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Infants' Visual Expectations and the Processing of Time

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Visual events are defined by a number of dimensions—their location in space, content (color, shape, etc.), and time tags (onset, duration, etc.). The role of time in infants' performance in the Visual Expectation Paradigm (VExP) was studied to evaluate whether infants encode in their expectation representation the timing of events in addition to their spatial location and content. In Experiment 1, 3-month-olds produced more anticipations in a temporally predictable condition than in an unpredictable condition, suggesting that their expectations included a timing component. No evidence was found, however, that infants processed events' precise timing, but they instead appeared to process events' average temporal flow rate. This was supported in Experiment 2, in which infants trained with a shorter flow rate exhibited an increase in anticipations after being shifted to a longer flow rate, whereas those trained with a longer flow rate exhibited a decrease when shifted to a shorter flow rate. These findings indicate 3-month-olds encode in their expectation representation the average temporal flow rate rather than the precise timing of events. The findings also suggest that the VExP may be useful for exploring infants' ability to make time estimates that involve action.

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> The past, present and future are only illusions, even if stubborn ones.
>
> —Albert Einstein (quoted in Davies, 2002)

Within the physical realm, there is no known quantity that corresponds to the passage of time (Davies, 2002). Yet, we perceive the world and events as embedded in the flow of time. The question then needs to be raised, what cognitive mechanisms are responsible for our perception and processing of time? Certainly, we have memories for events that occurred in the past, which include information about when they occurred, such as how old we were, what time of day it was, and perhaps how long the event lasted. We also predict and plan future events that are set to occur at a particular time in the future. Thus, although physics does not identify any quantity that specifies time, it is not an illusion but a real and ever-present characteristic of our cognitive processing.

When we consider everyday tasks, the processing of time plays a role in many of our behaviors, particularly those requiring anticipation and planning. For example, musicians process the duration of and interval between notes in order to plan and execute the playing of a piece of music. Many other tasks also require precise perception and processing of time in order to anticipate relevant events and plan appropriate motor behavior, such as typing, driving a car, walking across the street, and catching an object. Even infants' behavior, such as feeding and social interactions, requires the processing of time in order to match their execution to the timing of expected components of those events.

To date, research into infants' ability to process time has focused on their sensitivity to temporal parameters of events, for example, temporal markers for events that indicate their onset, duration, and offset. Furthermore, these temporal markers are likely encoded in their representations of the events, resulting in infants' capacity to discriminate between events that have difference temporal characteristics. Research that has shown temporal sensitivity in infancy has included investigations of conditioning (e.g., Fitzgerald, Lintz, Brackbill, & Adams, 1967), the developmental foundations of speech perception and auditory perception in general (Benasich & Tallal, 1993; Jusczyk, Pisoni, Walley, & Murray, 1980; Trehub, 1993), and the discrimination of auditory and visual frequency and sensitivity to auditory-visual synchrony for object motion and sound (e.g., Kuhl & Meltzoff, 1988; Spelke, 1979; see Lewkowicz, 1989, 1992 for literature reviews). Furthermore, recent research has demonstrated that young infants' attentional processing is sensitive to the time estimation of stimulus event occurrence (Colombo & Richman, 2002). Other studies have investigated a time-related processing capacity, namely, that of sequential order. Infants of various ages process, encode, and remember the sequential order in which events or event components occur relatively through time (Bauer, Hertsgaard, Dropik, & Daly, 1998; Carver & Bauer, 1999), even as young as 3 months of age (Gulya, Rovee-Collier, Galluccio, & Wilk, 1998).

Although the above studies and others demonstrate that young infants have a sensitivity to the temporal parameters of experienced events, they do not address the issue of whether infants have the ability to guide adaptive behavior that is based on temporal parameters—a capacity that would seem to be required in order to efficiently plan and execute event-appropriate behaviors. A few studies related to the issue of temporally guided adaptive behavior have been conducted. Studies by von Hofsten and colleagues (von Hofsten, 1980; von Hofsten, Vishton, Spelke, Feng, & Rosander, 1998), for example, have examined infants' anticipatory reaching to the predictable movement of targets, which requires adapting their reaching behavior to match the temporal characteristics of the moving object. Additional studies have also documented infants' anticipatory responding, both with reaching (Jonsson & von Hofsten, 2003; Spelke & von Hofsten, 2001) and eye movements (Johnson, Amso, & Slemmer, 2003), to the reappearance of targets that move behind an occluder. Although the anticipatory responding exhibited in these studies requires adaptation to the temporal dynamics of the target, the timing and temporal predictability of the target were not manipulated as independent variables. Moreover, these studies did not examine the ability of infants to track two distinct timings simultaneously. These studies, therefore, were not designed to assess the guidance of infants' adaptive behavior by the specific temporal dynamics of events. Consequently, understanding the nature, extent, and development of infants' temporal processing in the adaptation of responses is still in its early stages. Considering that time has been theorized to be an important factor in the development of cognitive processing (Lewkowicz, 1989; Rovee-Collier, 1995), the present study sought to extend these findings of temporally guided adaptive behavior by manipulating the temporal predictability of events and by examining infants' capacity of adapt their behavior to two distinct but simultaneously presented timings. That is, the present study was designed to assess infants' temporal processing within the context of forming expectations for when two distinct events would occur.

That infants form expectations in the first place has been established by previous studies that have reported that young infants rapidly learn to anticipate visual events that occur in a regular spatial pattern even when the appearance of these events is separated by a time interval. Specifically, evidence for the cognitive construct of expectations comes from infants' anticipatory eye movements to a spatial location before the forthcoming event appears or, in the absence of an anticipatory eye movement, a faster reactive eye movement to event onset than if the event was unpredictable (Haith, Hazan, & Goodman, 1988; Haith & McCarty, 1990; for reviews, see Haith, 1997; Haith, Wentworth, & Canfield, 1993). In the prototypic example of the Visual Expectation Paradigm (VExP), infants watch pictures that appear in a simple left-right (L-R) alternating sequence with an intervening time interval; picture duration is 700 msec, and the interstimulus interval (ISI) is typically 1000 msec. After several cycles of alternation, the infant typically moves her eyes during the ISI from the side on which the picture just disappeared to the opposite side before the next picture appears. When the infant fails to make an anticipatory eye movement, she still produces a faster reactive eye movement to the next picture's onset than when the picture sequence is not predictable. Enhancement of both anticipation frequency and reduction in the latency of the reactive eye movements during an alternating sequence, compared to an irregular sequence, have typically been taken as empirical evidence for the infants' formation of the cognitive construct of expectations. However, recent research suggests that anticipations and the facilitation of reactive eye movements may be at least partially dissociated, so these categories of eye movement may be controlled by different levels of information processing (Adler & Haith, 2003).

Other VExP studies have revealed that, in addition to simple spatial alternations, infants encode and form expectations for more complex spatial sequences (Canfield & Haith, 1991). For example, Canfield and Haith (1991) demonstrated that young infants can form expectations for events in an asymmetric (e.g., left-left-right) spatial sequence. Furthermore, 3-month-old infants form expectations for the content of visual events (Adler & Haith, 2003; Wentworth & Haith, 1992). Visual events in the world such as the appearance of mom or the availability of food or, as in expectation studies, the occurrence of a geometric stimulus, as well as having spatial and content components, also consist of a time component. That is, certain parameters that define events, including their duration and the timing of their onset and offset, occur in the temporal domain. Moreover, many events are time-locked such that behavior in anticipation and in reaction to those events is based on their particular temporal characteristics (Friedman, 1990; Haith, 1997). Accordingly, if infants can process timing information of events that occur on a millisecond scale, they might be able to form expectations for these events that include their temporal structure.

The present study, rather than varying picture location or number, focused on variations in picture timing. To address the issue of the development of time processing, three experimental questions were asked: Do infants' expectations for each event include a timing component? Can infants keep track of two time intervals simultaneously? Can infants form expectations for events that appear in asymmetric timing patterns? Three-month-olds were chosen as the population to answer these questions because there is extensive knowledge about this-age infants' encoding of event information, such as location and content, in their expectation representations (Adler & Haith, 2003; Canfield & Haith, 1991; Haith et al., 1988; Haith & McCarty, 1990; Wentworth & Haith, 1992). Consequently, direct comparisons at the same age can be made for the encoding of the different components of events in the formation of expectations. Additionally, 3 months of age has been recognized as a transition from environment-driven to endogenously driven, "voluntary" behavior (Atkinson, 2000; Johnson, 1996). Considering that expectations are manifested as voluntary behavior in the form of anticipatory eye movements, examining the contribution of different event components to the expectation representation at 3 months is crucial for understanding the transition to endogenously driven behavior.

