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Anticipatory reaching of seven- to eleven-month-old infants in occlusion situations

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ABSTRACT

The present study examined 7- to 11-month-old infants' anticipatory and reactive reaching for temporarily occluded objects. Infants were presented with laterally approaching objects that moved at different velocities (10, 20, and 40 cm/s) in different occlusion situations (no-, 20 cm-, and 40 cm-occlusion), resulting in occlusion durations ranging between 0 and 4 s. Results show that except for object velocity and occlusion distance, occlusion duration was a critical constraint for infants' reaching behaviors. We found that the older infants reached more often, but that an increase in occlusion duration resulted in a decline in reaching frequency that was similar across age groups. Anticipatory reaching declined with increasing occlusion duration, but the adverse effects for longer occlusion durations diminished with age. It is concluded that with increasing age infants are able to retain and use information to guide reaching movements over longer periods of non-visibility, providing support for the graded representation hypothesis (Jonsson & von Hofsten, 2003) and the two-visual systems model (Milner & Goodale, 1995).

At the age of 3–4 months infants start to intercept slowly moving objects (van Hof, van der Kamp, & Savelsbergh, 2002, 2006, 2008; von Hofsten & Lindhagen, 1979; von Hofsten, 1980, 1983). More specifically, infants adjust their reaching movements in such way that they are directed towards the future interception point of the object rather than to the object's present position, i.e., the infants reach in an anticipatory manner (von Hofsten, Vishton, Spelke, Feng, & Rosander, 1998; von Hofsten, 1980). However, infants' reaching gets considerably perturbed when the object is temporarily out of sight, for instance, when it moves behind an occluding screen to later reappear again. Most 3- to 4-month-olds cease reaching in these occlusion situations (Hespos, Gredebäck, von Hofsten, & Spelke, 2009; Jonsson & von Hofsten, 2003; Munakata, Jonsson, Spelke, & von Hofsten, 1996; Spelke & von Hofsten, 2001). In fact, it is only 2 months later at the age of 6 months that infants try reaching for an object that is temporarily occluded. However, these first reaches are made in reaction to the object's reappearance; they are initiated only after the object reappears from behind the occluder. In other words, 6-month-old infants do not yet consistently employ an anticipatory reaching strategy in occlusion situations, i.e., they do not initiate the reach in anticipation of the reappearance of the object (Hespos et al., 2009; Jonsson & von Hofsten, 2003; Spelke & von Hofsten, 2001; van der Meer, van der Weel, & Lee, 1994). Indeed, anticipatory reaching in occlusion situations is not observed before the age of 8 months (van der Meer et al., 1994), which is approximately 4 months after it first emerges in

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no-occlusion situations. Intriguingly, infants' visual tracking seems less perturbed by a similar occlusion situation. That is, infants as young as 4 months are able to track moving objects over occlusions with their eyes in an anticipatory manner (Rosander & von Hofsten, 2004; von Hofsten, Kochukhova, & Rosander, 2007). Hence, infants' visual tracking does not seem to account for the inabilty of 4- to 8-month-olds to reach in an anticipatory manner for objects that are temporarily occluded.

Despite the fact that reaching in occlusion situations has received a good deal of attention over the last couple of years (Hespos et al., 2009; Jonsson & von Hofsten, 2003; Spelke & von Hofsten, 2001; van der Meer et al., 1994), it remains unclear why it takes relatively long before infants reach in an anticipatory manner in occlusion situations. Indeed, the development of infants' anticipatory reaching in occlusion situations has not yet been fully portrayed. Consequently, it stays indecisive what factor confines infants' anticipatory reaching in occlusion situations. Unraveling the constraints on infants' anticipatory reaching, as well as age-related changes therein, may provide insight in the developmental processes that underlie the emergence and consolidation of anticipatory reaching (Thelen & Smith, 1994; Thelen & Ulrich, 1991). In occlusion situations, the distance over which the object is occluded, the velocity of the object, and the resulting occlusion duration affect (directly or indirectly) the time that the infant has to retain information about the object, and hence may or may not impede the occurrence of anticipatory reaching. As we will point out below, in previous studies these factors were often confounded, and disambiguating them may help us understand why infants younger than 8 months fail to consistently reach in an anticipatory manner for temporarily occluded objects.

