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Learning and memory facilitate predictive tracking in 4-month-olds

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ABSTRACT

We investigated 4-month-olds' oculomotor anticipations when viewing occlusion stimuli consisting of a small target that moved back and forth repetitively while the center of its trajectory was occluded by a rectangular screen. We examined performance under five conditions. In the *baseline* condition, infants produced few predictive relative to reactive eye movements. In the *full training* condition, anticipations were increased in frequency following prior exposure to a target moving along a fully visible trajectory. The *delay* condition tested the effects of training after a 30-min interval elapsed between training and test, resulting in a return to baseline performance. However, the training effect was reinstated in the *reminder* condition following another brief exposure to the training stimulus prior to test. Finally, in the *brief training* condition, we found that the brief exposure alone was insufficient to induce the training effect. Results are interpreted in the context of learning from short-term experience and long-term memory.

Introduction

Piaget (1937/1954) described a series of infants' behaviors that provided evidence for an emerging ability to keep track of objects that became occluded. According to Piaget's theory, active search, initiated by the children, is a critical feature of object concepts. Active visual search behavior emerged after 4 months, marking the beginnings of "true" search and, ultimately, object permanence. Among these behaviors was visual accommodation to rapid movements (e.g., when infants would respond

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to a dropped object by looking down toward the floor), behaviors observed by 6.5 months. Visual accommodation was proposed to become more consistent as infants gained manual experience with objects, providing direct experience with dropping and retrieval and developing in tandem with reconstruction of partly occluded objects from visible fragments and removal of covers to gain access to occluded objects. Piaget suggested that the accumulation of these behaviors and experiences was a critical developmental mechanism in imparting object concepts. In the current article, we examine this possibility directly in 4-month-olds by providing different levels of training and delays between training and test.

Recently, researchers have recorded eye movements in infants as they view repetitive events in which objects move behind an occluder and subsequently reemerge. The question is the extent to which infants produce anticipatory eye movements toward the place of reemergence, implying a functional representation of the object that guides oculomotor behavior. By definition, anticipatory behavior meets the requirements for inchoate object permanence described previously.

This research has led to three conclusions. First, older infants produce a greater proportion of oculomotor anticipations (vs. reactive eye movements) relative to younger infants. Johnson, Amso, and Slemmer (2003) presented infants with events in which a small target moved on a horizontal center-occluded trajectory and found that 6-month-olds produced a higher proportion of anticipatory eye movements directed toward the moving target ($M = 43.6\%$) relative to 4-month-olds ($M = 29.5\%$). Gredebäck and von Hofsten (2004) reported continued improvements in predictive tracking up until 12 months. Rosander and von Hofsten (2004) found no evidence of predictive tracking in infants younger than 12 weeks; however, anticipations became more consistent by 21 weeks. These results accord with the possibility that representations of occluded objects are initially weak and gradually strengthen across the first year after birth (Johnson & Munakata, 2005; Piaget, 1937/1954).

Second, 4 months is a time of transition toward veridical perception of occlusion (Bremner et al., 2005; Johnson, Bremner, et al., 2003), and oculomotor anticipation performance at this age can be facilitated. For example, Johnson et al. (2003) found that performance at 4 months is enhanced by "training," that is, viewing an unoccluded object trajectory immediately preceding the occlusion stimulus. Baseline performance was higher in von Hofsten, Kochukhova, and Rosander's (2007) study (47–50%), perhaps because von Hofsten and colleagues included only trials on which infants were determined to look at the object both before and after occlusion, whereas Johnson and colleagues included trials on which the object was not fixated prior to occlusion. Differences in performance may also stem from differences in stimulus complexity, for example, three-dimensional displays used by von Hofsten and colleagues versus high-contrast two-dimensional video displays used by Johnson and colleagues.

Third, by 6 months, infants begin to deal effectively with nonlinear trajectories, showing spatially accurate predictive eye movements when a target moves on a partly occluded circular (Gredebäck & von Hofsten, 2004) or angled path (Kochukhova & Gredebäck, 2007). In contrast, 4-month-olds construe nonlinear occlusion trajectories as discontinuous, and perception of continuity is disrupted when a linear object path is oriented diagonally relative to the occluder and background (Bremner et al., 2007).

