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Young Infants' Visual Expectations for Symmetric and Asymmetric Stimulus Sequences

Richard L. Canfield
Department of Human Development and
Family Studies
Cornell University

Marshall M. Haith
University of Denver

The formation of expectations for visual stimulus sequences was examined in 2- and 3-month-old infants. Two studies were undertaken in which infants' visual fixations were monitored while they viewed predictable and unpredictable sequences of stimuli. Analyses of anticipatory fixations and reaction times (RTs) indicated that by 2 months of age infants can rapidly (within 2 min) form an expectation for the reappearance of an alternate-side event. By 3 months of age, infants rapidly form expectations for asymmetric sequences. Age differences in RT and percent of anticipated pictures suggest rapid development in this domain. Results are discussed in relation to hypotheses of entrainment and global probability matching. It is concluded that young infants quickly develop a crude representation of the spatial, temporal, and possibly numerical parameters of stimulus sequences to anticipate future events.

The concept of expectation is central to modern cognitive and learning theories. When an individual forms an expectation, forecasts a future event, and produces anticipatory behavior, he or she demonstrates an ability to represent the environment and act in accordance with the representation rather than the current environmental stimuli alone. Labeled variously as "prospective memory" (Rovee-Collier & Hayne, 1987; Sherrington, 1906; Wasserman, 1986), "preparatory set" (Mowrer, 1938), "STM priming" (Wagner, 1978), or "anticipation" (Capaldi & Verry, 1981; Dodge, 1933; Hull, 1943; Schmidt, 1968), expectations imply active, future-oriented processing of information by mental structures akin to maps, scripts, goals, and plans that impose order on experience and provide a framework for the behavioral anticipation of events (Bolles, 1972; Honig, 1981; Miller, Galanter, & Pribram, 1960; Neisser, 1976).

Expectations have received inconsistent attention in early infancy, mostly confined to the domain of infant attention. Following a model proposed by Sokolov (1969), investigators have often proposed that novel-stimulus recovery in a habituation paradigm reflects expectancies. Presumably, the infant forms an internal model of the repeatedly presented familiarization stimulus. Each new input stimulus activates a process of comparison between the input and the model.

It is common for investigators to treat the infant's model or schema as an expectation for what will happen next (Neisser, 1976; Stephenson & Siddle, 1983). From this perspective, the novel stimulus produces a violation of that expectation. However, it is debatable whether or not the infant actually forecasts the impending event. If the baby does, the concept of expectation seems applicable. If not, then the novel stimulus triggers an attempted match sometime after the stimulus occurs. In this case, it seems reasonable to credit the baby with memory and comparison skills but not necessarily the ability to form an expectation.

Even if infants actually form expectations in the standard habituation experiment, the expectations play a passive role. That is, an expectation for the familiar event serves as a default —remaining in memory because of prior stimulation rather than activated for the purpose of perceiving a future event.

Passive expectancies provide one way to respond to a complex environment—they encourage the infant to expect no change in the future. However, passive expectations are of little use in dynamic and changing environments that constantly require the infant to preadapt his or her responses in anticipation of events that lie in the future. Therefore, it seems prudent to reserve the term *expectation* for processes that actively forecast upcoming events.

Some evidence of active forecasting has been demonstrated in young infants. In a study of memory retrieval, Fagen and his colleagues (Fagen, Morrongiello, Rovee-Collier, & Gekoski, 1984) trained 3-month-old infants to expect either constancy or change in a sequence of mobiles. When infants' expectations were subsequently violated, they had trouble using the unexpected mobile as a retrieval cue.

Examples of expectations in reaching have been more numerous. Infants preadapt their grasping actions to certain aspects of the to-be-grasped object before contact (Bruner & Kos-

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Correspondence concerning this article should be addressed to Richard L. Canfield, Department of Human Development and Family Studies, MVR Hall, Cornell University, Ithaca, New York 14853-4401.

lowski, 1972; Lockman, Ashmead, & Bushnell, 1984). Hofsten has shown that young infants deploy prereaching movements that anticipate the future position of a moving object (Hofsten, 1980, 1985). These studies show that with little or no reaching or grasping experience, infants quickly use general expectations for size, future location, and object orientation to guide action. Rather than passively waiting until an object contacts their hand and then showing surprise when the current hand orientation is inappropriate, infants use visual information to guide their arms and hands to an appropriate position or orientation in anticipation of actual contact. The kind of expectation used in these studies requires more active future-oriented processing than does simple detection of discrepancy. However, unlike habituation studies where infants must remember the sample stimulus during an interstimulus interval, objects remain visible in reaching paradigms, demanding little of memory.

In habituation studies, infants depend on memory to adapt to the situation. They may expect the past to recur but engage in no observable future-oriented activity. In grasping and reaching, one sees anticipatory behaviors, but they are based upon concurrent visual information. In fact, the early emergence of behavioral anticipations in the context of catching moving objects suggests that the ability is substantially preformed in the newborn (Hofsten, 1980). Investigators have recently asked whether young infants can form expectations on the basis of previous experience and also use their expectancies to anticipate future events.

In an early study of expectancy-guided action, Mundy-Castle and Anglin (1973) studied infants' ability to extract information from regular sequences of events and to use an internal model of the perceptual past to anticipate future events. Infants 4 to 36 weeks of age saw a brightly colored ball alternate between two windows. The recording of infants' looking behavior suggested that after a ball disappeared from one window, infants who were only 3 to 4 months old came to expect its reappearance in the alternate window. This result encouraged the authors to suggest that infants used their experience of past regularity to guide anticipatory looking. However, these conclusions must be tempered because infants were not observed in an unpredictable condition. It is possible that babies simply look at other salient targets in the visual field (the other window) after an event they are watching disappears. If so, "anticipatory" cross-looks during the interstimulus interval (ISI) may have been directed at the other visible window location rather than at a presently invisible but expected stimulus.

Several shortcomings of the Mundy-Castle and Anglin study were overcome by Haith, Hazan, and Goodman (1988), who monitored infants' visual fixations as they viewed a rapidly alternating sequence of pictures for about 2 min. The pictures appeared on a television monitor that was blank during the ISI so that infants could not use visible cues for directing their fixations. One-half of the picture series was predictable; it consisted of 30 pictures in left (L) to right (R) alternation with a 1-s ISI. The other half of the picture series was unpredictable, with pictures appearing in the same locations but with irregular spatial and temporal sequencing.

