The Co-Development of Looking Dynamics and Discrimination Performance

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The study of looking dynamics and discrimination form the backbone of developmental science and are central processes in theories of infant cognition. Looking dynamics and discrimination change dramatically across the 1st year of life. Surprisingly, developmental changes in looking and discrimination have not been studied together. Recent simulations of a dynamic neural field (DNF) model of infant looking and memory suggest that looking and discrimination do change together over development and arise from a single neurodevelopmental mechanism. We probed this claim by measuring looking dynamics and discrimination along continuous, metrically organized dimensions in 5-, 7-, and 10-month-old infants (N = 119). The results showed that looking dynamics and discrimination changed together over development and are linked within individuals. Quantitative simulations of a DNF model provide insights into the processes that underlie developmental change in looking dynamics and discrimination. Simulation results support the view that these changes might arise from a single neurodevelopmental mechanism.

Keywords: looking behavior, memory development, dynamic neural fields

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Looking is one of the few reliable behaviors that infants engage in. It is not surprising, then, that much of the scientific understanding of infant cognitive development comes from looking measures. They have been used to acquire a basic understanding of how infants form categories (Quinn, Eimas, & Rosenkrantz, 1993), detect statistical regularities (Saffran, Aslin, & Newport, 1996), perceive objects (Needham, 2000), and learn words (Rost & Mc-Murray, 2009). This reliance on looking measures builds upon seminal theories of infant habituation that described well how looking changes as infants become familiar with a stimulus and discriminate familiar from novel stimuli (Cohen, 1972). Despite this rich history, there remains a poor understanding of how looking dynamics and visual discrimination processes are linked on the real and developmental time scales. A recent theory of infant looking and memory formation posits that looking dynamics and discrimination processes share a common mechanistic source (Perone & Spencer, 2013). We probe this theoretical claim in this article.

Looking dynamics change in predictable ways during the first year. Much of the literature on this topic comes from the visual paired comparison (VPC) procedure. In this task, infants explore pairs of identical items during a familiarization phase. Then, during a test phase, they view the familiar item paired with a novel item. Infants' recognition of the familiar item can be inferred from a reliable familiarity preference (longer looking to the familiar item relative to total looking time) or a reliable novelty preference (longer looking to the novel item relative to total looking time). Historically, familiarity preferences have been interpreted as reflecting a point early in learning in which a stimulus is becoming familiar to infants and their memory is weak. Novelty preferences have been interpreted as reflecting a point later in learning in which one stimulus has become familiar to infants, and they are beginning to encode properties of a novel stimulus (for a review, see Hunter & Ames, 1988).

In the VPC, shift rate (rate of gaze switching between pairs of stimuli relative to total looking time), look duration (average look length), and peak look (longest look) have emerged as reliable indices of learning. With age, infants exhibit higher shift rates, shorter look durations, and shorter peak looks. Individual and developmental differences in these looking dynamics are associated with infants' recognition performance (Rose, Feldman, & Jankowski, 2001, 2002). In studies on visual recognition, infants are typically presented with highdimensional stimuli such as geometrical patterns and faces. For stimuli such as these, the basis of infants' recognition and discrimination is unclear. Thus, these studies leave unanswered whether looking dynamics and discrimination change together over development and how looking and discrimination might be related within individuals.

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In another body of literature, developmental changes in visual discrimination have been examined directly using stimuli with well-controlled similarity relations between familiar and novel items. Evidence indicates that infants' discrimination improves over the first year. For example, Brannon, Sumarga, and Libertus (2007) found that infants' made more precise discriminations of visual temporal duration between 6 and 10 months of age. They suggested that these results reflect increasingly precise representations over development (see also Lipton & Spelke, 2003). Much like the visual recognition literature, this literature has not explored the link between looking dynamics and discrimination.

Theories of infant looking have also treated developmental changes in looking dynamics and discrimination as separate issues. Conceptual and neural network models have largely focused on explaining the linkage between the time course of memory formation and infants' familiarity and novelty preferences (Cohen, 1972; Hunter & Ames, 1988; Sirois & Mareschal, 2004). Other (different) neural network models have focused on developmental changes in the precision with which infants' represent features (Westermann & Mareschal, 2004). It is important to note that none of these theories specify how the looking and cognitive dynamics that underlie discrimination are linked on the task or developmental time scale.

Our goal was to investigate how looking dynamics and visual discrimination are related. This investigation was inspired by simulations of a dynamic neural field (DNF) model of infant looking and memory formation that showed that looking and discrimination changed together over development in a single presentation habituation context (Perone & Spencer, 2013). The provocative claim of the model is that changes in looking and discrimination arise from a single neurodevelopmental mechanism.

In the present report, we tested this claim using a combination of empirical and theoretical methods. The empirical component involved examining whether looking and discrimination change together over development and are linked within individuals in the VPC. We chose to test this claim with 5-, 7-, and 10-month-old infants because there are marked changes in looking dynamics (Rose et al., 2001) and infants' ability to discriminate stimuli along continuous, metrically organized magnitude dimensions (Brannon et al., 2007) during this period. We used the VPC procedure to probe infants' discrimination of items from a new stimulus set with well-controlled metric properties along continuous color (hue) and shape (aspect-ratio) dimensions. We examined whether looking dynamics and discrimination change together in a consistent fashion and whether individual differences in looking dynamics predict discrimination performance.

The theoretical component involved two steps. First, we tested whether the same DNF model used to establish a link between looking and neurocognitive processes in the single presentation habituation task is also capable of producing the richer set of looking dynamics, recognition, and discrimination performance measured in the VPC. Second, we evaluated whether developmental changes in looking and discrimination performance could arise from a common mechanistic source by testing whether a single neurodevelopmental change in the DNF model could quantitatively simulate developmental changes in infants' looking dynamics and discrimination performance.

Experiment

Method

Participants. Forty-five infants who were 5 months old (M = 170.31 days, SD = 13.28 days), 39 infants who were 7 months old (M = 230.31 days, SD = 7.74 days), and 35 infants who were 10 months old (M = 303.11 days, SD = 11.43 days) participated in this study.

Stimuli. The stimuli were "buggles" (see Figure 1). Each buggle consisted of a value along continuous shape and color dimensions. Shape was defined by an aspect ratio. Each metric step was defined by a proportional change in height and width, generating six equidistant metric steps with the total area of each stimulus held constant. Aspect ratio is a relevant dimension along which categories can be discriminated. For example, Spivey (2007) found that adults parsed cups and bowls into categories based on aspect ratio rather than width or height alone (see also Oden, 1981). Twelve equidistant colors were sampled from a 360° continuous color space developed by the Commission Internationale de l'E'clairage (CIE*Lab 1976). The entire stimulus set consisted of 72 unique items.

