# The Development of Infants' Expectations for Event Timing

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**Abstract**

The capacity to process and incorporate temporal information into behavioural decisions is an integral component for functioning in our environment. Whereas previous research has extended adults' temporal processing capacity down the developmental timeline to infants, little research has examined infants' capacity to use that temporal information in guiding their future behaviours and whether this capacity can detect event-timing differences on the order of milliseconds. The present study examined 3- and 6-month-old infants' ability to process temporal durations of 700 and 1200 milliseconds by means of the Visual Expectation Cueing Paradigm in which the duration of a central stimulus predicted either a target appearing on the left or on the right of a screen. If 3- and 6-month-old infants could discriminate the milliseconds difference between the centrally-presented temporal cues, then they would correctly make anticipatory eye movements to the proper target location at a rate above chance. Results indicated that 6- but not 3-month-olds successfully discriminated and incorporated events' temporal information into their visual expectations. Brain maturation and the perceptual capacity to discriminate the relative timing values of temporal events may account for these findings. This developmental limitation in processing and discriminating events on the scale of milliseconds, consequently, may be a limiting factor for attentional and cognitive development that has not previously been explored.

**Keywords**

Temporal processing, visual expectations, attention, infancy, cognitive development, eye movements

## 1. Introduction

All events, both mental and environmental, occur in the thread that is the passage of time. Time, consequently, offers a source of information that individuals can use to better understand and more efficiently interact with their environment (Buhusi & Meck, 2005). Across the lifespan, individuals have been observed to detect, process,

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and modulate behaviour on the basis of events' temporal parameters (Allan, 1998; Grondin, 2010; Wearden, 2005). While the capacity to estimate events' temporal parameters is not precise (Hass & Herrmann, 2012), it remains non-random as the imprecision associated with time estimations is proportional to the temporal parameter being processed (Gibbon, 1977). The information gained from processing events' distinct timing has enabled individuals to include temporal information as a component in the functioning of their cognitive processes.

One such cognitive process, future-oriented thinking, enables individuals to plan and allocate resources towards the onset of an event prior to its occurrence (Haith, 1994). Forming expectations for an event's occurrence, therefore, enhances the efficiency of event processing. By forming expectations, which provide a foundation to facilitate behavioural allocation before a predictable future event begins (i.e., anticipation) rather than having to wait to react after the event's onset, more time to encode that future event's relevant information is afforded. That we readily form such expectations in which temporal information is encoded is demonstrated, for example, in a study by Grahn and Brett (2007) in which adults were able to form an expectation and reproduce rhythms that had accents occurring at regularly predictable intervals but not when they occurred at irregular intervals.

Developing the capacity for efficient event processing enables individuals to devote more time to processing event information by forming expectations of these events, which then can be used to develop a more enhanced knowledge base of these events and their future occurrences (Haith et al., 1993). Previous research has demonstrated that the formation of expectations for where and what events occur is readily exhibited in early infancy, likely increasing the efficiency of their processing of this information in the construction of their knowledge structures (e.g., Adler & Haith, 2003; Canfield & Haith, 1991; Haith & McCarty, 1990; Haith et al., 1988). To date, little research has been devoted to determining the role that the emergence of temporal information processing plays in the formation of expectations for future events. Considering that all natural events can be defined by their temporal parameters and infants as young as 3 months of age have been observed to form expectations (e.g., Haith et al., 1988), it seems likely that the processing of events' temporal information would be incorporated and enhance expectation and anticipation for the future occurrence of events, thereby enhancing processing efficiency further in early infancy.

Some investigations of infants' processing of events' temporal information have used a common variant of the familiarity/novelty-preference paradigm (Fagan, 1970; Fantz, 1964; Saayman et al., 1964), termed the violation-of-expectation paradigm (Baillargeon et al., 1985), to determine infants' ability to encode and detect changes in temporal sequences. In this paradigm, infants are exposed to a sequence of stimuli depicting a particular event. After multiple trials of familiarization, there is a novel trial. The novel trial is unique because it contains a stimulus event or parameter that does not conform to an experimenter-assumed

expectation that the infant is hypothesized to have. Researchers infer that any change in the infant's behaviour during the novel trial is indicative of the infant having that expectation and being able to detect the deviation from the expected event.

Using the violation-of-expectation procedure while recording changes in heart rate, Colombo and Richman (2002) exposed 4-month-old infants to a recurring flashing light stimulus on a screen. The light stimulus appeared onscreen for 2 s, then disappeared, leaving the screen dark for 3 (or 5, depending on the condition) s. The predictable onset and offset of the light stimulus occurred for eight consecutive trials. After the eighth trial, the light stimulus did not reappear on screen. Infants expressed decelerated heart rates at the expected recurrence of the light stimulus. This finding was subsequently replicated in a study by Addyman et al. (2014) with 4-, 6-, 10-, and 14-month-old infants that measured eye fixations rather than heart rate and also found that these infants could detect stimulus timings of 3 and 5 s. These findings with heart rate and eye fixation measures suggest that infants as young as 4 months of age contain a non-random capacity that enabled them to process temporal information on the scale of seconds, which can be encoded into their expectations for temporally predictable events.

Physiological findings in the form of event-related potentials (ERPs) have provided more evidence that infants may include temporal information in their expectations. Brannon et al. (2008) measured the mismatch negativity (MMN) waveform of 10-month-old infants as they heard a sequence of auditory tones. The tones were 50 ms in duration and occurred 1500 ms in succession of one another. On some trials, the tones randomly occurred 375, 500, 750, or 1000 ms after the previous tone's offset. Findings from the amplitude of the MMN waveform indicated that the size of the amplitude was mediated by the proportional difference between the standard (i.e., 1500 ms) and the random temporal occurrences of the tones. This suggested that infants can perceive and discriminate temporal information that differed from an expected temporal occurrence. Furthermore, these findings suggest that 10-month-old infants can encode temporal events on the scale of hundreds of milliseconds rather than seconds as in previous studies. Whether infants younger than 10 months of age can encode temporal events on the scale of *hundreds of milliseconds* remains an open question.

Despite these previous findings suggesting infants can include temporal information in the formation of expectations, there are methodological limitations that make these findings difficult to interpret. Perhaps counterintuitive to what the name suggests, the violation-of-expectation procedure used with younger infants does not necessarily measure expectations. An expectation is a representation and prediction concerning an event that will occur in the future. Only by measuring anticipatory behaviour prior to the expected event can one be sure the measure is investigating the underlying expectation. In contrast, changes in behaviour after an expected event has occurred — as is measured in

violation-of-expectation studies — does not require the formation of an expectation. Instead, changes in behaviour after viewing an expected event may reflect the current percept of the just-viewed event not matching a memory for the prior event. This argument does not negate the possibility that an expectation is formed and affecting behaviour in violation-of-expectation studies, but only that an expectation is not required nor definitively supported to account for the findings.