The authors distinguished between the cognitive construct of expectation and its possible behavioral indexes. They argued that an infant may have an expectation but not act on it, thus providing no behavioral measure of the cognitive state. However, two behavioral indexes were chosen as evidence for the proposed underlying cognitive state. The first index was termed *anticipation* and included those instances when the infant shifts fixation to the alternate side *before* a picture appears (or so quickly after onset that the eye movement command must have occurred prior to stimulus onset). The other index was termed *facilitation* and was based on reaction times (RTs) to picture onsets that were not anticipated. If the infant reacted more quickly to pictures appearing predictably than when they appeared irregularly, it was assumed that the infant had formed an expectation for their appearance.

Results from this study suggest that infants form expectations rapidly. During the predictable portion, infants were more likely to make anticipatory fixations to the opposite side and had lower RTs to fixate the pictures that were not anticipated. On the basis of evidence from these measures it was concluded that 3.5-month-old infants can rapidly develop expectations for a simple alternating picture sequence.[1]

Questions arise about whether it is legitimate to interpret these results as evidence for the formation of expectations. One could argue that infants possess an oscillatory rhythm whose frequency lies close to the L–R cycle that Haith et al. used. If so, as infants tracked the L–R sequence, their tracking activity might have been brought into resonance with the L–R cycle. Any tendency for this natural rhythm to speed up would look to an observer as periodic anticipations or enhanced RTs. This possibility was considered by the authors of the study, under the rubric of entrainment, and was deemed unlikely because the infants did not perform in a lock-step manner. However, an empirical approach seemed preferable to logical argument. In addition, we were interested in whether babies could form expectations for stimulus sequences that obeyed rules more complex than simple alternation. If infants can develop expectations for both symmetric and asymmetric sequences, the claim that they are able to build an active representation of sequential regularity would become more credible.

This article extends our work on the development of visual expectations by documenting young infants' ability to form expectations for pictures that appear in complex but predictable alternating sequences. In the first experiment we explored the ability of 3.5-month-old infants to form expectations for asymmetrical picture sequences. In Experiment 2 we explored age differences in 2- and 3-month-olds' expectations for both symmetric and asymmetric sequences. Results suggest that infants can form a crude representation of the spatial, temporal, and possibly numerical parameters of complex but predictable picture sequences and then can use this representation to antici-

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[1] An intriguing study of 5-month-old infants, using a somewhat similar method, has been reported by P. Hull Smith (1984); however, its direct relevance to the present line of research remains unclear. Expectations of the sort we are investigating may well be involved; however, stimulus positions remained visible during interstimulus intervals, giving infants known fixation locations. In addition, it is not reported whether infants actually responded to recalled event positions during test phases *before* they would have appeared during the training phase. These and other methodological differences prevent making easy comparisons to the paradigm used here.

pate visual events and to enhance their performance when events occur. We address issues of process and specificity of infants' expectancies to rule out entrainment and probability matching as explanations of the results.

Experiment 1

Experiment 1 was designed to explore the possibility that 3.5-month-old infants can develop expectations for an asymmetric sequence of pictures. Two sequences were used: 2/1 (L-L-R or R-R-L) and 3/1 (L-L-L-R or R-R-R-L).

Method

Overview

Each infant saw an asymmetrical sequence of computer-generated pictures that appeared to the left or right of visual center. The pictures moved up and down while they were on (700 ms) and were separated by a 1,000-ms ISI. A videotape image of the baby's eye permitted frame-by-frame analysis of the timing of visual fixations. We were interested in observing whether infants would detect the spatial and temporal regularity of the series and would form expectations for it as indexed by anticipatory fixations and facilitated reactions to picture onsets.

Subjects

Twelve 3.5-month-old infants participated (range = 108–122 days). Data from 10 additional babies were not used because they were inattentive ($n = 8$) or because equipment malfunctioned ($n = 2$). All infants were healthy, full-term babies with 1- and 10-min Apgar (1953) scores above 7, recruited from a population of middle and upper-middle class, two-parent families from the Denver metropolitan area. Six infants saw sequence 2/1 (L-L-R or R-R-L) and 6 saw sequence 3/1 (L-L-L-R or R-R-R-L).

Stimuli

The stimuli were generated on-line by a PDP 11/03 computer with a color graphics sprite board (Ti 9910 graphics chip). There were four different pictures and one "diversionary" stimulus. The pictures were checkerboards, vertical stripes, diamonds, and schematic faces in various combinations of red, blue, green, lavender, yellow, white, and black. Each picture occupied a square area measuring 4.5° on a side. Each picture remained on for 700 ms, centered at 5.7° either to the left or right of visual center and moved vertically at a rate of 4.4°/s, completing one up–down cycle during each 700-ms presentation. At the beginning of the session each infant first saw a diversionary picture (a white ball moving in a circular path around the screen) in order to maintain interest while the camera was being focused.

Apparatus

As shown in Figure 1, the baby lay supine and viewed the stimuli on a monitor by reflection from overhead mirror Y, tilted at 45° to the infant's line of sight. To the infant, the image appeared to be directly overhead at a distance of 35 cm. Mirror Y (Libby-Owens No. 956) reflected visible but transmitted infrared light. Above the mirror was a filtered, collimated light source. A high-pass filter (Corning 7-69) eliminated the wavelengths above 1,100 mu, and a low-pass filter (Kodak-Wratten 87c) eliminated wavelengths of less than 850 mu. As a result, only an invisible band of light was passed, between 850 mu and 1,100 mu.

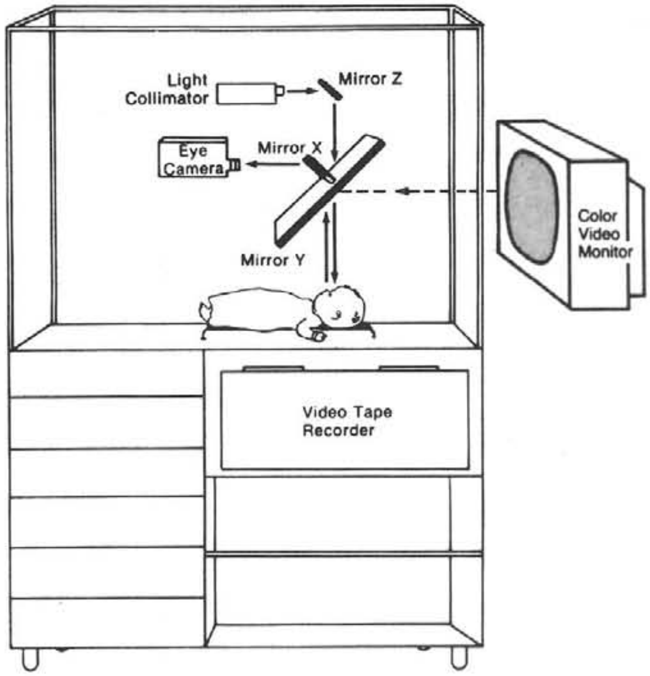

Figure 1. Illustration of the apparatus used in both studies reported. (The baby lay on its back and viewed the stimuli presented on the color video monitor reflected from overhead mirror Y. The light collimator provided infrared illumination for the eye camera, which recorded an image of the baby's eye onto video tape.)