To answer the questions of the present investigation, therefore, in the first experiment 3-month-old infants were presented with sequences of visual events in which those events could occur with one of two different timings. Whether infants exhibited differential expectation behavior when those two timings occurred in a predictable manner versus when they were unpredictable was assessed. In the second experiment, 3-month-old infants were presented with a sequence of events that occurred with an average timing value, rather than each event having a predictable specific timing, and then they were switched to a new average timing value. This procedure was implemented in order to assess whether infants' expectation formation and temporal processing consisted of the timing of individual events or of the average temporal flow rate at which those events occur.

EXPERIMENT 1

Though numerous infant expectation studies (Adler & Haith, 2003; Canfield & Haith, 1991; Haith et al., 1988; Haith & McCarty, 1990; Wentworth & Haith, 1992) have documented the ability of very young infants to form expectations for where future events will occur and what those events will be, they have not determined whether infants expect when those events will occur. The main limitation of the previous studies in determining expectations for event timing is that they have used a single, constant timing interval between picture presentations—typically around 1000 msec. Even if the timing of infants' anticipatory eye movements (the primary measure of the underlying expectations) is measured relative to the timing of picture onset, the use of a single timing interval precludes distinguishing whether infants form a expectation for the exact timing of the event which would require discrimination of and differential performance to at least two distinct timings.

In the classic visual expectation studies (e.g., Haith et al., 1988), infants' anticipatory responding is compared between events for which the spatial component is sequentially regular and predictable versus when it is sequentially random and unpredictable. Infants exhibit more anticipations to the future location of events when they are spatially predictable than when they are not, demonstrating that infants form an expectation for the spatial component of events. A comparable approach is taken in this experiment to determine whether 3-month-old infants form expectations for the time component of events. In this experiment, therefore, infants' performance is compared for events whose onset timing is regular and predictable or is random and unpredictable. If infants form expectations for the timing of events, then they should exhibit more anticipatory eye movements and faster reactive eye movements when the timing of the events is predictable than when it is not. Furthermore, similar to previous VExP studies demonstrating expectations for two different spatial locations, two different picture onset timing values are used here. If infants form expectations for the different onset timings, then the timing of their eye movements should be related to the two different onset values.

Method

Participants. The data from 32 infants at 3 months of age (range: 85–110 days; *M* = 97.3, *SD* = 6.9) were used in the analyses. Infants and mothers were recruited through a standing arrangement with the Colorado Department of Health. Once names were provided, parents were sent a letter and self-addressed postcard to inquire about their interest in having their infant participate in studies at the University of Denver. If they returned the postcard, they were contacted by phone and participated if they were interested in the study. The sample consisted primarily of infants from middle to upper SES white families and who were full-term at birth with no reported complications and who appeared to be in good health. An additional 16 infants participated, but the data from 1 of these infants were not used because of equipment problems. Insufficient data (i.e., data on less than 65% of the pictures) were collected from the remaining 15 infants because they were fussy (*n* = 7), fell asleep (*n* = 3), were inattentive (i.e., disinterested or looked at their hands or other parts of the visual field; *n* = 4), or had no recorded reason (*n* = 1).

Stimuli. The stimuli were computer-generated graphic images of checkerboards, schematic faces, vertical stripes, concentric circles, and diamond shapes in various combinations of green, red, yellow, blue, black, and white. The particular image type and colors were randomly determined for a given trial and counterbalanced across trials for a given infant. The infant viewed the images by mirror reflection on a Sony color monitor (model 1302) that was 20.3 cm high × 25.4 cm wide, at a distance of 40 cm. The stimuli were approximately 4.5° square and their centers were 5.7° to the left or right of the infant's visual center. Each stimulus moved vertically at a rate of 4.4°/sec, completing one up/down cycle for each presentation, which lasted 700 msec. The variations in stimulus objects and colors were combined with stimulus motion to maximize the infant's attention. All infants saw an alternating sequence of pictures that appeared on the left and right sides, and the pictures were preceded by an ISI of either 800 or 1200 msec. There were a total of 70 pictures presented, with the first 10 constituting a baseline phase during which the stimuli appeared randomly on either the left or the right sides and were randomly preceded by an ISI of either 800 or 1200 msec. The remaining 60 pictures constituted the experimental phase during which the stimuli alternated spatially between the two sides, and the two ISIs were used equally in either a predictable or a random sequence.

Apparatus. The infant lay supine on a mattress and viewed the stimuli by reflection from a visible-reflecting, infrared-transmitting mirror (Libby-Owens No. 956; for details, see Haith et al., 1988). The image of the infant's right eye (in a camera field of approximately 3.8 cm^2) was videotaped by a Panasonic CCD TV camera (model WV-CD20) from which the infrared lens filter was removed. (Unfiltered CCD elements are quite sensitive to near infrared light.) Light for televising this eye image was provided by an infrared source and collimator whose beam reflected from an infrared-transmitting, visible-reflecting mirror which was in the same optical path as the recording video camera (for details, see Haith et al., 1988). Part of the source light was reflected from the retina back through the pupil, and part was reflected from the corneal surface of the eye and formed a small, bright, white spot that served as a reference point for the center of the visual field. The eye image was combined with the output of a video time/date generator, which provided time increments of 1/100 sec for video recording.

Procedure. When camera focus and positioning of the infant were established, the experiment began. Initially, all infants saw 10 pictures that were presented in an irregular spatial and temporal sequence in order to collect baseline reactive latency data before expectations were formed. The infants then saw one of two sequences of pictures depending on their group assignment: 1) The temporally predictable group of infants ($n = 16$) saw a spatially alternating sequence of 60 pictures in which ISI alternated (e.g., 800-1200-800-1200) from picture to picture (see Figure 1); 2) The temporally unpredictable group of infants ($n = 16$) also saw a spatially alternating sequence of 60 pictures but the ISI, 800 or 1200 msec, varied randomly from picture to picture, with the restriction that the same ISI could not occur more than three trials in a row. For both groups, whether the experimental phase began with a picture on the left or on the right or began with an ISI of 800 or 1200 msec was counterbalanced across infants.

Data Reduction. To determine the eye movement locations from the videotape, an eye tracking computer program completed multiple runs on a given infant's video record to average out machine and tape noise in the detection of the pupil and corneal reflection. This system produced an eye movement timing resolution of 16.6 msec. Specially developed software displayed eye location data as a graph representing the horizontal and vertical locations of the infant's eye for each 16.6-msec sample and the video fields on which pictures were on and off.

A secondary computer program then identified which eye movements belonged to which of two measurement categories that were used to reflect what we have referred to as anticipation and facilitation (Haith et al., 1988). Anticipation refers to an appropriate eye movement that is triggered prior to a visual event, whereas facilitation refers to the latency of an eye movement following the event and to what degree that latency is reduced, presumably by knowledge about it (spatial location

