Using pupillometry to investigate predictive processes in infancy

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Abstract
Prediction, a prospective cognitive process, is increasingly believed to be crucial for adult cognition and learning. Despite decades of targeted research on prediction in adults, methodological limitations still exist for investigating prediction in infancy. In this article, we argue that pupillometry, or the measurement of pupil size, is an effective method to examine predictive processing in infants and will expand on existing methods (namely looking time and anticipatory eye movements). In particular, we argue that there are three specific features of pupillometry that make it particularly useful for augmenting the investigation of prediction in infancy. First, pupillometry has excellent temporal resolution that will facilitate the differentiation of prediction subcomponents. Second, pupillometry is highly continuous across the life span, allowing researchers to directly compare responses between infants and adults using an identical paradigm. Third, pupillometry can be used in conjunction with other behavioral measures, allowing for different yet complementary results. In addition, we review relevant adult and infant pupillometry studies that will facilitate infancy researchers to adopt this technique. Overall, pupillometry is particularly useful in investigating prediction in infancy and opens up several avenues for developmental research.
Prediction, a prospective process composed of several subcomponents (i.e., anticipation, expectation, prediction error, updating; Bubic, von Cramon, & Schubotz, 2010), connects what has been learned in the past with what one is currently experiencing. While the importance of prediction is well supported based on studies with adults, research investigating prediction in infancy is less advanced in part because of methodological constraints. In this article, we argue that pupillometry, or the measurement of pupil size, has the potential to be an effective method to examine predictive processes in infants.

The current review expands from previous related work through investigating the intersection of predictive processing and pupillometry in infancy. Previous reviews of prediction and its subcomponents have been exclusively focused on adults (Bubic et al., 2010; Den Ouden, Kok, & De Lange, 2012; de Lange, Heilbron, & Kok, 2018; Summerfield & Egner, 2009), and previous reviews of pupillometry have provided a useful and practical guide for applying the method in early developmental psychology studies (e.g., how to preprocess and analyze data; Gredebäck, Johnson, & von Hofsten, 2009; Hepach & Westermann, 2016; Sirois & Brisson, 2014) or in the use of pupillometry for other domains of study (Eckstein, Guerra-Carrillo, Singley, & Bunge, 2017; Gredebäck & Daum, 2015; Laeng, Sirois, & Gredebäck, 2012). For example, Laeng et al. (2012), Sirois and Brisson (2014) and Eckstein et al. (2017) all discussed pupillometry in the application of violation of expectation (VOE) paradigms to investigate the theory of core knowledge and related phenomena such as object permanence. While VOE can be considered as an index of prediction, the current review considers prediction as a broader perceptual-cognitive process and includes a much larger set of phenomena than these previous reviews. Therefore, this review provides a unique contribution to developmental science by discussing the intersection of pupillometry and prediction, broadly construed, in infancy.

While developmental science has generally investigated prediction under a broad definition, the current review uses a theoretical model of prediction which considers prediction as comprising a series of subcomponents (i.e., anticipation, expectation, prediction error, updating, Bubic et al., 2010). Explicit discussion of these subcomponents, while now common in the adult literature (Den Ouden et al., 2012; de Lange et al., 2018; Summerfield & Egner, 2009), has not occurred in relation to developmental studies. Moreover, we summarize research using pupillometry to measure prediction in adults and recent findings in the use of pupillometry in infants to investigate prediction. Ultimately, this review will give researchers an overview of how pupillometry can be used to investigate the subcomponents of prediction and the broad applicability of pupillometry as a tool for developmental research. We start with an overview of the physiology of the pupil and the established links between changes in pupil size and changes in cognition.

1.1 Overview of pupillometry

The pupil is the circular opening in the iris that allows light into the eye. Pupil size increases in darker environments to allow more light in and decreases in brighter environments. This automatic adjustment of pupil size based on light level is known as the pupillary light reflex and is important for achieving optimal vision across many environments.

In addition to being modulated by light levels, the pupil is also (subtly) modulated by cognition; therefore, pupillometry, or the measurement of pupil size, has been long embraced by psychology research. Before the invention of eye-trackers, pupil size was measured manually based on images taken of the pupil. These early practices were extremely time-consuming but were the first studies to reveal a link between cognition and pupil size for infants (Fitzgerald, 1968; Fitzgerald, Lintz, Brackbill,
With the invention of eye-trackers, pupil size is now automatically recorded at high temporal resolution. In addition to the wide adoption of eye-trackers for recording fixation patterns and looking time in the developmental science community (e.g., Aslin, 2007), the relative ease and accessibility of this method have generated a renewed interest in using pupillometry as a measure in cognitive psychology.

Pupil size is modulated by cognition through the actions of a brain region called the locus coeruleus (LC). This subcortical brain structure is the main producer of norepinephrine (NE), an important neurotransmitter in the central nervous system involved in attentional control (Aston-Jones & Cohen, 2005), memory retrieval (Sterpenich et al., 2006), and general arousal (Samuels & Szabadi, 2008). Especially relevant for pupil size is the finding that neurons in the LC-NE system (and correspondingly NE) have two modes: tonic and phasic (Aston-Jones & Cohen, 2005; Cohen, McClure, & Yu, 2007), and these two modes have been found to correspond to differences in information-seeking behaviors. Differences in information-seeking behaviors with respect to tonic and phasic mode have been considered as mapping onto the psychological concepts of explore and exploit, respectively (for a detailed review about these two modes of activity, see Aston-Jones & Cohen, 2005). The tonic mode leads to an increase in distractibility and is referred to as the exploration mode, and the phasic mode leads to focused attention and optimized performance on a task and is referred to as the exploitation mode. As a result, tonic and phasic pupil change also reveal distinct information about how humans process information.

The phasic mode, the focus of this review and the majority of infancy research, is analogous to time-locked or stimulus-locked pupil measurements (e.g., the change in pupil size from baseline in response to the presentation of a stimulus). For adults, phasic pupil change has been used to investigate a wide range of cognitive domains (Hartmann & Fischer, 2014; Sirois & Brisson, 2014), including the focus of this review, prediction (Gredebäck, Lindskog, Juvrud, Green, & Marciszko, 2018; Koenig, Uengoer, & Lachnit, 2018; Nassar et al., 2012; O’Reilly et al., 2013; Zhang, Jaffe-Dax, Wilson, & Emberson, 2018). For infants, phasic pupil change is viewed as a promising measure that has the potential of expanding the field of cognitive development (Laeng et al., 2012; Eckstein et al., 2017; for a list of infant and toddler pupillometry work, refer to Hepach & Westermann, 2016). Focusing on infant pupillometry studies that examine prediction, there is a large number of studies looking at VOE (Eckstein et al., 2017; Laeng et al., 2012; Sirois & Brisson, 2014), but few studies (and no reviews) have examined prediction outside of the context of VOE (Gredebäck et al., 2018; Zhang et al., 2018). Overall, this review will focus on phasic pupil studies because there is a substantial difference in the number of phasic pupil studies compared to tonic, and it has also been used to investigate prediction.