van der Meer et al. (1994) were probably the first to study reaching for moving objects in occlusion situations in two 4- to 11-month-old infants. They reported that with increasing age, the infants increasingly employed an anticipatory reaching strategy, but also that before 8 months they chiefly performed reactive instead of anticipatory reaches. Moreover, van der Meer et al. argued that the age-related differences in the relative occurrence of reactive versus anticipatory reaching were affected by object velocity. With increasing object velocity, infants were more inclined to reach in an anticipatory manner. However, in their study only object velocity was manipulated (i.e., with increasing age, the infants were presented with faster moving objects); the size of the occluding screen was kept constant. As a result, object velocity and occlusion duration were not varied separately. It therefore remains unclear whether object velocity or occlusion duration (or both) mediated infants' anticipatory reaching in occlusion situations. Indeed, von Hofsten and colleagues (Jonsson & von Hofsten, 2003; Spelke & von Hofsten, 2001) have suggested that occlusion duration is the primary constraint on infant reaching in occlusion situations. That is, with longer occlusion durations infants were found to be less proficient in performing an anticipatory reach.[1] However, these studies manipulated occlusion duration by changing the width of the occluding screen while keeping object velocity constant, thus confounding occlusion distance and occlusion duration. In addition, only 6-month-old infants were involved, who did perform hardly any anticipatory reaches in the occlusion situations (i.e., in less than 10% of the trials; see also van der Meer et al., 1994). Recently, also Hespos et al. (2009) investigated 6- and 9-month-old infants' anticipatory reaching in no-occlusion and occlusion situations. They found that the 9-month-olds performed more anticipatory reaches than the 6-month-olds in both the no-occlusion and occlusion condition. However, whether the occurrence of anticipatory reaching is affected by object velocity and/or occlusion duration remained unresolved, as only one occlusion situation was examined, i.e., there were neither variations in object velocity nor in occlusion distance or occlusion duration.

Therefore, the aim of the present study was to investigate the development of infants' anticipatory reaching in occlusion situations and to explore whether infants' reaching is constrained by occlusion duration. In addition, as duration is determined by object velocity and occlusion distance, we also examined how these variables are related to infants' reaching. To this end, 7-, 9-, and 11-month-old infants were presented with occlusion situations in which occlusion duration was varied by independently manipulating object velocity and occlusion distance. Our main interest was in the percentage of reactive and anticipatory reaching elicited in these occlusion situations. It is hypothesized that with increasing age infants perform more anticipatory reaches, with the occurrence of anticipatory reaching being a function of occlusion duration.

1. Methods

1.1. Participants

Eleven 7-month-old (*M* = 7.1 months, *SD* = 0.29), twenty 9-month-old (*M* = 9.1 months, *SD* = 0.30), and twelve 11-month-old (*M* = 11.0 months, *SD* = 0.42) healthy full-term infants participated in the study after their parents gave written informed consent. Ten additional infants (four 7-month-olds, five 9-month-olds, and one 11-month-old) were tested but excluded from the analysis as a result of fussing, crying or absence of any reaching behaviors. The experiment was approved by the local institution's ethical committee.

[1] It should be noted that von Hofsten and colleagues' (Hespos et al., 2009; Jonsson & von Hofsten, 2003; Spelke & von Hofsten, 2001) definition of an anticipatory reach departs from the definition we use here. They categorized a reach as predictive when the infant's hand was located within 7.5 cm around the object between 0.5–0.75 s after object reappearance. Put otherwise, reach onset was not taken into account, while we take reach onset before or after the reappearance of the object as the main criterion for anticipatory reaching.

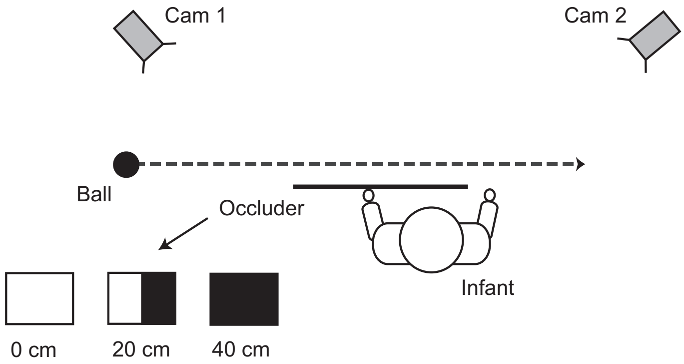

Fig. 1. Schematic representation of the experimental set-up.

1.2. Task and apparatus

Infants were presented with a small brightly colored ball (Ø = 5 cm) using the Ball Transport Apparatus (van der Kamp, Savelsbergh, & Smeets, 1997). A magnet attached the object to the end of a polystyrene rod (80 cm × 2 cm × 2 cm) connected to the Ball Transport Apparatus. The rod was set in motion by a Galil DMC-700 motion controller. The height of the rod was adjusted such that the object approached the infant from the side at shoulder height (Fig. 1). The object approached the infants from the left at three different velocities: 10 cm/s, 20 cm/s, and 40 cm/s. Infants sat in a specially designed infant chair with adjustable supports such that infants had their trunk straight, head upright in the body midline, and limbs free to move. The back of the seat had an angle of 72° from the horizontal. Between the infants and the approaching object, a plastic screen (70 cm × 40 cm) was positioned that was (a) totally transparent (i.e., no-occlusion condition), (b) half transparent and half opaque (i.e., 20 cm-occlusion condition) or (c) totally opaque (i.e., 40 cm-occlusion condition).[2] The infant chair was positioned slightly to the right of the screen, enabling the infants to reach with their right hand to the space where the object reappeared from behind the screen. Infants could only intercept the object within approximately 20 cm to the right of the occlusion screen.

