stopped reaching for the object almost altogether. When instead the room lights went out for the same period, reaching was first disrupted but gradually recovered over the subsequent trials (Jonsson & von Hofsten, 2003; Munakata, Jonsson, Spelke, & von Hofsten, 1996). These results suggest that more precise representations are required for reaching than for tracking. To reach for an object, one must know where it is, how big it is, what shape it is, and how it is moving. In contrast, tracking a temporarily hidden object only requires knowledge of its kinematic properties.

When do infants become able to predict the reappearance of an object that gets temporarily occluded? Van der Meer, van der Weel, and Lee (1994) found that 5-month-old infants observing a temporarily occluded, linearly moving object looked towards the reappearance side in an anticipatory way. In their study the object was occluded for 0.3–0.6 s. Below 5 months of age, there are almost no studies on visual tracking over temporary occlusions. In a qualitative study Sergienko (1992) reported that infants between 12 and 18 weeks of age made predictive saccades over an occluder twice the size of the occluded object. Another line of research has investigated infants' anticipatory saccades to when and where the next picture in a predictable left–right sequence was going to be shown (Canfield & Haith, 1991; Haith, 1994; Haith, Hazan, & Goodman, 1988). Saccades arriving at the position of the next picture within 200 ms of its presentation were considered anticipatory. From about 3 months of age, such anticipations were found to be significantly more frequent for a predictable than for an unpredictable sequence (Canfield & Haith, 1991). This research is interesting for several reasons. First, the series of pictures is not a stimulus for tracking and the picture appearances do not need to be anticipated in order to stabilize gaze on them. Secondly, as the pictures were distinctly different, it is doubtful whether they are perceived as one object moving back and forth. The infants, however, anticipated these picture sequences as if they were real life events. Thirdly, the left–right sequence of pictures followed an arbitrary rule rather than a physical principle. In spite of this, temporal regularities were rapidly learnt suggesting that infants are very sensitive to spatio-temporal contingencies and use them to predict what is going to happen next. Similar impressive learning has been demonstrated in somewhat older infants in the context of parsing sound sequences (Marcus, Vijayan, Bandi Rao, & Vishton, 1999; Saffran, Aslin, & Newport, 1996) or picture sequences (Kirkham, Slemmer, & Johnson, 2002).

In summary, the data on visual tracking and reaching suggest that infants become able to represent both visible and hidden moving objects during the first half year of life. The earliest reports of such representations come from 2–3-month-old infants as reported above. Munakata (2001), Scholl (2001), Spelke and von Hofsten (2001), and Jonsson and von Hofsten (2003) assumed that infants' object representations of moving objects depend on the same mechanisms as those used to represent and attentively track objects in adults. It was assumed that object representations are graded in strength and more precise, at all ages, when objects are at the center of the visual field than when they are at its periphery and that visible objects form more precise representations than hidden ones. There are two additional properties of object representations that will be further elaborated below. First, representations compete for attention: as more attention is devoted to one object, representations of other objects lose strength and precision (e.g. Rensink, O'Reagan, & Clark, 1997; Simons, 1996). An occluder will compete for attention and thus degrade the representation of the occluded object. Secondly, representations are subject to learning. The representation of a hidden object will increase in strength with the number of times it is hidden by the same occluder and degrade with time.

The attention effects are stronger for very young infants. Butcher, Kalverboer, and Geuze (2000) found that below 9 weeks of age infants rarely shifted gaze towards a new stimulus presented in the peripheral visual field if the stimulus the infant was fixating remained on. Infants' ability to shift attention to new objects improved dramatically between 9 and 12 weeks of age. Butcher et al. (2000) found that 12-week-old infants reliably turned gaze toward a new stimulus presented in the peripheral visual field whether or not the stimulus they were fixating remained on. If young infants' representations of occluded moving objects are weak, it is expected that they will continue to fixate the occluder edge after the object has disappeared and show a relative inability to regain tracking after the object has reappeared. As the representation of the hidden object improves it is expected that infants' ability to negotiate the temporary occlusion of a moving object will improve in corresponding ways. It is hypothesized that 9-week-old infants and younger will tend to continue to look at the place of disappearance but that 12-week-olds and older will more quickly regain fixation on the reappearing object.

The question of whether infants' object representations are subject to learning has received little attention in the past. Part of the problem is that the most common method for investigating object representation in infancy is habituation. Although this method relies on learning, this fact actually makes it unsuitable for studying learning over a single session. It is, however, well known that infants show rapid learning. The study on statistical learning cited above is quite telling (Kirkham et al., 2002; Marcus et al., 1999; Saffran et al., 1996). The studies by Haith and associates (Haith et al., 1988) also show how rapidly sequence regularities are picked up. In the context of occluder tracking, von Hofsten et al. (2000) showed that a new object trajectory behind the occluder was learnt within six trials. That representations become more precise with the number of encountered occlusion events is reflected in the increasing tendency over trials to predictively reach for an object that becomes temporarily non-visible by blackout (Jonsson & von Hofsten, 2003).

Another basic question concerns the persisting representation in itself. It is quite possible that the representation is rather simplified and that infants just move gaze to the opposite side of the occluder as soon as the object disappears. If the representation preserves the spatio-temporal continuity of the previously seen motion, however, moving gaze over the occluder should be geared to the reappearance rather than the disappearance of the object. In addition the velocity of the object should also be taken into account. Therefore, two kinds of motions were used in the present experiment; one sinusoidal and one triangular. The velocity of the sinusoidal motion changes continuously over the trajectory while the velocity of the triangular motion is constant and reverses direction abruptly at the endpoints. If infants use velocity information when extrapolating object motion, a difference in tracking performance is expected for the two kinds of motion at the peripheral occluder but not at the central one. If they do not use velocity information, a difference would be seen at the central occluder but not at the peripheral one. At the peripheral occluder the sinusoidal motion decelerated specifying reappearance on the same side, while the triangular motion continued to move with constant velocity specifying reappearance on the other side of the occluder. If infants cannot perceive velocity change, they will always predict that the object will appear on the other side of the peripheral occluder whether it is moving according to a sinusoidal or a triangular motion function. At the central occluder the sinusoidal motion accelerated at disappearance but not the triangular motion. Occlusion time was kept constant by using a wider occluder for the sinusoidal motion. If infants are sensitive to velocity change, they will correctly perceive that the two kinds of motion will result in the same duration of occlusion. However, if they are not sensitive to velocity change, they will assume that the object will remain hidden longer at the wider occluder (sinusoidal motion) and therefore tend to overestimate occlusion time in this condition.