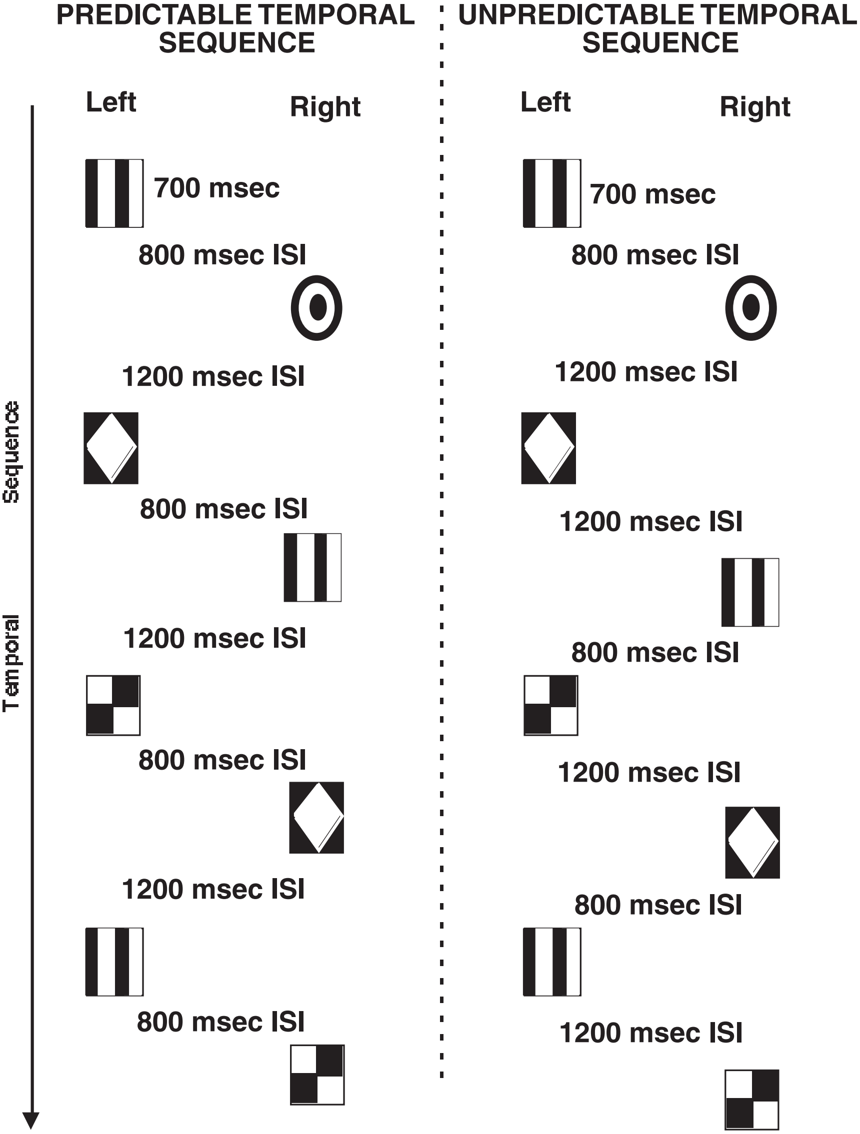

FIGURE 1 Example of the picture sequences of the predictable and unpredictable temporal conditions used in Experiment 1. In both conditions, the pictures appeared in a left-right alternating spatial sequence and each picture had a duration of 700 msec. In the predictable temporal sequence, the ISI alternated from 800 to 1200 msec. In the unpredictable temporal sequence, the ISI was randomly either 800 or 1200 msec.

and/or timing). An eye movement was categorized as an anticipation if it occurred during the ISI preceding an event or within 167 msec following its onset (i.e., faster than the lower limit of a reactive eye movement) and if the movement was directionally appropriate. Furthermore, in order for an anticipatory eye movement to be considered valid, it could not be transitory but had to remain at the anticipated located until the upcoming stimulus appeared. A percent of anticipation measure was computed by the formula:

$$\frac{\text{Number of anticipation trials}}{\text{Number of anticipation trials} + \text{Number of reactive trials}}$$

with the denominator reflecting the total number of pictures for which the scorer judged the infant to be looking. For those occasions on which the infant did not anticipate the event, but did make a directionally appropriate eye movement 168 msec or later, a reactive latency was recorded. Overall, in Experiment 1, infants responded on an average of 89% of the baseline trials and 82% of the experimental trials.

Prior studies have established the reliability in identifying the critical saccades between manual, frame-by-frame coding by a human coder and the computer coding system used in the present study by double coding 20% of the participants with a conventional manual, frame-by-frame, reduction method and the current computer coding system. Reliability was found to be well above 90% for both the direction and the timing of infant eye movements (e.g., Adler & Haith, 2003).

Results and Discussion

Before addressing the key question of whether infants process and encode the precise timing of visual event onset, we first addressed whether infants provided evidence, via anticipatory fixations and reduced reactive latencies, that they formed more expectations for the predictable temporal sequence than for the unpredictable temporal sequence.

Anticipatory eye movements. An analysis of variance (ANOVA) was conducted on the percentage of anticipations with predictability (predictable vs. unpredictable) as a between-subject variable and ISI (800 msec and 1200 msec) as a within-subject variable. The predictability factor was significant, $F(1, 60) = 4.43$, $p < .05$, with a higher frequency of anticipations during the predictable than the unpredictable temporal condition (see Figure 2). Even though the 1200-msec ISI provided 50% more time for an anticipation than the 800-msec side, there was little difference in the percentage of anticipations to the two sides, with a slightly higher percentage of anticipations to the short than the long side ($p > .45$). The interaction between predictability and ISI was not significant ($p > .75$). Thus, infants made

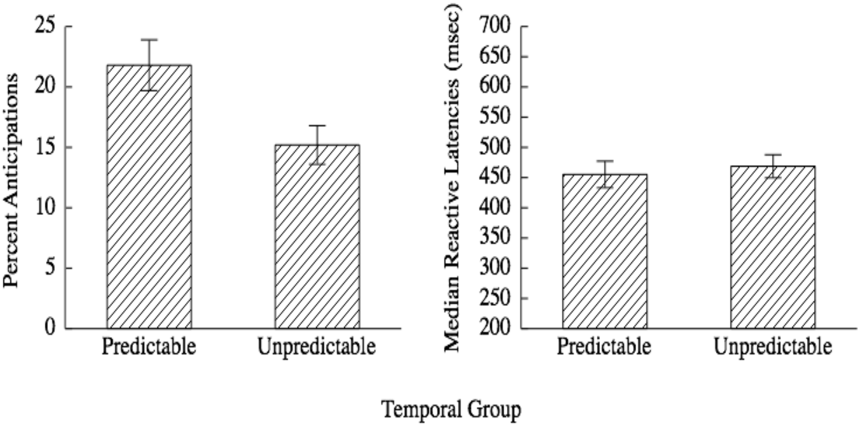

FIGURE 2 Percentage of anticipations (left graph) and median reactive latencies (right graph) as a function of temporal group (predictable and unpredictable) in Experiment 1. Vertical error bars indicate +/– SE.

more anticipations and expectation formation was more strongly supported in the predictable temporal condition than in the unpredictable condition.

Although the absolute level of anticipatory responding exhibited by the infants (see Figure 2) may seem low, it is consistent with previous expectation studies conducted for over 20 years (for reviews, see Haith, 1997, and Haith et al., 1993). One must also ask why infants would show an increase in anticipations in the temporal predictable condition relative to the unpredictable condition in the first place. There are a number of issues that address this question and highlight the remarkable fact that infants would even bother to anticipate. First, there is no easily identifiable reinforcer that distinguishes between the temporal predictable and unpredictable conditions that would support differential levels of anticipations. Furthermore, in this regard, there is no penalty for infants not anticipating since they will still be able to view and process the stimulus. Moreover, that infants anticipated at a greater rate in the predictable condition is impressive since the unpredictable condition was in fact equally spatially predictable, which has repeatedly been shown to be a strong factor in support of anticipations (e.g., Haith et al., 1988; Haith & McCarty, 1990). Finally, infants exhibited 43.4% more anticipations in the temporal predictable condition than in the unpredictable condition. This is a considerably greater difference than is found in preference studies where a difference of 10% (for example, looking 53% vs. 47% of the time at two stimuli) is touted as indicating remarkable perceptual and cognitive capacities. Consequently, that infants would anticipate at all and that they would anticipate at a greater rate simply based on the temporal predictability of the picture sequence even though all sequences were spatially predictable is remarkable.

Latencies of reactive eye movements. An ANOVA was conducted on the median latency of infants' saccadic eye movements after picture onset with predictability (predictable vs. unpredictable) as a between-subject variable and ISI as a within-subject variable. The predictability factor was not significant, with latencies being only slightly faster for the predictable than for the unpredictable temporal condition (455.2 msec vs. 468.7 msec; see Figure 2), $F(1, 60) = 0.46$, $p = .5$. The ISI factor was significant, $F(1, 60) = 6.29$, $p < .02$, with shorter latencies after a 1200-msec than an 800-msec ISI (436.9 msec vs. 486.9 msec). The interaction of predictability and ISI was not significant ($p > .9$), however, indicating that the faster eye movements after a 1200-msec ISI was not due to stronger expectation formation on those trials. Instead, the faster eye movements after a 1200-msec ISI was most likely due to infants having more time on those trials to prepare the eye movement system to make an eye movement when the stimulus eventually appeared, regardless of whether it was predictable or not.