Second, findings from studies using the violation-of-expectation procedure, which are influenced by the same parameters and factors as familiarity/novelty-preference paradigms (Hunter & Ames, 1988), can easily be explained as infants exhibiting a preference for the familiar rather than the novel information in the test events (Cashon & Cohen, 2000; Cohen, 2004; Schilling, 2000). Since there are aspects of test events that are familiar in violation-of-expectation studies, infants may be responding to that familiarity rather than to any novelty (Hunter et al., 1983), such as a change in timing. Interpreting findings from violation-of-expectation studies, therefore, is inherently difficult (Aslin, 2007).

Third, it is difficult to determine from the specific violation-of-expectation studies of temporal processing if infants are forming expectations for distinct temporal events or are simply expressing signs of entrainment to the repetitive stimuli. Since the novel test trial occurs after a sequence of repetitive learning trials, it is impossible to distinguish between whether they have processed and encoded specific temporal values or their measured behaviour has been synced to occur at the temporal rhythm of the events.

The present study overcomes these issues by using an eye movement task to investigate whether infants can form expectations on the basis of events' temporal information. By being able to cognitively index the temporal predictability of events and form expectations, infants would be able to make predictions about these events, anticipate them, and thereby have more time to process them. Having more time to process an event leads to more efficient information processing and better comprehension (Haith et al., 1994).

Initially designed to investigate infants' capacity to form expectations about events' distinct spatial parameters, the Visual Expectation Paradigm (VExP) assesses infants' ability to visually anticipate the future location of images on a screen (Haith et al., 1988). In the typical VExP, infants view images presented with a fixed duration (e.g., 700 ms) and a fixed interstimulus interval (e.g., 1000 ms) between stimulus presentations in a simple, left-right alternating sequence. If an infant learns the predictable sequence of stimulus events and constructs an expectation for where an image should appear, then initiating an eye movement to that particular area on a blank screen before that stimulus has been presented is a behavioural response (i.e., anticipation) that has been guided by an internal representation (i.e., expectation) of the predictable spatial sequence of events. Successive studies using the VExP have revealed that infants' anticipatory looking patterns occur even when the spatial complexity of the sequence of images

(Canfield & Haith, 1991) and the content predictability of the images (Adler & Haith, 2003; Wentworth & Haith, 1992) were manipulated.

But events are defined by more than just their spatial and content parameters, one example being their temporal properties. Yet, whether infants encode event-specific temporal parameters in their expectation representation had not been initially explored in the context of the VExP. To assess infants' capacity to form an expectation for the temporal parameters of events, Adler et al. (2008) attempted to determine if 3-month-old infants encode events' temporal parameters by manipulating both event duration and the interval between events, simultaneously. While 3-month-old infants failed to encode the timing of specific stimulus events, they did encode the overall temporal flow rate (i.e., the average timing of the event durations and intervals) of the sequence of stimulus events. This was observed by a change in the frequency of anticipatory eye movements being mediated by increasing or decreasing the temporal flow rate of events relative to the initial temporal flow rate encoded during expectation formation.

The purpose of the present study was to further investigate the emergence of temporal information in the formation of expectations for future events. Unlike previous research that investigated young infants' capacity to perceive differences in time with use of the violation-of-expectation paradigm, this study will use a variation of the VExP. In contrast to the Adler et al. (2008) VExP study on temporal encoding, however, the current study will manipulate only one of the events' temporal parameters, namely, their duration. Further, in contrast to most studies with young infants that have assessed capacity to discriminate and encode temporal durations that differed on the order of seconds, the current study tested infants younger than 10 months of age with temporal durations that differed instead on the order of milliseconds. Determining whether infants are capable of encoding and discriminating temporal durations on the milliseconds scale is critical as most significant perceptual events and components of events span and are distinguished by differences of hundreds of milliseconds in duration (Ivry & Spencer, 2004).

In order to investigate the development of temporal information encoding in the formation of expectations for future events, the present study used a variant of the VExP known as the Visual Expectation Cueing Paradigm (VExCP). In this paradigm, if infants are able to discriminate the perceptual parameter that distinguishes central cues, then infants should be able to correctly anticipate the location of spatially-associated target stimuli at a rate above chance performance (Baker et al., 2008; Comishen et al., 2019). In the current study, therefore, 6- and 3-month-old infants viewed stimuli in the VExCP that contained central cues that were perceptually distinguishable from one another by the duration for which they were displayed. One temporal cue duration (e.g., 700 ms) predicted a target appearing on one side of the screen (e.g., right), whereas a different temporal cue duration (e.g., 1200 ms) predicted a target appearing on the other side

of the screen (e.g., left). If infants could discriminate the milliseconds difference between the cues' temporal durations (700 vs 1200 ms) and were able to encode events' temporal information into their expectations, then they would be able to correctly anticipate the spatial location of the cued targets at a rate above chance.

## 2. Experiment 1 — Temporal Cueing in 6-Month-Old Infants

### 2.1. Materials and Method

#### 2.1.1. Participants
Twenty-four 6-month-old infants (11 males, 13 females), who ranged in age from 168 to 201 days ($M = 180.9$ days, SD = 8.8) and came predominately from middle social economic status (SES), were recruited from a mailing list supplied by a Toronto-area marketing company (Z Retail Marketing Company Inc., Toronto, ON, Canada) and participated in this study. The infants were of Caucasian ($n = 13$), Asian ($n = 2$), African ($n = 1$), Hispanic ($n = 2$), and Other ($n = 6$) ethnic backgrounds. An additional 20 infants participated in the study but were excluded due to crying or general fussiness ($n = 12$), inattentiveness (i.e., provided data on less than 65% of the trials; $n = 5$), or experimental error (e.g., eye-tracker failed to detect eye movements; $n = 3$). All infants were born at full term, in good health, and with no apparent visual, neurological, or other abnormalities as documented by parental report. Informed consent was given by a parent of each infant.

#### 2.1.2. Stimuli and Apparatus
The stimuli were computer-generated images that were approximately 4.5° in diameter. The cues were identical pink and grey checkerboards, whereas the target stimuli were images of vertical stripes, concentric circles, and diamond shapes in various colour combinations of red, green, blue, and yellow.