The beam from the light source was reflected from mirror Z toward the baby's eye through mirror X (primarily infrared reflecting, visible transmitting). Because the light source and the camera were on the same optical axis, light reflecting off the infant's retina created an image of a "backlit pupil." Part of the light was also reflected off the surface of the cornea and formed a small, bright, white spot that served as a reference point for determining the center of the visual field. The light emanating from the infant's eye traveled through mirror Y and reflected from mirror X into a TV camera (Panasonic WV-CD20), which was sensitive to light in the near infrared range (800–1,300 mu). By judging the position of the corneal reflection relative to the center of the pupil on the videotape record, the observer could judge changes in the direction of gaze easily and accurately.

The videotape record of the eye image also contained a record of the time and date, produced by a time–date generator (Panasonic WJ-810). One digit in this display indicated when a left-hand or right-hand picture was on, so the fixations could be measured in precise synchrony with the stimulus events.

Procedure

The infant was positioned with her head in a cloth sling to reduce head movement. The lights were extinguished as a pacifier was offered and the TV eye camera was focused. During this time, the diversionary picture was displayed. When focus and positioning were established, the experiment began.

Each infant watched for at least 100 s during a 120-s trial as the pictures appeared to the left and right. Infants in Condition 2/1 saw 20–23 repetitions of the L-L-R (R-R-L) set while those in 3/1 saw 15–17 repetitions of the L-L-L-R (R-R-R-L) set. Data from infants who failed to attend for at least 100 s were excluded from the analyses.

Data Reduction

The image of the infant's eye, the frame count, and the stimulus indicator digit were all recorded onto a VHS format tape by a Panasonic AG6300. Data reduction was accomplished by a two-step process. First, an observer viewed the tape in a combination of slow motion and stop-frame modes (maximum temporal resolution = 30 frames per second), writing down the frame number of each picture onset and each significant shift in eye position (approximately ≥ 5°). Second, the transcription of visual activity was reduced by obtaining the difference between the frame counts for picture onsets and fixation shifts to find the latency (in video frames) of the reaction. A multiplication of the number of frames by 33.33 ms/frame provided an RT latency or anticipation measure, scaled in milliseconds. Two observers independently scored 5% of the recorded data. Their judgments of latencies were identical more than 95% of the time.

Results

Separate analyses were carried out for fixations that met the criteria for anticipations and those that did not. Reaction times were based on the latter set.

Anticipation

As in the Haith et al. (1988) study, we considered fixations to the opposite side, during the ISI, to be anticipatory as well as fixations that occurred within 200 ms of the next picture onset. Because adults in our situation could initiate a fixation to a picture onset no faster than 196 ms, we reasoned that 3.5-month-old infants would not be able to react faster than 200 ms. Any latency longer than 200 ms (and less than 700 ms) was considered a reactive shift. Thus, an anticipation window was defined, consisting of 1,000 ms preceding an event plus the 200 ms interval following event onset.

If infants were unable to form expectations for subsequent events, they should have been equally likely to shift fixation to the alternate side during each anticipation window. On the other hand, a tendency for infants to correctly shift to the location of the next picture during the anticipation window would provide evidence for expectations.

We will refer to the location in which most of the pictures appeared as the "home" side, and the other location as the "target" side. Repeated measures analysis of variance (ANOVA) on percent fixation shifts[2] in the anticipation window was carried out for the 2/1 condition, with the number of home events as the within-subjects variable (one vs. two). Results showed that infants were more likely to shift fixation in the anticipation window after two home-side events (.25 vs. .07), $F(1, 5) = 21.6$, $p < .01$. A similar analysis of condition 3/1 yielded no stable effects; the proportions of fixation shifts after one, two, and three home-side pictures were .04, .00, and .08, respectively. We also predicted that infants in the 2/1 condition would be more likely to shift fixation after two home-side events than would those in the 3/1 condition. With the use of a between-groups ANOVA, this prediction was upheld (.25 vs. .00), $F(1, 10) = 27$, $p < .001$.

Infants might also have formed expectations for an event to reappear on the home side after the single target-side event. This possibility was examined with an analysis comparing the percent of fixation shifts during the anticipation window following the target picture offset with the percent following the offset of the first home-side picture. (These fixation shifts followed a single picture-location shift for both the 2/1 and 3/1 conditions.) This analysis produced a stable effect only for the 3/1 condition (.37 vs. .04), $F(1, 5) = 10.4$, $p < .05$.

Facilitation

The second measure of expectation was facilitated reactions to picture onsets for pictures that were not anticipated (those reactions between 200 and 700 ms). It was predicted that as infants formed expectations for the picture sequence, they could react more quickly to the appearance of subsequent pictures than if they had no expectations. In order to estimate a "raw" RT value—that is, a value not influenced by expectancies—the median of the first six saccadic latencies for each infant served as a baseline value and was used in a within-subjects comparison. These reactions were presumed to occur before any regularity had been detected.

For infants in Condition 2/1 there was no evidence that post-baseline responses to events on the target side were faster than to baseline events (both 442 ms). However, response facilitation was found for infants in Condition 3/1. Specifically, when infants reacted to the target side picture, their RT was lower than baseline (348 vs. 419, respectively), $F(1, 5) = 8.7$, $p < .05$. Reactions back to the home side showed no facilitation for either condition.

Discussion

Results from this small group of infants suggest that 3.5-month-old babies can form expectations for complex asymmetrical sequences. Infants showed anticipatory fixations to future picture locations and facilitated reactions in asymmetrical sequences, making it unlikely that they were simply entrained to a rhythm. Although the results were encouraging, they were not as definitive as one might hope. Evidence for anticipation was uneven both within and between experimental conditions, and evidence for response facilitation was found for only one comparison.

Several factors may help to explain why the results were not more pronounced. One concern with this study was the rate of subject attrition. Eight infants did not complete the study because they failed to attend for the required 100 s. In addition to concerns regarding the procedure, interpretive problems resulted from the lack of a comparison condition where pictures were presented in an unpredictable manner.