Infants' behaviors were recorded by two Super-VHS video cameras, which were positioned at a distance of 2 m at 45° from the sagittal plane of the infant's body at both sides. The cameras were linked to separate video recorders, which were synchronized by a time code generator. Video data were collected at 50 Hz.

1.3. Design and procedure

Once the infant was seated, a short familiarization period was introduced in which the experimenter played with the infant, and, among others, moved the object from the left to the right behind the transparent screen to elicit reaching behaviors by the infant. The experiment always started with the no-occlusion condition and the slowest object velocity (i.e., 10 cm/s). The infants received six trials in the no-occlusion condition in which each of the three object velocities was presented twice in random order, except for the first trial which was always set to 10 cm/s. Infants, who performed one or more reaching attempts in the no-occlusion condition, were subsequently presented with six trials in the 20 cm-occlusion and 40 cm-occlusion conditions. Infants who did not perform a reach in the no-occlusion condition were presented with three more trials (i.e., presenting each object velocity once) in this condition before introducing the 20 cm-occlusion condition. Infants who did not reach in the 20 cm-occlusion condition were presented with three more trials in the no-occlusion condition followed by six trials in the 40 cm-occlusion condition. Finally, each occlusion condition was repeated in the same order (i.e., no-occlusion, 20 cm-occlusion, and 40 cm-occlusion, respectively) for three more trials presenting each object velocity once. Prior to the first trials of the 20 cm- and 40 cm-occlusion conditions, short familiarization periods were introduced in which the experimenter showed the disappearance and reappearance of the object. The experiment was terminated when infants consistently refused to reach for the object or started crying. Occasionally a trial was repeated when, for instance, the infant pulled the screen (e.g., causing the object to drop). To prevent them from losing interest, infants were allowed to play with the object a couple of times during the experiment. The experiment lasted about 20 min.

1.4. Data analysis and dependent variables

Reaching behaviors were scored off-line from the videotape recordings. A reaching movement was defined as an arm movement of the infant directed towards the object. A reach was scored as a successful interception if it resulted in a contact

[2] We did not include a condition without screen, but a transparent screen was used in the no-occlusion condition. It is worth to note, however, that 9.5-month-old infants perceptually distinguish between transparent screen and no-screen events (Wilcox & Chapa, 2002).

with the object, otherwise it was categorized as a miss. For each reach several time frames were obtained: the moment that the object reappeared from behind the screen (either transparent or opaque) and the moment at which the infant initiated the reach (i.e., the moment at which the infant's right hand first moved in the direction of the object). The moment of object reappearance was obtained by averaging the time frames of both cameras at which the object reappeared. Each reach was then classified as a reactive or anticipatory reach depending on the moment of reach initiation relative to the moment of object reappearance taking into account a visuo-motor delay of 300 ms (see von Hofsten et al., 1998). A reach was classified as anticipatory when it was initiated prior to 300 ms after object reappearance; reaches initiated later were classified as reactive. Percentages of anticipatory reaches and reactive reaches, thus, add up to 100%. The same criteria were applied to no-occlusion trials (i.e., with the transparent screen) to enable comparison between occlusion conditions. For each condition the percentages of reaches and anticipatory versus reactive reaches were computed. A second independent rater analyzed 140 random trials, which is about 10% of the trials, to assess inter-rater reliability. Cohen's kappa was .93.

Finally, the experimental situation afforded more than reaching actions only. Therefore, also the other behaviors were categorized. When infants pulled or pushed the occlusion screen, this was classified as 'screen manipulation', when infants pulled or pushed the screen but at the same time performed a reach, this was classified as 'reach and screen manipulation', all other behaviors were simply categorized as 'no reach'. In a few trials, the pushing and pulling of the screen caused the object or the screen to drop on the ground. These trials were repeated and excluded from analysis.