This research is broadly consistent with Piaget's original descriptions of infant performance. There is little evidence of systematic predictive behavior prior to 4 months, after which time anticipations become robust and flexible, and performance continues to improve with age. It seems unlikely, however, that direct manual experience with objects is a principal developmental mechanism underlying predictive behavior given that oculomotor anticipations begin to become established prior to the onset of functional goal-directed reaching and manual object manipulation in developmental time (Konczak, Borutta, Topka, & Dichgans, 1995).

The goal of the current article was to examine another key tenet of Piagetian theory. Piaget (1937/1954) suggested that active search for hidden objects stems from the accumulation of repetitive behaviors as infants interact with objects. As noted previously, it is doubtful that manual object manipulation skills precipitate oculomotor anticipations. Nevertheless, the suggestion that the accrual of experience may strengthen predictive behavior has not been investigated systematically to our knowledge.

Recent experiments provide mixed evidence for short-term gains in predictive performance, gains that hypothetically might arise from repeated exposure to a target object that moves in a perfectly predictable manner (to adults). Rosander and von Hofsten (2004) found that predictive performance improved across four cycles of motion in 21-week-olds, who showed decreasing eye movement latencies as a function of trial. In contrast, Gredebäck and von Hofsten (2004) and Johnson et al. (2003) found that the proportion of oculomotor anticipations declined across trials in infants ranging from 4 to 9 months. Therefore, infants do not seem to capitalize on the predictable nature of trajectory occlusion stimuli.

However, in Johnson et al.'s (2003) study, anticipations in 4-month-olds were more frequent following exposure to a fully visible moving target. This facilitative effect was a product of training with a target moving either horizontally ($M = 46.3\%$ anticipations after training) or vertically ($M = 49.7\%$ anticipations after training); in the occlusion stimulus that followed, target trajectory always was horizontal. Results from the vertical condition imply that infants were not trained simply to produce horizontal eye movements; rather, anticipations were geared toward the moving object itself. Ensuing predictive performance in both of these conditions was comparable to performance of untrained 6-month-olds ($M = 43.6\%$).

A lingering question is whether the enhancement in performance is fleeting or more permanent, and it is unknown whether effects of training would survive delays. Here we address this question and the larger question of how infants begin to learn and remember trajectory information when presented with occlusion stimuli at an age when object representations may be difficult to form or access.

We examined performance under five conditions using methods first described by Johnson et al. (2003) to assess 4-month-olds' oculomotor behavior as they viewed trajectory occlusion stimuli (Fig. 1). In the *baseline* condition, infants viewed a series of occlusion displays. In the *full training* condition, infants viewed the same occlusion displays following a period of training with unoccluded object trajectories. In the *delay* condition, we examined effects of a 30-min delay between training and test. In the *reminder* condition, we considered the possibility that postdelay memory for occlusion might be prompted by a brief "reminder" trial. The final condition, *brief training,* was designed to control for the possibility that the brief reminder trial itself induced the facilitative effect independent of earlier training.

Method

Participants

A total of 60 4-month-olds comprised the final sample, 12 in each of the five conditions. Additional infants were observed but excluded from the analyses due to fussiness or inattention (12 infants), sleepiness (3 infants), equipment failure (2 infants), insufficient data due to excessive movement (14 infants), or an inability to calibrate the infant's point of gaze (POG) (1 infant). Infants were recruited by letter and telephone from a commercial list of new parents. All infants were full term and had no known developmental difficulties. Parents were provided with a small gift (a toy or baby T-shirt) for participation.