Tonic mode is analogous to pupil measurements that are collected continuously over a longer period of time (most of the time as a baseline measurement). For adults, tonic pupil size or baseline pupil size has been measured to study intelligence (Tsukahara, Harrison, & Engle, 2016), risk-taking behavior (Yechiam & Telpaz, 2011), motivation (Wykowska, Anderl, Schubö, & Hommel, 2013) and control state (Gilzenrat, Nieuwenhuis, Jepma, & Cohen, 2010), but overall, is measured less than phasic pupil size (Laeng et al., 2012). For younger populations, tonic pupil size has been used to investigate autistic spectrum disorder (Blaser, Eglington, Carter, & Kaldy, 2014), social cognition (Anderson, Colombo, & Jill Shaddy, 2006), emotion (Geangu, Hauf, Bhardwaj, & Bentz, 2011), and motivation (Hepach, Vaish, & Tomasello, 2012; Hepach, Vaish, & Tomasello, 2013). Similar to adults, there are fewer infant studies using tonic pupil size compared to phasic pupil size (Hepach & Westermann, 2016).

The paucity of studies using tonic pupil size in infancy is likely due to the fact that tonic/baseline pupil size requires a long period of time with little or no stimulation, which is especially difficult for infants to participate in. Moreover, tonic pupil size has not been used to investigate research related
to prediction. We assert that this is likely stemming from the methodological challenges associated with measuring tonic pupil size in infancy and not because it may not be useful in the investigation of prediction. In particular, tonic pupil size may be a good measure of anticipation because it is often measured before the stimulus is presented. For the same reason, however, tonic pupil size in practice is often used as baseline from which to measure phasic changes in pupil size. In addition, there are difficulties in using pupillometry measures to isolate anticipation from other cognitive processes that also affect pupil size (e.g., cognitive load), which we discuss further below. Finally, there are established behavioral measurements such as anticipatory eye movements that can effectively measure anticipation. Thus, while in principle tonic pupil size could be a useful measure in the study of prediction in infancy (particularly in the study of anticipation), there are a number of methodological challenges to doing so and a paucity of existing studies to review. Therefore, for the purpose of this review, we will focus on pupillometry studies that use phasic pupil change and how phasic pupil responses can be used to investigate prediction in infancy.

Moving onto the practical considerations of conducting pupillometry research with infants, first there are considerations that are not unique to pupillometry. For example, pupillometry studies require infants to stay relatively still in order to get a precise measurement of pupil size. Consequently, these studies rely on attention-grabbing videos to maintain infant attention. However, these issues are common to a number of methods used to investigate infants (e.g., EEG, fNIRS, eye-tracking more generally). There are also pupillometry specific factors to consider, such as the need for isoluminant stimuli (i.e., stimuli with the same light levels) because non-isoluminant stimuli confound the measurement of the pupil. However, if images are rendered isoluminant, it can result in highly distorted images and videos that are often less engaging or recognizable to infants which presents a challenge particularly for the investigation of familiar stimuli (e.g., processing of words with familiar referents). These and many other methodological challenges can be overcome but require careful consideration and a full discussion is outside the scope of this review. For a review focused on practical considerations specific to infant pupillometry studies, we recommend the reader to refer to Hepach and Westermann (2016).

1.2 | Benefits of pupillometry for developmental psychology

There are several advantages to using pupillometry with infants over existing methods. First, pupillometry allows for recording of the same physiological response across different ages in the same tasks (Ross-Sheehy & Eschman, 2019; Wetzel, Buttelmann, Schieler, & Widmann, 2016; Zhang et al., 2018). There are numerous studies using pupil size to measure a variety of cognitive processes in adults. If we use similar tasks across populations, we can uncover the development of these cognitive processes. It is important to point out that while maximal pupil size does change with age (Winn, Whitaker, Elliott, & Phillips, 1994), most studies tend to calculate change from baseline, which minimizes developmental (or individual) differences in raw pupil size (Eckstein et al., 2017; for more information on proper pupil size preprocessing steps, refer to Kret & Sjak-Shie, 2018). While, in principle, comparison across ages is possible with other dependent measures (e.g., with eye movements, neural responses as measured in event-related potential, ERP, and functional near-infrared spectroscopy, fNIRS), in practice, this is very difficult to do as the types of paradigms that elicit strong and reliable responses in infants and in adults differ (Hespos, Gredebäck, Von Hofsten, & Spelke, 2009). However, evidence of strong and reliable pupillometry responses across disparate developmental ages (e.g., adults and infants) using the same paradigm (Ross-Sheehy & Eschman, 2019; Vaish, Hepach,
Second, pupil size measurements are meaningful at each time point, which allows you to exploit the high temporal resolution of eye-tracking (e.g., one pupil measurement every 2 ms) to examine how cognitive processes unfold over time (Laeng et al., 2012). In this way, pupillometry can be used similarly to ERP without many of the constraints of ERP (Hepach & Westermann, 2016). Specifically, in ERP, changes in the dependent measure at different time points allow for different inferences, and similarly, changes in pupil dilation at different time points in relation to the task can indicate different cognitive processes (e.g., cognitive load or recognition or prediction error). This is in contrast to popular measures in developmental psychology, such as looking time and eye movements, which, despite being sampled with the same temporal resolution as pupillometry, is typically averaged over long time windows (e.g., fixations from 0 to 2,000 ms or looking time averaged over many trials). Thus, in practice, the temporal resolution of eye-tracking is rarely used to make meaningful inferences in infant research (Aslin, 2012; for a more extensive review of the challenges with measuring looking time, see Aslin, 2007). In addition to using pupil dilation to examine how cognitive processes unfold within a trial, pupil dilation can also be used to look at time-course information on a trial-by-trial basis. Indeed, trial-by-trial analyses are possible, in principle, with other behavioral measures such as looking time; this approach, however, is not practiced likely because of the inherent noisiness of these measures. On the other hand, trial-by-trial analyses of pupil dilation were used by Foroughi, Sibley, and Coyne (2017) to examine how mental effort changed while learning a new task and block-by-block analyses of pupil dilation was used by Koenig et al. (2018) to look at how prediction error changed for three different reinforcement learning conditions. Thus, pupillometry supports multiple levels of time-course analyses, from within a single trial to trial by trial to block by block.