Design and procedure. Infants were familiarized with pairs of identical items across six 10-s trials. Following the familiarization phase, there were two 20-s test trials (location of familiar and novel items were reversed after 10 s). No previous study has probed infants' discrimination with the metric organization of the color and shape dimensions that constitute the buggles. Thus, it was unclear how dissimilar the familiar and novel items needed to be to observe a robust preference. We therefore presented two test trials where we manipulated the metric similarity between the familiar and novel items, presenting a difficult discrimination first and an easier discrimination second. In infant-looking paradigms, it is common to present stimuli highly dissimilar to the familiarization stimulus last in a series of intervening discrimination tests (e.g., Oakes et al., 1997). This maximizes the likelihood of observing a robust preference for the more difficult discrimination that is presented first. There are disadvantages as well. The order with which stimuli with different properties are presented can influence the duration with which infants gaze on subsequent trials during familiarization (Bashinski, Werner, & Rudy, 1985) and test (Schöner & Thelen, 2006) phases.

In our design, the first test was the *similar test*, in which the familiar item was paired with an item that was novel by one metric step on a single dimension. The second test was the *dissimilar test*, in which the familiar item was paired with an item that was novel by three metric steps on the same dimension as the similar test. The direction of the similar and dissimilar tests was in opposite directions on the continuous dimension (see Figure 1). This was done to reduce interference on the dissimilar test that might arise from exposure to a novel item situated in between the familiar item and dissimilar novel item. As a consequence of our design, the first and sixth shapes that marked the beginning and end of the dimension were reserved as novel items, leaving Shapes 2–5 as familiar items.

We created 12 different familiar objects by pairing each of the 12 different colors with one randomly selected shape reserved for the familiarization item. Discrimination for each object could be probed on the shape or color dimension. The object and discrim-



Figure 1. Shows stimulus set of "buggles." Each buggle consisted of one value along a continuous shape (aspect ratio) and color (hue) dimension. The shape dimension consisted of six equidistant metric steps and the color dimension consisted of 12 equidistant metric steps sampled from a continuous 360° color space (from right to left, $91^{\circ}-271^{\circ}$ in 30° increments shown). Figure also shows experimental design. We selected one of the central five shapes and one of the 12 colors as the familiar item. The novel item on the similar test was novel by one metric steps, and the novel item on the dissimilar test was novel by three metric steps. The similar and dissimilar tests were always on the same dimension and in opposite directions from the familiar item on the dimension.

ination dimension probed was randomly assigned across infants. For the 12 familiar objects, the color dimension was probed at least once for all 12 at 5 months, 11 at 7 months, and all 12 at 10 months. The shape dimension was probed for 11 of the familiar objects at 5 months, 11 of the familiar objects at 7 months, and 12 of the familiar objects at 10 months. Thus, infants within each age group were exposed to discriminations across the entire stimulus set.

Stimuli were presented on a gray background on a 37-in. LCD monitor. Pairs of stimuli were centered equidistantly on the left and right portions of the monitor. Infants were tested in a dimly lit experimental room in which a black curtain divided the room. The curtain revealed the monitor and a low-light TV camera lens used to view infants' looking behavior. During the experimental session, infants sat on their parents' lap 100 cm in front of the monitor. Parents wore opaque glasses to prevent parental bias. A trained observer sat behind the curtain and presented stimuli on the monitor and also recorded infants' looking time on a computer while watching them on a black-and-white TV. At the beginning of each trial, a looming white circle appeared that periodically produced a chirping sound. Once the observer determined that the infant was looking at this attention-getting stimulus, the observer pressed one computer key to present the stimuli, one key when the infant was looking left, and one key when the infant was looking right. Looking time to locations other than left or right was not recorded. A second trained observer recorded the looking of 25% of the infants offline. Interobserver reliability was high: looking time on each trial, $r \ge .90$, shift rate, $r \ge .93$, and look duration, $r \ge .87$. The mean absolute difference between observers was low: looking time on each trial, $M \le .62$ s, shift rate, $M \le .06$, and look duration, $M \leq .15$ s.

Results

Analyses are presented across three sections: familiarization, test, and individual differences in looking and discrimination performance.

Familiarization. The goal of our first analysis was to characterize developmental change in infants' total looking time during familiarization, which typically decreases with age as infants more quickly form memories for visual stimuli (Colombo & Mitchell, 1990). A one-way analysis of variance (ANOVA) revealed that total looking time differed across age, F(2, 116) = 4.35, p < .05, $\eta_p^2 = .07$. Post hoc comparisons revealed total looking time was less at 10 months (M = 34.90 s, SD = 7.35) than at 5 months (M = 39.82 s, SD = 8.66), p < .05, d = 0.61. Total looking time was also less at 7 months (M = 35.15 s, SD = 9.52) than at 5 months, p < .05, d = 0.51. Thus, 5-month-old infants accumulated more total looking time than 7- and 10-month-old infants.

Figure 2A–2C shows developmental change in three measures of looking dynamics—shift rate (Panel A), look duration (Panel B), and peak look (Panel C). We evaluated developmental change in these looking measures using one-way ANOVA. The test for shift rate revealed a significant effect of age, F(2, 116) = 3.16, p <.05, $\eta_p^2 = .05$. Post hoc comparisons revealed that shift rate at 10 months (M = .53, SD = .16) was higher than at 5 months (M =.42, SD = .25), p = .05, d = 0.52. The ANOVA for look duration also revealed a significant age effect, F(2, 116) = 7.19, p < .001, $\eta_p^2 = .11$. Post hoc comparisons revealed that look durations were shorter at 10 months (M = 1.28 s, SD = 0.29) than at 5 months (M = 1.95 s, SD = 1.26), p < .01, d = 0.73, and shorter at 7 months (M = 1.41 s, SD = 0.56) than at 5 months, p < .05, d =0.55. Finally, the ANOVA for peak look revealed a significant age



Figure 2. Panels A–C show developmental changes in shift rate (A), look duration (B), and peak look (C) for infants. Panels D–F show developmental changes in shift rate (D), look duration (E), and peak look (F) for the dynamic neural field (DNF) model. Shift rate is the frequency of gaze shifting relative to total looking time, look duration is the average length of each look, and peak look is the length of the longest look. Error bars show \pm 0.5 *SD.* * p < .05.

effect, F(2, 116) = 8.43, p < .0001, $\eta_p^2 = .13$. Post hoc comparisons revealed that peak looks were shorter at 10 months (M = 3.85 s, SD = 1.70) than at 5 months (M = 5.6 s, SD = 2.61), p < .001, d = 0.79, and shorter at 7 months (M = 4.08 s, SD = 1.78) than at 5 months, p < .01, d = 0.68. Thus, duration measures decreased for infants between 5 and 7 months of age and shift rate increased for infants between 5 and 10 months of age.