Statistical analyses were performed on the percentages of reaches and anticipatory reaches using Generalised Estimating Equations (GEE) (Liang & Zeger, 1993). GEE is equivalent to a regression analysis but considers the measurements within participants as repeated measures and accounts for this dependency. Hence, GEE yields regression equations in which the dependent variable (i.e., percentage of reaches or percentage of anticipatory reaches) is predicted by factors included in the model (i.e., object velocity and occlusion distance or occlusion duration). The advantage of GEE is that it is suitable for data sets in which an unequal number of observations for each participant in a particular condition is obtained, which is often the case in developmental research. Consequently, GEE maximizes the number of participants that is included in the analysis since missing values do not result in excluding the participant. It should be noted that a higher occurrence of missing values might be expected in the more challenging conditions (i.e., higher object velocity and larger occlusion distance). Yet, it has been shown that GEE models remain relatively stable with missing values, also when they are not completely at random (Liang & Zeger, 1986; Twisk, 2003). GEE analyses were conducted using SPSS 16.0 with the correlation structure set to exchangeable.

Since occlusion duration is dependent on both object velocity and occlusion distance, separate analyses of the effects of object velocity and occlusion distance on reaching and the effects of occlusion duration on reaching were performed. First, we explored whether the percentage of reaching was related to object velocity, occlusion distance or the interaction between these variables. Note that this interaction term is not equivalent to occlusion duration, but merely indicates whether the effect of object velocity on reaching is different for different values of occlusion distance and vice versa. Therefore, a separate GEE was conducted that examined the effects of occlusion duration per se (i.e., irrespective of object velocity and occlusion distance). To assess whether this relation between occlusion duration and reaching was affected by age, age was then entered in the GEE model. Finally, we investigated possible contributions of the interaction between age and occlusion duration on the occurrence of reaching. The same procedure was followed for the percentage of anticipatory reaches. Only significant main and interaction effects are reported using a significance level of 5%.

2. Results

The forty-three infants completed a total of 1059 trials. Fig. 2 provides an overview of the infants' behaviors indicating that in approximately half of the trials infants reached for the object and approximately half of the reaches resulted in a successful interception. Table 1 reports the total number of reaches, interceptions, misses, anticipatory and reactive reaches for each age group. All except one 7-month-old infant succeeded in contacting the approaching object at least once.

Because they sometimes refused to reach, not all the infants received an equal number of trials in each condition. That is, the experiment resulted in an approximately equal number of trials across velocity conditions, but in fewer trials presented to fewer infants in the 40 cm-occlusion condition as compared to the 20 cm- and the no-occlusion conditions (Table 2).

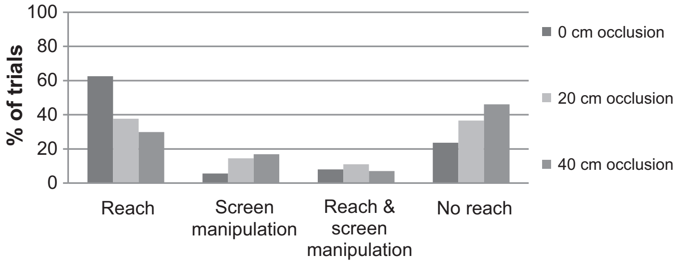

Fig. 2. Overview of behaviors of infants in the different occlusion distance conditions.

Table 1
Summary of infants' behaviors.

	7-Month-olds	9-Month-olds	11-Month-olds	Total
Number of trials	260	483	316	1059
Number of reaches	129	264	196	589
Successes (*% of reaches*)	43 (*33.3*)	107 (*40.5*)	88 (*44.9*)	238 (*40.4*)
Misses (*% of reaches*)	86 (*66.7*)	157 (*59.5*)	108 (*55.1*)	351 (*59.6*)
Anticipatory (*% of reaches*)	57 (*44.2*)	135 (*51.1*)	103 (*52.6*)	295 (*50.1*)
Reactive (*% of reaches*)	72 (*55.8*)	129 (*48.9*)	93 (*47.4*)	294 (*49.9*)

Table 2
Number of infants presented with a moving object as a function of object velocity and occlusion distance (and the number of infants that reached for the object).

Age	Object velocity			Occlusion distance		
	10 cm/s	20 cm/s	40 cm/s	0 cm	20 cm	40 cm
7 months	11 (11)	11 (11)	11 (10)	11 (11)	10 (9)	9 (6)
9 months	20 (19)	20 (19)	20 (19)	20 (20)	20 (16)	16 (14)
11 months	12 (12)	12 (12)	12 (12)	12 (12)	12 (12)	11 (11)

Table 3
Results of the GEE regression analyses by which the percentage of reaches and percentage of anticipatory reaches was predicted.