Lastly, pupillometry can also be used in conjunction with other measures such as looking time and eye movements (Cheng, Kaldy, & Blaser, 2019; Dörrenberg, Rakoczy, & Liszkowski, 2018; Kleberg, del Bianco, & Falck-Ytter, 2019; Pätzold & Liszkowski, 2019; Ross-Sheehy & Eschman, 2019; Tummeltshammer, Feldman, & Amso, 2019; for a study that combines looking time and eye movements see Daum, Attig, Gunawan, Prinz, & Gredebäck, 2012). Pupil dilation, looking time and eye movements have been used independently to understand various cognitive processes; thus, combining pupillometry with other dependent measures provides an unique approach to understanding infant cognition, as this could shed light on how different cognitive processes interact during the same task. Figure 1 illustrates an example of how pupillometry and looking time can be used in the same study to display complementary information. This powerful combination of dependent measures has been used to provide more insight into heated debates such as object permanence in infants (Jackson & Sirois, 2009; Sirois & Jackson, 2012), and it has the potential to shed light on another debate involving the replicability crisis of implicit false belief in infants. Specifically, some studies have failed to replicate infants’ ability to anticipate others’ action based on false beliefs, using implicit false belief tasks (Burnside, Ruel, Azar, & Poulin-Dubois, 2018; Poulin-Dubois, Polonia, & Yott, 2013; Poulin-Dubois & Yott, 2017; Yott & Poulin-Dubois, 2016). The standard dependent measure during infant false belief task is looking time, but this can be influenced by whether or not the participant has a novelty or familiarity preference (i.e., individual differences in what the child prefers to look at). Therefore, pupil size can be incorporated into future false belief studies because it can be measured at the same time (as looking time) and may be a more sensitive and possibly direct measure of surprise. Furthermore, pupillometry can also be used to measure how infants are processing the learning trials where infants are introduced to the scenario. These early moments
of the false belief task are crucial for learning the task and can be powerful predictors of whether or not infants will correctly anticipate. Taken together, incorporating pupillometry as a method in developmental psychology research will complement existing methods and extend mechanistic investigations of infant cognition.
Prediction is a prospective cognitive process linking past experience to the interpretation and response to current sensory input. Prediction has been argued to encompass several different subcomponents (Bubic et al., 2010). First, anticipation is the process of formulating an expectation that will facilitate the processing of incoming information (LaBerge, 1995). Specifically, an expectation is a representation of what you think will happen in the short-term (i.e., the near future), and this representation is sent to sensory or motor areas in the brain. Second, your expectation and the sensory information you actually receive from the real world is compared. If any mismatch between your expectation and sensory information occurs, a prediction error is formed (Friston, 2005; Hollerman & Schultz, 1998; McClure, Berns, & Montague, 2003; Rao & Ballard, 1999). Third, prediction errors can be the spark in attention and learning that change expectations to be more accurate in the future; this process is known as updating. For the purpose of this review, the term “prediction” refers to the general cognitive process linking past experiences to the interpretation and response to imminent events, and anticipation, expectation, prediction error, and updating refer to the subcomponents of prediction.

Each of these subcomponents of prediction (anticipation, expectation, prediction error, updating) has distinct cognitive characteristics and, we will argue, these subcomponents exhibit differential sensitivity to the variety of dependent measures available to developmental psychologists. Thus, breaking down prediction into subcomponents allows for specificity and clarity when designing a task, operationalizing measurements, and developing a mechanistic understanding of prediction, and its role in development.

However, for many scientific questions, it would not be necessary to consider prediction with consideration of these subcomponents. For example, if the scientific question concerns the presence or absence of prediction for a given age for a given task, one can make the assumption that all components of prediction operate similarly, and simply investigate a dependent measure that is sensitive to prediction (see below). Thus, while we argue that considering prediction in these subcomponents is useful for the purpose of understanding how best to investigate prediction and its role in developmental populations, we acknowledge that it is not necessary to have this level of detail in all investigations of prediction in infancy.

2.1 Comparison of current subcomponents with action prediction from Gredebäck and Daum (2015)

Our breakdown of prediction into the subcomponents of anticipation/expectation, prediction error, and updating has overlapping features with Gredebäck and Daum (2015). Gredebäck and Daum (2015) reviewed studies that investigated infants’ ability to perceive and interpret the actions of others. To this end, they separated action perception into three components: priming, prediction, and evaluation. Their three components of action perception are similar to the current breakdown of prediction but with some notable differences. First, there is overlap between priming, from Gredebäck and Daum (2015), and anticipation, from the current paper, where both components essentially describe the cognitive resources required to prepare for the future. Second, action prediction, from Gredebäck and Daum (2015), is defined as the overt gaze shift to the predicted goal. Thus, action prediction can be considered as the behavioral manifestation of anticipation and expectation, as anticipation and expectation can be measured using anticipatory eye movements (see Predictive Processing in Adults: Anticipation and Expectation). Lastly, evaluation, from Gredebäck and Daum (2015), is defined as evaluating the outcome of the agents’ action and how that outcome was achieved and, thus, is similar
to prediction error. In contrast, Gredebäck and Daum (2015) do not include a subcomponent for updating, which we define as the process of changing expectations based on new information.

In addition, beyond the identity of these three components, these reviews differ in their overall definitions of prediction. Here, prediction is considered as the overarching cognitive process composed of four subcomponents different components. In this approach, any of these subcomponents can be considered an essential aspect of prediction and all are considered prospective or future-oriented. Moreover, we consider prediction to be a process that can be indexed using a variety of measures including eye movements, activation patterns in the brain, and, central to this review, pupillometry. By contrast, Gredebäck and Daum (2015) definition of prediction is much more specific because it only captures the point when an individual looks toward the goal of an action but not the other components (which they consider to be reactive rather than predictive). In addition, Gredebäck and Daum (2015) argue that anticipatory eye movements are indexes of prediction but, for example, the pupil response to a violation of what is predicted is not part of a predictive process. Thus, their definition of prediction is much more restricted to a specific subcomponent and dependent measure than the current definition being proposed in the current review.