The infants were laid supine in a specialized crib and viewed the stimuli on a 19-inch LCD colour monitor with $1024 \times 768$ pixel resolution that was mounted 48 cm overhead (see Fig. 1). There was a $30 \times 30$ cm infrared-reflecting, visible-transmitting mirror between the infant and monitor. A remote, pan-tilt infrared eye-tracking camera (Model 504, Applied Science Laboratories [www.a-s-l.com], Bedford, MA, USA) emitted infrared light that was reflected off the mirror and into the infant's eye. The reflection of the infrared light coming back from the infant, through the pupil, and off the mirror was recorded by the camera at a temporal resolution of 60 Hz. To minimize outside light entry and distraction inside the crib, black felt curtains were drawn over and around the crib.

Infrared light emitted from the diodes on the camera reflected from the mirror into the infants' eye, and then reflected back from the infants' retina through the pupil, producing a backlit white pupil. In addition, the infrared light produced a point of reflection on the cornea of the infants' eye. Using proprietary software (Applied Sciences Laboratories), the eye position at every 60 Hz sampling was
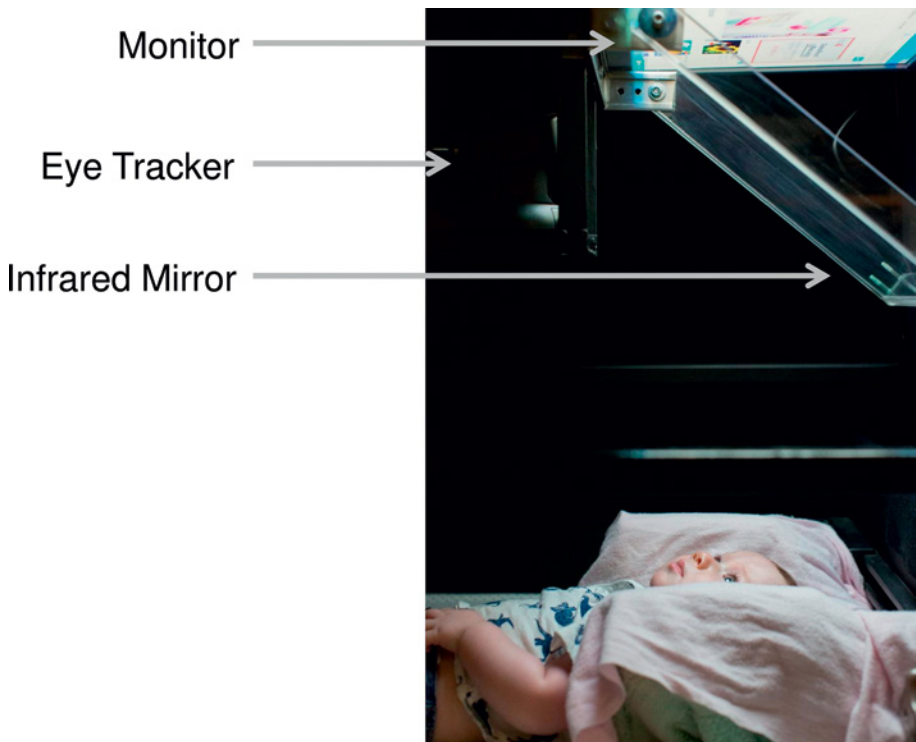
**Figure 1.** Image of the specialized crib used with infants, showing the monitor on which stimuli were presented, the model 504 infrared eye tracking camera, and the infrared mirror.

calculated as the relation between the centroid of the backlit pupil and the corneal reflection. The eye-tracker was calibrated by having each infant view a continuous loop of varying shapes and colours at two known locations on the screen. All future recorded eye-tracker fixation values were filtered through the calibration file to produce measures of eye position data.

Throughout each session, two Dell computers were used. One computer generated and presented the stimuli using the program DirectRT (Empirisoft Inc., New York, NY, USA; www.empirisoft.com/DirectRT.aspx). The stimuli generated and displayed by this computer were projected on the LCD monitor that was situated above the infant in the crib (see Fig. 1). The second computer was used to control the eye-tracker and record the eye movement data. The stimulus-generating computer sent a unique, time-stamped numerical code, indicating the onset and type of stimuli, through a parallel port to the data-collecting computer. Synchronization of the unique code with the eye movement data in the data file allowed coordination of the eye movement sequences to specific stimuli and their onsets.

### 2.1.3. Procedure

After being properly and comfortably situated in the crib, each infant was first exposed to a calibration protocol to equate their eye position with known spatial locations on the stimulus monitor. Following successful calibration, each infant was then exposed to 60 experimental trials. All trials started with either the 700 or 1200 ms cue being displayed at the centre of a greyscale screen for their respective duration. The cue duration displayed on any given trial was selected at random, but with the criterion that every infant was exposed to each cue duration for a total of 30 trials. After cue offset, an interstimulus interval (ISI) of 1000 ms followed during which the screen was blank. After the ISI, one of six target stimuli were randomly selected and presented either on the left or right side of the screen with a visual angle of 5.5° from the centre of the screen and the cue. The target remained fixed on the screen for 1000 ms. At target offset, the screen remained blank for an intertrial interval of 500 ms, after which the cue reappeared at the centre of the screen signalling the onset of the next trial (see Fig. 2). On average, each experimental session was about 30 minutes in duration.

Infants were randomly assigned to one of two conditions. In the predictable condition ($n = 12$), the cue duration indicated with 100% validity the subsequent target location; for example, a 700 ms cue duration always indicated that the
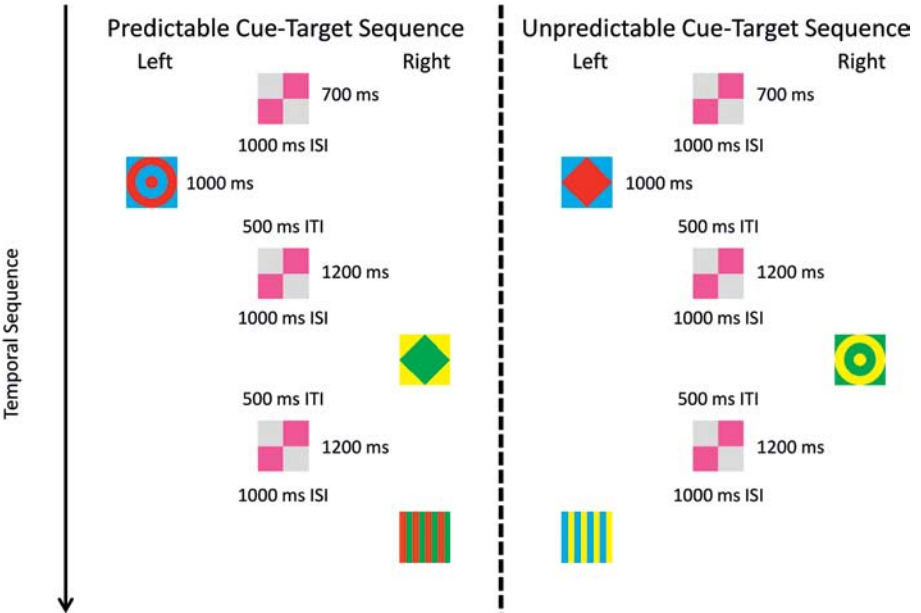