An additional study to follow up this preliminary evidence that infants can form expectations for complex picture sequences was designed to (a) replicate the findings from Experiment 1 with inclusion of a condition that permits between-group comparisons, (b) examine the relations between infants' performance with the alternating sequence Haith et al. (1988) used in the original study and the more complex sequences

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[2] Proportions were constructed as follows: (number of fixation shifts during the anticipation window) divided by (number of opportunities to shift fixation minus missing data). Missing data originated from trials with excessive head movement, blinks, or equipment malfunction.

used in Experiment 1, and (c) study age differences in the formation of expectations.

Experiment 2

Method

Subjects

Subjects were forty-eight 2-month-old (53–67 days) and forty-eight 3-month-old (83–97 days) infants with the same health and demographic attributes as those in Experiment 1. Data from 25 additional babies (fourteen 2-month-olds and eleven 3-month-olds) were not used because they were inattentive or fussy. Infants were randomly assigned within age to one of six stimulus conditions.

Apparatus and Procedure

The apparatus was identical to that used for Experiment 1, but the procedure was altered to increase the babies' interest and reduce attrition. A new picture set consisting of a revolving universe, a spinning arrow, an expanding square, and a starburst was used. The first two pictures revolved about their centers while the last two expanded and contracted about theirs. In addition, the pictures changed color several times during each presentation.

Each sequence began with eight pictures, each of which remained on for 1,000 ms, with a 1,000-ms ISI. Fixations to these pictures were used to determine the position of eye movements to known locations. To develop an estimate of the idiosyncrasies of each baby's fixations, these first eight "calibration" pictures appeared in four locations relative to visual center, +/– 5.7° horizontal and +/– 4.5° vertical. Thus, each infant began with the sequence left–right–up–down–left–right–left–right.

After the calibration set, infants at each age viewed one of six different stimulus sequences (see Figure 2 for examples):

Condition 1 (1/1):	Alternating L–R sequence.
Condition 2 (2/1 L):	Regular asymmetrical L–L–R sequence.
Condition 3 (2/1 R):	Regular asymmetrical R–R–L sequence.
Condition 4 (3/1 L):	Regular asymmetrical L–L–L–R sequence.
Condition 5 (3/1 R):	Regular asymmetrical R–R–R–L sequence.
Condition 6 (IR):	Irregular sequence.

In Condition IR, pictures appeared unpredictably in a constrained random sequence of L–R, L–L–R, and L–L–L–R, as well as their counterparts on the alternate side. One half of the pictures appeared on the left side and one half on the right side. Each postbaseline picture sequence lasted 2 min, resulting in 35 L–R sets in Condition 1/1, 23 L–L–R or R–R–L sets in Condition 2/1, and 17 L–L–L–R or R–R–R–L sets in Condition 3/1. Postbaseline pictures obeyed the same temporal constraints as did pictures in Experiment 1 (700 ms on, 1,000 ms ISI).

Data Reduction

Data reduction and scoring were carried out as in the first experiment,[3] except that we altered the limits of the RT category. Because we were hoping to uncover age differences as a function of varying levels of predictability, we changed our definition of a reactive shift to include shifts with RTs between 200 and 1,200 ms. Given previous research on saccadic latencies in infants of this age (Aslin & Salapatek, 1975), we were concerned that 2-month-olds might have relatively few RTs less than 700 ms, which was the cutoff for Experiment 1. Again, independent observers scored 5% of the recorded data and achieved 92% agreement of judged saccadic latencies.

Results

To simplify the reporting of results, Conditions 2 (2/1L) and 3 (2/1R), and Conditions 4 (3/1L) and 5 (3/1R) were combined for each age. The form of the sequence was identical (2/1 or 3/1), but the home and target sides were counterbalanced. Given no differences due to side, the data were collapsed across those conditions; the result was 16 infants in the 2/1 and 3/1 conditions and 8 infants in the 1/1 and IR conditions.

The analysis of anticipatory fixations again supported the hypothesis that infants detected and utilized the spatiotemporal regularity of the predictable sequences. Two-month-olds provided less evidence for expectations than did 3-month-olds, and the RT measures were quite variable and thus less informative. However, the pattern of RT findings was consistent with the findings for anticipation.

Anticipation Results: Three-Month-Olds

Given the results of Experiment 1 and the previous work of Haith et al. (1988), we predicted that 3-month-olds would form expectations for the spatiotemporal regularity in all three predictable sequences. Evidence was gathered from an analysis of anticipatory activity and RTs. Both between-subjects and within-subjects comparisons were made.

Comparisons between conditions. In Table 1 the proportion of fixation shifts during the anticipation interval is shown for the 3-month-olds. We predicted that infants who developed expectations for the left–right alternation of Condition 1/1 would be more likely to make shifts to the alternate side during the anticipation window than would infants in Condition IR (see Figure 2). Results of an ANOVA revealed a main effect of condition, $F(3, 44) = 3.1$, $p < .05$. However, comparisons between group means indicated that infants were not reliably more likely to shift to the alternate side in Condition 1/1 than they were to shift after one picture in the irregular sequence (.34 vs. .22), $F(1, 44) = 2.8$, $p > .1$. We also predicted that infants would be more likely to shift fixation after one picture in Condition 1/1 than after one home-side picture in either the 2/1 or 3/1 sequences. These comparisons capitalize on the enhancing effects of shifting after one picture in Condition 1/1, as well as suppression of shifting in the other two predictable conditions (where a fixation shift after one home-side picture was an "error anticipation," see Figure 2). Consistent with our predictions, infants were more likely to shift fixation after one picture in Condition 1/1 than they were to shift to the target side after one home-side picture in Condition 2/1 (.34 vs. .20), $F(1, 44) = 4.5$, $p < .05$, or Condition 3/1 (.34 vs. .14), $F(1, 44) = 9.2$, $p < .01$.

In order to determine whether infants in the 2/1 condition formed expectations for the target-side picture, we planned three between-subjects comparisons with the prediction that 2/1 infants would (a) shift fixation less frequently after one home-side picture than would IR infants, (b) shift fixation more frequently after two home-side pictures than would IR infants,

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[3] As in Experiment 1, infants who did not attend for at least 100 s during the postbaseline sequence were not included in the analyses. Those who were included attended to at least 29 sets of 1/1, 20 sets of 2/1, and 15 sets of 3/1.