Taken together, although there is some overlap regarding the definition of predictive processing between Gredebäck and Daum (2015) and the current review, the main difference is in what each model considered to be prediction versus related processes. Gredebäck and Daum’s (2015) definition of prediction focuses exclusively on action prediction measured using overt eye movements with processes before (e.g., anticipation) and after (e.g., prediction error and updating) not considered part of prediction. By contrast, the current review considers prediction as comprising four subcomponents including prediction error and updating and, relatedly, argues that prediction can be investigated using various measures.

3 | PREDICTIVE PROCESSING IN ADULTS

Predictive coding theory, a prominent framework explaining how and why prediction is used in perception (Friston, 2005; Rao & Ballard, 1999), states that the adult brain is extremely sensitive to prediction error such that only the prediction error signal, instead of the predictable input, is transmitted to other areas of the brain. This filtering of information minimizes redundancy and allows for the brain to function efficiently in an ever-changing environment. This efficiency also manifests itself in behavior by resulting in more efficient processing of sensory information (e.g., quickly interpret ambiguous information based on past experiences; Bar, 2007), which can improve performance (e.g., faster response; LaBerge, 1995). We will now review studies that have used pupillometry to study prediction in adults (for general reviews of prediction in adults, refer to Bubic et al., 2010; de Lange et al., 2018; Summerfield & Egner, 2009; Summerfield & de Lange, 2014).

3.1 | Anticipation and expectation

To the best of our knowledge, there are no adult pupillometry studies that investigate anticipation and expectation. Focusing on anticipation, one possible reason for the lack of pupillometry studies could be the difficulty in isolating anticipation from the cognitive load of anticipation. Higher cognitive load has been shown to result in larger pupil change (Ahern & Beatty, 1979; Alnæs et al., 2014; Borghini & Hazan, 2018; Hyönä, Tommola, & Alaja, 1995), and the more an individual anticipates, the more likely they are to engage in increasing cognitive load. Furthermore, pupil change is also modulated by uncertainty (Lavín, San Martín, & Rosales Jubal, 2014; Preuschoff, Hart, & Wolfgang., 2011). Since
the manipulation of certainty is one of the principle methods by which expectations are elicited, it is
difficult to dissociate pupillometry responses in anticipation of a stimulus from stimulus uncertainty
and cognitive load. Focusing on expectation, it is difficult to investigate sensory expectations using
pupillometry because pupil size is not a measure that can be used to qualitatively differentiate be-
tween, for example, a dog’s bark versus a cat's meow, independent of other tasks demands.

Until it is demonstrated that there is a way to dissociate anticipation from cognitive load and un-
certainty, we propose that the best possible alternative is to investigate expectation using different de-
pendent measures (i.e., not pupillometry). Specifically, imaging techniques such as fNIRS and fMRI
can measure patterns of activity in perceptual or motor systems. This approach would allow you to
determine when a particular neural pattern is activated in anticipation/expectation of a stimulus. In ad-
dition, one can use eye-tracking methods where anticipation and expectation can be indexed spatially
(e.g., through anticipatory eye movements to anticipated target locations).

To sum up, no adult pupillometry studies have specifically investigated anticipation and expecta-
tion. It is not clear how to use pupillometry to measure these components of predictive processing,
given that it is difficult to disentangle them from cognitive load and uncertainty and pupillometry does
not have the specificity to differentiate different expectations. However, we argue that there are other
dependent measures available to measure expectation.

3.2 | Prediction error

By contrast, several studies have found a link between larger pupil change and prediction error in
adults. Preuschoff et al. (2011) had participants complete an auditory gambling task and measured
pupil change during distinct stages of the task, to disentangle decision making, uncertainty, and re-
ward from each other. Preuschoff et al. (2011) found that pupil change signaled errors in judging un-
certainty (i.e., risk prediction error). Specifically, pupil change was largest when participants lost on
low risk (i.e., high chance of winning) trials and when participants won on high risk (i.e., low chance
of winning) trials. In other words, pupil change was largest when the participants’ expectation did
not match the outcome when considering both outcome and context (i.e., certainty or risk). Similarly,
BraemCoenen, Bombeke, van Bochove, and Notebaert (2015) measured participants’ pupil size while
they completed a flanker task. The results revealed larger pupil change following difficult correct tri-
als than easy correct trials and larger pupil change for easy incorrect trials than for difficult incorrect
trials. This study further corroborates the idea that larger pupil change reflects a mismatch between a
participants’ expectations of an outcome and the actual outcome rather than the outcome per se (e.g.,
errors produce stronger pupil responses over correct responses). Moreover, pupil change reflects dif-
ferent magnitudes of prediction error. In a predictive-inference task in which participants had to guess
the upcoming number, Nassar et al. (2012) found that the larger the error magnitude between the es-
timate and actual number, the larger the pupil change. This study suggests that pupil change is an ex-
tremely sensitive measure of prediction error or the mismatch between expectations and current input.

Pupil change also reflects prediction error in paradigms that do not require explicit responses. For
example, Scheepers, Mohr, Fischer, and Roberts (2013) used pupil change to investigate how different
types of limerick violations affected a reader. Participants listened to four limericks while having their
pupil sizes recorded. The researchers manipulated semantic, syntactic, rhyme, or metric violation and
found that only the rhyme violation led to a larger pupil change, despite the fact that all violations were
reliably detectable. This study suggests that listeners have the strongest expectation for limericks to
rhyme and experienced the strongest prediction error when the expectation was violated.
Lastly, pupil change has been linked to the Pearce–Hall theory, an error-driven learning theory (Pearce & Hall, 1980; Pearce, Kaye, & Hall, 1982; Pearce & Mackintosh, 2010). The Pearce–Hall theory states that the amount of attention given to a cue, which subsequently improves learning for the cue, is determined by prediction error. Furthermore, after learning the association between a cue and an outcome, uncertain cues that elicit more prediction error will attract more attention than the consistent cues. In a series of three experiments by Koenig et al. (2018), participants learned to associate different cues with different outcomes. All experiments were designed to examine pupil change during processing of cues that elicited no prediction error (i.e., cues that were consistently followed by the outcome) versus cues that elicited prediction error (i.e., cues that were sometimes followed by the outcome). The researchers were specifically interested in pupil change during anticipation of the outcome and how pupil change during that cue-outcome period changed over the course of learning. Although it is possible to argue that this period is more indicative of anticipation, the researchers noted that pupil change during this cue-outcome period changes as a function of error and, therefore, is more reflective of error instead of anticipation. Overall, Koenig et al. (2018) found evidence that pupillometry fit with the predictions of the Pearce–Hall model: During early learning trials, no prediction error cues caused larger pupil change than prediction error cues, but this effect reversed such that toward the end of the experiment, the prediction error cues caused a larger pupil dilation.