Apparatus and stimuli

A Macintosh G4 computer and 76-cm color monitor were used to present stimuli. An Applied Science Laboratories Model 504 corneal reflection eye tracking system was used to collect eye movement data. Stimuli were prepared with MetaCreations Infini-D software. Each stimulus trial consisted of a 30-s animation depicting a 6.7-cm (3.8° visual angle at the infant's viewing distance) green ball translating laterally across 45.4 cm (25.5°) at 18.2 cm/s (10.4°/s). The object changed direction (left–right) every 2.5 s. In the training stimulus, the ball was visible for the duration of the trial (Fig. 1). In the occlusion stimulus, the center of the ball's trajectory was occluded by a 21.5×17.7-cm ($12.3 \times 10.1°$) blue box. Objects were presented against a textured background (a 20×12 grid of white dots on black) measuring 48.8×33.0 cm ($27.4 \times 18.7°$). A nonrhythmic sound was played to maximize attention to the stimulus. Every trial consisted of six complete cycles of the object trajectory. Between trials, infants viewed an "attention-getter"—a blue and white checkerboard-patterned stimulus that expanded and contracted in time with a pulsing sound—to recenter the POG.

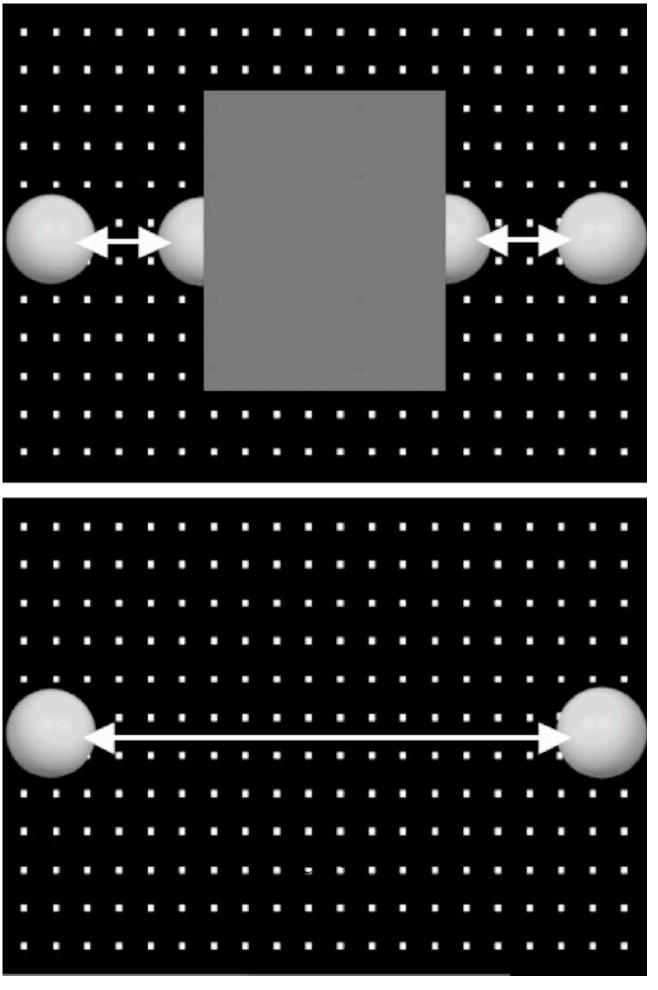

Fig. 1. Top: Trajectory occlusion display used to test oculomotor anticipations in all five experiments. Bottom: Unoccluded trajectory display used as a training stimulus in the full training, delay, reminder, and brief training conditions.

Procedure

Infants were tested individually seated in a caregiver's lap 100 cm from the monitor. Prior to testing, the room was darkened and each infant was shown a cartoon to engage his or her attention as the experimenter made adjustments to the eye tracker. The infant was then shown the attention-getter sequentially at two points on the screen (the upper left and lower right corners of an imaginary rectangle that contained the stimulus displays) to calibrate the POG. Calibration accuracy was verified by moving the attention-getter to random locations. If the POG was not centered at each location, the calibration routine was repeated.