Test. To determine whether discrimination performance interacted with test dimension over development, we conducted a repeated-measures ANOVA with novelty score (similar, dissimilar) as a within-subject factor and age (5, 7, and 10 months old) and dimension (shape, color) as between-subjects factors. There were no significant effects of dimension (all ps > .1). For our primary analyses, we collapsed across test dimension. We conducted two sets of analyses on infants' looking behavior during the test phase. The first set of analyses centered on infants' discrimination performance on the similar and dissimilar tests. Infants' novelty scores are shown in Figure 3A. To determine whether infants' novelty scores were significantly different than chance on the similar and dissimilar tests, we conducted a series of twotailed, one-sample t tests. Infants' preference on the similar test was not reliable at 5 months, t(44) = -1.26, p > .1, d = 0.28, 7 months, t(38) = 0.92, p > .1, d = 0.19, or 10 months, t(35) =-0.64, p > .1, d = 0.19. On the dissimilar test, 5-month-olds' preference was not reliable, t(44) = 1.06, p > .1, d = 0.25.

However, infants' novelty preference was reliable on the dissimilar test at 7 months, t(38) = 3.50, p < .001, d = 0.75, and 10 months, t(34) = 3.29, p < .01, d = 0.76. Thus, infants' novelty preferences on the dissimilar test were significantly different from chance at ages 7 and 10 months but not at age 5 months.

We also assessed whether there were any differences in test performance across development using a repeated-measures ANOVA. Test type (similar, dissimilar) was a within-subject factor and age (5, 7, and 10 months) was a between-subjects factor. Results revealed a main effect of test type, F(1, 116) = 11.35, p < .001, $\eta_p^2 = .09$, with higher novelty scores on the dissimilar test than on the similar test (see Figure 3A).

The next set of analyses examined whether shift rate and look duration during the test trials differed as a function of discrimination or over development. Previous studies have shown that stimulus differences influence how infants distribute their looks. For example, Ruff (1975) found that infants' shift rates were higher when looking at similar items than dissimilar items. One might expect, then, that infants' shift rates would be higher during the similar test than the dissimilar test. No previous study has examined this possibility when infants are looking at stimuli with well-controlled metric properties.

Figure 3 shows shift rate (Panel B) and look duration (Panel C) on the similar and dissimilar tests across development. To evaluate shift rate, we conducted a repeated-measures ANOVA with test



Figure 3. Panels A–C show developmental changes in novelty scores (A), shift rate (B), and look duration (C) for infants on the similar (black bars) and dissimilar (white bars) tests. Panels D–F show developmental changes in novelty scores (D), shift rate (E), and look duration (F) on the similar and dissimilar tests for the dynamic neural field (DNF) model. Dashed lines represent chance. Error bars show \pm 0.5 *SD.* * *p* < .05.

(similar or dissimilar) as a within-subject factor and age (5, 7, or 10 months) as a between-subjects factor. There was a significant Test × Age interaction, F(2, 116) = 3.43, p < .05, $\eta_p^2 = .06$. Tests of simple effects revealed that infants' shift rate was higher on the dissimilar test than the similar test at 10 months, F(1, 116) = 9.48, p < .01, $\eta_p^2 = .08$, but infants' shift rate did not differ across test trials at 5 months, F(1, 116) = 0.11, p > .1, $\eta_p^2 < .001$, or 7 months, F(1, 116) = 0.07, p > .1, $\eta_p^2 < .001$. Interestingly, older infants more frequently shifted gaze when looking at dissimilar familiar and novel items. We evaluated look duration using the same method. There were no significant results.

Individual differences. Previous studies have shown that individual differences in looking dynamics are predictive of novelty scores (Rose et al., 2001), indicating a mechanistic link between looking and recognition performance. Here, we used hierarchical regression to probe whether individual differences in looking are predictive of infants' discrimination performance on the similar and dissimilar tests.

All regression analyses are presented in tables with the same structure. On the left, the step and predictor variables entered on each step are presented. The tables present summary statistics including proportion of variance accounted for (R^2) , change in R^2 from one step to the next, *F* statistic change from one step to the next, and the probability value associated with the change in the *F*

statistic. These summary statistics indicate the proportion of variance in the dependent measure accounted for and, in steps after the first step, whether that proportion was above and beyond the proportion accounted for in previous steps. On the right side of the table are the unstandardized beta weights (*B*) and standardized beta weights (β). The weight is the unique contribution of each predictor. The sign of the weight indicates the direction of the relationship between a predictor variable and the dependent measure. The size of the weight indicates the slope, where steeper slopes indicate that the dependent measure changes more for each unit change in the predictor. The significance value of each predictor in the context of the other predictors entered on the step is also included.

The first analysis examined whether looking measures predict performance on the similar test after the contribution of age was controlled for. Age was entered as a predictor on the first step and novelty score on the similar test as the dependent measure. Results are shown in Table 1. Age did not account for a significant proportion of variance in novelty scores. In the second step, we entered shift rate, look duration, and peak look. These looking dynamics together did account for a significant proportion of variance in novelty scores, $R^2 = .08$. Evaluating the beta weights indicates that shift rate is the strongest predictor in the context of the others (for similar results, see Rose et al., 2001). It is notable that the slope of the beta weight is negative, indicating that lower novelty scores (familiarity preferences) were associated with higher shift rates. Peak look was also a significant predictor. The negative beta weight suggests that longer peak looks were associated with lower novelty scores on the similar test. These results are somewhat counterintuitive. The association between long peak looks and lower novelty scores fits the general observation that long peak looks and familiarity preferences are signatures of slow processing (for a discussion, see Colombo & Mitchell, 1990; Rose, Feldman, & Jankowski, 2007). However, the association between high shift rates and lower novelty scores does not fit previous observations; high shift rates are typically a signature of efficient comparison and strong novelty preferences (Rose et al., 2002).

In the next analysis, we conducted the same regressions on data from the dissimilar test. Results are shown in Table 2. The model was not significant on any step. Neither age nor looking measures were predictive of performance on the dissimilar test.

Discussion

Shift rate and look duration measures of looking dynamics changed between 5 and 7 months of age. Simultaneously, discrimination between items distributed along the continuous, metrically organized dimensions of color and shape that constitute the buggle objects emerged. These findings are consistent with the possibility that developmental change in looking dynamics and discrimination share a mechanistic source as suggested by the DNF model (see Perone & Spencer, 2013). To probe whether looking dynamics and discrimination were related within individuals, we used hierarchical regression. Individual differences in looking dynamics were predictive of discrimination performance on the similar, but not the dissimilar, test. This raises the possibility that how infants distribute their looks while learning is mechanistically linked to discrimination performance. In the next section, we describe testing whether a single neurodevelopmental mechanism implemented in the DNF model can quantitatively capture the empirical pattern of results reported here.