Interestingly, contrary to the hypothesis that both anticipations and facilitation of reactive eye movement latencies represent the same underlying cognitive construct of expectation (Haith, 1997; Haith et al., 1993), these results showed no evidence of an effect of predictable timing on reactive eye movement latencies. This dissociation between the presence of an effect of temporal predictability on anticipations versus absence of an effect on reactive eye movement latencies, however, is consistent with a similar dissociation found when examining expectation formation for predictable stimulus content (Adler & Haith, 2003). The failure to find latency differences as a function of timing predictability, whereas a difference was found in anticipations, suggests that the two measures are differentially sensitive to expected event timing.

Reactive eye movements are sensitive to sensory input and may be controlled by neural mechanisms such as the superior colliculus, which represents a spatial map of possible stimulus locations (Krauzlis, Liston, & Carello, 2004; Robinson & Kertzman, 1995; Schiller, 1995). Consequently, reactive latencies may be sensitive to the predictability of spatial location and less sensitive to event information that is not necessary for *reacting* to its onset, such as its timing or content. In contrast, anticipatory eye movements occur prior to sensory input and require involvement of distinct neural mechanisms, such as the frontal eye fields, which have been implicated in the generation of predictive saccades (Hanes, Patterson, & Schall, 1998; Keating, 1991). Considering that areas thought responsible for processing time are adjacent to frontal eye fields and project to it, differences in temporal predictability may be reflected in differences in anticipations. Thus, the facilitation of reactive latencies and the production of anticipations may reflect separate and distinct processing mechanisms, a differential sensitivity to event timing.

Analysis of time processing and discrimination. Although the prior analyses indicated that temporal predictability facilitates infants' formation of expectations for visual events, they did not address the primary question of whether infants processed and discriminated the different timing of the two ISIs. If infants were encoding the differential timing, then one might expect to see differential anticipatory behavior to the two temporal sides, especially in the predictable temporal condition, but there was not. The lack of a difference could be due to infants making their anticipations early in the ISI, in which case they were not separately adapting to the shorter and longer ISIs.

To address this possibility, how long infants waited after a picture offset to make an anticipatory fixation as a function of the ISI was analyzed. This analysis indicated that infants waited longer to make an anticipatory fixation for the 1200-msec side ($M = 942$ msec) than for the 800-msec side ($M = 828$ msec), $t(15) = 2.27$, $p < .05$. Unfortunately, a confound exists which almost necessarily produces these results. Because infants had 400 more msec to make an anticipatory eye movement for the 1200-msec than for the 800-msec side, the timing of anticipations could be biased toward longer elapsed times for the 1200-msec side. To negate this confound, the time frame for anticipations was equalized by establishing a 1000-msec timing cutoff for the inclusion of anticipations for both the 800-msec and 1200-msec trials. If infants were differentiating the interval timing for the two ISIs, we would expect them to make relatively fewer anticipations before the 1000-msec cutoff for the 1200-msec side, because they had 400 msec left to do so. The probability of the number of infants having a higher percentage of fast anticipations on either ISI in each temporal condition was subjected to a binomial probability test, with the null hypothesis being that 50% of infants in a given condition would have a higher percentage of fast anticipations on 800-msec trials.

The results are shown in Table 1. For the temporally predictable condition, consistent with the prediction, 13 infants (81.25%) had more fast anticipations on 800-msec trials than on 1200-msec trials, whereas 3 had the reverse ($p < .025$). For the temporally unpredictable condition, contrary to the prediction, the number of subjects was 13 (86.7%) and 2 ($p < .01$), respectively. So, when an early cutoff criterion was employed, the percentage of anticipations differed for the two sides.

These results are not definitive concerning the primary question of whether infants encode the precise timing of the expected events. If infants had been encod-

TABLE 1
Number of infants who had a higher percentage of anticipation prior to the 1000 msec cutoff during the 800 and 200 msec ISI trials.

	Interstimulus Interval	
Temporal Group	*800 msec*	*1200 msec*
Predictable	13	3
Unpredictable	13	2

ing the precise timing, then a greater number of infants would have exhibited more fast anticipations on 800-msec trials in the temporally predictable condition but *not* in the temporally unpredictable condition. That more infants in the temporally unpredictable condition exhibited more fast anticipations on 800-msec trials, even though they viewed the two ISI values in random order and thereby could not have known when a particular timing was to be presented, suggests that the different event timings were not encoded during expectation formation. Instead, infants must have based the timing of their anticipations on some other factor or cue in the sequence.

One such cue might be the overall temporal rate that visual information is presented in the sequence. Since the average ISI was 1000 msec and picture duration was 700 msec, the average temporal rate occurred at a value of 1700 msec. Consequently, infants, having experienced a particular ISI on one trial (e.g., 1200 msec), might expect the next trial to occur with an ISI (e.g., 800 msec) that preserves the expected temporal rate, regardless of the actual value of the ISI on the next trial. To test this possibility, we segmented consecutive pairs of events for the temporally unpredictable condition according to the ISI sequence (i.e., 800-800 msec, 800-1200 msec, 1200-800 msec, 1200-1200 msec), and then assessed the number of fast anticipations (before the 1000-msec cutoff) for the second picture in each pair. Results indicated that 73.7% of infants' fast anticipations in the temporally unpredictable condition occurred when the preceding trial had a 1200-msec ISI. Because an 800-msec trial was 50% more likely than a 1200-msec trial to follow a 1200-msec trial, the greater percentage of fast anticipations on trials following a 1200-msec trial produced the previous data, indicating that more infants had a greater number of fast anticipations on 800-msec trials than on 1200-msec trials even in the temporally unpredictable condition. Apparently, infants did use the timing of the previous trial as a predictive cue for the timing of the subsequent trial, suggesting that infants encode the average flow rate and not the precise timing of individual events, and pace their anticipatory behavior accordingly.

EXPERIMENT 2

In relation to the finding of the previous experiment that infants might be processing the temporal rate at which information flows, there has been some previous research, both adult and developmental, that has addressed the issue of information flow. This research, however, has typically been concerned with the processing of information flow in the context of motion perception and optic flow (Cutting & Readinger, 2002; Johnson & Mason, 2002), intermodal perception (Lewkowicz, 1992; Walker-Andrews, 1997), or perception of causality (Leslie, 1984; Scholl & Tremoulet, 2000) of singular, unitary events. In contrast, the interesting suggestion from the previous experiment was that infants may be able to process the information flow rate across multiple events as well.

Although the preceding results suggested that infants may have encoded the average temporal rate at which information flowed across a sequence of events, the first experiment was not designed to specifically test this type of temporal processing. To test the possibility that infants were processing the temporal rate of information flow, the second experiment was designed in a manner similar to that of a typical learning paradigm used in examining the discrimination of reinforcement schedules by training with one rate and then switching to either a greater or a lesser rate (e.g., Church, Meck, & Gibbon, 1994; Herrnstein, 1970; McSweeney & Weatherly, 1998; Williams, 2002). To examine infants' ability to encode the temporal flow rate, therefore, infants were trained with an alternating sequence of pictures in which the ISIs and picture durations each varied among three possible values, and, therefore, the timing of individual events was unpredictable, but in such a way that the overall timing of every two events (picture-ISI-picture-ISI) in the sequence always equaled some total value or flow rate. After this particular average rate of information flow was learned, the rate was switched to either a longer or a shorter value. If infants form temporal expectations for information flow rate, then switching from a long information flow rate to a shorter one should result in a reduction in the number of anticipations because the events would more often precede the anticipation for their later temporal onset. Infants who are switched from a short rate to a longer rate should have the opposite effect—an increase in the number of anticipations.

Method

Participants. The data from 36 infants who participated in the study at 3 months of age (range: 87–111 days; $M = 98.2$, $SD = 7.5$) were used in the analyses. Infants and mothers were recruited and contacted as in Experiment 1. The sample consisted primarily of infants from middle to upper SES white families and who were full-term at birth with no reported complications and who appeared to be in good health. An additional 15 infants participated, but the data from these infants were not used because of insufficient data (i.e., data on less than 65% of the pictures) due to fussiness ($n = 5$), falling asleep ($n = 3$), or disinterest (i.e., looking at their hands or other parts of the visual field; $n = 7$).