Dependent variable	Eq.		Coefficient	S.E.	*p*-value
% Reach	1.1	Constant	83.67	4.12	<.001
		Velocity	−0.36	0.14	<.05
		Distance	−0.49	0.23	<.05
		Velocity × Distance	−0.02	0.01	<.05
	1.2	Constant	64.14	3.57	<.001
		Duration	−5.07	1.63	<.01
	1.3	Constant	18.08	19.51	>.1
		Duration	−5.14	1.63	<.01
		Age	5.09	2.14	<.05
% Anticipatory reaches	2.1	Constant	41.52	6.83	<.001
		Velocity	0.95	0.22	<.001
		Distance	−1.09	0.24	<.001
		Velocity × Distance	−0.02	0.01	<.05
	2.2	Constant	57.56	3.35	<.001
		Duration	−17.80	1.45	<.001
	2.3	Constant	57.66	3.35	<.001
		Duration	−37.48	7.35	<.001
		Age × Duration	2.11	0.83	<.05

2.1. The effect of duration, velocity and occlusion on the percentage of reaches

As compared to the 9- and 11-month-olds, fewer 7-month-old infants performed a reach in the 40 cm-occlusion condition (i.e., 66.7% versus 87.5% in 9-month-olds and 100% in 11-month-olds; Table 2). This difference in percentage of infants that performed a reach across age groups, however, did not reach significance ($\chi^2(2, N=36)=4.65$, $p=.1$).

To explore whether infants' reaching was affected by variations in object velocity (i.e., 10, 20, or 40 cm/s) and occlusion distance (i.e., 0, 20, or 40 cm), a GEE was conducted that assessed the separate involvement of object velocity and occlusion distance and their interaction on the percentage of reaches (see also Table 3):

$$\%\,\text{Reach} = 83.67 - 0.36 \times \text{Velocity}\,(\text{cm/s}) - 0.49 \times \text{Distance}\,(\text{cm}) - 0.02 \times \text{Velocity} \times \text{Distance}\,(\text{cm}^2/\text{s}) \quad (1.1)$$

This analysis showed that both object velocity and occlusion distance and their interaction constrain infants' reaching behavior. That is, fewer reaching attempts are made with increasing object velocity and occlusion distance. Note that this significant interaction between object velocity and occlusion distance is not equivalent to occlusion duration, but rather indicates how the effect of object velocity on the percentage of reaching is different for different values of occlusion distance and vice versa.[3] To examine the effects of occlusion duration (i.e., 0–4 s) on the occurrence of reaching, an additional GEE

[3] This equation may be interpreted as each 10 cm/s increase in object velocity causing a decline in reaching of (1) 3.6% in case of an occlusion distance of 0 cm, (2) 7.6% in case of an occlusion distance of 20 cm, and (3) 11.6% in case of an occlusion distance of 40 cm. In a similar vein, each 10 cm increase in occlusion distance results in a decrease in reaching of (1) 6.9% for an object velocity of 10 cm/s, (2) 8.9% for an object velocity of 20 cm/s, and (3) 12.9% for an object velocity of 40 cm/s. In addition, the intercept of the regression line is lower for each increase in occlusion distance (4.9% for each 10 cm) or object velocity (3.6% for each 10 cm/s), which suggests that infants are less inclined to perform a reach under more challenging conditions. However, because we aim to reveal *qualitative* rather than *quantitative* effects of the experimental manipulations on infants' reaching behavior, we restrict our interpretations to qualitative changes in infants' reaching behavior indicated by the GEE equations.

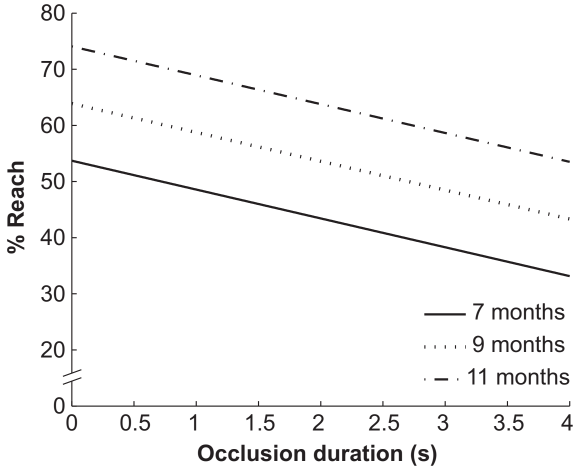

Fig. 3. Representation of the percentage of reaches predicted by the GEE model for occlusion duration and age.

was conducted. This GEE revealed a significant main effect of occlusion duration on the percentage of reaches, with the regression equation being:

$$\%\,\text{Reach} = 64.14 - 5.07 \times \text{Duration}\,(\text{s}) \tag{1.2}$$

Hence, with increasing occlusion duration infants made fewer reaches towards the moving object. Subsequently, we examined whether the relation between duration and percentage of reaches was mediated by age:

$$\%\,\text{Reach} = 18.08 - 5.14 \times \text{Duration}\,(\text{s}) + 5.09 \times \text{Age}\,(\text{months}) \tag{1.3}$$

This analysis showed that age did not influence the relation between occlusion duration and the percentage of reaches (i.e., change in the coefficient of duration was less than 10%; see Eq. (1.2)). However, the significant effect of age indicates that older infants performed more reaches irrespective of occlusion condition. Another GEE was performed that included the interaction between age and duration in order to investigate whether the decline in reaching attempts with increasing occlusion duration was less for older infants as compared to younger infants. This interaction effect was not significant ($p > .1$; Fig. 3).