Data coding

Eye movements were coded for instances of "perceptual contact." In each of the object excursions presented to the infant, an eye movement was entered into the data set if the POG was directed toward a region of the display within 1.5° horizontally and 3.0° vertically of the moving object trajectory as it was visible on either side of the occluder after a starting position of the POG outside this region. Trials in which the POG did not leave the "anticipation region" were not counted, as when the infant remained fixated on one side of the display. Eye movements leading to perceptual contact initiated less than 150 ms subsequent to object emergence were coded as anticipations, and those initiated later than 150 ms were coded as reactions. The 150-ms criterion was derived from past reports of predictive and reactive eye movements in infants (Canfield, Smith, Brezsnyak, & Snow, 1997) and adults (Fischer & Weber, 1993). Our dependent measures were (a) proportions of anticipations versus reactions as a function of eye movements meeting coding criteria described previously and (b) latencies of eye movements relative to object emergence.

Conditions

In the baseline condition (5 girls and 7 boys, mean age = 125.6 days, *SD* = 5.7), infants viewed eight trials of the occlusion stimulus. In the full training condition (6 girls and 6 boys, mean age = 121.3 days, *SD* = 8.5), infants viewed four trials of the unoccluded trajectory stimulus, followed by four trials of the occlusion display. In the delay condition (4 girls and 8 boys, mean age = 124.9 days, *SD* = 9.4), infants viewed four trials of the unoccluded trajectory stimulus, followed by four trials of the occlusion display. A delay of 30 min was imposed between training and test, during which time infants did not take a nap. The reminder condition (8 girls and 4 boys, mean age = 129.2 days, *SD* = 9.4) was identical to the delay condition with one exception: Immediately prior to testing with occlusion stimuli, infants viewed one additional 30-s training stimulus consisting of an unoccluded trajectory. Finally, the brief training condition (4 girls and 8 boys, mean age = 123.2 days, *SD* = 7.1) was designed to control for the possibility that performance in the reminder condition could be explained by exposure to a single training stimulus (the reminder) followed immediately by the occlusion display, as opposed to full training, followed by the delay plus reminder. Infants in the brief training condition viewed a single 30-s trial with six cycles of unoccluded object motion, followed immediately by seven trials with the occlusion stimulus.

Results

Proportions

A 2 (Sex) × 5 (Condition) analysis of variance (ANOVA) on mean proportion of anticipations yielded a reliable main effect of condition, $F(4, 50) = 4.04$, $p < .05$, partial $\eta^2 = .244$, due to differences across conditions in proportions of predictive eye movements, and no other significant effects (baseline *M* = 26.62%, *SD* = 10.27; full training *M* = 39.93%, *SD* = 15.90; delay *M* = 24.49%, *SD* = 7.43; reminder *M* = 32.63%, *SD* = 11.95; brief training *M* = 22.66%, *SD* = 9.09). Simple effects tests revealed no reliable differences in anticipations among the baseline, delay, and brief training conditions or between the full training and reminder conditions, all *p*s > .70. There were significant differences between the full training condition and each of the baseline, delay, and brief training conditions as well as between the reminder condition and each of the baseline, delay, and brief training conditions, all *p*s < .05.

Latencies

A 2 (Sex) × 5 (Condition) ANOVA on mean eye movement latencies yielded a reliable main effect of condition, $F(4, 50) = 4.21$, $p < .01$, partial $\eta^2 = .252$, due to differences across conditions in latencies, and no other significant effects (Fig. 2). Simple effects tests revealed no reliable differences in latencies among the baseline, delay, and brief training conditions or between the full training and reminder conditions, all *p*s > .83. There were significant differences between the full training condition and each of the baseline, delay, and brief training conditions as well as between the reminder condition and each of the baseline, delay, and brief training conditions, all *p*s < .05.

