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Visual feature binding in early infancy

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Abstract. How does the developing brain of the human infant solve the feature-binding problem when visual stimuli consisting of multiple colored objects are presented? A habituation – dishabituation procedure revealed that 1-month-old infants have the ability to discriminate changes in the conjunction of a familiar shape and color in two objects. However, this good earlier performance was followed by poorer performance at 2 months of age. The performance improved again at 3 months of age. Detailed analysis of the oculomotor behaviors revealed that the age of 2 months was a period of drastic transition when the tendency to stay with the fixated objects disappeared and repetitive saccades between the two objects emerged. Our findings suggest that the ability to perceive conjunctions of features is available to infants very early, that the perceptual/neural basis at 1 and at 3 months of age may be fundamentally different, and that feature integration by vigorous eye movements or selective attention may be the key functional difference between the age groups.

1 Introduction

Studies of the visual perception of infants have revealed that newborns can discriminate between visual objects with simple shapes and colors (Fantz 1963; Banks and Salapatek 1983; Adams et al 1990). However, infants are usually confronted with complex scenes containing multiple objects with different features. Such a situation may pose the feature-binding problem (Treisman and Gelade 1980; Shimizu et al 1985; von der Malsburg and Schneider 1986; Singer 1993; Wolfe and Cave 1999) if the visual system processes separate features through distributed cortical modules (Zeki 1993). How the developing brains of young infants accomplish visual feature binding is a central issue in perceptual development.

An experiment by Slater et al (1991) showed that newborns are able to perceive visual objects as compounds of features. This suggests that integrated perception of shape and color is available to infants very early and that the cortical modules for separate features may differentiate later, if ever. In contrast, other studies have implied that differentiated modules for features may be innately provided, and the integration of modules may develop at 3 months or later (Cohen 1973; Bushnell and Roder 1985; Mundy 1985; Burnham and Vignes 1988). Thus, controversy remains whether the integration or the differentiation of modules for separate features occurs first during development. The former theory predicts that the feature binding is available to infants very early, while the latter theory predicts that young infants are not able to bind features and that their performance improves at some age in the course of the perceptual development. This issue may be resolved by studying the infants' capability for the feature binding of shape and color when two colored objects are presented simultaneously, a task which has not been tested directly in the previous studies.

In this study, we examined evidence of discrimination of changes in conjunctions of familiar shape and color in two objects by young infants ranging in age from 1 to 4 months, using the habituation – dishabituation procedure (Horowitz et al 1972; Cohen 1973; Bertenthal et al 1983). In addition, we analyzed developmental changes in oculomotor control during a looking task to reveal the mechanism underlying the feature integration. We demonstrated that 1-month-old infants have a visual system organized to discriminate between different objects. Further, we showed that the visual system of infants experiences dynamic changes at approximately 2 months of age for the acquisition of the adult-like capability of attention-based integration of features.

2 Methods

2.1 *Subjects*

Subjects were full-term infants with no known visual abnormalities. Informed consent was obtained prior to the initiation of experiments. Approval for the human experiments was obtained from the review board of University of Tokyo. We obtained experimental data from 1-month-olds ($N = 18$; mean age = 41 days; range: 28 to 53 days), 2-month-olds ($N = 22$; mean age = 70 days; range: 57 to 81 days), 3-month-olds ($N = 28$; mean age = 100 days; range: 84 to 111 days), and 4-month-olds ($N = 21$; mean age = 125 days; range: 114 to 139 days). An additional twenty-nine infants were tested, but were not included in the data because of fussiness.

2.2 *Experimental design*

Infants were shown the stimuli illustrated in figure 1 according to the infant-control habituation – dishabituation procedure (Horowitz et al 1972). During the habituation phase, infants were shown simultaneous presentations of two objects, each consisting of a shape (circle or triangle) and a color (red or green). The left/right positioning of the objects was changed in each trial to rule out the infants' discrimination of a new conjunction of features simply by detecting a change in the particular location of features. When the criterion for habituation had been met, objects with a new conjunction of the familiarized shapes and colors were displayed as test trials for approximately half of the infants (test group). The rest of the infants were subjected to two additional habituation trials, and then shown the test trial display (lag group). This design is called the partial-lag design (Bertenthal et al 1983), in which the additional habituation trials were given to exclude a possible artifact from spontaneous regression. In our study, we did not use a linear-regression procedure to determine spontaneous regression effects as in the original partial-lag design since a large variance of spontaneous-regression can cause imprecise estimation of the mean spontaneous regression for calculating the corrected looking scores. A significant increase in looking time on novel trials relative to the looking time on the preceding two familiar trials was used to indicate discrimination in both infant groups mentioned above. Thus, successful discrimination in our experiment was statistically defined as a significant dishabituation to the objects with a new conjunction of familiarized shapes and colors, as compared with the spontaneous regression to the same objects. The dishabituation score was derived as the difference in duration of looking time between the last two habituation trials and the first two test trials in the test group and between the additional two habituation trials and the two test trials in the lag group. The spontaneous-regression score was derived as the difference in duration of looking time between the last two habituation trials and the two additional habituation trials in the lag group. It is important to note that we can control for the spontaneous regression without requiring a group of infants exclusively for control purposes when it is not