2. Method

2.1. Subjects

Altogether 39 infants from six different age groups were analyzed (four boys and three girls in the age range 7:0–7:6 weeks, four boys and three girls in the age range 8:4–9:6 weeks, seven boys and one girl in the age range 12:0–13:5 weeks, three boys and six girls in the age range 17:0–17:6 weeks, and five boys and three girls in the age range 20:3–22:1 weeks). An additional six infants were excluded from the experiment due to fussing and two due to malfunctioning electrooculogram (EOG). All infants were healthy and born within 2 weeks of the expected date. Four adults were also included in the study.

2.2. Apparatus

The apparatus used has earlier been described in detail (Rosander & von Hofsten, 2000; von Hofsten & Rosander, 1996, 1997). The infant was placed in an infant chair, especially designed to give full support of the trunk, while allowing free movements of the limbs. It was placed at the center of a drum, 100 cm in diameter and 100 cm high. The rotational axis of the drum corresponded approximately to the dorsal column of the infant. The head of the subject was lightly supported with pads so that it could rotate without falling aside. During the experiments, the chair and the drum were comfortably inclined at an angle of 40°. Fig. 1 shows a subject in the drum.

The inside of the cylinder was homogeneously white, except for a narrow horizontal slit right in front of the infant's face. The slit was 60 cm long and had a movable stimulus placed in it. The adult subjects sat on a chair close to the cylindrical base of the drum,

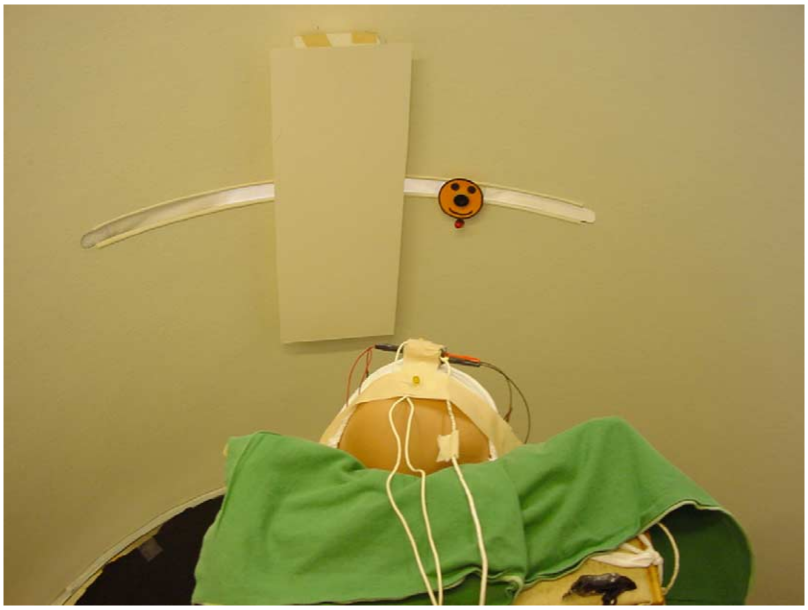

Fig. 1. Photo of the experimental set-up. The infant subject is placed at the center of the drum. On the head, the LEDs and the amplifier are seen. The subject is looking at the object, a happy face, that is moving along the slit. An occluder is centrally placed.

and put their head in its center. Then, the chin was resting on the baby chair thus creating a support for the head.

2.3. Stimuli

The object was a circular yellow "happy face", 5.6 cm in diameter corresponding to a visual angle of approximately 8.5°, with a black wide contour around it. In the middle of the schematic face, at the position of the nose, there was a mini video camera (Panasonic WV-KS152). Its black front had a diameter of 15 mm or 2.2° of visual angle. The "happy face" oscillated in front of the infant according either to a sinusoidal or a triangular motion function at 0.25 Hz with an amplitude of 25° of visual angle. The maximum speed was 39°/s (sinusoidal) or 25°/s (triangular). At some trials the object motion was occluded by a rectangular white piece of cardboard at the center of its trajectory and at others at the left end of its trajectory (due to technical reasons). In an attempt to equate the duration of occlusion for the sinusoidal and the triangular motions different occluders were used for the trials where the object was occluded at the center of its trajectory. For the sinusoidal motion, the occluder was 12.5 cm wide covering 19° of visual angle and for the triangular motion it was 10.5 cm wide covering 16° of visual angle. The occluders were positioned over the motion trajectory at a distance of 2 cm from the cylinder wall to which they were attached by means of velcro. In both conditions the object was completely covered by the occluder for 0.3 s (see Fig. 1).

When the object was occluded at the end of its trajectory, the 10.5 cm wide occluder was always used. The occluding edge was positioned 12° from the turning point in the case of the triangular motion and 8° in the case of the sinusoidal motion. In both cases the object was completely occluded for 0.7 s.

2.4. Measurements

2.4.1. Eye movements

EOG was used to measure eye movements. The electrodes were of miniature type (Beckman) and had been soaked in physiological saline for at least 30 min before use. They were then filled with conductive electrode cream (Synapse, Med-Tek Corp.) and attached to the outer canthi. The ground electrode, a standard EEG child electrode, was placed on the ear lobe. Between trials the base level of the EOG signal was adjusted (for further details see von Hofsten & Rosander, 1996). Before analysis, the slow drift of the EOG was eliminated from the records. The position accuracy of the EOG was about ± 0.4° of visual angle and the velocity accuracy was ± 1.5°/s.