**Figure 2.** Schematic of experimental procedure and stimulus temporal sequence in conditions in which the cue duration–target location relation was either predictable or unpredictable. Each infant was assigned to one of the two condition types. In the predictable condition, the cues' durations predicted the location of the target, but no such relations existed in the unpredictable condition — the target stimuli appeared randomly on the left and right side of the screen.

subsequent target would appear on the left. The particular cue duration–target location relation was counterbalanced across participants. In the unpredictable condition ($n = 12$), the cue duration–target location relation was random from trial to trial; for example, on one trial a 1200 ms cue duration might be followed by a target on the left, on the subsequent trial the 1200 ms cue duration might be followed by a target on the right. Consequently, in this condition, the cues' durations provided no reliable information as to side of the screen on which the target stimuli would appear. The unpredictable condition, therefore, served as a baseline assessment for infants' chance eye movement performance when there were no predictable relations upon which to form expectations.

### 2.1.4. Data Reduction and Analysis

The raw digital data recorded by the eye-tracker were imported into a MATLAB toolbox called ILAB for analysis (Gitelman, 2002). ILAB separated individual eye movements into their horizontal and vertical components, displaying them on a trial-by-trial basis. ILAB also displayed the scan path of the eye, which allowed eye movements to be analysed based on the timing, direction, and distance relative to the stimuli shown on the screen.

For an eye movement to be included in the final data sample, it had to meet a number of criteria. First, as the critical question is whether infants encode a cue's temporal information when forming expectations, the infants had to fixate on the cue for any trial to be considered valid. Second, in order for an eye movement to be counted as anticipatory it needed to occur between 133 ms after cue offset and 133 ms after target onset. This latency value was chosen as the anticipation cut-off because it has been previously determined that 6-month-old infants cannot make eye movements in reaction to the onset of a stimulus faster than 133 ms (Canfield et al., 1997). If the eye movement occurred between 133 ms after target onset and 133 ms after target offset, it was considered reactive in nature. Third, in order for an infant's data to be included in the final sample, they must have looked at the stimuli on a minimum of 65% of the trials to ensure adequate attention was present throughout the task (e.g., Adler & Haith, 2003; Adler & Orprecio, 2006). Finally, the eye movement to the target had to trace a path that was more than 50% of the distance between the cue and the target. The 50% criterion has been used in previous studies using infants' eye movements (e.g., Adler & Haith, 2003; Adler & Orprecio, 2006) and is typically taken as an indication that the eye movement was intentional and not random.

Infants' eye movement data were analysed in terms of three dependent measures. First, a total anticipation score was calculated by taking the percentage of all valid eye movements that were made to the targets that were anticipatory (correct and incorrect). Second, a correct anticipation measure was calculated as the percentage of all anticipations that localized the correct target locations. Finally, the median reactive latencies of all eye movements towards the target that were not anticipatory were calculated because reactive eye movements have been theorized

to also be facilitated by underlying expectations (Haith & McCarty, 1990; Haith et al., 1988, 1993), though this is not always the case (Adler & Haith, 2003; Adler et al., 2008). As neither the location of the target (Total Anticipations: $F = 0.04$, ns; Correct Anticipations: $F = 1.50$, ns; Reactive Latencies: $F = 0.003$, ns) nor the gender of the participants (Total Anticipations: $F = 0.77$, ns; Correct Anticipations: $F = 0.80$, ns; Reactive Latencies: $F = 1.68$, ns) were significant for any of the three measures, these variables were not considered any further in the analyses.

## 2.2. Results and Discussion

### 2.2.1. Total Anticipations

Initially, data needed be analysed to ensure that any possible differences between groups in correct anticipatory eye movements were not due to differences in the total number of anticipations made. The percent of total anticipations is shown in Table 1. A $2 \times 2$ mixed-design analysis of variance (ANOVA) was performed on the percent of total anticipations, with Condition (predictable, unpredictable) as a between-participant factor and Cue Duration (700, 1200) as a within-participant factor. The analysis revealed a significant main effect of Cue Duration, $F(1,22) = 4.69$, $p < 0.05$, $d = 0.54$, indicating that 6-month-old infants made more anticipations after viewing the 1200 ms cue ($M = 44.54\%$, SE $= 5.19$) than the 700 ms cue ($M = 35.63\%$, SE $= 4.25$). Neither the main effect of Condition nor the interaction between Condition and Cue Duration were significant, both $F$s $< 1.71$ . Cue duration likely influenced the total number of anticipations made due to infants having more time with the 1200 ms cue to process an expectation and program an anticipatory eye movement. Since neither condition, however, elicited a difference in the total number of anticipations, any difference subsequently observed in correct anticipations as a function of condition cannot be attributed to differences in total anticipations.

### 2.2.2. Correct Anticipations

To determine if 6-month-old infants can discriminate and encode distinct temporal information when forming expectations, the percentage of anticipations that correctly predicted the target's location was assessed. If 6-month-old infants encode event-specific temporal information when forming expectations, then because there are predictable cue duration–target location relations in the predictable condition, correct anticipations should occur at a rate greater than chance performance (i.e., 50%). In contrast, infants in the unpredictable condition should make
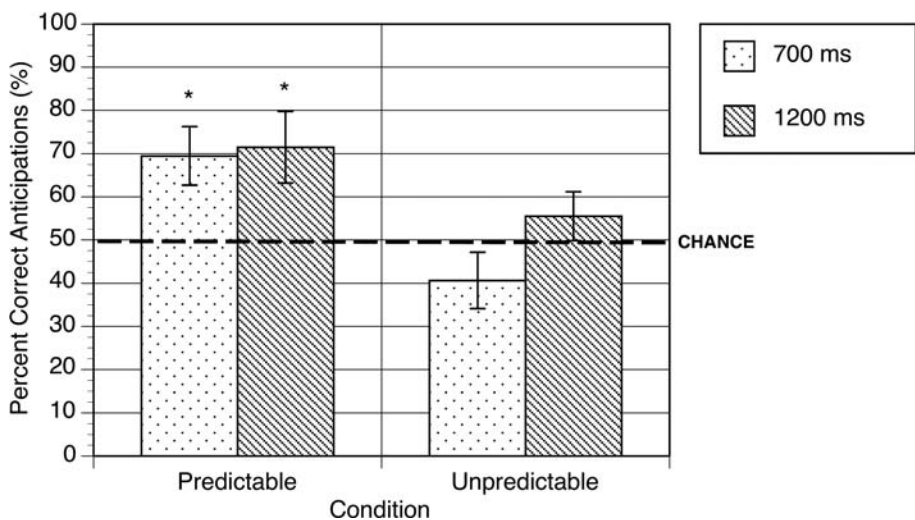
**Table 1.**
Percent of total anticipations (standard error) made during Experiment 1.