Stimuli and apparatus. The stimuli and apparatus were the same as used in Experiment 1. The only difference in the stimuli was in their timing parameters. That is, infants viewed spatially alternating picture sequences that had three possible durations and ISIs that combined to equal one of three possible flow rates (2600, 3400, or 4200 msec; see Table 2) for every two-picture event sequence (picture-ISI, picture-ISI). For example, for a flow rate of 2600 msec, a two-picture

TABLE 2
The three possible picture durations, three possible interstimulus intervals (ISIs), and samples of two-picture event sequences for the three different temporal flow rates used in Experiment 2.

	Temporal Flow Rates		
	Short - 2600 msec	*Medium - 3400 msec*	*Long - 4200 msec*
Picture durations	400, 600, 800	600, 800, 1000	800, 1000, 1200
ISIs	500, 700, 900	700, 900, 1100	900, 1100, 1300
Sample two-picture event sequences (**Duration**-ISI-**Duration**-ISI)	**800**-500-**400**-900 **600**-700-**800**-500 **400**-900-**600**-700	**800**-900-**600**-1100 **600**-1100-**1000**-700 **1000**-700-800-900	**1000**-1100-**800**-1300 **800**-1300-**1200**-900 **1200**-900-**1000**-1100

event sequence might consist of a picture with duration of 600 msec followed by an ISI of 700 msec, and then the second picture with a duration of 800 msec followed by an ISI of 500 msec. Additional examples of timings for two-picture event sequences for each flow rate are listed in Table 2.

Procedure. The procedure was essentially the same as in Experiment 1 except that instead of viewing pictures, each of which with predictable timing, infants viewed picture sequences whose temporal flow rate was predictable. Initially, all infants again saw an alternating sequence of pictures that appeared on the left and right sides. There was a total of 70 pictures presented, with the first 10 constituting a baseline phase during which the stimuli randomly appeared on either the left or the right side and were randomly presented in one of three durations and ISIs. The next 40 pictures constituted the flow rate training phase during which the stimuli spatially alternated between the two sides, and the three possible durations and ISIs combined to equal one of three possible flow rates (2600, 3400, or 4200 msec) for every two-picture event sequence (picture-ISI-picture-ISI; see Table 2 and Figure 3). After the flow-rate training phase, infants were switched to one of the other flow rates, depending on their assigned condition, for a testing phase of 20 pictures.

Which flow rates infants experienced depended on their assigned condition. In the Long/Medium Flow Group, infants ($n = 12$) first viewed a long flow rate (4200 msec) and were then switched to a shorter flow rate (3400 msec). In the Short/Medium flow, infants ($n = 12$) first viewed a short flow rate (2600 msec) and were then switched to a longer flow rate (3400 msec). In the Medium/Medium Flow Group (control condition), infants ($n = 12$) consistently viewed a steady flow rate of 3400 msec. A schematic of temporal flow rates in each condition is presented in Figure 3. Note that in each condition, infants ended with the same temporal flow (3400 msec) and, therefore, any differences in performance after the flow rate switch could not be due to differences in the final flow rate.

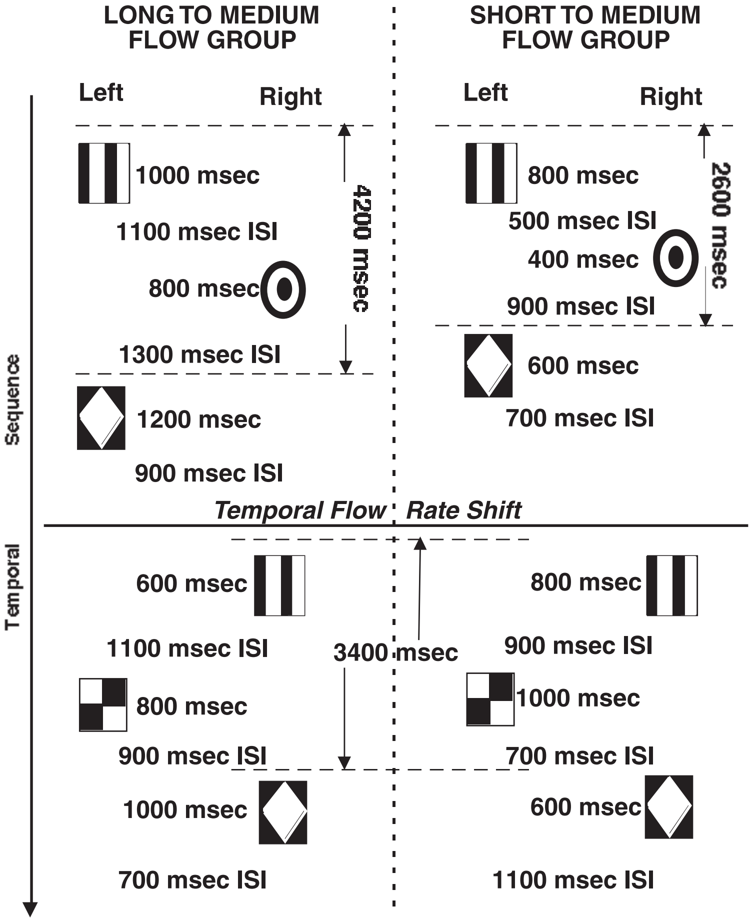

FIGURE 3 Schematic of the picture sequences and temporal flow rates of the Long/Medium and Short/Medium Flow Groups in Experiment 2. For both groups, the pictures appeared in a left-right alternating spatial sequence. Each group viewed 40 pictures at one flow rate (the temporal span of each picture-ISI-picture-ISI pair) and then were shifted for 20 pictures at a different flow rate. For each flow rate, three different picture durations and three different ISIs were used to produce that flow rate. The 4200-msec flow rate was produced from a combination of 800-, 1000-, and 1200-msec durations with 900-, 1100-, and 1300-msec ISIs. The 2600-msec flow rate was produced from a combination of 400-, 600-, and 800-msec durations with 500-,700-, and 900-msec ISIs. The 3400-msec flow rate was produced from a combination of 600-,800, and 1000-msec durations with 700-, 900-, and 1100-msec ISIs. The Long/Medium Flow Group first viewed a flow rate of 4200 msec and was then shifted to a shorter flow rate of 3400 msec. The Short/Medium Flow Group first viewed a flow rate of 2600 msec and was then shifted to a longer flow rate of 3400 msec. A control condition, the Medium/Medium Flow Group (not depicted here), viewed a consistent flow rate of 3400 msec across the entire picture sequence.

Results and Discussion

Anticipatory eye movements. To assess whether the different groups, all of whom initially viewed a different flow rate, exhibited equivalent levels of anticipations before the flow rate shift, a one-way ANOVA was conducted on the percentage of anticipations during the 40 pictures of the pre-shift flow rate, with flow group (Long/Medium, Short/Medium, and Medium/Medium) as the between-subject variable. Results indicated that the different flow-rate groups did not differ in their level of anticipation during the pre-shift flow rate, $F(2, 33) = 0.42$, *ns*, even though each group viewed a different flow rate value during the initial 40 pictures (see Figure 4). The relatively low rate of anticipation in each group most likely reflects the relatively complex temporal structure in these picture sequences compared to those of Experiment 1. This possibility is supported by the anticipatory behavior of the Medium/Medium group whose percentage of anticipations continued to increase, though not significantly, in the post-shift phase (see below and Figure 4). Regardless, this finding indicates that any difference exhibited by the groups after the flow-rate shift was not due to differences in anticipation rate that existed before the shift to the final flow rate.