A DNF model of infant looking and memory. DNF models provide an effective set of concepts for thinking about the linkage between brain and behavioral dynamics (for a review, see Spencer, Perone, & Johnson, 2009). The DNF model used here is derived from a model of adult visual working memory and change detection performance (Johnson, Spencer, Luck, & Schöner, 2009; Johnson, Spencer, & Schöner, 2009). The same architecture used here has been used to provide an account of developmental change in infant habituation (Perone & Spencer, 2013), visual working memory capacity in infants (Perone, Simmering, & Spencer, 2011) and children (Simmering & Patterson, 2012), and spatial recall

Table 1 Infants' Similar Test

Predictor	R^2	R ² change	F change	р	В	β	р
Step 1 Age Step 2	.001	.001	.08	.78	.002	.03	.78
Shift rate Look duration Peak look	.083	.083	3.42	.02	26 04 02	37 21 30	.01 .14 .05

Table 2Infants' Dissimilar Test

Predictor	R^2	R ² change	<i>F</i> change	р	В	β	р
Step 1 Age Step 2	.013	.013	1.49	.23	.009	.11	.23
Shift rate Look duration Peak look	.03	.017	.67	.57	05 .01 01	07 .04 2	.65 .77 .20

performance in children (Schutte & Spencer, 2009). In the following text, we first describe the model's architecture. Next, we illustrate how looking and neurocognitive dynamics are linked in the model. Finally, we present simulations of developmental change in looking dynamics and discrimination in the VPC task. Model equations and parameter settings are presented in the online supplemental materials (Appendix).

Model architecture. Figure 4 shows the DNF model architecture. The model consists of a fixation and a neurocognitive system that is situated in a virtual world where task-relevant stimuli appear at left and right locations, attention-getting stimuli appear at a center location, and task-irrelevant stimulation appears at away locations. The fixation system consists of a collection of nodes that fixate the left (L), right (R), center (C), and away (A) locations in a winner-take-all fashion.

The presence of stimuli at left and right locations biases the fixation system to look to the displays (black arrow from space to fixation system in Figure 4). Fixating left or right opens a perceptual gate into a perceptual field (PF) that consists of a population of neurons with receptive fields tuned to continuous dimensions (e.g., color).¹ PF encodes items. Encoding has two functions. First, encoding supports continued fixation via an excitatory connection between PF and the fixation system (see black bidirectional arrow). Second, encoding passes excitatory activation to a working memory (WM) layer which can maintain neural activity associated with an item in the absence of input from PF.

The next critical aspect of neural interactions in the model is reflected in the pattern of connectivity from WM to PF. Interactions between PF and WM are set such that strong activation in WM inhibits similarly tuned neurons in PF via a strongly tuned connection to a shared inhibitory layer (not shown for simplicity; see gray arrow from WM to PF). This inhibition suppresses encoding of fixated inputs that match remembered items, weakening PF support for fixation. This, in turn, leads to the release from the current fixation state. PF and WM are also reciprocally coupled to Hebbian layers (not shown; see HL) that instantiate a form of Hebbian learning to capture changes that occur with repeated presentation of items across trials. These layers strengthen encoding of previously encoded items in PF and facilitate the maintenance of items in WM.

¹ Note that the neurocognitive system consists of two identical networks reciprocally coupled to the fixation system. This allows the model to encode and form memories for color and shape information in parallel. Only one network is shown for simplicity. Only one dimension is needed to illustrate how the model works, because we only probed memory on one dimension for infants and the model. See the online supplemental materials (Appendix) for further details.



Figure 4. Dynamic neural field (DNF) model architecture. At the top is the virtual world at which the model looks. The presence of "buggles" biases the fixation system to look left (L) or right (R; see black arrow from space to fixation system). Fixating one location acts like a perceptual gate and allows the stimulus from space to be input to the cognitive system, which consists of a perceptual field (PF) and working memory (WM) field. PF and WM are reciprocally coupled to a shared layer of inhibitory interneurons (Inhib, not shown). Strong activity in PF supports fixation (black bidirectional arrow between PF and fixation system). Strong WM activity suppresses PF activity via a strongly tuned connection from WM to Inhib (see gray bidirectional arrow between PF and WM). PF and WM activity are also influenced by a Hebbian layer, HL_{PF} and HL_{WM}, respectively, which accumulates slowly over learning and facilitates encoding in PF and memory formation in WM. C = center location; A = away location.

Looking and neurocognitive dynamics. Figure 5 illustrates the mechanisms underlying memory formation, recognition, and novelty preferences in the model. The left portion shows the state of PF and WM while looking at pairs of identical items early in familiarization. Initially, the model is looking left (Panel A; the infant head indicates gaze direction), and the gray color excites selectively tuned neurons in PF. Local excitatory/lateral inhibitory interactions within PF create an activation peak (black line, left y axis), which estimates the specific feature value of the stimulus, supports continued fixation, and feeds into WM. Peaks in PF enable Hebbian learning to occur at active sites, priming previously excited neurons to respond more robustly (gray line, right y axis).

Stochastic forces within the fixation system enable it to spontaneously switch gaze. In this example, the model happens to look "away" where no task-relevant stimulation appears and PF activity subsides (Panel B). We refer to this stimulus-dependent activity in PF as *encoding*. After looking away, the model switches gaze again. This time the model looks right, the location at which an identical item is present (Panel C). The stimulus is again input to PF, and activity in WM is beginning to emerge (see bottom panel in C).

Across a series of fixations and stimulus presentations, WM activity and Hebbian learning associated with WM increases. This is evident in the state of PF and WM during the test phase, illustrated in the right portion of Figure 5. During the test phase, the model, like infants, is presented with the familiar item paired with a novel item. In this example, the familiar and novel items are dissimilar. Initially, the model looks left (Panel D) and the familiar (shown as gray) item is input to PF. WM activity is robust and is creating strong inhibition in PF (see trough around peak in PF) that suppresses encoding. This is the neural mechanism of recognition in the model. This, in turn, leads to weak support from PF to continue fixation, and the model tends to switch gaze away from the familiar item, the behavioral signature of recognition in the VPC task.

PF activity is very different when the model looks to the dissimilar novel item (Figure 5E). Here, PF activity associated with the dissimilar (shown as black) item is robust and provides support for continued fixation. Notice that PF activity at sites associated with the familiar item remains suppressed by the maintenance of the item's color in WM. Consequently, when the model switches gaze to look again at the familiar item, support for fixation is weak and look durations are short. The duration fixation to left and right locations in the model, like infants, can be measured (see online supplemental materials [Appendix]). This enables us to calculate a novelty score, shift rate, look duration, and peak look for each simulation of the model.

The final issue we tackle here is whether changes in looking dynamics and discrimination arise from a single neurodevelopmental mechanism. Previous simulations of the DNF model in a single presentation habituation task have shown that the model produces canonical developmental changes in habituation curves and discrimination between familiar and novel items that vary in their metric similarity (Perone & Spencer, 2013). It should be noted that both of these changes emerged from a single mechanism—the spatial precision hypothesis (SPH), which posits that excitatory and inhibitory interactions become stronger over development as children accumulate experience across diverse contexts (Perone et al., 2011; see also Schutte & Spencer, 2009). In the following section, we describe the SPH in greater detail in the context of our simulation method.