| Cue duration | Predictable | Unpredictable |
| --- | --- | --- |
| 700 ms | 30.63 (3.67) | 40.64 (4.82) |
| 1200 ms | 44.93 (5.91) | 44.16 (4.47) |

correct anticipations at a rate not different than chance performance since there are no predictable cue duration–target location relations.

A 2 × 2 mixed-design ANOVA was performed on the percent of correct anticipations with Condition (predictable, unpredictable) as a between-participant factor and Cue Duration (700, 1200) as a within-participant factor. The analysis revealed a significant main effect of Condition, $F(1,22) = 10.44$, $p < 0.01$, $d = 0.94$, indicating that 6-month-old infants made more correct anticipations in the predictable condition ($M = 70.49\%$, SE $= 5.25$) than in the unpredictable condition ($M = 48.05\%$, SE $= 4.49$). This finding indicates that 6-month-old infants were able to discriminate the cues' durations and successfully use the temporal information when the cue duration–target location relations were predictable. There was no main effect of Cue Duration or a significant interaction between Condition and Cue Duration, both $Fs < 1.53$, however, indicating that there was no difference in the percentage of correct anticipations between the two temporal cues overall or across each condition. These data are shown in Fig. 3.

Whereas the previous analysis exhibited a difference in percentage of correct anticipations due to condition type, it did not take into account if the 6-month-old infants made correct anticipations at a rate that was significantly greater than chance (i.e., 50%). One-tailed, one-sample $t$-tests using the Benjamini–Hochberg procedure with a false discovery rate of 0.05 indicated that 6-month old infants in the predictable condition made correct anticipations at a rate greater than 50% after viewing cues with a duration of 700 ms, $t(10) = 2.76$, $p < 0.05$, $d = 0.83$, and 1200 ms, $t(11) = 2.59$, $p < 0.05$, $d = 0.75$. Six-month-old infants in the
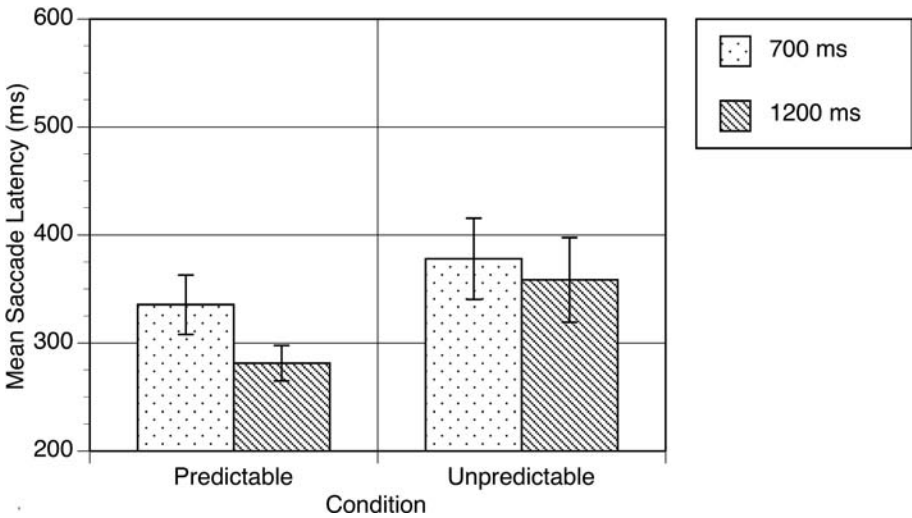


**Figure 3.** Mean percent of correct anticipations that 6-month-old infants initiated to the targets as a function of cue duration in both the predictable and unpredictable conditions. Asterisks indicate performance that was significantly greater than chance performance. Error bars represent +/− 1 standard error of the mean.

unpredictable condition, however, made correct anticipations at a rate not significantly greater than chance after viewing cues with a duration of 700 ms, $t(11)$ = 1.44, ns, or 1200 ms, $t(11)$ = 0.97, ns. These findings indicate that infants processed, discriminated, and encoded the different time values and formed expectations for target location as a function of event-specific temporal information (see Fig. 3).

### 2.2.3. *Reactive Latencies*

As intimated from the total anticipation levels, infants do not exhibit anticipations on every trial but instead exhibit eye movements to targets in reaction to their onset. Some previous expectation studies have suggested that facilitation of reactive latencies occurs when any expectation is formed for predictable events (e.g., Haith et al., 1988), whereas other studies suggest that the facilitation only occurs under particular conditions (e.g. Adler & Haith, 2003). A $2 \times 2$ mixed-design ANOVA was therefore performed on median reactive latencies, with Condition (predictable, unpredictable) as a between-participant factor and Cue Duration (700, 1200) as a within-participant factor. This analysis revealed that neither the main effect of Condition, $F(1,22)$ = 3.06, ns, nor Cue Duration, $F(1,22)$ = 1.65, ns, were significant. The interaction between Condition and Cue Duration, $F(1,22)$ = 0.37, ns, was also not significant. Though the reactive latencies are somewhat shorter in the predictable than the unpredictable group, the results from this analysis indicate that the predictability of the cue duration–target location relations did not influence 6-month-old infants' reactive latencies towards the targets (see Fig. 4).



**Figure 4**. Mean reactive latencies of eye movements that 6-month-old infants initiated to the targets as a function of cue duration in both the predictable and unpredictable conditions. Error bars represent +/− 1 standard error of the mean.