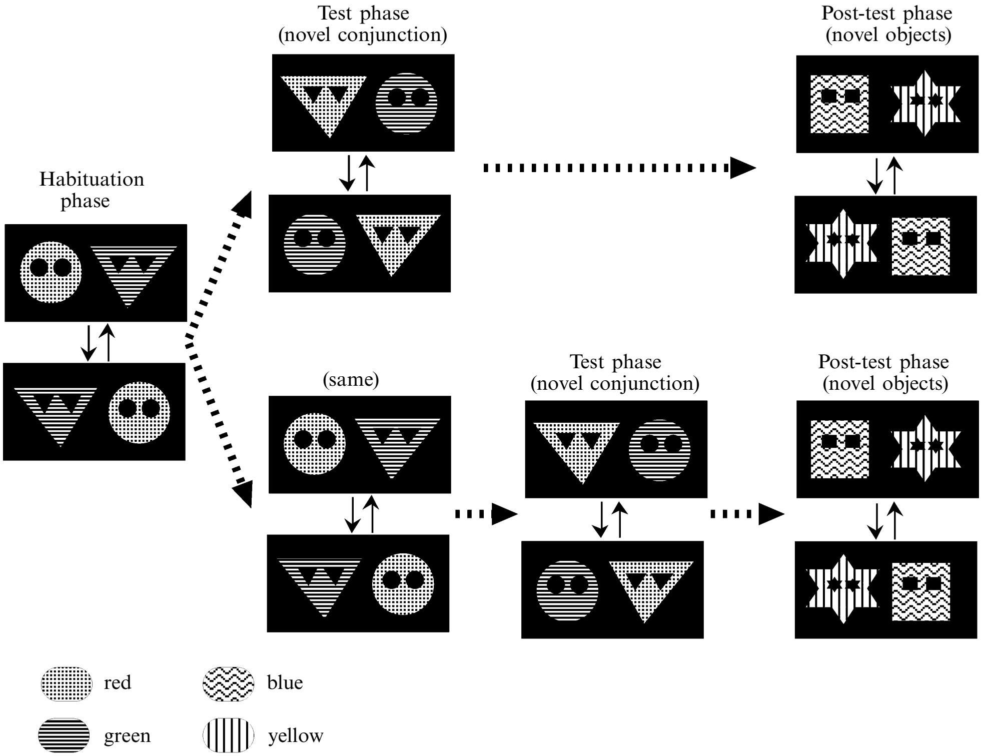

Figure 1. Schematic representation of stimuli used in experiments on infants' perception of changes in shape – color conjunction of two objects.

easy practically to test a large number of young infants. Following at least four test trials, a post-test stimulus composed of two novel objects with novel shapes and colors was shown to both groups. This presentation was included to ascertain that the infants were sufficiently alert, even after the long habituation experiment, to demonstrate a response to novelty of some sort.

2.3 *Stimuli*

A circle (13 deg diameter) with two circular blobs (3 deg diameter) and a triangle (16 deg × 14 deg) with two triangular blobs (4.0 deg × 3.6 deg) were shown side by side. The distance between the center of each object was 17 deg. We chose these shapes to have a close resemblance to a face pattern because newborn infants are known to follow a slowly moving schematic face stimulus with their head and eyes (Johnson et al 1991). Data on neonatal visual acuity (Banks and Salapatek 1983) suggest that the youngest infants in our study could resolve the small blobs in the objects. Each object was colored red or green against a black background. The colors were approximately equated for brightness by adult observers, and the luminance values of the red and green objects were 16 and 21 cd m^{-2}, respectively. It has been claimed that newborns can discriminate red and green stimuli from white when equated in luminance, provided that the stimulus size is at least 8 deg (Adams et al 1990).