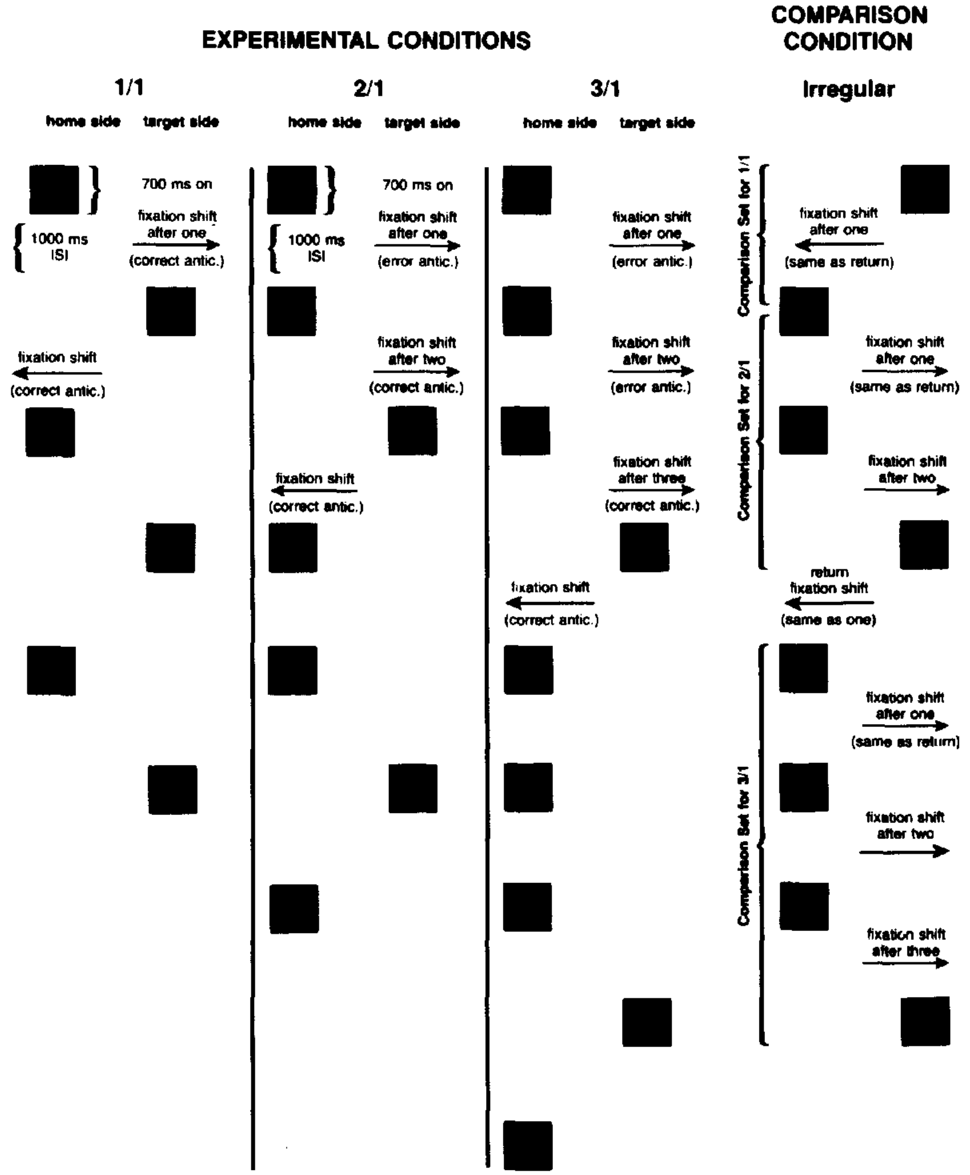

Figure 2. A schematic layout of four stimulus conditions used in Experiment 2. (Each black box represents one stimulus [700 ms in duration] that an infant saw, and the space between stimuli represents the 1,000-ms interstimulus interval [ISI]. Time moves vertically. The comparison condition [Irregular] is constructed of "comparison sets" for each of the experimental conditions. For example, the comparison set for 2/1 provides data for fixation shifts after one home-side picture and fixation shifts after two home-side pictures that are directly comparable to the same data in the predictable Condition 2/1. Similarly, within-subjects comparisons were constructed, for example, by comparing the proportion of fixation shifts after one home-side picture in Condition 2/1 with the proportion of fixation shifts after two home-side pictures in the same condition. Antic. = anticipations.)

and (c) shift fixation more frequently after two home-side pictures than would infants in Condition 3/1. The results provided modest support for these predictions. Although infants in the 2/1 condition shifted fixation after one and two home-side pictures at about the same rate as infants in Condition IR (.20 vs. .22 and .23 vs. .34, respectively), they were more likely to shift after two pictures than were infants in Condition 3/1, (.34 vs. .18), $F(1, 37) = 6.8$, $p < .05$.

Two comparisons between Conditions 3/1 and IR were used to determine if 3/1 infants formed expectations for the target event. If 3/1 infants formed expectations, they should have shifted fixation less frequently after one or two home-side pictures than should IR infants, and they should have shifted sides more frequently after three home-side pictures than should IR infants. The results of these analyses provided minimal indication that babies formed expectations in the 3/1 condition. In-

Table 1
Proportion of Fixation Shifts During the Anticipation Window for 3-Month-Old Infants

	Condition (Group)				
Stimulus location	1/1(I)	2/1(II)	3/1(III)	IR(IV)	Between-group comparisons
No. of pictures on home side					
One (a)	.34	.20	.14	.22	I > II,* I > III**
Two (b)	—	.34	.18	.23	II > III*
Three (c)	—	—	.25	.29	
Return from target side (d)	—	.42	.47	.22	II > IV,* III > IV**
Within-group comparisons		a < b** a < d*	a < c* b < c* a < d*** b < d**		

Note. IR = irregular.
* $p < .05$. ** $p < .01$. *** $p < .001$.

fants were not significantly less likely to shift fixation after one or two home-side pictures in Condition 3/1 than in Condition IR (.14 vs. .22 and .18 vs. .23, respectively). In addition, IR infants were slightly more likely to shift fixation after three pictures (.29 vs. .25). None of these comparisons reached conventional levels of statistical significance.

We also predicted that infants in Conditions 2/1 and 3/1 would form an expectancy for the return of the home-side picture and shift fixation during the anticipation window following the target picture more than IR infants would shift fixation after one event on a side. This prediction was confirmed for the 2/1 infants (.42 vs. .22), $F(1, 37) = 6.6$, $p < .05$, as well as for the 3/1 infants (.47 vs. .22), $F(1, 37) = 9.9$, $p < .01$.