2.4.2. Head and object motions

An opto-electronic device, Selspot (Selcom AB, Partille, Sweden), was used to measure the movements of the head of the subject and the object. The signal-emitting part of the system consisted of infrared light emitting diodes (LED) of 4 mm in diameter (for details see von Hofsten & Rosander, 1996). Two LEDs were used to record the head position of the infant. They were placed mid-sagittally on the head and about 7–9 cm apart. A third LED was placed on the "happy face" to record its motion. After filtering, the positional accuracy was about ± 0.2° of visual angle and velocity accuracy was ± 0.8°/s. Data were collected from the EOG and the LEDs on the object and the head simultaneously at 200 Hz. For the adults, eye movements were measured in the same way as in the infants. Head movements were not measured in the adult group.

2.5. Experimental procedure

At each visit, the same routine was applied. Before starting the experiment, it was assured that the infant had been recently fed and was in an alert state. After informing the accompanying parent about the experiment he/she signed the consensus form. The video camera at the center of the stimulus monitored the face of the infant so that the parents and the experimenter could observe the infant during the experiment. As the camera moved with the object and was always directed at the face of the infant, it was possible to determine whether the infant fixated the object or not.

Each infant was presented with six experimental trials. After calibration, two trials without an occluder were presented, one with sinusoidal motion and one with triangular motion. Then four occluder trials followed in randomized order, two centrally occluded (one sinusoidal and one triangular) and two peripherally occluded (one sinusoidal and one triangular). If the infant fussed or fell asleep during a trial, the experiment was interrupted temporarily, after which the last trial was repeated and the experiment continued. Such interruptions were uncommon. The experimental session had a duration of around 10 min.

The EOG signal was calibrated in the following way: the experimenter moved the object back and forth between the center (0°) and the extreme positions of the trajectory (± 25° of visual angle). Each stop lasted around 1 s and if there was any doubt that the infant's fixation was on the object, it was shaken a little to further attract the infant's gaze. In comparison to previous studies (von Hofsten & Rosander, 1996, 1997) the following improvement for checking whether the infant fixated the object at the stops was introduced. At each fixation stop the experimenter flashed a small red LED situated immediately below the video camera in the middle of the object and directed at the infant's eyes. When the infant fixated the object, the light was reflected back from the eyes of the infant. In the adult subjects, the same procedure was applied.

2.6. Data analysis

Of the 39 subjects analyzed, four centrally occluded trials, i.e. 5%, could not be analyzed because of malfunctioning EOG. They originated from different subjects. These trials were replaced with the timing values of the other recorded centrally occluded trial for the same subject. There were altogether ten missing values in the middle of a trial (cases where the subject did not move gaze over the occluder). They were interpolated with the timing value for the previous and subsequent passage. There were a total of 29 missing values at the end of trials due to disinterests. They were extrapolated from the last measured passage. Thus, the learning effects at the end of trials may have been slightly underestimated. All calculations of head and eye movements and their relationship with the object motion were performed in the rotational plane which had its origin on the rotation axis (for details see von Hofsten & Rosander, 1996, 1997). All statistical analysis was performed in SPSS, applying the General Linear Model.

2.6.1. Analysis of visual tracking in the non-occluded trials

The gain and timing of head, eye and smooth pursuit was routinely calculated. To calculate the smooth pursuit component, eye movement velocities higher than 50°/s were eliminated from the composite, raw eye movement record and the periods between were interpolated according to the low frequency component of the tracking. Gain was calculated with Fourier analysis. In this analysis the head movements were normalized to the object motion, and the eye movements were normalized to the head slip. The head slip is the motion of the object relative to the head, because the task of the eye movements is to compensate for this slip. For estimation of the phase, the timing, between two signals cross-correlation analysis was used.

2.6.2. Analysis of visual tracking over the central occluders

The tracking was analyzed in a spatial-temporal frame of reference. First, the occluder boundaries were identified from the object motion record. Then the interval where the object was completely occluded was identified. As the marker on the object was placed at its center, half the object was still visible when that marker got occluded. Only when the object was fully occluded did the subject have to rely on its representation. Therefore, the position in space-time of the full occlusions was marked and it was situated half an object width inside the occluder borders (see Fig. 2). Gaze was considered to have arrived

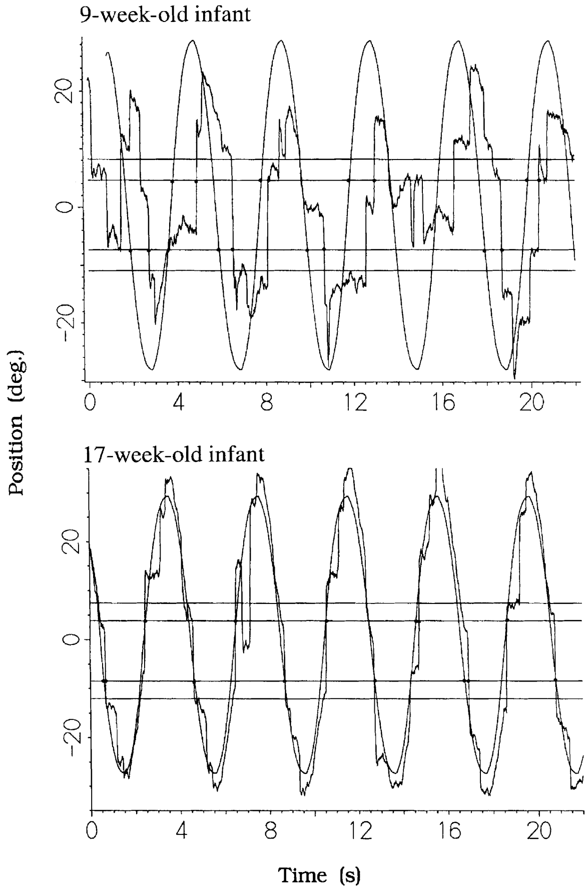

Fig. 2. Recorded gaze movements plotted together with the object motion for single sinusoidal trials with central occlusion. The graph depicts the event over time (horizontal axis) and space (vertical axis). The outer horizontal lines in the figures signify the occluder boundaries. As a centrally placed marker measured the position of the object, only half the object was occluded when the marker passed the occluder boundaries. Therefore, the inner horizontal lines are needed to signify the position of the object marker when the object was totally occluded. These are thus positioned half the object width inside the occluder.