2.4 *Procedure*

The infant sat on the parent's lap facing a computer display. The distance between the display and infant's eyes was set at approximately 30 cm. The parent was instructed not to direct the infant's attention in any way during the experiment. We devised a novel method to display stimuli in order to attract the attention of young infants during repetitive trials. When the infant was not attending to the stimulus, the stimulus was moved back and forth in the horizontal direction at a speed of 5.5 deg s^{-1}. This speed was chosen because it has been reported that newborn infants can follow a schematic face stimulus moving at a rate of approximately 5.0 deg s^{-1} (Johnson et al 1991). If the infant oriented toward the stimulus, the motion was terminated and the trial was initiated. This operation was controlled by two experimenters, who observed the infant on a video monitor and were blind to the visual stimuli being presented to the infant. Each independently pressed a key as long as the infant fixated the stimulus and released it when the infant looked away. The looking time of the infant was determined as the time during which both experimenters pressed the key. When the trial was terminated, the stimulus was turned off and the stimulus for the next trial was displayed with motion. Habituation of the infants was judged on the criterion that the infant's looking times for any three consecutive trials totaled less than half of the largest sum of the looking times for any three previous consecutive trials. This was determined automatically through a computer program. When looking time exceeded 20 s, the trial was terminated compulsorily and the display for the next trial appeared 1 s later. There were two reasons for choosing 20 s as the cap on trials. Our preliminary experiments showed that a longer cap often made 1-month-old and 2-month-old infants distressed because they had a too long looking time before the habituation criterion had been met. Another reason was that a longer cap sometimes caused a chance habituation. If duration of one trial was extremely long, the habituation criterion could be easily met by a fluctuating short looking time.

During experiments, we recorded the close-up of the infant's gaze and the presented stimuli simultaneously using a multi-viewer unit, which combined two video signals. We used a scan converter to produce the video signals of the stimuli that were generated by a computer. We were able to analyze the relationship between the infant's gaze and the visual stimuli within the accuracy of the video rate (60 Hz). After the experiments, the number of saccades in each trial of the habituation phase was scored by the observers from the video recordings. The observers were blind to the age of infants. We obtained the total number of saccades during the habituation phase by accumulating the number of saccades of each trial. The looking scores that had been obtained on-line during the experiment were used to calculate the following gaze parameters. The mean fixation time during the habituation phase was derived by dividing the accumulated duration of looking time by the total number of saccades during the habituation phase. The mean number of saccades per trial during the habituation phase was derived by dividing the total number of saccades by the total number of trials.

3 Results

The numbers of infants in the test and the lag groups, respectively, were eight and ten for 1-month-olds, nine and thirteen for 2-month-olds, thirteen and fifteen for 3-month-olds, and eleven and ten for 4-month-olds. These infants reached the habituation criterion. Table 1 shows group means of trials to criterion, accumulated looking time, fixation duration in habituation and test trials, and looking scores, which indicate changes in duration of looking time when familiar or novel stimuli were presented.

3.1 *Habituation trials*

The number of trials to reach the habituation criterion was analyzed with a 2 (Group: test versus lag) × 4 (Age: 1, 2, 3, and 4 months) ANOVA. This analysis yielded no significant main effects or interactions, indicating that the number of trials to criterion was not significantly different between the different age groups. On the other hand, the accumulated duration of looking time until the habituation criteria had been met exhibited age-dependent changes. Figure 2 plots individual accumulated durations of

Table 1. Mean trials to criterion, accumulated looking time, fixation duration, and change in looking time.

Dependent variable	Group/months old							
	1		2	3	4			
	test	lag	test	lag	test	lag	test	lag
Trials to criterion	9.6	8.9	9.1	11.2	7.9	8.3	8.0	9.6
	9.1		10.2		8.1		8.7	
Accumulated looking time/s	114.1	96.2	104.8	150.5	63.0	79.5	43.2	36.3
	104.1		131.8		71.8		39.9	
Fixation duration/s								
habituation trials (−6, −5)	15.1	12.6	15.4	13.6	10.0	12.7	6.4	3.5
habituation trials (−4, −3)	12.4	13.2	12.1	12.5	9.8	9.2	7.7	4.9
habituation trials (−2, −1)	6.3	5.3	5.2	5.6	3.3	5.0	2.9	1.7
test trials (1, 2)	14.5	–	11.9	–	5.2	–	5.4	–
additional habituation trials (1, 2)	–	4.9	–	9.3	–	5.2	–	3.6
lag test trial (3, 4)	–	7.4	–	10.1	–	10.3	–	3.0
post-test trials (−2′, −1′)	6.3	5.9	5.5	5.9	5.1	6.4	4.1	2.1
post-test trials (1′, 2′)	20.0	15.1	11.1	13.4	9.6	11.3	7.1	4.0
Change in looking time/s								
spontaneous regression	−0.4		3.8		0.2		1.9	
dishabituation to novel conjunction	4.9		3.2		3.3		1.0	
dishabituation to novel objects	11.2		6.8		4.8		2.3	