### 3. Experiment 2 — Temporal Cueing in 3-Month-Old Infants

Considering the findings from Experiment 1 and previous time perception studies with new-borns (de Hevia et al., 2014) and younger infants (e.g., Adler et al., 2008; Boswell et al., 1994; Clifton, 1974) the possibility exists that the encoding of temporal information in infants' visual expectations may occur earlier in life. The purpose of this experiment was to attempt to determine a developmental timeline for the capacity to detect differences in time on the scale of milliseconds and if such information can be encoded in infants' expectations. To this end, Experiment 2 was identical to Experiment 1 with the notable exception that 3-month-old infants were the population of interest. Furthermore, since 3-month-old infants have been observed to encode the spatial (Canfield & Haith, 1991) and content information (Adler & Haith, 2003; Wentworth & Haith, 1992) of individual events into their visual expectations, this experiment had the potential of determining whether event-specific temporal information was as well. Thus, the current experiment was intended to determine whether 3-month-old infants can discriminate and encode event-specific temporal information in the service of moderating active behaviour.

#### 3.1. Method

#### 3.1.1. Participants
Twenty-four 3-month-old infants (15 males, 9 females), who ranged in age from 91 to 127 days ($M = 104.2$ days, SD = 9.0) and came predominately from middle SES, were recruited from a mailing list supplied by a Toronto-area marketing company (Z Retail Marketing Company Inc., Toronto, ON, Canada) and participated in this study. The infants were of Caucasian ($n = 13$), Asian ($n = 3$), African ($n = 2$), Hispanic ($n = 1$), and Other ($n = 5$) ethnic backgrounds. An additional 16 infants participated in the study but were excluded due to crying or general fussiness ($n = 5$), or inattentiveness (i.e., provided data on less than 65% of the trials; $n = 11$). All infants were born at full term, in good health, and with no apparent visual, neurological, or other abnormalities as documented by parental report. Informed consent was given by a parent of each infant.

#### 3.1.2. Stimuli and apparatus
The stimuli and apparatus used for Experiment 2 were identical to those used in Experiment 1.

#### 3.1.3. Procedure
The procedure used for Experiment 2 was identical to that used in Experiment 1. On average, each experimental session was about 30 minutes in duration.

#### 3.1.4. Data Reduction and Analysis
Data reduction and analysis for Experiment 2 was identical to that for Experiment 1 with one exception. In order for an eye movement to be counted as anticipatory

it needed to occur between 167 ms after cue offset and 167 ms after target onset. This latency value was chosen as the anticipation cut-off because it has been previously determined that 3-month-old infants cannot make eye movements in reaction to the onset of a stimulus faster than 167 ms (Canfield et al., 1997). If the eye movement occurred between 167 ms after target onset and 167 ms after target offset, it was considered reactive in nature. Again, as neither the location of the target (Total Anticipations: $F = 0.004$, ns; Correct Anticipations: $F = 0.13$, ns; Reactive Latencies: $F = 1.44$, ns) nor the gender of the participant (Total Anticipations: $F = 0.46$, ns; Correct Anticipations: $F = 0.68$, ns; Reactive Latencies: $F = 0.15$, ns) were significant for any of the three measures, these variables were not considered any further in the analyses.

## 3.2. Results and Discussion

### 3.2.1. Total Anticipations

The percent of total anticipations is shown in Table 2. A 2 × 2 mixed-design ANOVA with Condition (predictable, unpredictable) as a between-participant factor and Cue Duration (700, 1200) as a within-participant factor revealed that neither of the main effects nor the interaction were significant, all $Fs < 1$. Since neither condition elicited a difference in the total number of anticipations, any difference observed in correct anticipations by condition type cannot be attributed to a difference in total anticipations.
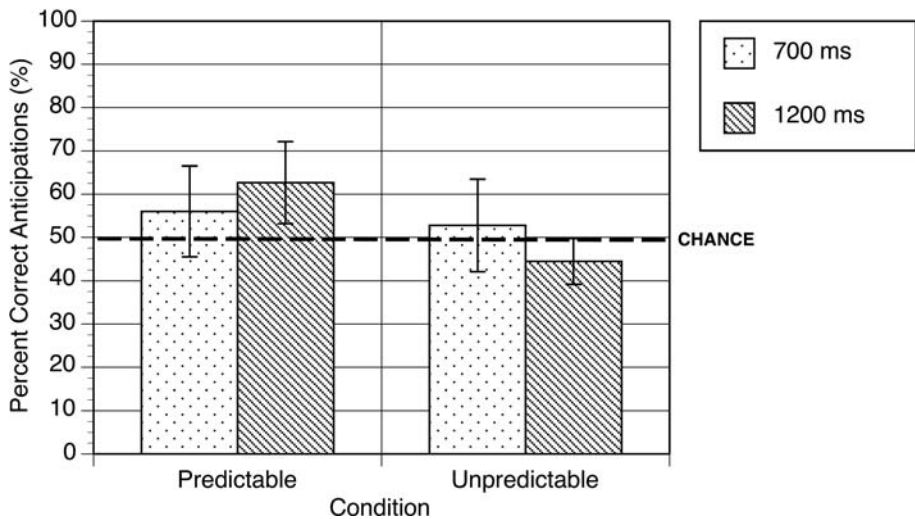
### 3.2.2. Correct Anticipations

To determine if 3-month-old infants can discriminate and encode distinct temporal information when forming expectations, the percentage of anticipations that correctly predicted the target's location was assessed. A 2 × 2 mixed-design ANOVA with Condition (predictable, unpredictable) as a between-participant factor and Cue Duration (700, 1200) as a within-participant factor revealed that neither of the main effects nor the interaction were significant, all $Fs < 1.29$, suggesting that infants made correct anticipations in the predictable ($M = 59.32\%$, SE = 6.95) and unpredictable ($M = 48.61\%$, SE = 5.88) conditions at rates that were not different from each other, regardless of cue duration. These data are shown in Fig. 5.