The pattern of pupil change over the course of learning in Koenig et al. (2018) also has overlapping features with the Hunter–Ames model (Hunter & Ames, 1988), a prominent learning model in developmental research. The Hunter–Ames model states that infants exhibit a familiarity preference during the early stages of learning that changes to a novelty preference over time (Hunter & Ames, 1988). Tying the two together, adults and infants appear to have an initial preference for the more familiar/consistent event that, over time, turns to a preference for a novel/surprising event. These patterns of results suggest that during a novel experience (e.g., an experiment), humans prefer familiarity or consistency because the opposite may be too overwhelming. Through the course of learning, as humans become accustomed to the experience, they prefer the more novel or surprising event because it provides more information gain. Overall, there seems to be a parallel between infants’ familiarity and novelty response with adults’ preference for consistent than inconsistent cues, which could be explored with pupillometry.

Taken together, pupillometry can measure prediction error more directly and has been successfully used in adults, as reviewed in this section. Research studies using a variety of tasks all reach the same conclusion: Larger pupil change indicates prediction error or greater mismatch between expectations and outcome. Furthermore, this section illustrates how pupillometry can be used in conjunction with behavioral measures and learning models to investigate how prediction error supports learning in a more systematic way.

3.3 | Update

To date, few studies have investigated the process of updating via pupillometry, likely due to prediction error and updating being strongly correlated in most experimental designs (O’Reilly et al., 2013). However, O’Reilly et al. (2013) were able to disentangle surprise and update to directly examine changes in pupil size as a result of updating. In this study, participants completed a saccadic eye movement task where the goal was to look at the target as quickly as possible and then return to center fixation. Trials were presented in runs such that all the targets appeared in close proximity to each other in a single run. The start of a new run was indicated by changing the color of the target. These trials were used to measure surprise and update because the location of the new target
was unpredictable (i.e., surprising) and signaled to participants that all the upcoming targets would show up roughly around the new location. These trials were compared against one-off trials where the target appeared in a random location 25% of the time and was colored gray. Participants received explicit instructions that one-off trials had no importance for future trials and acted as a pure measure of surprise. O’Reilly et al. (2013) found that pupil dilation showed opposite patterns at different time points for surprise and updating. Specifically, surprise led to a positive pupil change starting at 600 ms after target, which aligns with other findings reviewed in the above section. Interestingly, updating led to a decrease in pupil change (i.e., pupil constriction) 1,000 ms after target. Overall, O’Reilly et al. (2013) showed that it is possible to disentangle surprise and updating with an innovative paradigm and a suitable population.

A couple of other studies have used pupillometry to investigate updating, albeit in a more indirect way. While measuring participants’ pupil size, Murphy, Van Moort, and Nieuwenhuis (2016) had participants complete an auditory, four-choice reaction time (RT) task where they had to press a letter on the keyboard with a specific finger. For example, every time the participants heard the letter “A,” they had to press it with their left middle finger. The study showed that participants had larger pupil changes during trials in which they made a mistake (i.e., experienced prediction error) and, importantly, the magnitude of pupil change predicted RT slowing and improved accuracy on the subsequent trial. In a separate study, Browning, Behrens, Jocham, O’Reilly, and Bishop (2015) investigated how anxiety influenced decision making. Using pupillometry, Browning et al. (2015) showed that different levels of anxious participants did not differ on their response to surprising adverse outcomes but did differ on their response to volatile versus stable environments. Specifically, highly anxious participants were insensitive to whether an environment was volatile or stable and, therefore, had difficulties updating their outcome based on their current environment. These studies suggest that error is adaptive and alters behavior and, conversely, that a deficit in error detection and updating can also be revealed using pupillometry.

3.4 | Summary

As a result of methodological and conceptual challenges, pupillometry is most suited for investigating prediction error. A large number of studies have shown that prediction error is related to larger pupil change. Investigations of anticipation and expectation are best investigated using other methods (e.g., eye-tracking, neuroimaging). Investigations of updating will require more creative paradigms to dissociate updating from prediction error and may also be better served using other methods as well.

4 | PREDICTIVE PROCESSING IN INFANTS

Given the potentially central role of prediction in adult cognition, it is important to determine what role, if any, prediction plays in infant cognition. A number of studies provide preliminary evidence for the same components of prediction (anticipation/expectation, prediction error, updating) in infants as adults. Here, we review a variety of studies that have investigated prediction in infancy. This purpose of this review is not to be exhaustive but to give a sense of the findings of studies that have most directly targeted prediction across a number of domains of investigation in early infancy. In addition, we compare the current review to previous reviews on related topics.

Studies using eye movements as a dependent measure have established that infants anticipate future events. Beginning with classic visual expectation paradigms (VExP) created by Marshall Haith
and colleagues in the 1980s, researchers found that young infants can anticipate where images will show up next when the spatial location follows a simple pattern (Canfield & Haith, 1991; Haith, Hazan, & Goodman, 1988). Specifically, infants made anticipatory eye movements (AEMs) to the location of the target before the target even appeared. The discovery of AEMs in young infants suggests that they are capable of engaging in predictive processing (for a review, see Wentworth, 2009). Recent studies have used AEMs in a more sophisticated manner. For example, Romberg and Saffran (2013) used AEMs to look at how 12-month-olds learned from a target that always appeared in the same location versus a target that could appear in multiple locations. They found that AEMs reflected an infants’ prior experience. Furthermore, Reuter, Emberson, Romberg, and Lew-Williams (2018) measured AEMs in 12- to 24-month-old infants and found that the ability to update AEMs was correlated with vocabulary size. These recent studies provide a more detailed description of how AEMs actually work and impact infant cognition. Similarly, infants also exhibit predictive eye movements in the context of action prediction (Gredebäck & Falck-Ytter, 2015) and object occlusion (Gredebäck & von Hofsten, 2007). Taken together, infants’ ability to anticipate is well established in the field and has been investigated using anticipatory eye movements.

To the best of our knowledge, Emberson, Richards, and Aslin (2015) is the only study that provides evidence that expectation, or a representation of what will occur in the future, can impact the visual system in infants. In this study, Emberson et al. (2015) used fNIRS, an infant-friendly optical imaging technique that uses infrared light to record changes in the hemodynamics of the brain to investigate top-down sensory prediction in 6-month-old infants as they completed an audiovisual omission task. During familiarization, infants learned to associate audiovisual pairs such that after hearing the auditory cue, they should anticipate the upcoming visual stimulus. After familiarization, unexpected visual omission trials in which the auditory cue was followed by a blank screen were introduced. Results showed that 6-month-old infants had significant visual system activity even during the visual omission trials, suggesting infants formed a visual expectation based on prior experience of seeing a visual stimulus appear after the sound. This provides some evidence of the specificity of the expectations of infants and that they are not simply anticipating a spatial location but, likely, more specific sensory aspects of their upcoming sensory input.