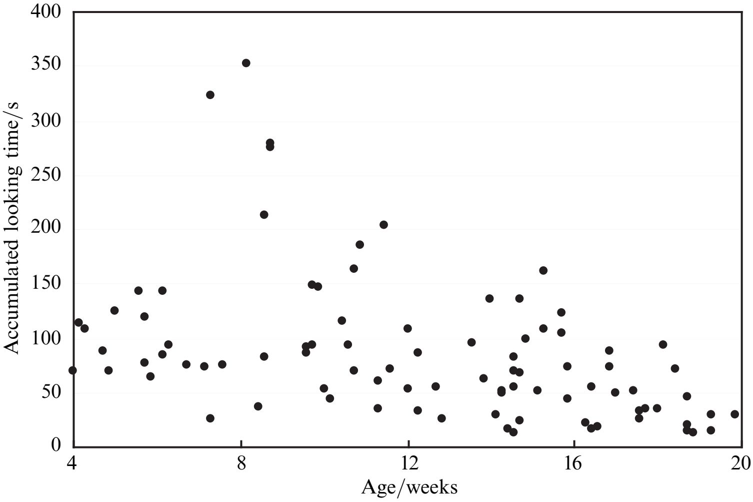

Figure 2. Accumulated duration of looking time taken to reach the habituation criterion as a function of age.

looking time as a function of age. Infants took longest to habituate to the stimuli at approximately 8 weeks of age. Seven out of twenty-two infants aged 2 months took more than 150 s to reach habituation. Figure 3 shows age-group means of the accumulated duration of looking time. A 2 (Group: test versus lag) × 4 (Age) ANOVA showed that there was a significant effect of Age ($F_{3,88} = 10.06$, $p < 0.001$). Group was not a main factor and there was no interaction. A posteriori doubly multivariate analyses

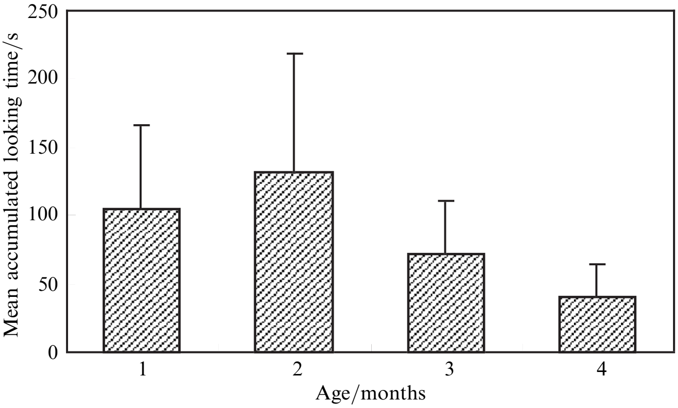

Figure 3. Group means of accumulated duration of looking time taken to reach the habituation criterion. Group means and associated standard errors for the four age groups are shown.

revealed that 2-month-olds significantly differed from 3-month-olds and 4-month-olds ($p < 0.01$) and that 1-month-olds significantly differed from 4-month-olds ($p < 0.01$).

The mean fixation durations of two trial blocks during habituation were analyzed with a 2 (Group) × 4 (Age) × 3 [Trial block: (-6, -5), (-4, -3) and (-2, -1)] repeated-measures ANOVA. Group and Age were between-subjects factors and Trial block was a within-subjects factor. Over trial blocks there was a significant decrease in duration of visual fixation ($F_{2,254} = 118.1$, $p < 0.001$). There was a significant effect of Age ($F_{3,254} = 21.5$, $p < 0.001$), indicating that younger infants showed longer duration of fixation. There was significant interaction between Trial block and Age. There was no significant effect of Group.

3.2 *Performance in discrimination of novel conjunctions of shape and color*

The mean fixation durations of two post-habituation trials were analyzed with a 2 (Group) × 4 (Age) ANOVA. There were main effects of Group ($F_{1,88} = 9.28$, $p < 0.01$), Age ($F_{3,88} = 12.12$, $p < 0.001$), and Group × Age interaction ($F_{3,88} = 5.31$, $p < 0.01$). A posteriori doubly multivariate analyses revealed that the duration of test trials with a novel conjunction of shape and color in the test group was significantly longer than the duration of the two additional habituation trials in the lag group, but only for 1-month-olds ($p < 0.01$). This provided evidence that 1-month-olds can discriminate the novel conjunction of shape and color.

However, the group comparison of duration of looking time for the test and lag groups may not reflect individual increases or decreases in looking time when the test or the same stimuli were presented. We therefore derived individual changes in durations of looking time. The dishabituation score was derived as the difference in duration of looking time between the last two habituation trials and the first two test trials in the test group and between the additional two habituation trials and the two test trials in the lag group. The spontaneous-regression score was derived as the difference in duration of looking time between the last two habituation trials and the two additional habituation trials in the lag group. The dishabituation score for the novel objects in the post-test phase was derived as the difference in duration of looking time between the last two test trials and the first two post-test trials. In the lag group, we could not obtain the dishabituation scores of two 1-month-olds, three 3-month-olds, and one 4-month-old because of a technical problem. As a result, we obtained the dishabituation scores for the novel conjunction from sixteen (eight from the test group and eight from the lag group) 1-month-olds, twenty-two (nine from the test group and thirteen from the lag group) 2-month-olds, twenty-five (thirteen from the test group and twelve from the lag group) 3-month-olds, and twenty (eleven from the test group and nine from the lag group) 4-month-olds.