Within-subjects comparisons. For the three conditions having multiple events on a side (2/1, 3/1, and IR), within-subjects analyses were also carried out for the home-side events. Again, these comparisons reflect the within-subjects relative effects of suppression of shifting when the next picture appeared on the same side, and they show enhancement of shifting when the next picture appeared on the opposite side. These comparisons should be more powerful than the between-subjects comparisons because they provide a control for individual differences in rates of shifting.

If 2/1 babies were developing expectations, they should have shifted fixation more after two home-side pictures than after one home-side picture, and Condition 3/1 infants should have shifted more frequently after three home-side pictures than after either one or two home-side pictures. These predictions were well supported by the data (see Table 1). Repeated measures ANOVA revealed that 2/1 infants were more likely to shift to the alternate side after two home-side pictures than after one (.34 vs. .20), $F(1, 15) = 15.8$, $p < .01$, and 3/1 infants shifted more after three home-side pictures than after one (.25 vs. .14), $F(1, 15) = 7.3$, $p < .05$, or two home-side pictures (.25 vs. .18), $F(1, 15) = 5.8$, $p < .05$.

Within-subjects comparisons can also be used to investigate infants' expectations for the return of the first home-side picture. We predicted that 2/1 and 3/1 infants should have shifted fixation more frequently back to the home side following the one target picture than they had shifted to the target side after one home-side picture. This prediction was well-supported for both the 2/1 (.42 vs. .20), $F(1, 15) = 8.5$, $p < .05$, and 3/1 groups (.47 vs. .14), $F(1, 15) = 30.6$, $p < .001$. Finally, we predicted that 3/1 infants would shift more after the target picture than after two home-side pictures, and again, our prediction was upheld (.47 vs. .18), $F(1, 15) = 17$, $p < .01$.

When the within-subjects analyses are considered as a whole, we can see that 3-month-old infants in Condition 2/1 tended to shift fixation to the target side after two pictures and then to shift back to the home side after the target picture disappeared. By comparison, their rate of shifting to the target side after only one home-side picture was quite low. Similarly, infants in Condition 3/1 were more likely to shift to the target side after the third home-side picture and then to shift back to the home side than they were to shift to the target side after either one or two home-side pictures. Finally, comparable within-subjects analyses of Condition IR indicated that infants were not responding differentially in that condition (see Table 1).

Anticipation Results: Two-Month-Olds

Studies of visual tracking by 2-month-olds (Aslin, 1981) suggest that infants lack predictive control at this age. It seemed unlikely that infants would show much evidence of predictive saccades before predictive tracking; therefore, we expected that the younger infants would be unable to anticipate pictures to the same degree as the 3-month-olds. If the younger infants were unable to form expectations at all, they should have perceived all conditions as if they were unpredictable. Again, Condition IR served as the between-subjects control for these comparisons. As with the 3-month-olds, within-subjects controls were also used.

Comparisons between conditions. The percent of anticipatory fixation shifts for 2-month-olds is shown in Table 2. One-way ANOVA, with condition as the between-subjects factor, revealed a main effect of condition, $F(3, 44) = 3.7$, $p < .05$. Planned comparisons revealed that infants were not significantly more likely to shift fixation to the alternate side in Condition 1/1 than in Condition IR, although the direction of the difference was the same as for 3-month-olds (.27 vs. .19). Other planned comparisons suggest that Condition 1/1 enhanced the tendency to shift after one picture or that Conditions 2/1 and 3/1 suppressed shifting in the same context (i.e., after one home-side picture) or that both processes were partially active. Specifically, infants were more likely to shift fixation after one picture in Condition 1/1 than they were to shift after one home-side picture in Condition 2/1 (.27 vs. .11), $F(1, 44) = 8.0$, $p < .01$, or in Condition 3/1 (.27 vs. .11), $F(1, 44) = 8.6$, $p < .01$.

Between-subjects comparisons involving Conditions 2/1, 3/1, and IR provided little evidence to indicate that infants were expecting the target-side picture. As for 3-month-olds, we predicted that if 2/1 infants actively forecast the target picture, they would be more likely to shift fixation to the target side after the second home-side picture than would infants in Condition IR or 3/1. Such was not the case because 2/1 infants shifted at the same rate as IR infants after two home-side pictures (.23) and at nearly the same rate as infants in 3/1 (.21, see Table 2). Similarly, if 3/1 infants developed expectancies, they should have been more likely to shift fixation after three home-side pictures than should IR infants. Again, this was not the case because IR infants shifted at about the same rate as 3/1 infants (.15 vs. .14).

These analyses also revealed no indication that 2-month-olds in Condition 2/1 or 3/1 developed expectations for the home-side picture. When compared with IR infants, those in Condition 2/1 shifted back to the home side at virtually the same rate (.19 vs. .18) while those in Condition 3/1 shifted slightly but not reliably more (.28 vs. .19).

Within-subjects comparisons. As for the 3-month-olds, we predicted that if 2/1 infants had developed expectations for the target-side picture, they should have had a higher proportion of fixation shifts to the target side after the second home-side picture than after the first. And 3/1 infants' expectancies would be reflected in more shifting after the third home-side picture than after the first or second.

Evidence for expectations was found only for 2/1 infants because they were more likely to shift after two than one home-side picture (.23 vs. .11), $F(1, 15) = 13.8$, $p < .01$. On the other hand, 3/1 infants showed no evidence for expectation, because their tendency to shift after one, two, or three home-side pictures did not differ in a stable manner (.11, .21, and .14, respectively).

Analyses of shifts back to the home side after the offset of the target picture suggested that 2/1 and 3/1 infants had come to expect the return of the first home-side picture. Infants in Condition 2/1 showed a slight tendency to shift back to the home side after the target-side picture more than they shifted to the target side after one home-side picture (.18 vs. .11), $F(1, 15) = 3.1$, $p < .1$. Infants in Condition 3/1 also had a higher proportion of shifts back to the home side than to the target side after one picture (.28 vs. .11), $F(1, 15) = 10.5$, $p < .01$.

Finally, results from Condition IR were consistent with the prediction that infants would not form accurate predictions in the absence of regularity. The proportion of fixation shifts after one, two, and three pictures did not differ in a stable manner (.19, .23, and .15, respectively).

Anticipation Results: Age Differences

Age differences in anticipation showed that the older group of infants was more likely to shift fixation appropriately than was the younger group. Specifically, in Condition 2/1, 3-month-olds were more likely to shift fixation back to the home side after one target-side picture (.42 vs. .18), $F(1, 30) = 13.1$, $p < .01$.