To assess whether a shift in flow rate produced a change in anticipation performance, a repeated measures 3 × 2 ANOVA was conducted on the percentage of anticipations with flow group (Long/Medium, Short/Medium, and Medium/Medium) as the between-subject variable and phase (pre-shift and post-shift) as the within-subject variable. Neither the main effect of flow group, $F(2, 33) = 2.49$, nor

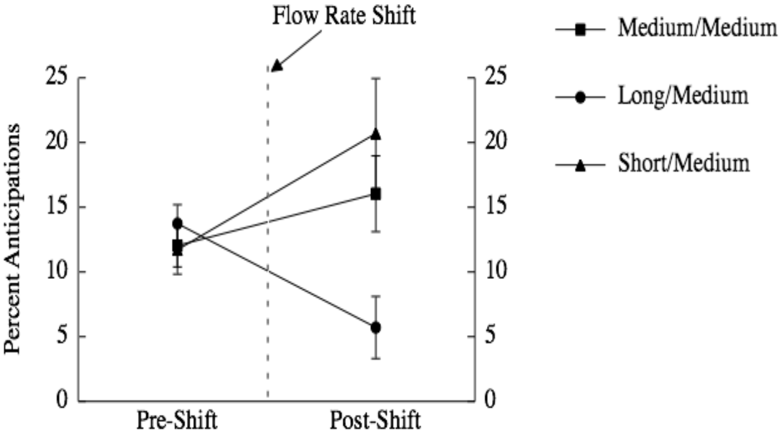

FIGURE 4 Percentage of anticipations as a function of flow group (Medium/Medium, Long/Medium, and Short/Medium), and phase (pre-shift and post-shift) in Experiment 2. Vertical error bars indicate +/- SE

phase, $F(1, 33) = 0.84$, was significant. This result indicates that across all trials (pre- and post-shift combined), the groups did not differ in their level of anticipatory eye movements and that across all groups there was an equivalent level of anticipations before the flow rate shift and after. The interaction of flow group and phase, however, was significant, $F(2, 33) = 7.90, p < .002$, indicating that the number of anticipations after the shift relative to the number before the shift was not equivalent for the three groups. That is, the significant interaction suggests that the average number of infants' anticipations changed from pre-shift to post-shift and that the direction of this change differed between the groups.

In order to examine this interaction effect in more detail, independent paired *t*-tests were conducted comparing the percentage of anticipations before the shift to the percentage of anticipations after the shift for each group. For the Medium/Medium flow group, this analysis revealed no significant difference between the percentage of anticipations in the post-shift phase ($M = 16.04\%$, $SD = 10.15$) relative to the pre-shift phase ($M = 12.04\%$, $SD = 5.71$), $t(11) = 1.85$, *ns*, with a 95% confidence interval of 22.48–15.67%. The slight increase in anticipations exhibited by this group, however, as mentioned before, was most likely due to continued learning of the spatiotemporal picture sequence whose temporal structure was relatively complex. For the Long/Medium flow group, the percentage of anticipations in the post-shift phase ($M = 5.71\%$, $SD = 8.31$) decreased significantly relative to the pre-shift phase ($M = 13.74\%$, $SD = 5.06$), $t(11) = 2.92, p < .015$, with a 95% confidence interval of 10.99–16.96%. This result suggests that infants in this group had formed an expectation for the longer flow rate during the pre-shift phase and delayed their eye movements during the shorter flow rate of the post-shift phase, resulting in a decrease in the number of anticipations. For the Short/Medium flow group, the percentage of anticipations in the post-shift phase ($M = 20.70\%$, $SD = 14.72$) increased significantly relative to the pre-shift phase ($M = 11.72\%$, $SD = 6.55$), $t(11) = 2.19$, $p = .05$, with a 95% confidence interval of 30.06–15.89%. Infants in this group apparently formed an expectation for the shorter flow rate during the pre-shift phase, and when the flow rate changed to a longer one, infants based their anticipations on the pre-shift flow rate, leading to an increase in the number of anticipations.

Latencies of reactive eye movements. To assess whether the different groups showed comparable saccadic reactive latencies, a one-way ANOVA was conducted on the median reactive latencies for the 40 pictures of the pre-shift flow rate phase, with flow group (Long/Medium, Short/Medium, and Medium/Medium) as the between-subject variable. The reactive latencies of the different flow groups did not differ during the pre-shift flow rate, $F(2, 33) = 0.42$, *ns*, of 40 pictures (see Figure 5). Thus, any difference between the groups that might occur after the flow-rate shift could not be due to differences in performance before the shift.

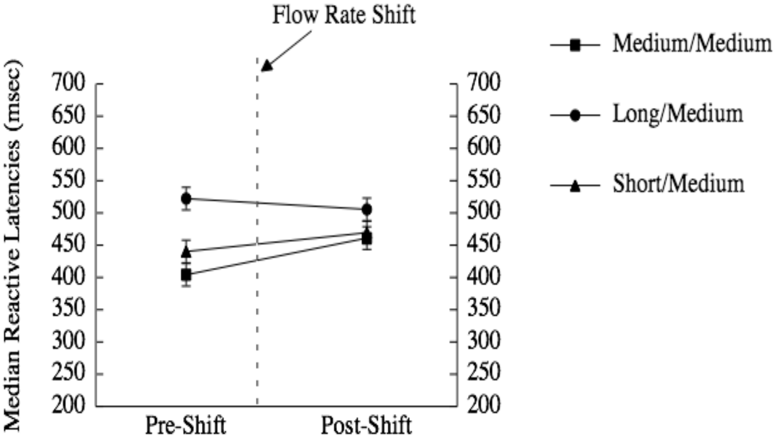

FIGURE 5 Median saccadic latencies as a function of flow group (Medium/Medium, Long/Medium, and Short/Medium), and phase (pre-shift and post-shift) in Experiment 2. Vertical error bars indicate +/– SE.

To assess whether shifting infants from one flow rate to another led to a change in median reactive latencies, a repeated measures 3 × 2 ANOVA was conducted on the infants' saccadic latencies after picture onset with flow group (Long/Medium, Short/Medium, and Medium/Medium) as the between-subject variable and phase (pre-shift and post-shift) as the within-subject variable. The main effect of flow group, $F(2, 66) = 3.98$, $p < .05$, was significant. Post-hoc *t*-tests indicated that the Long/Medium group had longer latencies overall than either the Short/Medium group, $t(22) = 2.46$, $p < .05$, or the Medium/Medium group, $t(22) = 2.53$, $p < .02$ (see Figure 5). However, the Short/Medium and the Medium/Medium groups did not differ from each other, $t(22) = 0.81$, *ns*. Neither the main effect of phase, $F(1, 66) = 0.91$, nor the interaction of flow group with phase, $F(2, 66) = 0.78$, was significant (see Figure 5). These results indicate that, as in Experiment 1, the manipulation of temporal information in this experiment had no systematic effect on infants' saccadic reactive latencies, even though it did on their anticipations.

Both the current finding of an anticipation/latency dissociation and the one found by Adler and Haith (2003) is contrary to the theoretical assumptions and previous findings outlined in Haith et al. (1993) in which anticipations and facilitation of eye movement latencies were both considered as measures of the same expectation process. The current findings, in conjunction with those of Adler and Haith (2003), call into question the theoretical assumptions of Haith et al. (1993) regarding the relation of anticipation and reactive eye movements to the construct of expectations, and suggests that a rethinking of this relation is required.

GENERAL DISCUSSION

The purpose of the current study was to examine how time information affects infants' behavioral efficiency. Findings from both experiments in this study indicate that 3-month-old infants do process time information of event onset and that their behavioral efficiency in terms of the frequency of anticipatory eye movements reflect temporal processing. Specifically, Experiment 1 demonstrated that infants were more efficient when the timing of events was predictable than when it was unpredictable, resulting in a higher frequency of anticipations in the temporally predictable condition. In Experiment 2, infants' anticipation frequency was sensitive to their processing of the temporal flow rate, which became manifest through its dependence on the direction of change in the temporal flow rate. These studies demonstrate that infants' cognitive mechanisms include the capacity to process time on a millisecond scale and that their subsequent behavior is in part based on the encoded event timing.

The developmental existence of such temporal processing and its importance in the development of cognitive processing and behavior has been contemplated since practically the beginning of the field of developmental science, as Lewkowicz (1989) noted. Though a few studies have demonstrated infant capacities related to time processing, including the sensitivity to audiovisual synchrony (e.g., Kuhl & Meltzoff, 1988; Spelke, 1979; for literature reviews, see Lewkowicz, 1989, 1992) and remembering events' temporal order (e.g., Bauer et al., 1998; Gulya et al., 1998), they have not assessed the processing of specific timing information as opposed to relative timing information. The present study was designed, therefore, to address whether young infants can process specific time information by allowing infants to respond differentially to two different timings with a behavior (i.e., anticipatory eye movements) that could be temporally matched to the timing information in the event. Initially, findings indicated that infants did indeed match the timing of their anticipations to the timing of event onset in the temporally predictable condition in Experiment 1. That is, infants' anticipations occurred later and therefore closer to the onset of the expected event when the ISI was 1200 msec than when it was 800 msec. This finding suggested that 3-month-old infants were capable of processing and encoding the specific timing of event onset and did so for two timings simultaneously. Analysis of the temporally unpredictable condition, in which infants also apparently delayed the timing of their anticipations on 1200-msec ISI trials relative to 800-msec trials, although they had no basis for knowing the forthcoming ISI for a picture, however, made the conclusion from the temporally predictable condition untenable. Instead, another temporal parameter in the event sequence must have been supporting the timing of infants' anticipations in both the temporally predictable and unpredictable conditions.