Figure 4 shows individual scores of the dishabituation to the novel conjunction and the spontaneous regression as functions of age. On the whole, a lot of infants showed positive dishabituation scores, as shown in figure 4a. In contrast, most of the scores of the spontaneous regression were within the range of ±4 s except those of 2-month-olds, as shown in figure 4b. The numbers of subjects who showed more than 4 s recovery after criterion were none out of ten at 1 month, seven out of thirteen at 2 months, two out of fifteen at 3 months, and one out of ten at 4 months.

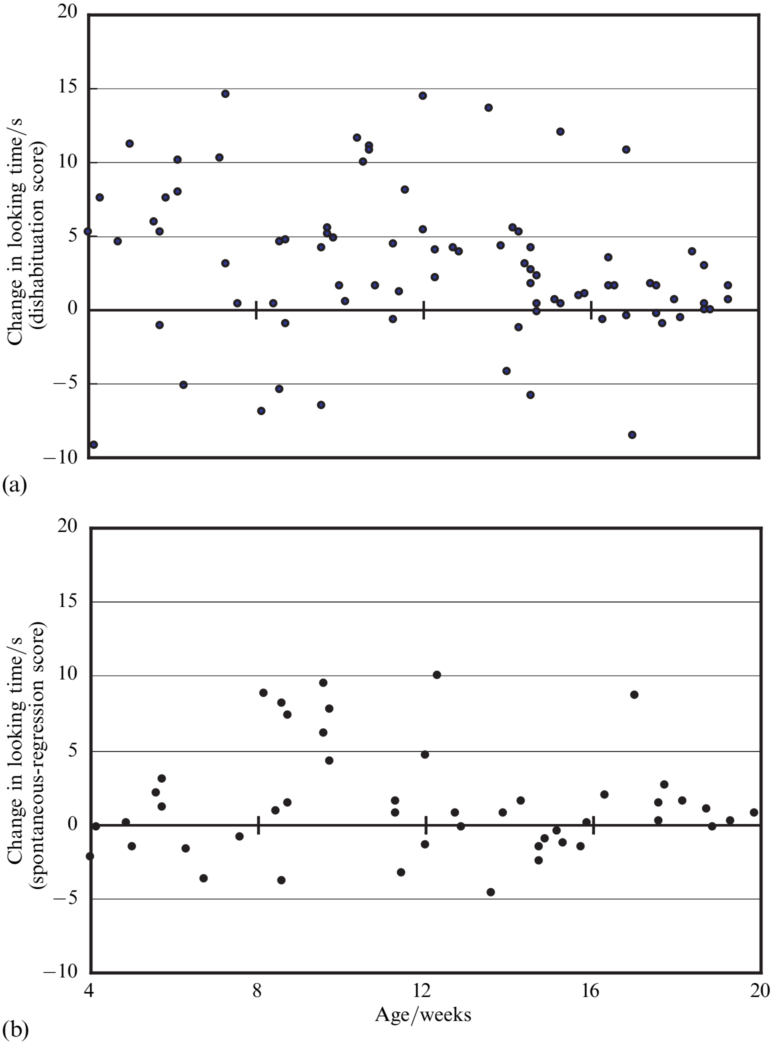

Figure 4. Looking scores for each infant as a function of age (weeks). (a) Dishabituation scores when infants were presented the objects with a novel conjunction of shape and color (the test condition). (b) Spontaneous-regression scores when they were presented the same objects (the lag condition). A positive value indicates an increase in looking time.

Figure 5 shows the group means of the three measures (the spontaneous regression to the same objects, the dishabituation to the novel conjunction of shape and color, and the dishabituation to the novel objects) and four age groups. Comparisons of the looking scores were conducted with a 3 (Measure) × 4 (Age) ANOVA. There was