Prediction error is the most straightforward subcomponent of predictive processing to study in infants as a result of constraints in task design (i.e., must design a task that is engaging for infants) and interpretations of results. Electroencephalography (EEG) studies have found evidence of prediction error in infants. Kouider et al. (2015) designed an audiovisual cueing task where 12-month-old infants learned to associate an auditory cue (sound A, B) with a visual category (face or flower) during familiarization. For example, every time infants heard sound A, they would see a face at the same time (valid trial). After familiarization, infants were introduced to invalid trials 25% of the time where the sound was presented with the other, unassociated visual category. For example, sound A was now presented with a flower. Results revealed an increased ERP response for the invalid trials during the late processing stages. The authors attributed this response to a conscious prediction error signal in infants. Similarly, Ylinen, Bosseler, Junttila, and Huotilainen (2016) found that 12-month-olds’ ERP responses to novel word forms (interpreted as a prediction error response) correlated with their vocabulary score. These two studies provide initial evidence of neural prediction error early in life.

Similar to adults, prediction error is also where pupillometry is most involved. In a series of studies, Gredebäck and Melinder (2010) first demonstrated that 12-month-old infants who have a good amount of experience being fed had larger pupil change when a feeding action was violated, specifically when the infant saw food reaching a person’s hand instead of their mouth. The same action violation did not result in larger pupil change for 6-month-olds, suggesting that, as a group, 6-month-olds do not experience prediction error. As a follow-up, Gredebäck et al. (2018) approached the same experiment from
an individual differences perspective. The researchers showed 6-month-old infants videos of a person eating and found that some 6-month-olds indeed can predict another person's actions by looking at a person's mouth before the spoon reaches their mouth. Interestingly, the infants that made these correct anticipations had larger pupil change when they later saw a violation of feeding actions.

Infants also experience prediction error as a result of unexpected communicative cues. Research has shown that 12-month-old infants understand the goal of pointing is to indicate a referent, which then leads the infant to follow the point and search for the referent (Bertenthal, Boyer, & Harding, 2014; Leung & Rheingold, 1981; Morissette, Ricard, & Décarie, 1995). In a recent study by Pätzold and Liszkowski (2019), 12-month-old infants were found to have larger pupil change when they saw a person point to an occluder that was lifted to reveal an empty surface. This omission of a referent violates infants' expectation that one points to a referent. Eight-month-olds who have been shown to not produce the pointing gesture do not show this effect. These results provide strong evidence for infants having an internal model of certain behaviors (in this case, feeding and pointing) as well as prediction error when their expectations are violated.

Infants' pupil change is also graded and scales with prediction error. Tamási, McKean, Gafos, Fritzsch, and Höhle (2016) showed 30-month-old children a picture and an auditory label that matched the picture. The labels were words that 30-month-olds knew. The researchers manipulated the auditory label such that there were different levels of label violation. The findings showed that there was an overall pupil difference between correct and incorrect labels, with larger pupil change for incorrect labels. Furthermore, the incorrect labels that deviated more from the correct label had larger pupil change than incorrect labels that deviated less. These results suggest that, similar to adults, pupil change is also a sensitive measure of prediction error for the younger population.

Infant pupillometry data can also be used in conjunction with error-driven learning models to provide a deeper understanding of infant learning and compare prediction across the life span.

Zhang et al. (2018) had adults and 6-month-old infants complete an identical implicit learning task designed to help participants learn associations between sounds and pictures. The researchers found significantly larger pupil change for visual omission trials (i.e., trials elicited prediction error) compared to visual present trials (i.e., trials that confirmed participants’ predictions) in both age groups (Figure 2). Furthermore, the researchers used the Rescorla-Wagner model (Rescorla & Wagner, 1972), another error-driven learning model, and found that the two age groups exhibited similar learning trajectories.
suggesting similar predictive processing ability (Figure 3). The ability to use pupillometry to make a direct comparison between infants and adults without modifying the experimental task is powerful.

Related to prediction error are studies involving violation of expectation (VOE). Generally, VOE studies use looking time as their dependent measure. These studies provide either exposure to a particular type of stimulus and then violate that prior exposure or they present violations of the types of experiences that infants have in their daily lives (e.g., the physical properties of the world). These studies anticipate greater looking to the violating (novel) stimulus compared to the not violating (familiar) stimulus and use this increase in looking to indicate that infants have experienced a violation of their expectations. The drawbridge study designed by Renee Baillargeon to test infants’ knowledge of physical objects (Baillargeon, 1987) is a canonical VOE paradigm. In this paradigm, infants are familiarized to a possible event or a drawbridge that is lowered until it is blocked by a box. After familiarization, infants are shown the possible event and an impossible event in which the drawbridge appears to pass through the box. Baillargeon (1987) found that infants look longer at the impossible event, suggesting that infants were surprised by the impossible event because it violated the underlying assumptions they had about solid objects.

We consider VOE studies to most closely index prediction error. However, there are a couple of limitations associated with VOE studies that are worth mentioning. First, the interpretation of looking time in VOE studies has been debated (Jackson & Sirois, 2009). Most notably, it is difficult to disentangle the effects of event novelty (Hunter & Ames, 1988; Roder, Bushnell, & Sasseville, 2000) from complexity (Bashinski, Werner, & Rudy, 1985; Kaplan & Werner, 1986) and informativeness (Kidd, Piantadosi, & Aslin, 2012) of the novel or violating event. In addition, infants often show greater looking to the familiar stimulus, and current models are highly limited in using novelty or prediction error to explain this change in infant looking behavior (e.g., Hunter and Ames). At minimum, the sensitivity of infant looking to both familiarity and novelty suggests that looking time in these paradigms does not exclusively index prediction error. Finally, for the majority of these studies, it has not been established that infants actually anticipate the upcoming or familiar stimulus, and, given the other complexity in establishing that looking time in VOE studies is an index of prediction error, this would be a useful demonstration to help better establish that looking time in VOE tasks are indeed measures of prediction error. For example, it is possible that this type of looking time changes is arising from offline comparison of memory and current input (post-diction) rather than arising from prediction (anticipation of a given stimulus changing the processing of the stimulus in relation to prediction

![Figure 3](image.png)

**FIGURE 3** Comparing simulated parameters generated from the Rescorla–Wagner model for adults and infants on a trial-by-trial basis. (a) Prediction error. (b) Prediction. Although infants and adults start off distinct from one another, their prediction error and prediction quickly converge. Importantly, the predictions converged accurately (i.e., in this task, the visual stimulus showed up 66% of the time). Reprinted with permission from Zhang et al. (2018)
error). It is an open question how important it is to differentiate these types of models but the model of prediction that is being employed in this paper requires that infants anticipate before you can have a prediction error.