It seemed likely that the cue that enabled infants to match their anticipatory timing to picture events was the ISI timing of the previous event. That is, if the previous timing was long (1200 msec) then the infants expected the next event to have a short timing onset (800 msec) and thereby timed the execution of the anticipation accordingly, and vice versa. This analysis suggested that infants were processing not the timing of individual events, but the average timing at which events flowed in the sequence. That infants were processing the average flow rate and not specific event timing was supported by the findings of Experiment 2, in which infants who were trained with one flow rate and were then switched to either a shorter or longer flow rate exhibited either a decrease or an increase in anticipations, reflecting the carryover of their expectation for the training flow rate to the new flow rate. Thus, though the present study failed to find evidence that 3-month-old infants process and encode the timing of individual events, they do seem capable of processing the average flow or timing rate of event sequences and can time their anticipations accordingly, demonstrating a sophisticated temporal processing capacity.

The temporal processing capacity identified in the present study might be a basis for infants' cognitive processing of their natural environment which typically consists of event flow rather than the occurrence of individual events. Predators, for example, depend on the flow rate of the motion of prey for successful attack rather than on the anticipated appearance of a target at a specific time and place. Lee (1980) has elegantly described the diving performance of the Gannett as it fishes. In free fall, the Gannett processes the flow rate of the visual expansion of reflections on the water so that it can fold its wings just milliseconds before it hits the water, thereby preventing breaking the wings on impact. Infants also seem to process event flow in order to detect and anticipate nipple presentation in coordination with mouth opening or to track and catch objects in motion (Berthier, Bertenthal, Seaks, Sylvia, Johnson, & Clifton, 2001; Spelke & von Hofsten, 2001; von Hofsten, Kochukhova, & Rosander, 2007) or to blink or otherwise avoid objects approaching the face before contact (Kayed & van der Meer, 2007; Nanez & Yonas, 1994; Schmuckler, Collimore, & Dannemiller, 2007; Yonas, 1981). Furthermore, whether infants appreciate the animate motion from point-light displays likely relies on the processing of the temporal flow rate of the set of point lights rather than individual ones (Arterberry & Bornstein, 2002; Bertenthal, 1993; Bertenthal, Proffitt, Spetner, & Thomas, 1985).

Similarly, one of the more important cognitive capacities that requires the processing of information flow occurs during language development, where the temporal rate of speech sounds needs to be processed in order to detect and discriminate phonemes, words, and sentences (e.g., Jusczyk, Rosner, Reed, & Kennedy, 1989). Further support of the critical role of temporal flow rate processing during language acquisition comes from the fact that disruption of the capacity to process the flow of temporal information has been suggested to be related to language disorders such as dyslexia (Benasich, 2002; Benasich & Tallal, 2002). Thus, the capacity to process temporal flow rate information in infancy seems to underlie the cognitive processing of varied types of information involved in infants' detection and interaction with an array of natural events, including feeding, probable collisions, and language. The present modification of the VExP has demonstrated that the processing of events' temporal flow rate information is present in infants at 3 months and likely serves as an important mechanism in their detection and learning about the regularity of and consequential interaction with environmental events.

The present modification of the VExP, which taps the ability of infants to form expectations for temporal regularity of events, also contributes to an articulation of the constituents of infants' expectations and points to cognitive functioning. The findings from several studies indicate that infant performance in the VExP reflects cognitive activity. Infant performance in the VExP is related to early childhood performance on IQ tests (DiLalla, Thompson, Plomin, Phillips, Fagan, Haith, Cyphers, & Fulker, 1990; Dougherty & Haith, 1997), to the IQ of the infants' parents (Benson, Cherny, Haith, & Fulker 1993), and to fetal exposure to teratogens, such as alcohol, that are thought to affect cognitive functioning (Jacobson, Jacobson, & Sokol, 1994). Wentworth and Haith (1992) discussed the what, where, and when of expectations in a study that demonstrated that infants form expectations for event content (also see Adler & Haith, 2003) as well as for location and time. Previous visual expectation studies have focused primarily on expectations for events' spatial, or where, information (e.g. Haith et al., 1988), and a couple of studies have investigated expectations for events' content, or what, information (Adler & Haith, 2003; Wentworth & Haith, 1992). Perhaps future investigations with the VExP will permit investigators to assess not only the precision of infants' time estimates but also to what extent individual differences in the formation of expectations reflect processing of the time, space, and content components.

This study began by posing three questions: (1) Do infants' expectations for each event include a timing component? (2) Can infants process and encode two time intervals simultaneously? (3) Can infants form expectations for events that appear in asymmetric timing patterns? The answer to the first question is that infants' expectations clearly contain a time component. However, in answering no to the second question, the time component did not take the form of processing and encoding the specific timing of two individual events but was in the form of processing and encoding the average temporal flow rate at which events occurred in the sequence. Finally, in answer to the third question, infants were able to form an expectation for events that had asymmetric timing patterns. Future research into the development of infants' temporal processing capacity will determine when infants are able to process and encode the timing of individual events and what the relation is between infants processing of specific event timing and other aspects of their temporal cognition. In the end, for the infant, time is not an illusion but a real parameter in their information processing.

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REFERENCES

Adler, S. A., & Haith, M. M. (2003). The nature of infants' visual expectations for event content. *Infancy, 4*, 389–421.

Arterberry, M. E., & Bornstein, M. H. (2002). Infant perceptual and conceptual categorization: The roles of static and dynamic stimulus attributes. *Cognition*, *86*, 1–24.

Atkinson, J. (2000). *The developing visual brain*. Oxford, UK: Oxford University Press.

Bauer, P. J., Hertsgaard, L. A., Dropik, P., & Daly, B. P. (1998). When even arbitrary order becomes important: Developments in reliable temporal sequencing of arbitrarily ordered events. *Memory, 6*, 165–198.

Benasich, A. A. (2002). Impaired processing of brief, rapidly presented auditory cues in infants with a family history of autoimmune disorder. *Developmental Neuropsychology*, *22*, 351–372.

Benasich, A. A., & Tallal, P. (1993). An operant conditioning paradigm for assessing temporal processing in 6- to 9-month-old infants. *Annals of the New York Academy of Science, 682*, 312–314.

Benasich, A. A., & Tallal, P. (2002). Infant discrimination of rapid auditory cues predicts later language impairment. *Behavioral Brain Research, 136*, 31–49.

Benson, J. B., Cherny, S. S., Haith, M. M., & Fulker, D. W. (1993). Rapid assessment of infant predictors of adult IQ: Midtwin/midparent analyses. *Developmental Psychology, 29*, 434–447.

Bertenthal, B. I. (1993). Infants' perception of biomechanical motions by infants: Intrinsic image and knowledge based constraints. In C. Granrud (Ed.), *Visual perception and cognition in infancy* (pp. 175–214). Hillsdale, NJ: Erlbaum.

Bertenthal, B. I., Proffitt, D. R., Spetner, N. B., & Thomas, M. A. (1985). The development of infant sensitivity to biomechanical motions. *Child Development*, *56*, 531–543.

Berthier, N. E., Bertenthal, B. I., Seaks, J. D., Sylvia, M. R., Johnson, R. L., & Clifton, R. K. (2001). Using object knowledge in visual tracking and reaching. *Infancy*, *2*, 257–284.

Canfield, R., & Haith, M. M. (1991). Active expectations in 2- and 3-month-old infants: Complex event sequences. *Developmental Psychology, 27*, 198–208.

Carver, L. J., & Bauer, P. J. (1999). When the event is more than the sum of its parts: 9-month-olds' long-term ordered recall. *Memory*, *7*, 147–174.

Church, R. M., Meck, W. H., & Gibbon, J. (1994). Application of scalar timing theory to individual trials. *Journal of Experimental Psychology: Animal Behavior Processes, 20*, 135–155.

Colombo, J., & Richman, W. A. (2002). Infant timekeeping: Attention and temporal estimation in 4-month-olds. *Psychological Science, 13*, 475–479.