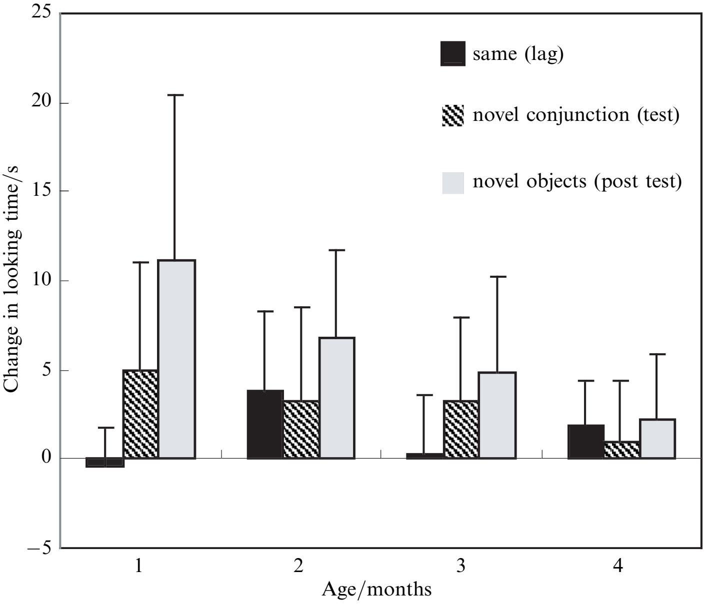

Figure 5. Group means of looking scores for the three conditions (the spontaneous regression to the same objects, the dishabituation to the objects with a novel conjunction of shape and color, and the dishabituation to the novel objects) and for the four age groups (1, 2, 3, and 4 months of age). Group means and associated standard errors are shown.

a significant effect of Measure ($F_{2,199} = 10.24$, $p < 0.001$) and Age ($F_{3,199} = 5.90$, $p < 0.001$). There was a significant interaction between Measure and Age ($F_{6,199} = 2.78$, $p < 0.05$). Thus we executed planned comparisons between the dishabituation and spontaneous regression for each age as follows.

1-month-old infants showed a sharp dishabituation to the objects with a new conjunction of familiarized shapes and colors ($M_{\text{novel}} = 4.91$ s, SD = 6.17 s, $N = 16$), as compared with the spontaneous regression to the same objects ($M_{\text{same}} = -0.37$ s, SD = 2.06 s, $N = 10$). The one-tailed t-test with Welch's correction revealed a significant difference in mean ($p = 0.0025$). This is the first evidence that 1-month-old infants pass the binding test of shape–color combinations with a pair of two objects, which are simultaneously presented.

However, we found that infants at 2 months of age show a decline in performance of discrimination. We did not obtain a significant difference ($p = 0.36$) between the dishabituation to the novel conjunction of shape and color ($M_{\text{novel}} = 3.19$ s, SD = 5.37 s, $N = 22$) and the spontaneous regression to the same objects ($M_{\text{same}} = 3.80$ s, SD = 4.51 s, $N = 13$). Conspicuous characteristics of the 2-month-old infants were their strong attention to the stimuli and the spontaneous increase in the duration of looking time when they were presented the same objects, even after the habituation criteria had been met. It is likely that 2-month-old infants can discriminate novel objects in the post-test trials ($p = 0.04$).

3-month-old infants again showed a significant dishabituation to the novel conjunction ($p = 0.011$; $M_{\text{novel}} = 3.26$ s, SD = 4.72 s, $N = 25$; $M_{\text{same}} = 0.22$ s, SD = 3.40 s, $N = 15$). This result is the first evidence that 3-month-old infants pass the binding test of shape–color combinations with a pair of two objects, which are simultaneously presented.

4-month-old infants did not show a significant dishabituation ($p = 0.22$; $M_{\text{novel}} = 1.01$ s, SD = 3.41 s, $N = 20$; $M_{\text{same}} = 1.85$ s, SD = 2.55 s, $N = 10$). Although this result is similar to that of 2-month-olds, the reasons may be different. The stimuli were likely to be uninteresting to most of the 4-month-old-infants, since the duration of looking time of 4-month-old-infants was very short, and dishabituation to even new objects was not significant as compared with the spontaneous regression to the same objects ($p = 0.36$; $M_{\text{novel}} = 2.26$ s, SD = 3.66 s, $N = 18$; $M_{\text{same}} = 1.85$ s, SD = 2.55 s, $N = 10$).

To ensure the developmental changes in performance, we calculated indexes of the novelty preference (P) and the spontaneous regression (R) from looking time (T):

$$P = T_{\text{ft}}/(T_{\text{lh}} + T_{\text{ft}})\%\,,$$

and

$$R = T_{\text{lah}}/(T_{\text{lh}} + T_{\text{lah}})\%\,,$$

where T_{ft} is the looking time for the first two test trials, T_{lh} is the looking time for the last two habituation trials, and T_{lah} is the looking time for the last two additional habituation trials.

Significant differences were obtained from 1-month-old infants ($p = 0.025$; $M_P = 0.62\%$, SD = 0.19%, $N = 16$; $M_R = 0.48\%$, SD = 0.12%, $N = 10$) and 3-month-old infants ($p = 0.0040$; $M_P = 0.63\%$, SD = 0.16%, $N = 25$; $M_R = 0.50\%$, SD = 0.11%, $N = 15$), by using the one-tailed t-test. No significant differences were obtained from 2-month-old infants ($p = 0.40$; $M_P = 0.59\%$, SD = 0.13%, $N = 22$; $M_R = 0.60\%$, SD = 0.14%, $N = 13$) and 4-month-old infants ($p = 0.074$; $M_P = 0.56\%$, SD = 0.13%, $N = 20$; $M_R = 0.63\%$, SD = 0.10%, $N = 10$). Both 1-month-old and 3-month-old infants showed robust evidence of discrimination of the novel conjunction of shape and color, while a decline in performance occurred at 2 months and 4 months of age.