In sum, with increasing age, infants were more inclined to reach for the object. Moreover, longer occlusion durations caused a significant decline in the occurrence of reaching irrespective of age.

2.2. The effect of duration, velocity and occlusion on the percentage of anticipatory reaches

Fewer 7- and 9-month-olds than 11-month-olds performed an anticipatory reach in the presence of an occluding screen ($\chi^2(2, N = 37) = 10.8$, $p < .01$). More specifically, for the 7-month-olds only four out of nine infants that performed a reach, reached in an anticipatory manner (44.4%) and a comparable percentage was observed for the 9-month-olds (i.e., seven out of sixteen; 43.8%). By contrast, all 11-month-olds were able to anticipate the object's reappearance.

We examined whether infants' movement strategy (i.e., the percentage of anticipatory reaches, which is complementary to the percentage of reactive reaches) was a function of object velocity and occlusion distance. A GEE revealed that both factors and their interaction significantly constrained the percentage of anticipatory reaches:

$$\%\,\text{Anticipation} = 41.52 + 0.95 \times \text{Velocity}\,(\text{cm/s}) - 1.09 \times \text{Distance}\,(\text{cm}) - 0.02 \times \text{Velocity} \times \text{Distance}\,(\text{cm}^2/\text{s}) \tag{2.1}$$

Infants were more inclined to perform an anticipatory reach with higher object velocities, but showed less anticipatory reaches with larger occlusion distances. The regression indicates that not only object velocity and occlusion distance mediated infants' anticipatory reaching separately, but that also the interaction between the two factors influenced the occurrence of anticipatory reaches. To assess whether the percentage of reaches was a function of occlusion duration, we conducted a second GEE with occlusion duration as an independent factor:

$$\%\,\text{Anticipation} = 57.56 - 17.8 \times \text{Duration}\,(\text{s}) \tag{2.2}$$

The regression indicated that with increasing occlusion duration, infants were less inclined to perform an anticipatory reach (or alternatively, were more likely to perform a reactive reach). Age-related effects were examined by adding age to the

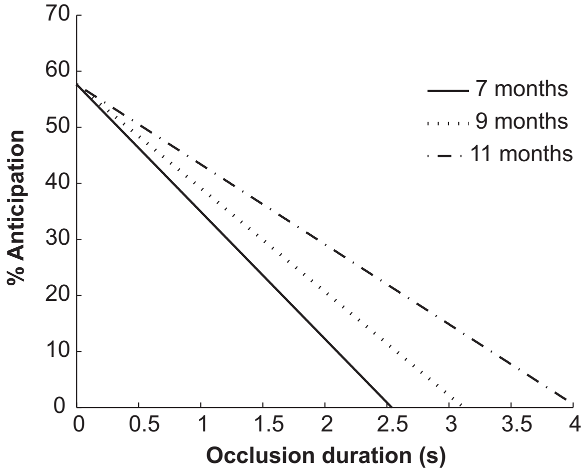

Fig. 4. Representation of the percentage of anticipatory reaches predicted by the GEE model for occlusion duration and age.

GEE regression model. It was found that with increasing age, the percentage of anticipatory reaches did not increase ($p > .1$). However, an interaction between age and duration was apparent:

$$\%\,\text{Anticipation} = 57.66 - 37.48 \times \text{Duration}\,(\text{s}) + 2.11 \times \text{Age} \times \text{Duration}\,(\text{months} \times \text{s}) \quad (2.3)$$

As illustrated in Fig. 4, with increasing age, infants were able to cope with longer occlusion durations. That is, the decrease in the percentage of anticipatory reaches with increasing occlusion duration reduced with age.

3. Discussion

To date, studies that explored infant reaching in occlusion situations left undecided which of the three candidate variables, i.e., object velocity, occlusion distance and occlusion duration, mediated infants' anticipatory reaching (Hespos et al., 2009; Jonsson & von Hofsten, 2003; Spelke & von Hofsten, 2001; van der Meer et al., 1994). In these studies either object velocity or occlusion distance was varied. Any changes in these variables were thus confounded with changes in occlusion duration. In fact, detailed descriptions of the developmental changes in anticipatory reaching in occlusion situations after 6 months of age are relatively scarce, asking for a more thorough investigation. Hence, the aim of the present paper was to assess age-related differences in 7-, 9-, and 11-month-old infants' anticipatory reaching in occlusion situations. In particularly, we examined whether infants' anticipatory reaching was constrained by object velocity, occlusion distance or occlusion duration and if so, whether these constraints were related to age. In doing so, object velocity and occlusion distance were varied independently, which resulted in variations in occlusion duration. The current findings not only showed that more reaches were performed with increasing age, but also that these reaches were more often anticipatory under increasingly challenging situations.