Model Simulations

Method

The goal of the model simulations was to elucidate the neurocognitive processes that might underlie looking dynamics, learning, and discrimination performance on the task and developmental time scales. To test whether a single mechanism might underlie developmental changes in looking and discrimination, we created 5-, 7-, and 10-month-old models by implementing the SPH. This involved manipulating the strength of excitatory and inhibitory interactions within PF and WM such that these interactions were stronger over development (Perone et al., 2011; Perone & Spencer, 2013; Schutte & Spencer, 2009; Simmering & Patterson, 2012).



Figure 5. Illustrates the linkage between looking and learning during familiarization (Panels A-C) and the basis for discrimination during the test phase (Panels D and E) in the dynamic neural field (DNF) model. The left y axis shows the strength of activation in perceptual field (PF)/working memory (WM; black line), and the right y axis shows the strength of the Hebbian layer activation of PF (HL_{PF} ; top panel, gray line) and the WM (HL_{WM}; bottom panel, gray line). Initially, in Panel A, the model is fixating the left location and the brown stimulus is being encoded (see activation peak centered at Site 90 in PF). Notice that activity in HL_{PF} has already begun to accumulate. In Panel B, the model spontaneously switches gaze to an away location at which no task-relevant stimulus is present. Activity in PF subsides. In Panel C, the model reacquires fixation and is looking at an identical gray stimulus at the right location. This stimulus is again input into PF, and encoding is strengthened due to the accumulated activity in HL_{PF} (see gray line, right y axis). Activity in WM is also starting to emerge (see black line in lower panel). After the familiarization phase, the model enters the test phase and, like infants, is presented with the familiar stimulus and a novel stimulus. In this example, the novel stimulus is dissimilar on the color dimension. Panel D shows the state of PF and WM when the model looks at the familiar stimulus. Here, HL_{WM} (gray line, right y axis) has accumulated across the familiarization phase, and WM is actively maintaining a peak associated with the familiar item (black line). Consequently, PF activity generated by the familiar stimulus is strongly inhibited by WM and support for looking low. Panel E shows the state of PF and WM when the model looks at the novel stimulus. Here, the sustained WM peak associated with the familiar item continues to suppress PF activity at the familiar site. However, inhibition at sites tuned to the dissimilar novel item is minimal, PF activity strong, and support for looking is high.

Table 3 shows the strength of these parameters over development. As can be seen, the strength of excitation within PF (a_{uu}) and WM (a_{ww}) increased most strongly between 5 and 7 months, the strength of inhibition from Inhib to PF (a_{uv}) increased most strongly between 7 and 10 months, and the strength of inhibition from Inhib to WM steadily increased over development (a_{wv}) .

We situated each model in the same procedure as infants. The model was familiarized with pairs of identical items across six 10-s trials (one time step = 5 ms). Stimuli were Gaussian inputs centered over a specific site (e.g., a specific hue value) in a field consisting of 180 neurons (so each unit in the field equaled, for instance, 2° in color space). Recognition of the familiar item was

assessed across two 20-s test trials, the similar and dissimilar tests. On the similar test, the model was presented with the familiar item paired with a novel item that differed by 15 units (e.g., 30°) in one direction. On the dissimilar test, the model was presented with the familiar item paired with a novel item that differed by 45 units in the opposite direction as the similar test.

We conducted 200 simulations with each parameter set (i.e., at each age). Perone and Spencer (2013) showed that this number of simulations produced means for looking behavior that were quantitatively close across repeated batches of simulations. This is important because it ensures that the model's behavior can be attributed to the parameter settings and not simulation-to-simulation variation that

Table 3Spatial Precision Hypothesis Parameter Manipulations

Parameter	5 months	7 months	10 months
Strength of excitation in perceptual field (a_{-})	0 1041	0 2028	0.2867
Strength of excitation in working memory (a_{ww})	0.7741	0.9676	0.972
Strength of inhibition in perceptual field (a_w)	1.106	1.1642	1.4553
Strength of inhibition in working memory (a_{wv})	0.1781	0.1875	0.2037

arises from stochastic fluctuations in the fixation and cognitive systems. Moreover, large batches of simulations for a single parameter setting enable us to pull out structure across simulations and examine how the neurocognitive dynamics of the DNF model specified by the parameter settings give rise to the developmental changes in behavior that we aimed to reproduce.

Parameters were fit by hand to capture the behavior of the 5-month-old infants. The four SPH parameters were then increased to capture the behavior of 7- and 10-month-old infants until a parameter set that produced a good quantitative fit across a wide range of looking behaviors over development was achieved. To evaluate the fit between the model and infant data, we calculated the root-mean-squared error (RMSE) for means and standard deviations across all ages for three categories of measures: shift rate (shift rate during familiarization, similar test, and dissimilar test), looking lengths (peak look as well as look duration during familiarization, similar test, and novelty scores (novelty score on similar test and dissimilar test). We also computed the RMSE for a second batch of 200 simulations at each age to ensure that the model produces quantitatively similar means in looking measures across simulation batches.

A summary of the RMSE for the original and replication simulation batches is shown in Table 4. The RMSE was comparable for the original simulations and the replication simulations. The model fit for means and standard deviations was good across the board. In particular, for the original batch of simulations, the mean shift rate ratio for the model was within .10 of empirical values, mean look durations within .31 s of the empirical values, and mean novelty scores were within 3% of the empirical values. The model simulations also quantitatively fit the empirically measured standard deviations for novelty preferences quite well. The standard deviation fits for shift rate and duration measures were not as close because the model produced less variable behavior in these measures during familiarization when the model looked back and forth at identical items than it did during the test phase when it looked back and forth at different items.

Results

We examined the model's performance in three sets of analyses that parallel the empirical results reported previously. We begin with analyses of the model's performance during familiarization, followed by test, and finally by individual differences in looking dynamics and discrimination performance.

Familiarization. The DNF model captured developmental change in looking dynamics quite well. Figures 2D–2F shows the

looking dynamics of the 5-, 7-, and 10-month-old parameter sets. As the strength of neural interactions increased, the model exhibited a higher shift rate (Panel D), shorter look durations (Panel E), and shorter peak looks (Panel F). The model captured the developmental pattern in some detail—the decline in look duration from 5 to 7 months, for instance, was steeper than from 7 to 10 months.

Figure 6 illustrates the neurocognitive dynamics underlying these behavioral changes. The top portion of the figure shows the sum of PF activity when the model looked at the familiar stimulus on each trial. By Trial 3, PF activity was robust for the 5-month-old model (Panel A). This led to strong support for fixation, which, in turn, led to long look durations. Consequently, shift rates were low and peak looks were long. By contrast, PF activity shows a clear decline during later trials for the 7- and 10-month-old models. This led to weaker support for fixation, which, in turn, led to shorter look durations. Consequently, shift rates were higher and peak looks shorter.