3.3 *Developmental changes in oculomotor control and attention*

Note that the U-shaped developmental profile that we found during the 1–3 month period is consistent with the majority of findings in the literature (Cohen 1973; Bushnell and Roder 1985; Mundy 1985; Burnham et al 1988; Slater et al 1991), although we have provided the first evidence for the successful discrimination of novel conjunction of color and shape of two objects at 1 and 3 months of age. Yet, what is not resolved is the issue what exact functional change is responsible for these developmental changes in feature binding. To address this issue, we further analyzed eye movements during this experiment to investigate the mechanism underlying the changes in the performance of visual perception. Two different parameters, as a function of age, showed that drastic changes occur around 2 months of age, as shown in figure 6.

First, the mean fixation time during the habituation phase indicated that the infants between 6 and 10 weeks of age exhibited a very prolonged fixation on the stimulus, as shown in figure 6a. The tendency to stay with the fixated objects disappeared dramatically at 12 weeks, and infants older than this age never fixated on the stimulus for more than an average of 2 s. Figure 7a shows group means of the mean fixation time. Statistical analysis of this parameter (a one-way ANOVA with Age as the factor) showed the significant difference with age ($F_{82,3} = 19.1$, $p < 0.001$). A posteriori doubly multivariate analyses revealed that 1-month-olds and 2-month-olds are significantly different from 3-month-olds and 4-month-olds ($p < 0.001$). This result suggests that the mechanism of gaze control and attention may change between 2 and 3 months of age.

Second, the mean number of saccades per trial during the habituation phase showed that the most striking change in the oculomotor control occurred at the end of 2 months of age, as shown in figure 6b. Repetitive saccades occurred primarily in 3-month-old infants and declined after 4 months of age. Figure 7b shows the group means of the mean number of saccades per trial. Statistical analysis of this parameter

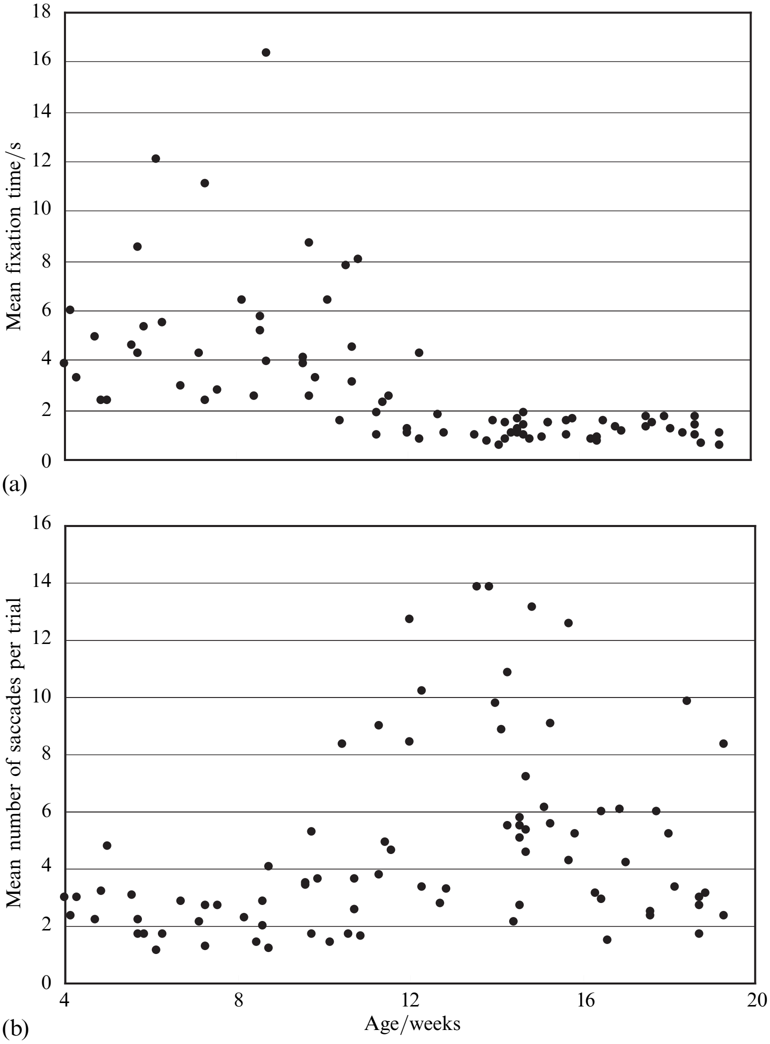

Figure 6. Changes in parameters of looking behaviors for each infant as a function of age. (a) Mean fixation time during habituation phase. (b) Mean number of saccades per trial during the habituation phase.