The observed gradual increase in the frequency of reaching (irrespective of whether they were reactive or anticipatory) in occlusion situations between 7 and 11 months of age corroborates previous reports that after approximately 6 months of age, infants start to reach progressively more for temporally occluded objects (van der Meer et al., 1994). Moreover, the frequency of reaching was a function of both object velocity and occlusion distance and their interaction (Eq. (1.1)). In addition, a critical role for occlusion duration was found in which with longer occlusion durations infants were less inclined to perform a reach (i.e., either reactive or anticipatory; Eq. (1.2)). Even though 11-month-old infants reached more frequently, they were similarly affected by an increase in occlusion duration as 7-month-old infants (Fig. 3).

Also with respect to infants' reaching strategies (i.e., anticipatory versus reactive reaching), independent effects of both occlusion distance and object velocity and their interaction were revealed to mediate infants' reaching strategy. Over and again, occlusion duration also emerged as a key constraint on infants' anticipatory reaching between 7 and 11 months of age. In addition, whilst infants' tendency to reach in an anticipatory manner did not differ with increasing age, older infants were less affected by an increase in occlusion duration (Fig. 4). This was supported by the finding that, with increasing age, more infants were able to perform an anticipatory reach in occlusion situations. Hence, the present study is the first to demonstrate the role of occlusion duration in the emergence and consolidation of anticipatory reaching in occlusion situations and confirms earlier empirically unsupported suggestions about the role of occlusion duration (Hespos et al., 2009; Jonsson & von Hofsten, 2003; Spelke & von Hofsten, 2001).

Although the findings point towards occlusion duration as a critical factor that constrains infants' reaching, also independent effects of occlusion distance and object velocity on infants' reaching were revealed. That is, with larger occlusion distances, infants were less inclined to perform a reach and to reach in an anticipatory manner (Eq. (2.2); see also Jonsson & von Hofsten, 2003; Spelke & von Hofsten, 2001). Moreover, the findings are in line with van der Meer et al. (1994) who reported that with increasing object velocity infants are more likely to reach in an anticipatory manner. The same holds for the current data, since more anticipatory reaches were performed with increasing object velocity (Eq. (2.1)). Together these findings indicate that anticipatory reaching emerges in the context of high object velocities. Higher velocities force infants to perform anticipatory reaches, because reacting to the object after it reappears is less likely to result in a successful interception. However, in van der Meer et al.'s study, object velocity was confounded with age, that is, the higher object velocities were only presented at the older ages. Moreover, object velocity and occlusion duration were not varied separately. This convolutes any inference as to the role of age, object velocity or occlusion duration in the occurrence of anticipatory reaching. Indeed, the present data suggest that object velocity mediates infants' reaching in occlusion situations, yet they also demonstrate a critical role for occlusion duration.

Jonsson and von Hofsten (2003) proposed the 'graded representation hypothesis' as an explanation for the developmental changes in infant reaching during occlusion situations (Munakata, 2001; Munakata, McClelland, Johnson, & Siegler, 1997). They argued that infants and adults form mental representations about the properties of visible objects. These representations degrade when the object is hidden from view, and increasingly so the longer the duration of non-visibility (Jonsson & von Hofsten, 2003). From this point of view, therefore, it is anticipated that the duration of the occlusion impedes infants' anticipatory reaching rather than object velocity or occlusion distance. Clearly, the present finding that occlusion duration is a critical constraint for the occurrence of anticipatory reaching in occlusion situations provides further support for the graded representation hypothesis. With respect to developmental changes, this hypothesis states that representations become more durable with increasing age, which, in turn, would enable older infants to deal with longer occlusion durations (see also Hespos et al., 2009). Again, our finding that the effect of occlusion duration on the occurrence of anticipatory reaching is mediated by age (i.e., older infants were able to cope with longer occlusion durations) is also in accordance with the graded representation hypothesis. Yet, it is important to recognize that the graded representation hypothesis does not distinguish between information *retention* (i.e., forming representations about the object) and information *usage* to guide a reach in occlusion situations. This is an important distinction, because (arguably) similar information of temporarily occluded objects can be used for other purposes at a younger age, such as, for instance, tracking the object with the eyes (Rosander & von Hofsten, 2004; von Hofsten et al., 2007).