This difference in PF activity is a consequence of the SPH. This can be seen in Figures 6D–6F, which show the state of PF and WM averaged across the interstimulus inteval after each familiarization trial. PF activity is more robust and WM activity weaker for the 5-month-old model than the 7- and 10-month-old models. For the older models, stronger neural interactions gave rise to more robust WM activity and suppression of PF activity after a few trials; that is, the SPH led to speeded encoding and memory formation. For the older models, WM activity is also near threshold (i.e., 0) toward the end of the familiarization phase. This strongly influences test performance, which we describe in the following section. Note that although the dynamics appear very similar at 7 and 10 months, the strength with which the neurons interact is different, which leads to the small behavioral changes seen. We discuss how these subtle differences impact looking dynamics at test.

Test. The SPH can capture developmental changes in infants' looking dynamics during familiarization. Does the same neurodevelopmental mechanism also capture infants' discrimination performance? As can be seen in Figure 3D, like infants, only the 7and 10-month-old models exhibited a robust novelty preference on the dissimilar test. These developmental differences arise from a shift in the contribution of PF activity when the models look at the familiar and novel stimuli. Figures 7A-7C shows the sum of PF activity while the model is looking at the familiar (black bar) and novel (gray bar) items across development. For the 5-month-old model (Panel A), PF activity was comparable while looking at the familiar and novel items. This led to equal support for looking at each item and a null preference. For the 7- (Panel B) and 10-(Panel C) month-old models, PF activity associated with the novel item was stronger than the familiar item. This led to more fixation support while looking at the novel item and, consequently, a novelty preference.

Table 4Root-Mean-Squared Error Model Fit

	Shift	Shift rate		ation	Novelty score		
Simulations	М	SD	М	SD	М	SD	
Original Replication	0.10 0.10	0.12 0.12	0.31 0.32	0.50 0.50	0.03 0.03	0.04 0.03	



Figure 6. Neural dynamics in the dynamic neural field (DNF) model underlying looking behavior during familiarization phase. Top row shows sum of perceptual field (PF) activity while looking on each trial across the familiarization phase for the 5-month-old model (Panel A), 7-month-old model (Panel (B), and 10-month-old model (Panel C). PF activity was stronger for the 5-month-old model than the 7- or 10-month-old model. Error bars show \pm 0.5 SD. Bottom row shows the state of PF and working memory (WM) during the interstimulus interval after each familiarization trial, averaged across simulations. Neural interactions were weaker in the 5-month-old model (Panel D), leading to stronger PF activity than in the 7- (Panel E) and 10- (Panel F) month-old models with stronger neural interactions. The stronger neural interactions of the older models gave rise to less total looking, higher shift rates, shorter look durations, and shorter peak looks relative to the weaker neural interactions in the younger model.

The shift in the contribution of PF activity associated with the familiar and novel items over development arises from changes in the interaction between PF and WM. This can be seen in the bottom portion of Figure 7, which shows the state of PF and WM while looking at the familiar (black line) and novel (gray line) stimulus on the dissimilar test across development.² For illustrative purposes, the familiar stimulus is shown as black and the novel stimulus is shown as gray. When the 5-month-old model looks at the familiar black item and dissimilar novel gray item (Panel D), activation associated with each stimulus is quite similar and the model looks equally at the two items. For the 7- (Panel E) and 10- (Panel F) month-old models, however, activation is stronger while looking at the dissimilar novel gray item than while looking at the familiar black item. This leads the model to look longer to the dissimilar novel gray item than the familiar black item.

Where does this developmental change come from? The older models are able to maintain a working memory of the familiar black item even while exploring the dissimilar novel gray item. This is reflected in the activity of the WM layer shown in Panels E and F (see gray line at Site 90 on the x axis = the black item). Importantly, the gray line shows the state of WM while the model is looking at the novel stimulus. In other words, when the model is looking at the dissimilar gray novel item, it is maintaining a working memory representation of the familiar black item. This has an important consequence—WM produces inhibition in PF at the site associated with the familiar item, even when the model is looking at the novel item. Thus, when the model refixates on the

² Note that the black line shows the state of the entire field while looking at the familiar item, showing activation at the site tuned to the familiar item (see Site 90, black line) but also ongoing neural activity at the site tuned to the novel item (see Site 135, black line). Similarly, the gray line shows the state of the entire field while looking at the novel item, showing activation at the site tuned to the novel item (see Site 135, gray line) and also ongoing neural activity at the site tuned to the familiar item (see Site 90, gray line).



Figure 7. Neural dynamics in the dynamic neural field (DNF) model that underlie developmental change in discrimination on the dissimilar test. Top row shows the sum of perceptual field (PF) activity while looking at the familiar item (black bars) and novel dissimilar item (gray bars) for the 5-month-old (Panel A), 7-month-old (Panel B), and 10-month-old (Panel C) models. Perceptual field (PF) activity associated with the familiar item decreased over development. This led the older models to preferentially look at the novel item relative to the familiar item. Error bars show \pm 0.5 SD. The bottom row shows the state of PF and working memory (WM) while looking at the familiar item (black line) and novel dissimilar item (gray line). That is, the black line shows the activity of neurons at sites tuned to the familiar item and the novel item while looking at the familiar item. Similarly, the gray line shows the activity of the neurons at sites tuned to the familiar item and novel item while looking at the novel item. For illustrative purposes, the black buggle is the familiar item and the gray buggle the dissimilar novel item. Their relative similarity is represented on the feature dimension (x axis). For the 5-month-old model, activation was comparable while looking at the familiar and novel items (Panel D), leading to a null preference. For the 7-month-old (Panel E) and 10-month-old (Panel F) models, activation was stronger while looking at the novel item than while looking at the familiar item. This arises from suprathreshold activity associated with the familiar item in WM (see arrows), which produces strong inhibition in PF. WM activity associated with the familiar item remains suprathreshold even when the model is looking at the dissimilar novel item (see gray line at familiar site in 7- and 10-month-old models relative to gray-line in 5-month-old model).

familiar item, support for fixation is weak, and the model looks away.

The same analysis of the model's performance on the preceding test, the similar test, is shown in Figure 8. Again, for illustrative purposes, the familiar item is black, and the similar novel item is gray. Here, activation in PF associated with the familiar black item and that associated with the similar novel gray item were comparable, which led to a null preference for the 5-, 7-, and 10-monthold models.