Finally, to determine whether infants actually discriminated and were able to encode the specific cue durations in an expectation, enabling successful

**Table 2.**
Percent of total anticipations (standard error) made during Experiment 2.

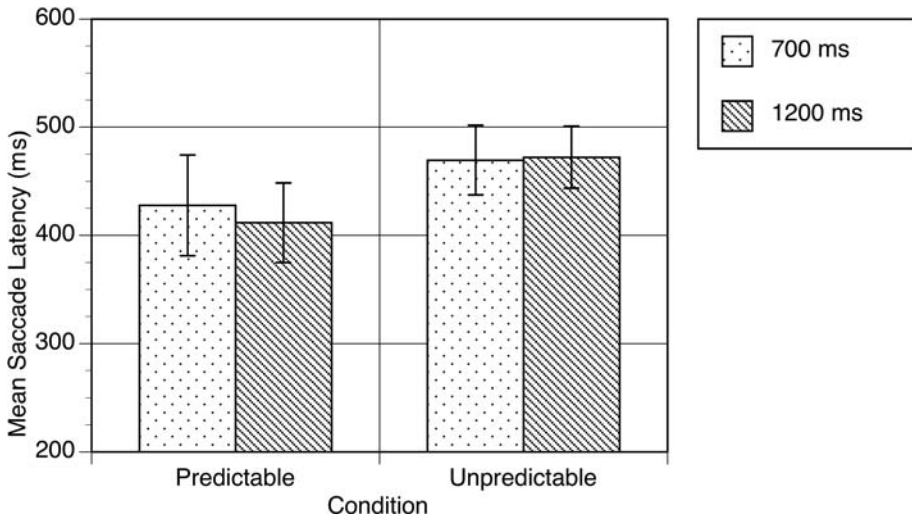| Cue duration | Predictable | Unpredictable |
| --- | --- | --- |
| 700 ms | 40.84 (6.06) | 35.67 (4.49) |
| 1200 ms | 43.17 (7.44) | 41.90 (4.69) |

**Figure 5.** Mean percent of correct anticipations that 3-month-old infants initiated to the targets as a function of cue duration in both the predictable and unpredictable conditions. Error bars represent +/− 1 standard error of the mean.

anticipation of a target's location, correct anticipations were compared to chance anticipatory performance (i.e., 50%). One-tailed, one-sample $t$-tests using the Benjamini–Hochberg procedure with a false discovery rate of 0.05 indicated that 3-month-old infants, in contrast to 6-month-olds, in the predictable condition did not make correct anticipations at a rate greater than 50% after viewing cues of either 700 ms, $t(10) = 0.54$, ns, or 1200 ms, $t(10) = 1.27$, ns. As expected, 3-month-old infants in the unpredictable condition also made correct anticipations at a rate no different than 50% after viewing cues of 700 ms, $t(11) = 0.26$, ns, or 1200 ms, $t(11) = 1.06$, ns. These findings seem to strongly indicate that 3-month-old infants did not discriminate the two temporal values and consequently had no basis on which to make correct anticipations at a rate any greater than chance, even when the cue duration–target location relations were predictable (see Fig. 5).

### 3.2.3. Reactive Latencies

In order to assess the effect of predictability and cue duration on the potential secondary expectation measure of the latencies of reactive eye movements, a 2 × 2 mixed-design ANOVA was performed on median reactive latencies, with Condition (predictable, unpredictable) as a between-participant factor and Cue Duration (700, 1200) as a within-participant factor. This analysis did not reveal any significant main effects or interaction, all $F$s < 1.66. Though the reactive latencies are again somewhat shorter in the predictable than the unpredictable group, these results indicate that the predictability of the cue duration–target location

**Figure 6.** Mean reactive latencies of eye movements that 3-month-old infants initiated to the targets as a function of cue duration in both the predictable and unpredictable conditions. Error bars represent +/− 1 standard error of the mean.

relations did not influence 3-month-old infants' reactive eye movements made towards the targets (see Fig. 6).

## 4. General Discussion

Events and their individual components typically occur and differ from one another on the order of milliseconds and hundreds of milliseconds. For infants, for whom regularity and predictability of events form a basis for coming to understand their world (Haith, 1994; von Hofsten, 2007), the capacity to detect, discriminate, and encode temporal regularities would provide them with information of when and for how long to allocate processing resources to any given event, thereby increasing the efficiency of their event processing. As a consequence, including event timing in addition to event location and content in their expectation representations would enable infants to have more time to process event information, facilitating the construction of their knowledge base and their behaviour in relation to those events (Haith et al., 1993).

Though some studies exist that purportedly show that infants as young as neonates can discriminate event timing differences including on the order of milliseconds (e.g., Brannon et al., 2008; de Hevia et al., 2014; Provasi et al., 2011) and that they might use event timing in exhibiting expectations (e.g., Addyman et al., 2014; Colombo & Richman, 2002), none of these assessed event timing on the order of milliseconds, performance in young infants, and appeal to an expectation

to account for the findings all at the same time in the same study. The purpose of the current study, therefore, was to further investigate infant time perception by assessing the combination of these parameters in the same study, that is, by examining if young infants possess the capacity for processing time information on the milliseconds scale and if they encode that event-specific time information when forming a representation for the regularity of events, present and future, in their environment. To this end, the current study used the VExCP (Baker et al., 2008; Comishen et al., 2019) methodology since it probes infants' capacity to detect predictable associations between cue parameters, such as duration, and a target's subsequent location. The use of the VExCP also allowed for the separation of timing predictability from spatial predictability — a lack of separation of these parameters was a problem for a previous infant temporal expectation study (Adler et al., 2008), as the different temporal values were presented with stimuli at the same central spatial location. If infants could discriminate the two temporal cues from one another and learn their respective associations with the subsequent target's location in the VExCP, consequently, then infants would form expectations regarding the predictability of the target's future location as a sole function of the temporal duration of the cue.

Findings from across two experiments indicate that the capacity to discriminate, encode, and include temporal information on the order of milliseconds into visual expectations as expressed by anticipatory eye movements develops over the first half year. In Experiment 1, 6-month-old infants were found to be able to discriminate temporal cues of 700 and 1200 ms durations and encode this temporal information in an expectation. When the timing of the cues predicted the location of subsequent target stimuli, the infants successfully anticipated the location of subsequent stimuli above chance performance. In contrast to the 6-month-old infants, however, 3-month-old infants were not observed to discriminate the temporal cues and encode this information into their expectations. This was evident as 3-month-old infants were unable to anticipate the locations of target stimuli or exhibit facilitated reactive eye movements even when predictable cue duration–target location relations were present. As a consequence, the ability to discriminate specific event timings on the order of milliseconds and use those timings in the expression of an expectation representation towards future events seems to develop between 3 and 6 months of age. That 6- but not 3-month-old infants were able to discriminate and encode event-specific temporal durations into their expectations might be explained by differences in their sensitivity to the relative timing of the stimuli used in the present study. Infants as young as 4 months of age have been previously observed to discriminate temporal durations that differ by ratios as small as 1:3 (Provasi et al., 2011), with this ratio decreasing with increasing age (Brannon et al., 2007; McCormack et al., 1999). This means that the younger the infant, the greater the difference between the timing values to be discriminated needs to be. Considering that the durations of the temporal cues used

in the present study differed by a ratio of less than 1:2, it is possible that this ratio was too small for 3- month-old infants to discriminate, but not for 6-month-olds. By using temporal durations that differ in magnitude by a ratio greater than 1:3, perhaps even 3-month-old infants might exhibit the capacity to discriminate and encode temporal durations on the scale of milliseconds into their expectations.