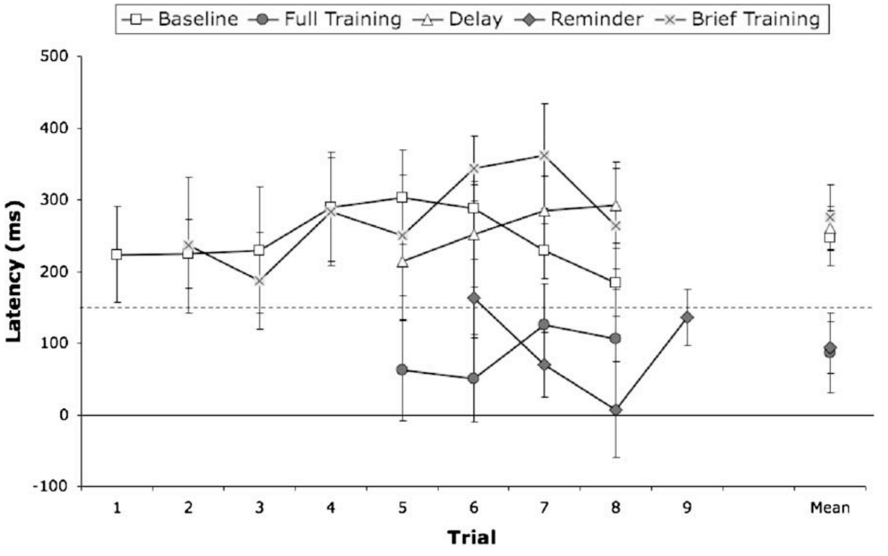

Fig. 2. Latencies of all codable eye movements as a function of trial in the five conditions. The solid line represents emergence of the object from behind the occluder (i.e., 0 ms). The dotted line represents the upper bound for categorizing eye movements as predictive (i.e., 150 ms).

Discussion

We recorded 4-month-olds' oculomotor behavior as they viewed events in which an object moved back and forth repeatedly as the center of its trajectory was temporarily hidden by a screen. Our goal was to gauge the facilitative effects of prior training with an unoccluded stimulus on predictive performance as well as the effects of a delay imposed between training and test. Rates of oculomotor anticipation were higher in the full training condition (four 30-s training trials) relative to the baseline (untrained) condition, but imposing a delay of 30 min between training and occlusion test trials brought performance to baseline levels. A single, brief reminder trial reinstated the facilitative effect of full training after a 30-min delay, but a single, 30-s learning trial alone was not sufficient to produce the learning effect (the brief training condition).

Our study adds to a growing literature demonstrating that young infants capitalize on prior experience in object perception tasks. For example, Needham (1998) reported that infants at 4.5 months were found to expect two distinct objects to be physically connected when they were in direct contact. When given the opportunity to view either object alone prior to testing, however, infants appeared to construe the two adjacent objects as segregated (Needham & Baillargeon, 1998). Visual experience also aids infants in object individuation tasks where one or more objects are moved from behind a screen and viewed one at a time. Infants are observed for evidence of perceiving a single object or multiple objects as participating in the event. When infants were shown events prior to testing in which color or pattern served to highlight an object's function (e.g., as a tool to pound another object or as a container, both with similar shapes), individuation by color and by pattern were observed several months earlier than in untrained infants (Wilcox & Chapa, 2004).

The current experiment corroborates that immediate prior experience viewing visible object trajectories facilitates predictive behavior when 4-month-olds view occlusion events, a principal criterion of object concepts according to Piaget. Currently, it is unclear precisely what mechanisms underlie the facilitative effect, but there is little indication (with the exception of the Rosander and von Hofsten (2004) study) that oculomotor anticipations are induced from watching repetitive events. Consider, in addition, the visual expectation paradigm (VExP), in which infants view alternating static pictures on either side of a display (Haith, 1993). Performance on this task does not improve over trials within a single session, nor does it improve from 2 to 12 months when assessed longitudinally (Canfield et al., 1997). Rates of anticipation in the VExP range from 12 to 24%, values not far out of line with those that we observed (Table 1). Performance in occluded trajectory tasks, in contrast, shows age-related improvements. It seems likely, therefore, that the basis for performance in VExP and in occlusion tasks diverges across the first postnatal year as object concepts strengthen and play a stronger role in guiding oculomotor behavior.

Infants' memory skills also have been well documented. Habituation tasks yield a decrement of interest on repeated presentations of a single stimulus, even in neonates (Slater, 1995). Experiments investigating deferred imitation of behaviors have found that infants as young as 6 weeks imitated facial gestures (Meltzoff & Moore, 1994) and that 6-month-olds imitated actions demonstrated with a puppet (Barr, Dowden, & Hayne, 1996) and retained information about occluded objects (Kochukhova & Gredebäck, 2007) after a 24-h delay. In addition, 6-month-olds have been shown to imitate target actions viewed when they were 3 months of age, providing additional evidence for early functionality of neural substrates for long-term memory stores (Campanella & Rovee-Collier, 2005).