at the other side of the occluder when it was within 2° of its opposite boundary. In this way, the time difference between the reappearance of the object and the arrival of gaze was analyzed for each occluder passage. Delays less than 200 ms were considered predictive as this is the minimum time required to program a saccade to an unexpected event both in adults (Engel, Andersson, & Soechting, 1999) and in infants (Haith et al., 1988).

2.6.3. Analysis of visual tracking at the peripheral occluder

As the appropriate strategy at the peripheral occluder was to remain at the boundary where the object disappeared, it was not possible to obtain an appropriate timing measure for predictive behavior. The same behavior was also expected when infants remained at the occluder edge because they had no idea of what happened to the occluded object. Therefore, the behavior in this condition was only coded in terms of whether infants made a saccade over the occluder or not. In order to do that, the boundary of the peripheral occluder and the point in time where the object was completely occluded was identified. Then for each such event it was determined whether gaze stayed at the occluder boundary until the object appeared there again or moved over to the opposite side of the occluder.

3. Results

3.1. The non-occluded trials

Tracking performance is shown in Table 1. No difference was observed between the sinusoidal and triangular motion with respect to eye gain and they are therefore merged in Table 1. The gain was close to 1.0 from 12 weeks of age but significantly smaller for the two youngest age groups ($F(4,34) = 5.388$, $P < 0.01$). Head gain increased with age ($F(4,34) = 4.107$, $P < 0.01$). The smooth eye tracking component showed a dramatic increase in gain up to 12 weeks of age ($F(4,34) = 24.78$, $P < 0.001$) after which it leveled off. The largest average lag for the sinusoidal motion (117 ms) was obtained for the 7-week-old infants and the timing improved significantly with age after that ($F(4,33) = 3.064$, $P < 0.05$). Considering that lags less than 125 ms are regarded as predictive when tracking a sinusoidally moving target as found for adults by Robinson (1965), then timing of the smooth tracking of the sinusoidally moving object is predictive from 12 weeks on ($t(7) = 4.266$, $P < 0.01$). Also for the triangularly moving target the lag decreased linearly with age ($F(4,31) = 3.262$, $P < 0.05$). Applying the criterion that response lag to abrupt changes in motion direction is predictive below 200 ms (see Section 2), then infants' tracking of the triangularly moving target is predictive from 17 weeks of age ($t(8) = 2.557$, $P < 0.05$).

Table 1
Average tracking performance on the non-occluded trials for each age group

Age (weeks)	Head gain	Eye gain	Eye lag	SP gain	SP lag (sinus)	SP lag (triangular)
7	0.05	0.76	−494	0.20	−117	−225
9	0.07	0.74	−389	0.31	−88	−268
12	0.07	1.01	−139	0.65	−6	−152
17	0.20	0.94	−126	0.60	114	11
21	0.25	0.95	−70	0.64	−8	−12
Adults	0	0.97	−1	0.86	34	−18

Three tracking components are presented: head, eye, and the smooth pursuit component of the eye movements (SP). The head movements were normalized to object motion (head gain) and the eye and SP movements were normalized to head slip (eye gain and SP gain, respectively). The lags are expressed in ms.

3.2. Visual tracking over the central occluder

Typically, infants moved their gaze across the occluder in one saccade. This response was observed for 7-, 9-, 12-, 17-, and 21-week-old infants in 52, 51, 84, 83, and 88% of the trials, respectively. Two or three saccades were seen for the rest of the subjects. Pursuing the object smoothly across the occluder was only observed at two out of 780 passages, both at 21 weeks. This strategy was more frequent for the adults, and one adult smoothly pursued the occluder in most trials.

3.2.1. Timing of gaze for the different age groups

The analysis of the time difference between the reappearance of the object and the arrival of gaze showed a strong age effect. This effect is demonstrated by the two tracking records in Fig. 2, one non-predictive tracking from a 9-week-old infant and one predictive tracking from a 17-week-old infant. Fig. 3a shows the average time difference between