Cutting, J. E., & Readinger, W. O. (2002). Perceiving motion while moving: How pairwise nominal invariants make optical flow cohere. *Journal of Experimental Psychology: Human Perception and Performance, 28*, 731–747.

Davies, P. (2002). That mysterious flow. *Scientific American, 287*, 40–47.

DiLalla, L. F., Thompson, L. A., Plomin, R., Phillips, K., Fagan, J. F., Haith, M. M., Cyphers, L. H., & Fulker, D. W. (1990). Infant predictors of preschool and adult I.Q.: A study of infant twins and their parents. *Developmental Psychology, 26*, 759–769.

Dougherty, T., & Haith, M. M. (1997). Infants' use of constraints to speed information processing and to anticipate events. *Infancy, 3*, 457–473.

Fitzgerald, H. E., Lintz, L. M., Brackbill, Y., & Adams, G. (1967). Time perception and conditioning of an autonomic response in young infants. *Perceptual and Motor Skills, 24*, 479–486.

Friedman, W. (1990). *About time: Inventing the fourth dimension*. Cambridge, MA: MIT Press.

Gulya, M., Rovee-Collier, C., Galluccio, L., & Wilk, A. (1998). Memory processing of a serial list by young infants. *Psychological Scienc*e*, 9*, 303–307.

Haith, M. M. (1997). The development of future thinking as essential for the emergence of skill in planning. In S. Friedman and E. Scholnick (Eds.), *Why, how and when do we plan? The developmental psychology of planning* (pp. 25–42). Hillsdale, NJ: Erlbaum Associates.

Haith, M. M., Hazan, C., & Goodman, G. S. (1988). Expectation and anticipation of‹‹dynamic visual events by 3.5-month-old babies. *Child Development, 59*, 467–479.

Haith, M. M., & McCarty, M. (1990). Stability of visual expectations at 3.0 months of age. *Developmental Psychology, 26*, 68–74.

Haith, M. M., Wentworth, N., & Canfield, R. L. (1993). The formation of expectations in early infancy. In C. Rovee-Collier & L. P. Lipsitt (Eds.), *Advances in infancy research* (Vol. 8, pp. 251–298). Norwood, NJ: Ablex Publishing.

Hanes, D. P., Patterson, W. F., & Schall, J. D. (1998). Role of frontal eye fields in countermanding saccades: Visual, movement and fixation activity. *Journal of Neurophysiology, 79*, 817–834.

Herrnstein, R. J. (1970). On the law of effect. *Journal of the Experimental Analysis of Behavior, 13*, 243–266.

Jacobson, S. W., Jacobson, J. L., & Sokol, R. J. (1994). Effects of fetal alcohol exposure on infant reaction time. *Alcoholism: Clinical and Experimental Research, 18*, 1125–1132.

Johnson, M. H. (1996). From cortex to cognition: Cognitive neuroscience studies of infant attention and perception. In C. Rovee-Collier & L. Lipsitt (Eds.), *Advances in infancy research* (Vol. 10, pp. 161–218). Norwood, NJ: Ablex Publishing.

Johnson, S. P., Amso, D., & Slemmer, J. A. (2003). Development of object concepts in infancy: Evidence for early learning in an eye-tracking paradigm. *Proceedings of the National Academy of Science, 100*, 10568–10573.

Johnson, S. P., & Mason, U. (2002). Perception of kinetic illusory contours by two-month-old infants. *Child Development, 73*, 22–34.

Jonsson, B., & von Hofsten, C. (2003). Infants' ability to track and reach for temporarily occluded objects. *Developmental Science, 6*, 86–99.

Jusczyk, P. W., Pisoni, D. B., Walley, A., & Murray, J. (1980). Discrimination of relative onset time of two-component tones by infants. *The Journal of the Acoustical Society of America, 67*, 262–270.

Jusczyk, P. W., Rosner, B. S., Reed, M. A., & Kennedy, L. J. (1989). Could temporal order differences underlie 2-month-olds' discrimination of English voicing contrasts? *Journal of the Acoustic Society of America*, *85*, 1741–1749.

Kayed, N. S., & van der Meer, A. L. (2007). Infants' timing strategies to optical collisions: A longitudinal study. *Infant Behavior and Development*, *30*, 50–59.

Keating, E. G. (1991). Frontal eye field lesions impair predictive and visually-guided pursuit eye movements. *Experimental Brain Research, 86*, 311–323.

Krauzlis, R. J., Liston, D., & Carello, C. D. (2004). Target selection and the superior colliculus: Goals, choices and hypotheses. *Vision Research, 44*, 1445–1451.

Kuhl, P. K., & Meltzoff, A. N. (1988). Speech as an intermodal object of perception. In A. Yonas (Ed.), *Perceptual development in infancy: The Minnesota symposia on child psychology, 20*, 267–281.

Lee, D. N. (1980). Visuo-motor coordination in space-time. In G. E. Stelmach & J. Raquin (Eds.), *Tutorial to motor behavior* (pp. 281–295). Amsterdam: Elsevier.

Leslie, A. M. (1984). Spatiotemporal continuity and the perception of causality in infants. *Perception, 13*, 287–305.

Lewkowicz, D. J. (1989). The role of temporal factors in infant behavior and development. In I. Levin & D. Zakay (Eds.), *Time and human cognition: A life-span perspective* (pp. 9–62). Amsterdam: Elsevier.

Lewkowicz, D. J. (1992). The development of temporally-based intersensory perception in human infants. In F. Macar, V. Pouthas, & W. J. Friedman (Eds.), *Time, action and cognition* (pp. 33–43). Dordrecht, The Netherlands: Kluwer.

McSweeney, F. K., & Weatherly, J. N. (1998). Habituation to the reinforcer may contribute to multiple-schedule behavioral contrast. *Journal of the Experimental Analysis of Behavior, 69*, 199–221.

Nanez, Sr., J. E., & Yonas, A. (1994). Effects of luminance and texture motion on infant defensive reactions to optical collision. *Infant Behavior and Development*, *17*, 165–174.

Robinson, D. L., & Kertzman, C. (1995). Covert orienting of attention in macaques. III. Contributions of the superior colliculus. *Journal of Neurophysiology, 74*, 713–721.

Rovee-Collier, C. (1995). Time windows in cognitive development. *Developmental Psychology, 31*, 147–169.

Schiller, P. H. (1985). A model for the generation of visually guided saccadic eye movements. In D. Rose and V.G. Dobson (Eds.), *Models of the visual cortex* (pp. 62–70). New York: Wiley.

Schmuckler, M. A., Collimore, L. M., & Dannemiller, J. L. (2007). Infants' reactions to object collision on hit and miss trajectories. *Infancy, 12*, 105–118.

Scholl, B. J., & Tremoulet, P. D. (2000). Perceptual causality and animacy. *Trends in Cognitive Science, 4*, 299–309.

Spelke, E. S. (1979). Perceiving bimodally specified events in infancy. *Developmental Psychology, 15*, 626–636.

Spelke, E. S., & von Hofsten, C. (2001). Predictive reaching for occluded objects by 6-month- old infants. *Journal of Cognition and Development, 2*, 261–281.

Trehub, S. E. (1993). Temporal auditory processing in infancy. *Annals of the New York Academy of Science, 682*, 137–149.

von Hofsten, C. (1980). Predictive reaching for moving object by human infants. *Journal of Experimental Child Psychology, 30*, 369–382.

von Hofsten, C., Kochukhova, O., & Rosander, K. (2007). Prediction tracking over occlusions by 4-month-old infants. *Development Science, 10,* 625–640.

von Hofsten, C., Vishton, P., Spelke, E. S., Feng, Q., & Rosander, K. (1998). Predictive action in infancy: Tracking and reaching for moving objects. *Cognition, 67*, 255–285.

Walker-Andrews, A. S. (1997). Infants' perception of expressive behaviors: Differentiation of multimodal information. *Psychological Bulletin, 121*, 437–456.

Wentworth, N., & Haith, M. M. (1992). Event-specific expectation of 2- and 3-month-old infants. *Developmental Psychology, 28*, 842–850.

Williams, B. A. (2002). Behavioral contrast redux. *Animal Learning and Behavior, 30*, 1–20.

Yonas, A. (1981). Infants' responses to optical information for collision. In R. N. Aslin, J. Alberts, & M. Petersen (Eds.), *Development of perception: Psychobiological perspectives: The visual system* (Vol. 2, pp. 313–334). New York: Academic Press.