Table 1
Mean trial-by-trial percentages of anticipations and reactions in each experiment

Trial	Anticipations (%)	Reactions (%)
Baseline condition		
1	34.71 (6.47)	42.36 (6.02)
2	31.93 (5.11)	47.23 (3.89)
3	29.88 (5.76)	40.27 (5.00)
4	20.31 (6.27)	46.53 (5.75)
5	16.40 (3.80)	48.17 (5.73)
6	25.70 (3.15)	43.75 (3.72)
7	24.32 (3.47)	36.12 (4.63)
8	27.78 (5.46)	36.11 (4.39)
Mean	26.63 (2.96)	42.55 (3.09)
Full training condition		
5	43.07 (6.63)	43.05 (6.55)
6	40.28 (4.90)	43.06 (4.57)
7	38.88 (5.16)	42.36 (4.86)
8	34.03 (5.85)	31.24 (4.94)
Mean	39.92 (4.59)	37.68 (4.23)
Delay condition		
5	26.38 (4.45)	50.00 (6.32)
6	26.40 (5.11)	42.35 (6.52)
7	21.53 (3.62)	40.28 (4.08)
8	23.63 (4.21)	40.28 (6.23)
Mean	24.49 (2.15)	43.20 (3.24)
Reminder condition		
6	36.11 (4.39)	42.36 (4.86)
7	38.19 (5.93)	31.24 (4.60)
8	31.93 (5.97)	25.68 (6.02)
9	24.30 (4.41)	35.41 (7.54)
Mean	32.63 (3.45)	33.67 (4.52)
Brief training condition		
2	29.18 (4.04)	47.23 (6.98)
3	25.00 (4.59)	36.79 (5.47)
4	22.21 (5.55)	43.73 (6.33)
5	20.14 (4.64)	38.20 (5.93)
6	20.83 (4.17)	37.51 (3.63)
7	17.35 (2.98)	48.61 (6.14)
8	23.96 (3.84)	47.79 (6.18)
Mean	22.66 (2.62)	42.84 (3.16)

Note. Standard errors are in parentheses. These data encompass all trials, not only eye movements that met the criteria for anticipations or reactions, to highlight changes in response across trials. Numbers do not sum to 100 because on some trials eye movements were directed to locations other than the object or otherwise did not meet criteria for inclusion in the data set.

Providing infants with brief reminder cues of the training context after a temporal delay can reactivate the recognition memory from long-term storage (Cornell, 1979; Rovee-Collier, 1999).

Our task also shares features with many memory paradigms used with adults. Learning was successful only after repeated presentations of the unoccluded trajectory display, and the latency reduction observed in the full training and reminder conditions is reminiscent of findings from studies with adults demonstrating increased accuracy and reduced reaction times with repeated training (Reber, 1967; Schacter, Chiu, & Ochsner, 1993). Repeated exposure to target stimuli with shorter time lags between exposures yielded robust repetition memory effects and revealed that retrieval is stimulus specific and time lag dependent (Bentin & Moscovitch, 1988).

Nevertheless, our task is unique in important ways. First, our paradigm taps learning of a general feature of the visual environment, namely, object occlusion. Second, observers do not necessarily need prior experience with our occlusion displays to produce oculomotor anticipations when they are first viewed. In unpublished experiments, adult participants produced an anticipation during every trial (except the very first one). Finally, our task assessed recall of a representation built from exposure to a different stimulus (the unoccluded trajectory display). Our results are consistent with a view stressing the importance of long-term repeated exposure to occlusion events, and repeated opportunities to interact with events with oculomotor and manual action systems, as providing vital kinds of experience on which to build representations of objects as permanent (Piaget, 1937/1954). Our findings further demonstrate the importance of training and test cues in memory retrieval. We showed that development of object concepts in young infants benefits from exposure to relevant training stimuli and that memory for this exposure persists across a delay.

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