Development of infants' sensitivity to the relative difference in the timings to be discriminated might also account for the finding in Adler et al. (2008). In the Adler et al. (2008) study, 3-month-old infants were not able to discriminate the timings of individual events, consistent with the current findings, but were able to discriminate the overall temporal flow rate of a set of events. Interestingly, even with the wide range of temporal values used in that study, the best ratio for relative timing values was 1:2, a value which 3-month-olds may have difficulty discriminating. The possibility then exists that, as in the current study, the 3-month-olds in the Adler et al. (2008) study could not discriminate and hence encode the timings of individual events because the relative timings to be discriminated were not sufficiently separated and discrete. A future study will therefore have to determine whether 3-month-olds can discriminate and encode the timings of individual events if the relative separation between their temporal parameters is greater with a ratio of at least 1:3.

Another account for why the ability to discriminate and encode event-specific temporal information improves with age in early infancy may be attributable to neural development. Processing of millisecond timing information including temporal organization (Shima & Tanji, 1998; Tanji, 2001) and temporal duration (Ferrandez et al., 2003) have been linked to the activity of neurons in the pre-supplementary and supplementary motor areas; areas that have also been linked to controlling self-initiated actions (Mushiake et al., 1991), such as anticipatory eye movements. In addition, these neurons have exhibited selective activation to the presence of particular temporal, rather than the content, information of a viewed event (Mita et al., 2009). That these neurons exhibit temporal encoding properties is functionally important, but perhaps of equal importance may be where these structures reside cerebrally.

The supplementary and pre-supplementary motor areas share projections with the frontal areas including the frontal eye fields (Coull & Droit-Volet, 2018; Gould et al., 1986; Huerta et al., 1987), and the frontal eye fields have been associated with generating anticipatory saccades (Hanes et al., 1998; Keating, 1991; Ramkumar et al., 2016). Considering their close proximity and shared projections, it is possible that the temporal information processed neurally in the supplementary and pre-supplementary motor areas may be integrated with the mechanism for generating anticipatory saccades from the frontal eye fields. Developmentally, structural maturation of myelin occurs within these brain structures between 6 and 8 months of age (Deoni et al., 2011), leading to developmental changes in the transmission rate of information projected between these neural regions. If verified, this proposition would seem to provide physiological evidence supporting the

developmental superiority of 6-month-old infants over 3-month-old infants in the capacity to discriminate and encode event-specific temporal information on the order of milliseconds into their expectations and initiate anticipatory eye movements on the basis of that temporal information. An important question would be whether the possible developmental differences in sensitivity to relative timing ratios is connected to the development of these neural mechanisms in infancy. This is an open question, however, as no study has explored this possibility, though one study has attempted to examine the development of neural mechanisms of timing but with participants only as young as 10-years-old (Smith et al., 2011).

### 4.1. Anticipatory/Reactive Eye Movement Dissociation

A secondary finding from the current study was that the predictability of the cue duration–target location association did not influence infants' latencies to initiate eye movements in reaction to target onset, but only influenced eye movements in anticipation of target onset. This dissociation between reactive and anticipatory eye movements in their sensitivity to different event parameters is consistent with previous studies that have found similar dissociations when expectations for the content of events was manipulated (Adler & Haith, 2003) as well as when events' temporal information was previously manipulated (Adler et al., 2008). Adler and Haith (2003) speculated, later supported by Adler et al. (2008) and now by the current findings, that because anticipatory eye movements are generated by higher cortical levels (Hanes et al., 1998) and reactive eye movements by lower subcortical levels (Krauzlis & Dill, 2002; Krauzlis et al., 2000), then the different event parameters are processed at different cortical levels. Like content information, temporal information is proposed to be processed by higher cortical levels whereas spatial information is processed by lower subcortical levels (Adler & Haith, 2003).

Neurophysiological evidence supports the proposed discrete processing of event parameters (Ferrera & Lisberger, 1995; McIntosh & Schenk, 2009; Schiller & Logothetis, 1990). The lower-level, more primitive, superior colliculus, which represents a spatial map of possible stimulus locations (Robinson & Kertzman, 1995; Schiller, 1985), has been shown to influence the generation of reactive eye movements to those spatial locations (Krauzlis & Dill, 2002; Krauzlis et al., 2000; Wang et al., 2012). Higher levels of neural processing such as the visual cortex and temporal areas have been shown to process content information such as colour, shape, and even faces (Ungerleider & Haxby, 1994). Other higher-level areas, such as supplementary motor cortex, have been shown to process temporal information (Ferrandez et al., 2003). Furthermore, these higher levels of neural processing have projections to the frontal eye fields, which have been shown to be involved in the initiation of anticipatory eye movements (Hanes et al., 1998; Zhou & Thompson, 2009). Thus, the sensitivity of anticipations to event timing and content manipulations and the lack of sensitivity to these event parameters by reactive eye movements may reflect the functioning of higher-level neural processing.

In terms of expectation theory, both the current finding of an anticipation/reactive latency dissociation and the ones found by Adler and Haith (2003) and Adler et al. (2008) are contrary to the theoretical framework previously outlined in Haith et al. (1993), and the numerous experimental findings, in which anticipations and facilitation of eye movement latencies were both considered as measures of the same expectation process. In total, the findings of these studies call into question the theoretical assumptions of Haith et al. (1993) regarding the relation of anticipatory and reactive eye movements to the construct of expectations, and suggest that a revision to this relation is required.

### 4.2. Conclusion

In summary, the purpose of the present study was to investigate whether infants have the capacity to process time information on the scale of milliseconds encode such information when forming expectations, and then use that temporal information in the expression of that expectation. A possible developmental transition point was observed between 3 and 6 months of age in the capacity to process event-specific temporal information, as the latter age was associated with the emergence in the ability to discriminate and encode such information on the scale of milliseconds into expectation representations. This result may be associated with neural development, and perhaps a greater necessity for processing smaller temporal durations in response to the development and functioning of additional cognitive processes, such as goal planning and directed behaviour (von Hofsten, 1980, 1998; Wentworth et al., 2000), and episodic memory (Hellmer et al., 2018; Tulving, 2002). By studying infant time perception with a methodology that can be used across the lifespan (Adler & Gallego, 2014; Adler & Orprecio, 2006), future research could be devoted to better understanding the development of temporal processing and how it shapes early cognitive development.

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