In Condition 3/1 the older group shifted more after three home-side pictures (.25 vs. .14), $F(1, 30) = 4.8$, $p < .05$, and shifted back more after the target-side picture (.47 vs. .28), $F(1,$

Table 2
Proportion of Fixation Shifts During the Anticipation Window for 2-Month-Old Infants

	Condition (Group)				
Stimulus location	1/1(I)	2/1(II)	3/1(III)	IR(IV)	Between-group comparisons
No. of pictures on home side					
One (a)	.27	.11	.11	.19	I > II,** I > III**
Two (b)	—	.23	.21	.23	
Three (c)	—	—	.14	.15	
Return from target (d)	—	.18	.28	.19	
Within-group comparisons		a < b*** a < d*	a < d***		

Note. IR = irregular.
* $p < .1$. ** $p < .05$. *** $p < .01$.

30) = 5.5, $p < .05$. No age differences were found for Conditions 1/1 and IR.

Although we expected very little evidence for expectations in 2-month-olds, these young babies showed important competencies. In Conditions 1/1 and 2/1, 2-month-old infants showed they had detected and utilized some of the predictive relations between pictures when the complexity was not too great.

Facilitation Results: Three-Month-Olds

The second measure of expectations was a facilitation of fast reactions to picture onsets. In order to judge whether infants were able to develop faster reactions under conditions of predictability, a baseline RT (median) was calculated for the first six alternating pictures during the calibration sequence. Results of an ANOVA revealed no differences in baseline responding as a function of age or condition. However, when the drop in RT from baseline was used as an indication of whether infants had developed a readiness to respond, stable differences were found.

RT results are shown in Table 3. When all postbaseline RTs were combined, infants in the regular conditions showed either a large or small drop in RT from baseline, whereas those in the irregular condition showed a small rise from baseline. In Conditions 1/1, 2/1, and 3/1 the mean drop from baseline RTs were 129 ms (29%), 81 ms (21%), and 22 ms (6%), respectively, while Condition IR showed a small increase of 24 ms (4%). Results of one-way ANOVA on mean drop in RT with condition as a between-subjects factor revealed that the means were not reliably different; however, when data from infants in the three regular conditions were combined, they had a somewhat greater average drop from baseline than did infants in Condition IR (average drop of 77 ms vs. increase of 24 ms), $F(1, 42) = 3.49$, $p < .1$. Additionally, there was a significant linear trend indicating that as pattern complexity increased (from 1/1 to 2/1 to 3/1 to IR), percent drop from baseline decreased, $F(1, 42) = 5.55$, $p < .05$ (see Figure 3).[4]

Facilitation Results: Two-Month-Olds

The RT results for 2-month-olds indicate that infants showed little change from baseline in any condition (see Table 3).

Facilitation Results: Age Differences

The most consistent results from RT measures come from comparing postbaseline median RTs in 2- and 3-month-olds. Older infants were faster in responding to picture onsets than were younger infants across all conditions (529 ms vs. 612 ms), $F(1, 94) = 8.28$, $p < .01$ (see Table 3). In addition, an age comparison of percent drop in RT as a function of condition showed that only the 3-month-olds' RTs were linearly related to sequence complexity. Specifically, an Age × Condition interaction testing for a linear trend of condition was marginally reliable, $F(1, 84) = 3.02$, $p < .1$, with a nonsignificant residual (see Figure 3).

Discussion

This experiment replicates the results of Experiment 1 and of Haith et al. (1988) in finding that young infants can form expectations within a single 2-min experiment. Further, it extends our understanding by investigating the nature of age differences in anticipatory skill and the role of sequential pattern complexity. Finally, by observing anticipatory skills in a range of experimental conditions, important clues regarding performance mechanisms were revealed.

In accordance with previous work by Haith et al. (1988), we found that 3-month-old infants can rapidly form expectations for visual events even when they have no control over those events. Infants consistently showed higher levels of anticipatory behavior to pictures occurring in highly predictable sequences (1/1, 2/1, and 3/1) than for a less predictable sequence (IR). Infants also showed reduced RT in the highly predictable conditions.

Results from Conditions 2/1 and 3/1 extend our understanding of these expectancies by revealing that infants are not limited to detecting and utilizing only the simplest levels of spatial and temporal predictability, nor is there anything unique about symmetrical alternating sequences that accounts for the prior results. Within-subjects analyses revealed that infants were able to detect the regularity of asymmetrical, multiple-event sequences.[5] In fact, 3-month-old infants predicted future stimulus positions on both home and target sides within the 2-min experiment.

Performance of 3-month-olds in the complex sequences permits the elimination of several hypotheses regarding the processes tapped by the paradigm we used. After considering an alternate hypothesis, we will argue that infants detected the spatial, temporal, and possibly numerical properties of the multiple-event sequences; they used this information to build a crude cognitive map of the sequential regularity and then used this representation to guide anticipatory fixations and speeded reactions to future picture locations.

It is possible that infants were responding in a probabilistic manner. The major assumption of a probability learning model is that infants strive to maximize their overall chances of seeing a picture appear. One way of accomplishing this involves a global probability matching strategy (Staddon, 1983) where the probability of shifting fixation to the alternate side depends upon the global probability of a picture's appearing on that side. Thus, for Condition 2/1 the infant should be twice as likely to shift to the home side as to the target side. Similarly, for Condition 3/1 infants should shift with a 3:1 ratio. Furthermore, the model predicts that infants should be more likely to shift away from the home side in 2/1 than 3/1 because infants in Condition 2/1 see a higher proportion of pictures on the target side.

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[4] Given that infants had fewer opportunities to learn the more complicated sequences, this analysis confounds number of pattern repetitions with pattern complexity. However, when data from Conditions 1/1 and 2/1 are limited to 17 picture side shifts (the total possible for 3/1), the results do not change. The average drop from baseline is again marginally greater for the predictable conditions as compared with Condition IR, $F(1, 42) = 3.68$, $p = .06$, and the linear trend remains significant, $F(1, 42) = 6.6$, $p = .01$.

[5] It is not clear why the irregular condition provided such a weak base for the between-subjects comparisons. One possibility is that Condition IR is actually quite predictable. Pictures appeared in only two locations separated by a constant interval of time, and no more than three consecutive pictures appeared on a side. In addition to the conservative nature of the control, it is possible that infants who lacked specific expectations may have engaged in blind searching behavior, thus contributing to a high rate of responding in the ISI—albeit for a different reason than infants in the predictable conditions.