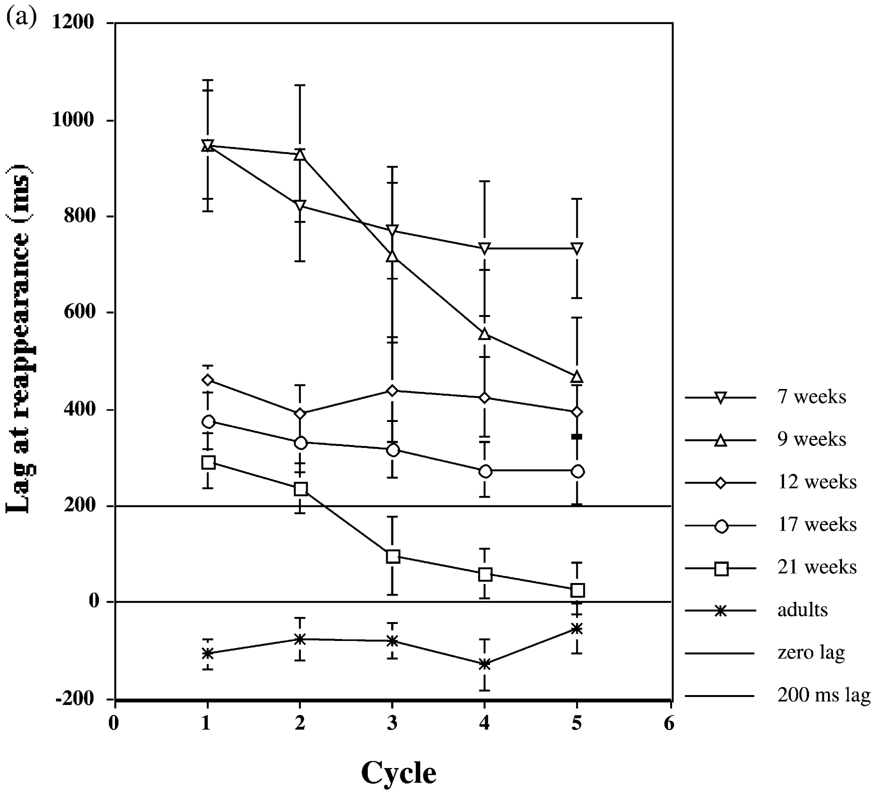

Fig. 3. The average time differences and SE between object and gaze reappearance at each cycle of the centrally occluded trials. Separate graphs are shown for the sinusoidal (a) and the triangular motion (b). Each data point is the average of one occluder passage in each direction for all subjects in a specific age group. The upper line corresponds to the minimum time required for adults to program a saccade to an unexpected event (200 ms).

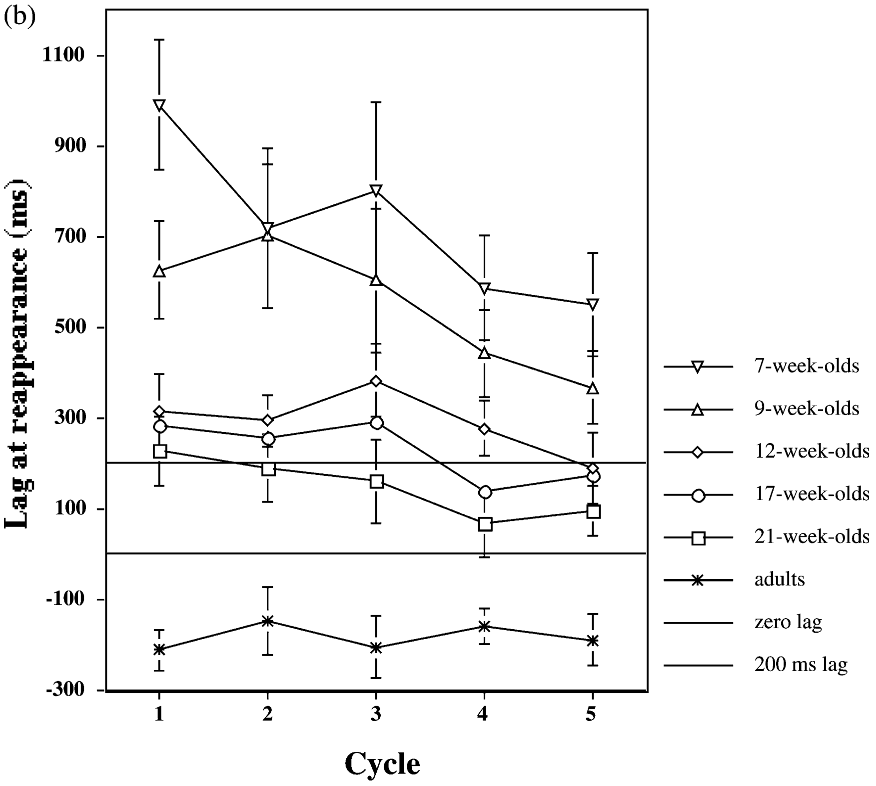

Fig. 3 (*continued*)

the reappearance of the object and the arrival of gaze at each cycle of motion at each age level for the sinusoidal motion and Fig. 3b shows the corresponding result for the triangular motion. The difference in timing between the reappearance of the object and the arrival of gaze differed significantly between the age groups for both the sinusoidal ($F(1,34) = 14.39$, $P < 0.001$) and the triangular motion ($F(1,34) = 8.686$, $P < 0.001$). The 7- and 9-week-old infants first seemed totally unaware of what happened to the object behind the occluder irrespective of motion type. Indeed, it took the 7-week-olds 970 ms to re-fixate the object after it had disappeared at the first cycle of motion, by which time the object had already turned and started to move back toward the occluder again. The change in performance over age is especially evident between the 9- and the 12-week-olds. The initial gaze lag at reappearance is halved between these two age groups.

As shown in Fig. 3 there are significant linear trends of decreasing gaze delays over cycles in a trial both for the sinusoidal ($F(1,34) = 28.57$, $P < 0.001$) and for the triangular ($F(1,34) = 30.32$, $P < 0.001$) motions. This learning effect is quite dramatic for the younger age groups. There are also linear interaction trends between age and cycle for both the sinusoidal ($F(4,34) = 3.643$, $P < 0.02$) and triangular motions ($F(4,34) = 2.914$, $P < 0.05$). This interaction is very distinct between the 9- and the 12-week-olds.

Performances for these two age groups start off as being quite different but they tend to merge toward the end of the trials. In contrast to the substantial learning effects during a single trial, no learning effects between the two centrally occluded trials were observed not even when they were consecutively presented ($F(1,17) = 1.254$). This suggests that the learning may be rather transient.

It is clear from Fig. 3a,b that the infants reacted differently from the adults to the occlusions of the object ($F(1,41) = 22.58$, $P < 0.001$). The adults always predicted the reappearance and their gaze arrived at the opposite side of the occluder slightly before the object.