Putting aside these limitations in using VOE as a measure of prediction error, there is evidence that pupillometry responses differ between violating and non-violating trial types. For example, Jackson and Sirois (2009) conducted a study demonstrating how pupillometry can be used to supplement looking time data in a VOE paradigm. In this study, Jackson and Sirois (2009) designed a 2 × 2 study to effectively contrast two types of events: perceptual familiar (novel, familiar) and conceptual familiar (possible, impossible). These two factors often confound each other in standard VOE paradigms, and previous studies had not been able to tease them apart. By measuring pupil dilation, Jackson and Sirois (2009) found infants were surprised by the impossible event only when they viewed a novel train. Interestingly, pupil dilation and looking time results did not correlate in this study as the cumulative looking time results were unclear; infants looked longer at possible events when the trains were familiar, but longer at impossible events when the trains were novel, suggesting looking time and pupil dilation are indexing different cognitive processes. Aside from Jackson and Sirois (2009), other developmental studies have also found larger pupil dilation for more novel events (Gredebäck & Melinder, 2010; Wetzel et al., 2016).

However, if looking time (as has been argued broadly in the literature) and pupillometry (as is being argued here) can both measure prediction error or surprise, is there any value added to using pupillometry over looking time? Which dependent measure is used for a given study is a complex question based on many factors. Above, we argued that there are reasons to believe that looking time is not an exclusive measure of prediction error and, in fact, is affected by many other factors. Even in contexts where looking time does index prediction errors or violations similarly to pupillometry, there are benefits to using pupillometry. Specifically, the main benefit of pupillometry over looking time is in its ability to provide a moment by moment measure of prediction error. For example, when infants view a surprising event versus a non-surprising event, summary statistics of looking time (e.g., average looking time over X numbers of trials) can allow us to compare the two events. Pupillometry, on the other hand, gives us both summary statistics (e.g., average pupil size) and timing information that indicates exactly when the surprise occurs (view Benefits of Pupillometry for Developmental Psychology above, for more information). It is this additional temporal component that makes pupillometry valuable because it allows researchers to pinpoint the precise moment of an event (e.g., at X ms after stimulus presentation infants become surprised). In addition, researchers can pinpoint what aspects of the events are surprising and whether there are differences in processing across different age groups. For example, in Jackson and Sirois (2009), the pupil time course of a trial is plotted with important events labeled, such as when the stimulus begins moving and when the surprising action occurs. For both of these events, pupil change becomes visibly larger after the event occurs. Moreover, there may be cases where measuring pupillometry and looking time result in similar conclusions, but as the work of Jackson and Sirois (2009) has shown, there are certainly cases where they will give different opportunities to answer different questions. In sum, we argue that there are numerous benefits to measuring pupillometry in addition to or instead of looking time.

Evidence for infants and young children's ability to update their internal understanding of the world after experiencing a prediction error is few but increasing. In one of the first studies, Stahl and Feigenson (2015) found that 11-month-old infants are better at learning sound-object mapping if the object was presented in a situation that was vastly different from their everyday lives (e.g., hovering car) compared to when the object behaved normally (e.g., not hovering). Building upon this study, Stahl and Feigenson (2017) found that 3- to 6-year-old children learned novel words better after experiencing an event that violated their expectations compared to an event that did not violate...
expectations. Furthermore, the learning was specific, such that it did not transfer to unrelated objects. Two recent studies were published that examined infants’ ability to update predictive models using different methods but a similar task (EEG: Kayhan, Meyer, Meyer, O’Reilly, Hunnius, & Bekkering, 2019; pupillometry: Kayhan, Hunnius, Hunnius, O’Reilly, & Bekkering, 2019). In this task, infants were exposed to a sequence of audiovisual events that were preceded either by an update cue, indicating the upcoming visual stimulus will appear at a new location or a surprise cue, indicating the upcoming visual stimulus will appear in the same location as before. The EEG results revealed that infants’ predictive models were not influenced by the cues (Kayhan, Meyer, et al., 2019) whereas the pupil results showed that infants were able to update their models based on the cues (Kayhan, Hunnius, et al., 2019). The incongruent results were attributed to differences in age and task demands between the two studies and can be viewed as another example of why it is important to practice convergent methods. Overall, these studies suggest that violations of any expectations provide special opportunities for learning.

4.1 Summary

Overall, a number of studies have provided preliminary evidence that the same subcomponents of prediction are present in infants and toddlers. However, the majority of these subcomponents remain under investigated. In particular, there are very few direct investigations of expectations (i.e., the content of anticipatory processes), and updating is not as amenable to standard developmental methods (e.g., looking time or eye movements) and, thus, is more rarely studied. The exceptions are anticipation and prediction error. Anticipation can be readily indexed using eye movements, and thus, there have been numerous studies demonstrating anticipation in young infants. In this review, we have also noted which dependent measures are well suited to study different subcomponents of prediction. Emerging from this is evidence that pupillometry is particularly well suited to investigate prediction error in infants (an argument that we will refine in the following section) and perhaps ill-suited in the application to other subcomponents (most notably anticipation and expectation).

5 Using Pupillometry to Investigate Prediction in Infancy

5.1 Targeting different subcomponents of prediction

Above, we outlined a model that considers prediction to be comprised of four subcomponents: anticipation, expectation, prediction error, and updating. In our review of relevant studies of prediction in infancy, we also outlined evidence that pupillometry is readily useable to study one of these subcomponents, prediction error. Note: All of the studies discussed used phasic pupil change or stimulus-induced increase in pupil diameter, not tonic pupil change or a pre-stimulus baseline period. There is convergent evidence that prediction error is related to larger pupil change for infants and adults. Moreover, pupil change also scales with prediction error. These features both provide strong evidence that pupil change is a robust index of prediction error but also makes pupillometry an ideal candidate for researchers interested in examining how prediction error changes across the life span (see below as well). Pupillometry is also an effective target for researchers interested in combining dependent measures with learning models. Error-driven learning models allow researchers to quantify and assess prediction error more precisely, which is difficult to do in developmental research due to constraints in
task design and duration. Overall, numerous studies using pupillometry to investigate prediction error are summarized above and demonstrate convergent evidence that pupillometry can be used to study prediction error in early developmental populations.