Table 3
Median Reaction Times (RTs, in Milliseconds) to Pictures not Anticipated

	Condition							
	1/1		2/1		3/1		IR	
Reaction time	2 mo	3 mo	2 mo	3 mo	2 mo	3 mo	2 mo	3 mo
Baseline	569_a	635_a	648_b	591_b	570_c	645_d	529_d	
Postbaseline by stimulus location								
No. of pictures on home side								
One	563_a	506_a	—	—	—	—	646_a	554_b
Two	—	—	656_a	509_b	—	—	675_c	521_c
Three	—	—	—	—	540_a	556_a	619_b	573_b
Return from target side	563_a	506_a	703_b	512_c	565_d	543_d	646_e	554_e
Overall postbaseline	563	506	680	511	552	549	647	553

Note. Within a row and within a condition, entries with a common subscript do not differ at $p < .05$ by a two-tailed *t* test. Mo = months.

Finally, it predicts that infants should be more likely to shift away from the target side in 3/1 than 2/1 because in Condition 3/1 they see a higher proportion of pictures appear on the home side.

The obtained pattern of means for 3-month-olds fits this hypothesis well. Every prediction made by the model is evident in the data (see Table 1). However, the within-subjects analyses imply more competence than simple probability matching. Simple probability matching predicts equal probabilities for shifting after one, two, or three home-side pictures. However, the within-subjects analyses revealed that infants shifted fixation more after two home-side pictures in Condition 2/1 (as compared with shifting after one home-side picture), and they made more anticipations after three home-side pictures in Condition 3/1 (as compared with one or two home-side pictures). Evidently, the infants had a more accurate representation of the picture sequences than simply knowing the proportion of pictures appearing on each side. Infants must have had some appreciation of the numerical and/or temporal structure of the home side. Future studies will be required before we can disentangle the relative effects of temporal and numerical information.

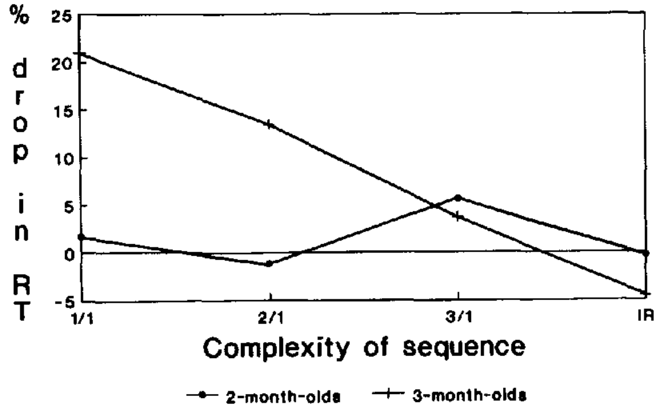

Figure 3. Plot of percent drop in reaction time (RT) as a function of complexity of stimulus sequence. (For this figure, the four stimulus conditions were placed on a putative scale of complexity. The percent drop was calculated as the percentage of possible drop from baseline RT; that is, because the lowest possible RT score was 200 ms, the percent drop score was adjusted accordingly. IR = irregular.)

We have so far discussed the results of data gathered only from 3-month-olds. Their behavior is much better accounted for by a time-number model than is the behavior of the 2-month-old infants. However, the younger infants did not behave in a random manner. First, counter to our predictions, the percent of anticipations in Condition 1/1 was substantially higher than in Condition IR. Although the statistical test did not reach an acceptable level of significance, we believe it was due mainly to a lack of power. Most revealing was that the younger infants were more likely to shift sides in Condition 1/1 than after one home-side picture in Conditions 2/1 and 3/1. These results suggest that they may have detected differential structure in these sequences and formed some expectancy.

It is important to remember that a limitation to the methods used in this study is that they may be quite conservative in revealing expectations. That is, infants were required to perform three possibly separate tasks in order to generate accurate anticipations. First, they had to detect the regularity of the picture onsets. Second, they had to form some sort of expectation and, third, they had to use their expectation to support action. For each of these tasks, one can imagine obstacles the infant managed to overcome. For example, there was very little time to detect the regularity because the entire procedure lasted only 2 min. Although they had to form an expectation for the spatial, temporal, and possibly numerical regularity in order to correctly anticipate, there was no way to prevent them from allocating their attention to the visual patterns of the different pictures or some other nonpredictive aspect of the experimental situation. Finally, the occurrence of anticipatory eye movements was entirely gratuitous from the experimenter's point of view. There was no way to motivate the infant to anticipate picture onsets—it just happened. In light of all these potential roadblocks, it seems remarkable that evidence for expectations was found at all. We believe it points out the fundamental role that expectations and anticipatory behaviors play in the normal flow of action.

In this light, it is useful to consider why infants are motivated to anticipate picture onsets. This sort of functional explanation is important for understanding the role of expectations and anticipation in everyday adaptive action. One way to address this issue is to consider how behavior that is guided by expectations differs from behavior that is reactive, that is, guided by feedback. The first attribute that distinguishes feedback-guided behavior is its sensitivity to input. The ability of humans to adapt to unusual environments is a testament to the value and flexibility of reactive behavior. Without feedback, one would never learn to walk on ice or to roller skate. However, there is a price to be paid for this flexibility.

When action is guided by feedback, it is slow, and very often it is too slow to be adaptive. In order to produce behaviors that achieve goals in a dynamic environment, those behaviors must be appropriately timed (Schmidt, 1968).

Feedback-guided action has another serious drawback. One must keep feedback synchronized with the action, or it can have a destabilizing effect. When a telephone-line error feeds back one's own voice a second or two after speaking, most people experience serious difficulties expressing themselves. However, we hear our own voices every time we speak. The difference is the way the feedback is synchronized with speaking. We can easily compensate for feedback when we have an expectation for its time of arrival; otherwise, it can seriously disrupt our action programs. By using expectations for guiding actions, an organism can gain internal control over its behavior, with the result that actions can be executed more smoothly and stably in a complex and changing environment.

The development of internal control may be the most valuable feature of anticipatory behavior—especially in early infancy. In the development of skill, expectations mark the transfer of control from domination by environmental elicitors to regulation by the organism. And internal control is necessary for guiding behavior toward a goal when environmental circumstances fluctuate wildly. This feature of expectations shares important qualities with central functions of higher cognition. Planning, avoiding distraction, and resolving conflicting perceptual cues are functions that all depend heavily upon the development of internal, expectancy-based control. The research reported here suggests that by 2 months of age the human infant is driven to gain this kind of control.

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