3.2.2. The effect of motion type

The two kinds of motions gave rise to significantly different timing performances ($F(1,34) = 13.196$, $P < 0.001$). At all age levels except for the 21-week-olds, the infants had smaller gaze lags at the reappearance of the object when it moved with constant velocity, i.e. triangular motion, than when it moved sinusoidally. When the object moved with constant velocity, the average lag at reappearance for the 12-week-old infants was within the predictive range (<200 ms) at the last cycle of motion. For the 17-week-olds, gaze arrived within the predictive range at the two last cycles in this condition, and for the 21-week-olds it arrived within the predictive range at all cycles except the first one. When the object moved sinusoidally, the average lag at reappearance was not within the predictive range until 21 weeks of age and then only at the last three cycles.

Adults' gaze always arrived at the opposite side of the occluder ahead of the target. It arrived there significantly earlier for the triangular than for the sinusoidal motions ($F(1,3) = 43.82$, $P < 0.01$). In fact, at the last cycle, adults' timing of gaze crossing in the sinusoidal condition was not significantly different from the timing of the 21-week-olds in the same condition (the SEs overlap in Fig. 3a).

3.2.3. Learning and individual differences

Fig. 4 shows, for each of the 39 infants in the study, the gaze lag at object reappearance for the first two cycles in the central occlusion trials plotted against the gaze lag at the last two cycles. The two velocity conditions have been merged in this plot and each data point is thus the average of the gaze lag at eight passages behind the occluder. First, Fig. 4 shows that there are very consistent learning effects over single trials. Thirty-four of the 39 infants tested improved their performance between the first two and the last two cycles of a trial. Secondly, Fig. 4 shows that there were large individual differences. One 12-week-old infant predicted the reappearance of the object on all passages except the first two in the sinusoidal condition. At the same age other infants had large lags. Six of the eight 21-week-old subjects predicted the reappearance of the object while two of them did not.

3.2.4. Comparison between the centrally occluded and the non-occluded trials

For the infants, the gaze lag at object reappearance was found to be highly correlated with the lag of visual tracking in the non-occluded trials. The correlation between the average gaze lag summarized for sinusoidal and triangular motions and average tracking lag in the non-occluded trials was found to be 0.85. The corresponding figures for sinusoidal and triangular motions considered separately were 0.81 and 0.75.

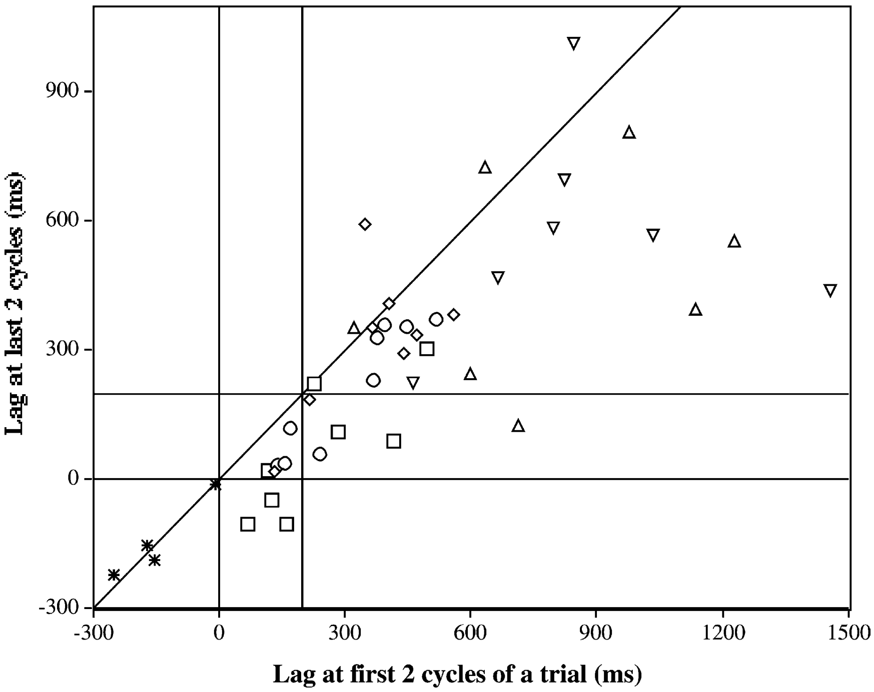

Fig. 4. The average timing for the first two cycles of motion in the centrally occluded trials plotted against the average timing for the last two cycles for each of the subjects (symbols, see Fig. 3).

3.3. Visual tracking at the peripheral occluder

The result showed an increasing tendency with age to move gaze across the peripheral occluder, thus anticipating the reappearance of the object on the opposite side ($F(4, 34) = 6.594$, $P < 0.001$). The percentages of such predictive occluder crossings are shown in Fig. 5 as a function of age and motion type. It is observed that, for both motion types, the strongest increase occurs after 12 weeks of age. Each age level (Fig. 5) was tested separately with the Wilcox non-parametric test. It was found that there were fewer gaze crossings in the sinusoidal condition than in the triangular one for the 21-week-olds ($P < 0.05$) but not for any of the other age groups. All the adult subjects stopped their gaze at the peripheral occluder and started to track again when the object returned.

No learning effects were noticed in this condition. At no age level did the number of crossings decrease during a trial in spite of the fact that the object never appeared on the other side of the occluder. This contrasts with the strong learning effects in the central occluder conditions. The fact that the peripheral occluder conditions only included five passages behind the occluder instead of ten in the central occluder conditions could not explain the difference. When only the first five passages in the central occluder conditions were analyzed the learning effect was still statistically significant. It was most clearly expressed as a linear trend ($F(1, 34) = 7.608$, $P < 0.01$). This trend depended on the age of the subjects ($F(4, 34) = 5.524$, $P < 0.01$).