It is also possible to use pupillometry to investigate updating, a second subcomponent of prediction. In adults, the use of a highly innovative paradigm with complex task instructions allowed O’Reilly et al. (2013) to investigate updating independent of prediction error in adults. We believe this paradigm might be applied to young children and, potentially, infants though the complexity of the task structure would make this difficult. Another approach mentioned earlier in the review is to use pupillometry to study updating indirectly. This approach will likely involve comparison of conditions without explicit instructions (e.g., a condition where infants update through exposure of rewarding and highly associated stimuli and another where infants receive random information that makes it impossible to update) and how pupil change differs during these two conditions. There is much to discover about how infants update their internal models. Pupillometry, with its high temporal resolution and ease of comparison across the life span, is likely to be a useful tool though innovative paradigms must be developed to disentangle updating from prediction error.

In both adults and infants, however, there are issues with dissociating anticipation from uncertainty and cognitive load (both of which have been shown to modulate pupil size). Moreover, pupillometry cannot be used to investigate expectations, as it is not able to distinguish different patterns of activity in particular sensory or motor regions (e.g., pupillometry cannot dissociate visual system responses to a cat and a dog). Thus, until there is a method of measuring anticipation independent of these two other processes, we do not recommend using pupillometry to measure anticipation.

5.2 Investigating different age groups

Another major contribution of pupillometry to the investigation of prediction is through direct comparisons between different age groups. As developmental psychologists, we are interested in how cognition develops; therefore, comparing the same cognitive process across different age groups is essential. While this is true of most of our methods in principle, in practice, we often have to change paradigms or add tasks to elicit similar behaviors in adults as infants. However, pupillometry appears to be an excellent method to compare infants and adults because the pupil response appears to be largely the same across age groups and similarly automatic, making it an efficient tool for both longitudinal and cross-sectional studies. One consideration to keep in mind is that pupil change may be slower for certain age groups compared to others. Based off of Zhang et al. (2018), the optimal time window to compare prediction error response between infants and adults is soon after the presentation of the stimulus, with the infants’ response being slightly delayed (~300 ms) compared to adults. Future studies interested in this comparison will have to be especially careful when determining the length of a trial, making sure it is long enough for the pupil response to evolve for all participants.

5.3 Sensitivity of measurement

Pupil change has also been established as a measure sensitive enough to represent varying degrees of prediction error in both infants and adults (e.g., the degree of mismatch between an expectation and an outcome or the magnitude of a prediction error). This sensitivity allows pupillometry to advance research interested in finding the optimal amount of prediction error for learning and in asking more specific questions related to prediction error rather than quantifying it as an all-or-nothing response.
In addition, this degree of sensitivity allows prediction error to be modeled effectively using learning models (see above).

Moreover, the temporal sensitivity of pupil change allows it to map how prediction error changes over time. This temporal sensitivity manifests at two different timescales. First, pupillometry can be used to investigate changes over the course of an experiment (e.g., earlier trials to later trials). In addition to the time-course findings of Zhang et al. (2018, Figure 2), Koenig et al. (2018) found that, in early trials, the predictable cue elicited larger pupil change while the less predictable cue elicited larger pupil change in later trials. Of course, looking at time-course effects over trials is in principle possible using some other methods available to infancy researchers. This aspect of temporal sensitivity is not unique to pupillometry.

On a more fine-grained timescale, pupillometry is also meaningful at each time point collected within a given trial. This high temporal resolution supports the investigation of how processing unfolds in a single trial, and differs from eye movements, which are sampled from the same resolution but are averaged so each moment is no longer psychologically meaningful. However, pupillometry does have its limitations as it is not well suited for investigating types of learning or cognition with a strong temporal component (e.g., fast-paced statistical learning of sequential information). Pupil change requires a sufficient amount of time to return to baseline (approximately 6 seconds according to Murphy et al., 2016) to prevent carry-over effects. It can, however, be adapted to investigate single violations within a sentence (Byers-heinlein, Morin-lessard, & Lew-williams, 2017). Overall, pupil change is well suited for measuring how processing changes across different time scales compared to more traditional measures of learning, such as looking time.

5.4 Combining pupillometry with other methods for convergent methodological investigations

Lastly, pupillometry can be readily combined with other dependent measures. Most notably, pupillometry is readily combinable with eye movements (Gredebäck et al., 2018) and computational models (Zhang et al., 2018) to provide convergent investigations into the ways in which the predictability of events affects infants’ learning. Employing multiple measures in the same task would provide the unique opportunity to systematically compare such measurements. These comparisons across measures have multiple potential benefits. Given the separate biological underpinning of different eye behaviors (e.g., LC-NE system for pupil size and frontal eye fields for eye movements), similarities or differences between eye-tracking measurements can also reveal more information about neurodevelopment. Moreover, given that different measures might reflect different subcomponents of prediction (e.g., anticipatory eye movements reflect anticipation/expectation and pupil response reflects prediction error), we can start to investigate how these subcomponents operate together and develop. With respect to computational modeling, combining it with pupillometry has unveiled novel findings about how infants learn, information we would not have been able to collect without such mathematical models. For example, in Zhang et al. (2018), fitting the RW model to pupil change revealed a learning rate and initial prediction. These model parameters allowed us to quantify how quickly participants learned and what predictions they started the experiment with, respectively, which is difficult, if not nearly impossible, to infer otherwise. Overall, these innovative combinations can promote new ways of framing research questions and expand the field of developmental psychology.
The goal of this article is to provide researchers with an overview of how pupillometry has been used to investigate predictive processing in adults and to better understand how we can do the same in infants. Given the characteristics of pupillometry we discussed above—similar physiological response across the life span, high temporal resolution, and sensitivity, and it being capable of being used in conjunction with other measurements and computational modeling—pupillometry has much to offer developmental research, including innovation. Furthermore, pupillometry can also be used outside of the context of predictive processing (see Goldinger & Papesh, 2012, for a pupillometry review on memory; see van der Wel & van Steenbergen, 2018, for a review on how pupillometry has been used to study cognitive control). Overall, pupillometry has the potential to advance the research of prediction and its subcomponents, and, most specifically, prediction error and its relation to other subcomponents of prediction in infants.

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