It is notable that across the test phase, activation in PF associated with the familiar item decreased for the older models (compare Panels 7B and 7C with Panels 8B and Panel 8C). This



Figure 8. Neural dynamics in the dynamic neural field (DNF) model that underlie performance on the similar test. Top row shows the sum of perceptual field (PF) activity while looking at the familiar item (black bars) and novel similar item (gray bars) for the 5-month-old (Panel A), 7-month-old (Panel B), and 10-month-old (Panel C) models. PF activity associated with the familiar and novel item was comparable across development, leading to null preferences on the similar test for each model. Error bars show \pm 0.5 SD. The bottom row shows the state of PF and working memory (WM) while looking at the familiar item (black line) and novel similar item (gray line). That is, the black line shows the activity of neurons at sites tuned to the familiar item and the novel item while looking at the novel item. For illustrative purposes, the black buggle is the familiar item and gray buggle the similar novel item. Their relative similarity is represented on the feature dimension (*x* axis). Activation associated with the familiar and novel item were comparable for the 5-month-old (Panel D), 7-month-old (Panel E), and 10-month-old (Panel F) models. However, in the older models, activation associated with the familiar item should be activity, which surfaced during the subsequent dissimilar test trial (see Figure 6).

decrease in activation in PF associated with the familiar item and relatively stronger neural dynamics of the 10-month-old model led this model to release fixation from the familiar item more quickly on the dissimilar test. This, in turn, enabled the model to capture the critical empirical finding that 10-month-old infants exhibited a higher shift rate (Figure 3 Panel E) on the dissimilar test than on the similar test.

Individual differences in looking and discrimination. A unique feature of the DNF model is that it produces looks that can be directly measured. This enabled us to quantitatively capture

developmental change in an unprecedented array of looking measures and provide an account of the linkage between neurocognitive and behavioral dynamics. But are looking dynamics in the DNF model meaningfully linked to discrimination performance, as they are in infants? To explore this possibility, we conducted the same regressions on the model data as with infants. Note that stochastic fluctuations in the fixation and neurocognitive systems are the only source of simulation-to-simulation variation in the model data. Put differently, we did not manipulate any parameters to make some simulations exhibit different patterns of looking. Rather, the model spontaneously generated patterns of looking and learning over trials in the task, and we asked whether this produced patterns of covariation between looking and discrimination performance that mimic our sample of infants.

Table 5 shows results of the first hierarchical regression predicting novelty score on the similar test. On the first step, age was entered as a predictor. Age accounted for a significant proportion of variance in novelty scores on the similar test. On the second step, shift rate, look duration, and peak look were entered. Consistent with the empirical results, looking dynamics together accounted for a significant proportion of variance in novelty scores on the similar test above and beyond the effects of age (change in $R^2 = .02$). The regression results for the dissimilar test are shown in Table 6. As in the infant analyses, the model was not significant on any step.

In summary, individual differences in looking dynamics in the model across simulations were predictive of discrimination in ways comparable to analyses of infants' performance. It is notable that the proportion of variance in novelty scores accounted for by looking measures was comparable for infants and for the model. Thus, the DNF model captures a realistic magnitude of the relationship between looking and discrimination. We discuss these results in greater detail in the following section.

General Discussion

Over the past several decades, a rich empirical database has shown that looking dynamics and recognition change together over development and are linked within individuals (e.g., Rose et al., 2001). During this same developmental period, infants' discrimination abilities improve for stimuli with well-controlled similarity properties (Brannon et al., 2007). Simulations of a recent DNF model of infant looking and memory formation (Perone & Spencer, 2013) posits that developmental changes in looking dynamics and discrimination performance in a single presentation task can arise from a common mechanistic source. Here, we probed this claim by testing whether looking dynamics and discrimination change together over development and are linked within individuals. Further, we tested whether a single mechanism in the DNF model—the SPH—could capture developmental changes in infants' behavior.

Empirical results from our study revealed that looking dynamics and discrimination change together over development. As with previous studies, with age infants' shift rates were higher, look durations shorter, and peak looks shorter. With age, infants' also began to discriminate along the metrically organized color and shape dimensions that constitute the buggle objects. These findings

Table 5 Model Similar Test

Predictor	R^2	R ² change	<i>F</i> change	р	В	β	р
Step 1 Age Step2	.007	.007	4.22	.04	005	08	.04
Shift rate Look duration Peak look	.022	.015	2.98	.03	13 .04 .002	08 .09 .01	.20 .21 .83

Table 6Model Dissimilar Test

Predictor	R^2	R ² change	<i>F</i> change	р	В	β	р
Step 1 Age Step 2	.001	.001	.51	.48	.002	.71	.48
Shift rate Look duration Peak look	.002	.001	.25	.86	05 01 .01	03 02 .03	.58 .75 .58

are consistent with the possibility that developmental changes in looking dynamics and discrimination share a common mechanism. The regression analyses supported this view. Results showed that looking dynamics predicted discrimination performance on the similar test. This indicates that looking dynamics and discrimination are meaningfully linked within individuals.

The DNF model simulations also support the view that developmental changes in looking dynamics and discrimination share a common mechanism. We implemented the SPH by increasing the strength with which excitatory and inhibitory neurons governing encoding and working memory formation interact. This led to quick encoding and robust memory formation, enabling the model to detect novelty along continuous dimensions. Behaviorally, the SPH led to a quicker release of fixation for remembered items, giving rise to higher shift rates, shorter look durations, and shorter peak looks over development.

The SPH might capture a confluence of neurodevelopmental processes happening during infancy that influence visual memory. For example, the SPH might reflect changes in the visual processing pathways projecting to primary visual cortical areas involved in processing visual information such as color. In fact, in adults, strong neural activity in primary visual cortical areas is associated with working memory performance (Sligte, Scholte, & Lamme, 2009). The SPH might also reflect decreases in neuronal noise during the first year of life. Skoczenski and Norcia (1998) proposed that noise in neural transduction processes early in development limits infants contrast sensitivity. They found that neuronal responsivity was similar for visual contrasts with and without external noise, which they attributed to internal noise sources. This difference decreased with age and was associated with improvements in contrast sensitivity from 6 to 30 weeks of age. Perone and Spencer (2013) similarly found that high levels of neural noise in the DNF model were required to capture developmental change in infants' looking behavior from 6 to 12 weeks of age. Interestingly, an emergent consequence of the SPH is resistance to interference from noise, as the SPH leads to increasingly stable neuronal states. We are currently probing how experience-dependent changes in neural connectivity within DNFs influences basic perceptual and memory processes as well as the stability of neuronal states underlying WM formation.

The DNF model also produced patterns of covariation between looking dynamics and discrimination performance. Individual differences in looking have long been interpreted as reflecting variation in neurocognitive ability (for reviews, see Colombo, 1995; Colombo & Mitchell, 1990; Rose et al., 2007). In the simulations of the DNF model, there were no individual differences of this sort. However, the DNF model is a historical system, and each simulation of the model creates a unique trial-to-trial pattern of behavior (see Perone & Spencer, 2013). For example, when the model spontaneously exhibits a long look, encoding is sustained, and robust memory formation ensues. This, in turn, impacts the state of perceptual and working memory processes in the model upon entering the test phase and, ultimately, can influence relative dwell time to familiar, remembered items and novel items. We probed whether this type of variation was predictive of discrimination performance. Remarkably, the DNF model produced comparable patterns of covariation between looking and discrimination as infants. Looking measures in the model, as in infants, were predictive of discrimination performance on the similar but not dissimilar test.