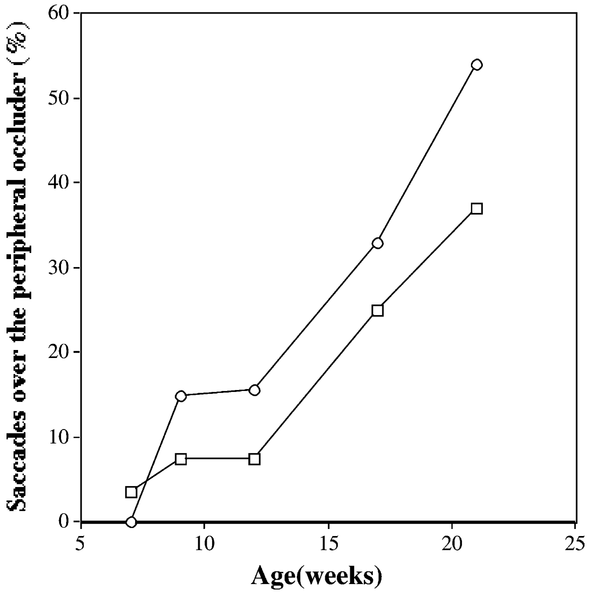

Fig. 5. The average proportion of gaze crossings over the peripheral occluder as a function of age. The squares depict the results of the sinusoidal motion and the circles the results of the triangular motion.

4. Discussion

The results show clearly that infants below 12 weeks of age do not predictively track objects that become temporarily occluded for 300 ms. For the youngest infants the occluder edge itself appeared to become the focus of attention after object disappearance and this impaired the infants' ability to represent the occluded object and switch gaze to it when it reappeared. It was found that the gaze of 7- and 9-week-old infants remained at the occluder edge of disappearance almost 1 s after the object had reappeared on the other side. This means that in many cases the object had already reversed direction of motion and was approaching the occluder again before the infants re-focused their gaze on the object. This relative incapability to quickly regain tracking had more or less disappeared for the 12-week-olds. At that age level, infants moved gaze to the reappearance point as soon as the object became visible. Initial gaze delay at object reappearance was only about half that of the 9-week-olds. Furthermore, the 12-week-olds showed signs of being able to represent the moving object. The mean gaze lag at reappearance for the last cycle of the trial with the triangular motion was below 200 ms showing that they began to anticipate object reappearance in this condition.

The fact that also the younger infants became more aware of the reappearing object with experience over a trial suggests that they acquired some kind of representation of the occluded object. This representation might, however, be too weak to compete for attention with the visible occluder. It is therefore possible that these younger infants might have performed better in a situation where an object becomes temporarily invisible because of blackout rather than occlusion (Jonsson & von Hofsten, 2003; Munakata et al., 1996).

The emergence of predictive occluder tracking parallels the finding that smooth pursuit developed rapidly during the same age period. The gain of smooth pursuit was twice as high for the 12-week-olds as it was for the 9-week-olds. Both smooth pursuit and predictive occluder tracking are founded on an ability to anticipate future motion. The present results indicate that they share a common mechanism for extrapolating object motion.

The obtained results are in general agreement with the numerous habituation studies that have investigated infants' emerging ability to represent temporarily occluded moving objects. The individual data show that 9–12-week-old infants begin to predict the reappearance of the object towards the end of the centrally occluded trials. One 12-week-old infant predicted all object reappearances except at the first one in the sinusoidal condition. Thus, it is not inconceivable that some 2.5-month-old infants would look longer at a display where a moving object (a tall rabbit) did not appear in a slit in the occluder as expected (Aguiar & Baillargeon, 1999). The result is also in agreement with the result by Johnson et al. (2003) indicating that 2-month-olds have problems with temporary occlusion of moving objects. The reason why the present study can be in agreement with both these studies that seem to generate conflicting results is because none of them have considered either individual differences or learning. In fact, habituation is not able to consider these aspects. The present study, however, shows how extremely important such considerations are for an understanding of how infants acquire an ability to represent objects during temporary occlusion.

Individual differences and the effects of learning are so great that it is not quite meaningful to discuss certain age levels where predictive occluder tracking is present or absent. It all depends on the capability of the specific infant tested and what experience that infant has had immediately prior to the occluder event in question. While one infant showed consistent predictive occluder behavior at 12 weeks of age two other infants did not even show such behavior at 21 weeks of age (see Fig. 4). The learning effects imply that infants' ability to predict the reappearance of a temporarily hidden object changes radically over a single 20 s trial. For the triangular motion the average gaze lag at the first occluder passage at 21 weeks of age was greater than the gaze lag at the last occluder passage at 12 weeks of age. In fact, after 12 weeks of age most of the improvements in occluder tracking are accounted for in terms of rapid learning over single trials. Even the 21-week-olds, as a group, did not anticipate the reappearance of the object at the beginning of a trial. Only after a couple of encounters of occlusion did they consistently do so.

Another remarkable feature of the learning is that it seems to fade away as rapidly as it is acquired. There was no evidence that the improvement in timing observed over one trial was transferred to the next trial with central occlusion. The experiment was not primarily designed to study such learning effects and therefore trials with central and peripheral occlusion were randomly ordered. The intervening trials with peripheral occlusion where the object appeared on the same side of the occluder could therefore have interfered with the memory of the previous centrally occluded trial. However, even when just those infants were analyzed for whom the two centrally occluded trials appeared consecutively, there were no improvements between trials.

Both the rapid learning and the short retention have interesting parallels in adults' tracking of temporarily hidden objects. It is a well known fact that anticipatory smooth pursuit eye movements greater than 4–5°/s cannot normally be made at will in the absence of a moving target (Kowler & Steinman, 1979). Attempts to perform faster open-loop smooth eye movements invoke saccades (Heywood & Churcher, 1971). In a series of elegant experiments, however, Barnes and associates (Barnes & Asselman, 1991; Barnes, Barnes, & Chakraborti, 2000; Barnes, Grealy, & Collins, 1997; Chakraborti, Barnes, & Collins, 2002; Ohashi & Barnes, 1996; Wells & Barnes, 1998, 1999) found that anticipatory smooth pursuit at the reappearance of the target can be built up with a few prior transient views of the moving stimulus. The smooth pursuit starts just before the object appears and accelerates in such a way that the eyes move with the appropriate speed and in the appropriate direction when it appears. The advantage of such ability is that the eyes can stabilize on the appearing object without an initial slip that will blur the retinal image. Barnes et al. (1997) suggested that moving stimuli charge a putative internal store of information but that it decharges quickly with time. Chakraborti et al. (2002) found that under optimal conditions, no significant decay was observed for gap intervals up to 14.4 s. It is not a motor memory because it can be built by just viewing rather than pursuing the moving target (Barnes et al., 1997).