Indeed, the two-visual systems model of Milner and Goodale (Goodale & Milner, 1992, 2004; Milner & Goodale, 1995, 2008), might provide an important addition to the graded representation hypothesis, as it makes this distinction between information retention and information usage. The model contends that two functionally and structurally dissociated visual systems exist. On the one hand, the vision for movement system that is involved in the *online* visual control of movements and, on the other hand, the vision for perception system that is concerned with the recognition and identification of objects, events, and situations. Although much attention has been focused on the dissociation, it is clear that both visual systems are closely intertwined in the course of an action (Milner & Goodale, 1995, 2008; Rossetti & Pisella, 2002; van der Kamp, Rivas, van Doorn, & Savelsbergh, 2008; van Doorn, van der Kamp, & Savelsbergh, 2007). This interaction becomes particularly evident when vision for movement is compromised, for instance, by introducing a time delay between object detection and movement onset. In such occlusion situations, the *online* use of information to control the movement is perturbed, because the vision for movement system can only retain information for very brief periods of time. In contrast, the vision for perception system has a more robust memory and retains information over much longer periods of time. Adult research indicates that in occlusion situations, vision for perception replaces vision for movement to guide the ongoing movement especially for occlusion durations longer than 2 s (e.g., Bridgeman, Gemmer, Forsman, & Huemer, 2000; Bruno & Franz, 2009; Bruno, Bernardis, & Gentilucci, 2008; Gentilucci, Chieffi, Daprati, Saetti, & Toni, 1996; Rossetti & Pisella, 2002; Rossetti, 1998; Westwood & Goodale, 2003; Westwood, McEachern, & Roy, 2001).

The current findings also fit well with the two-visual systems model. As in adults, a key factor that constrains successful anticipatory reaching is the duration of occlusion. The two visual systems model would account for this in terms of an interaction between vision for movement and vision for perception. This implies that – at least in older infants – vision for perception can replace vision for movement to successfully guide the infants' arm movements. Consequently, after 6 months age-related differences in anticipatory reaching in occlusion situations would then reflect developmental changes in the interaction between the two visual systems (see also Atkinson, 2000; Bertenthal, 1996; Berthier et al., 2001; van der Kamp & Savelsbergh, 2000; van der Kamp, Oudejans, & Savelsbergh, 2003; van Wermeskerken, van der Kamp, & Savelsbergh, 2010). More specifically, infants as young as 2.5 months perceive that a moving object continues to exist and pursues on a continuous path of motion when occluded for less than 2 s (Aguiar & Baillargeon, 1999; Spelke, Breinlinger, Macomber, & Jacobson, 1992). With increasing age, however, infants were found to be able to deal with longer occlusion durations (Diamond, 1985; Johnson, Bremner, et al., 2003). Indeed, 6-month-olds were found to retain information of a stationary object in an occlusion situation for as much as 30 s (Wilcox, Nadel, & Rosser, 1996). Hence, for perception 6-month-olds presumably are able to *retain* information about the occluded object for occlusion durations up to at least 2 s. And although infants at this age are able to track moving objects over occlusions with their eyes in an anticipatory manner for occlusion durations up to at least 1.7 s (Rosander & von Hofsten, 2004; von Hofsten et al., 2007), they do not consistently anticipate the object's reappearance in occlusion situations when reaching (Jonsson & von Hofsten, 2003; Spelke & von Hofsten, 2001; van der Meer et al., 1994). The infants primarily react to the object's reappearance or refuse to reach. Together, these observations suggest that although they are able to *retain* information about the object over the period of occlusion, 6-month-olds are not yet able to *use* the retained information to guide reaching. According to the two-visual system model, this implies that the development of (anticipatory) reaching in occlusion situations not only reflects vision for perception becoming more resilient (i.e., an enhanced ability to *retain* visual information), but also that additional developmental changes occur around 6 and 7 months with respect to the interaction between vision for movement and vision for perception (i.e., improved ability to *use* the retained visual information by replacing the perturbed vision for movement system). And while this interaction is still relatively fragile at 7 months, it further stabilizes until at least 11 months.

In conclusion, the current study presents clear evidence that occlusion duration is a critical factor in the development of infants' anticipatory reaching. Around 7 months of age, infants start to anticipate the reappearance of a temporarily occluded object successfully in order to intercept it and learn to cope with longer occlusion durations with increasing age. An important question for future research is whether, and if so, how experience constrains the development of this interaction in occlusion situations. Johnson and colleagues (Johnson, Amso, & Slemmer, 2003; Johnson & Shuwairi, 2009), for instance, recently showed that infants as young as 4 months are able to learn to perform anticipatory eye movements from experiencing a few related visual events only. Can experience also accelerate development of anticipatory reaching?

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