Why might looking dynamics be predictive of discrimination performance only on the similar test? In the DNF model, looking between the familiar and novel items on the similar and dissimilar tests are influenced by neural dynamics within PF and WM very differently. Figures 8D-8F shows the state of PF and WM while looking at the familiar and similar novel items. The state of PF and WM are both influenced by looking and learning across the familiarization phase. If PF and WM activity associated with the familiar item are robust, Hebbian learning in PF can support brief looking to the familiar item. If WM is also robust, inhibition surrounding the familiar item will be strong. This, in turn, leads to quick suppression of PF activity associated with the similar novel item and release of fixation. Indeed, Figures 8A-8C shows that activation in PF associated with the familiar item is slightly stronger than activation in PF associated with the similar novel item. In other words, subtle differences in looking and learning across the familiarization phase that lead to robust encoding and memory formation impact the neural dynamics that influence looking between highly similar familiar and novel items.

An emerging challenge in developmental psychology is to map the rich set of behavioral dynamics we observe in the laboratory to cognitive dynamics at the level of the individual. The scope of this challenge has become increasingly salient as technological advances have enabled researchers to obtain massive quantities of data on the temporal dynamics of behavior from individual infants (Adolph, Robinson, Young, & Gill-Alvarez, 2008; Franchak, Kretch, Soska, & Adolph, 2011). Here, we provided an account of the neurocognitive sources of looking measures that are aggregated across a series of trials. Can the DNF model also account for the linkage between ongoing behavioral and cognitive dynamics at the level of the individual? Like infants, the model does produce complex patterns of looking through time. Figure 9 shows the shift rate (Panel A) and look duration (Panel B) of three individual infants (solid squares) and three hand-selected simulations (dashed circles) from those reported here. As can be seen, the DNF model produces patterns of looking that mirror those of infants. These individual differences stem from stochastic fluctuations in the DNF model, which was sufficient to produce a pattern of covariance between looking and discrimination that resembles the pattern of infants.

Given that all three simulation trajectories in Figure 9 were generated from the same model in the same paradigm with the same parameters, are variations in these individual trajectories simply the result of noise and therefore not meaningful or indicative of "real" individual differences? This is an oversimplified interpretation for several reasons. First, stochastic variations have a role in how infants distribute their looks (Robertson, Bacher, & Huntington, 2001) and may have an important role in visual foraging more broadly (Mobus & Fisher, 1999). Thus, fluctuations in performance are interesting in their own right. Second, the individual patterns in Figure 9 are a result of a complex looking and memory formation system at work. Consequently, these individual patterns do not just reflect the effects of noise; rather, they reflect the effects of noise on the operation of a real-time system and how real-time variations create differential patterns of looking and learning over time. Third, several studies have shown that individual differences in looking and memory formation processes are robust over development (for a review, see Rose et al., 2007). In this context, the question is not whether individual differences in looking performance are meaningful; the question is which aspects of individual differences are meaningful.

The DNF model can be a useful tool on this front because we can probe the full range of possible trajectories that could arise for a given parameter setting. This allows us test specific hypotheses about the origin of individual differences in infants' performance. For instance, we could hypothesize that the variation in infants' performance shown in Figure 9 comes from real-time stochastic fluctuations in looking and not from substantive individual differences across these infants. This predicts that if we tested these same infants and the same DNF model in, for instance, the single presentation habituation paradigm used by Perone and Spencer (2013), we should find that the individual trajectories of both the infants and (some of) the simulations once again align. If they do not, then we clearly failed to capture a critical source of individual differences in the DNF model.



Figure 9. Shift rate (Panel A) and look duration (Panel B) of three individual infants (solid squares) and three individual dynamic neural field (DNF) model simulations (dashed circles) across the six familiarization trials (T). i = infants; s = simulations.

What might we be missing? One missing source of individual differences in the model is a long-term learning history. Infants' familiarity with a stimulus influences how they look and what they remember (Bahrick & Pickens, 1995; Martin, 1975; Quinn, Yahr, Kun, Slater, & Pascalis, 2002). A simulation study by Perone and Spencer (2013) showed that the DNF model can capture this source of individual differences. They observed that high levels of familiarity with a stimulus in the model was associated with low levels of initial looking, fast memory formation, and low levels of looking across trials in a single presentation task.

The second source of individual differences is parametric differences across infants that reflect variations in each infant's neurodevelopmental state. This form of individual differences most closely resembles what individual and population differences in looking are attributed to in the literature (see, e.g., Rose et al., 2001, 2002). This view stems from the observation that individual differences in looking resemble developmental differences in looking. For instance, individual infants who exhibit relatively higher shift rates than similarly aged peers also exhibit higher novelty scores, much like older infants exhibit higher shift rates and higher novelty scores than younger infants. Gilmore and Thomas (2002) probed this type of individual difference, fitting exponentially decreasing functions to individual infants' habituation rates across trials and identifying clusters of fast and slow habituators. This work is promising but has some limitations. For example, this work does not specify the neurocognitive processes that underlie habituation rate or looking as an active dynamical behavior distributed in time and space. The DNF model overcomes these limitations and may shed light parametric differences between individuals. For instance, Perone and Spencer (2013) showed that the parameters modified according to the SPH can capture individual differences in looking that resemble developmental differences. They simulated a series of fine-grained changes in the SPH parameters. This yielded individual differences in models that generated looking and discrimination behaviors ranging from relatively less to relatively more mature.

We contend that the DNF model can be a powerful tool to shed new light on the origin of individual differences in performance and can be used to tease apart how real-time stochastic forces impact learning trajectories, how longer term learning about individual stimuli and stimulus dimensions impacts performance, and how parametric differences in infants' neurodevelopmental state impact performance. Understanding individual differences at this level will clearly require a substantive empirical and theoretical effort. On the empirical front, we must observe infants' behavior across multiple contexts and at multiple points over development. On the theoretical front, we must develop ways to differentiate how classes of learning trajectories generated by the DNF model are influenced by the multiple factors that can create individual differences.

To summarize, measures of infant looking form the basis of the scientific understanding of infant cognition. A large body of literature has accumulated describing individual, developmental, and population differences in infants' looking dynamics, recognition performance, and discrimination abilities. Here, we observed that looking dynamics and discrimination change together over development and are linked within individuals. Simulations of a DNF model of infant looking and memory support the view that developmental changes in looking and discrimination share a common mechanistic source. The DNF model simulations also provide new insights into how looking is linked to neurocognitive processes in real time, over learning, and over development. Finally, our simulations raise the exciting possibility that a richer theoretical account of how individual infants create their own development is within reach.

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