To be able to deal with objects that come in and out of view, to identify them and to act on them, such a short term memory store makes much sense. Most occlusions are much shorter than 14 s and there is no real need to preserve the preparedness to act any longer. In fact, preserving the representations indefinitely of objects that pass out of view would pose serious problems to the representational system. These properties of a temporary store for representing object motion fit also very well with the graded representation concept (Munakata, 2001; Spelke & von Hofsten, 2001). Thus, the ability to represent a temporarily hidden moving target is not something that is either present or absent at a certain age. It builds up with viewing time and decays with time out of view. Instead of asking whether a child at a certain age can represent a moving object over occlusions, one should therefore ask whether the child has the capability to acquire such a representation while viewing the visible object before it disappears behind the occluder.

What are the properties of the persistent representations that allow infants to predict the reappearance of a temporarily occluded moving object? First of all, it is not a question of behavioral inertia. Infants do not continue to track the object over the occlusion with smooth eye movements. Instead, the tracking stops before one or two saccades are made to the other side. Is it just a question of learning the contingencies of two events, the disappearance and the reappearance of an object? Infants are quite clever in picking up such dependencies and use them to predict what is going to happen next (see e.g. Haith, 1994; Kirkham et al., 2002; Saffran et al., 1996). The ability to predict the reversal of a constant velocity motion (i.e. the triangular motion in the present study) could be accounted for in such terms. However, the data indicate that this description is too simplified to account for predictive occluder tracking, because subjects not only predict what is going to happen but also where and when. If contingency was the only factor determining predictive occluder tracking, infants would make a saccade to the other side of the occluder when they saw the object disappear behind it just as they reverse tracking predictively when the triangular motion reverses. In contrast, the present data show clearly that the saccades over the occluder are geared to the reappearance of the object, not the disappearance. If they had been geared to the disappearance, gaze should have arrived to the other side long before the object arrived there. That the representations preserve the spatio-temporal properties of object motion behind the occluder is further supported by Gredebäck, von Hofsten, and Boudreau (2002). They found that 9-month-old infants adjusted the latency time of the gaze crossing to the occlusion time of the object. The tracking stopped almost 3 s for object occlusions of 5 s, 1 s for object occlusions of 2 s, etc. Furthermore, experiments in which paradoxical occlusions have been shown where the object started to reappear immediately after it had disappeared indicate that infants are bewildered by such an event (Moore et al., 1978). They found that both 5-month-old and 9-month-old infants look back and look away more in this situation than in a control condition with a normal occlusion. Moore et al. (1978) interpreted this as evidence that the display violated the infants' expectations that spatio-temporal continuity of the motion is preserved over occlusion.

Preserving the spatio-temporal continuity has to do with assumptions of how the motion will proceed behind the occluder. Inertia provides one such basic rule that governs object motion. It predicts that an object disappearing on one side of an occluder will reappear on the other side. In almost 50% of the peripheral occlusions, the 21-week-olds made predictive saccades over to the other side of it. They did this throughout the peripheral trials in spite of the fact that the object always reappeared on the same side in these trials. This agrees with results obtained by von Hofsten et al. (2000) on 6-month-old infants.

There are also other indications that the spatio-temporal properties of the motion are preserved during occlusion. Thus, for the 12- and 17-week-old infants, gaze arrived later for the wide occluder than for the narrow one, indicating both that gaze crossing is geared to occluder width and that the representational system assumes that the object moves behind the occluder with constant speed. However, for the oldest infants in the present study, the representations were not just determined by linear extrapolation. The 21-week-old infants were found to be sensitive to velocity change and this sensitivity biased their behavior both at the peripheral and the central occluder. At the peripheral occluder, they made fewer false crossings when the motion was sinusoidal than when it was triangular. The sinusoidally moving object decelerated strongly before disappearance while the object moving according to a triangular function moved with constant speed. Thus, only the sinusoidal motion conveyed information about the reversal of its motion. Sensitivity to velocity change would also have implications for the timing at the central occluder. Only if the subjects perceived the acceleration of the sinusoidal motion before the object disappeared behind the central occluder would they realize that the occlusion time was the same for both occluders. This was the case for the 21-week-old infants but not for the younger infants.

The development of smooth pursuit eye movements and the timing of the occluder crossings were found to be highly correlated (0.85). This is to be expected if there is an underlying more general development of infants' ability to represent both visible and non-visible object motion. Just like the persisting representations of object motion during temporary occlusion, smooth pursuit eye movements are stimulated by an "internal signal representing expected target motion, and based on the processing of symbolic cues in the environment" (Kowler, 1990, p. 44). If the gain of smooth pursuit was merely a reflection of how effectively the motion sensitive structures can drive it when the moving object is visible, there is no reason for a close relationship between the gain of smooth pursuit and timing of saccades over the occluder.

The present method constitutes a powerful addition to the existing methods of studying infants' emerging object representation. In addition to evaluating group results, it allows estimates of individual infants' ability to represent moving objects at single trials. This opens up a more diversified study of the development of object representation. The present experiment is an effort in this direction. It needs to be followed up in several different ways. Systematic manipulation of occluder size and occluder duration will inform about infants' expanding peripheral visual attention and their emerging ability to represent motion over space and time. Systematic manipulation of the motion function will inform about the emerging ability to represent motion form and extract motion invariance.

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