(a one-way ANOVA with Age as the factor) showed the significant difference with age ($F_{82,3} = 14.8$, $p < 0.001$). A posteriori doubly multivariate analyses confirmed that only 3-month-olds were significantly different from other age groups ($p < 0.001$). 1-month-olds and 2-month-olds did not often shift their gaze. 3-month-old infants are likely to perceive two objects by shifting attention overtly. 4-month-old infants are likely to perceive two objects without overt shifts of attention. This drastic change in the saccadic pattern of eye movements suggests that the mechanism of perception of multiple objects may change between 2 and 3 months of age.

Taken together, each group from 1 to 4 months of age showed distinctive patterns of looking behaviors. This finding may account for the age-dependent changes in performance on the binding test of shape–color combinations with a pair of objects.

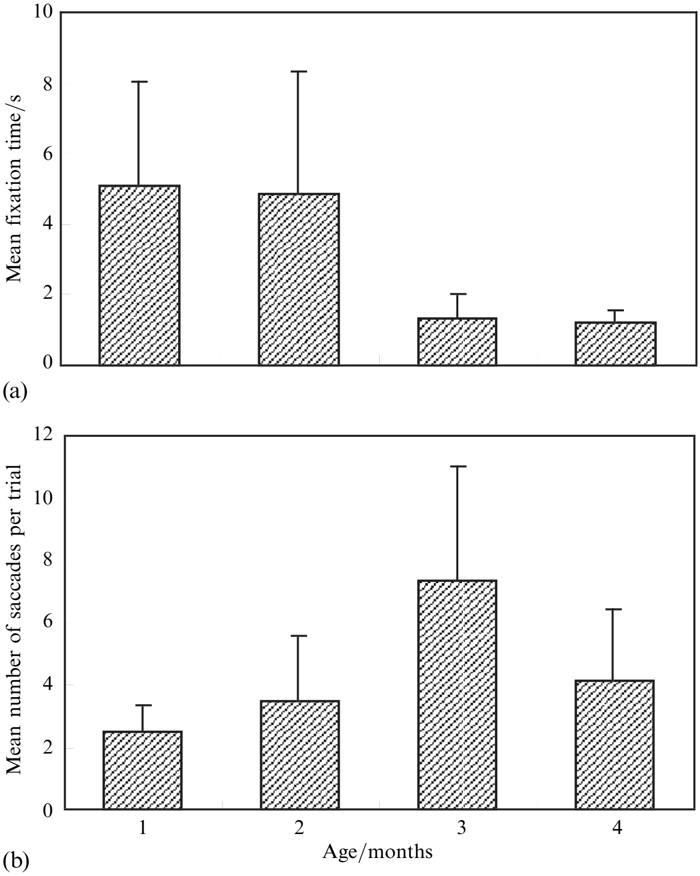

Figure 7. Group means of changes in parameters of looking behaviors. (a) Mean fixation time during habituation phase. (b) Mean number of saccades per trial during the habituation phase. Group means and associated standard errors are shown.

4 Discussion

Our results demonstrate that the performance of visual feature binding is not simply progressive in early development. 1-month-old infants have the ability to discriminate changes in the conjunction of a familiar shape and color of two objects. However, a good early performance was followed by poorer performance at 2 months of age. The performance improved at 3 months of age. We also found that the looking behavior during the task changed in accordance with the change in performance. The distinctive changes of gaze shift over age suggest that the perceptual/neural basis for good discrimination performance at 1 and 3 months of age may be fundamentally different.

The ability of 1-month-old infants to detect new conjunctions of shape and color in the two objects may be attributed to an undifferentiated manner of perception. This result supports the view that young infants have an innate ability to process and remember shape–color combinations, not just each attribute per se (Slater et al 1991). If the modular organization for processing shape and color has not been differentiated at this developmental stage, different features belonging to the same objects are already bundled together, and the binding problem will not arise. If it is the case, 1-month-old infants will perceive objects with a new conjunction of shape and color simply as new objects.

We could not obtain evidence of discrimination of changes in features at 2 months of age owing to the large increase in the spontaneous regression. Although we cannot conclude that 2-month-olds are not able to discriminate changes in features of objects, it is clear that the form of attention and orienting behavior drastically changes at this age. The prolonged fixation on a stimulus at 2 months is consistent with previous reports of 'obligatory attention' (Stechler and Latz 1966). A longitudinal study by Hood et al (1996) also showed that infants exhibited the longest duration in total looking time during habituation at 2 months of age. The poorer performance of 2-months-olds may be related to difficulty with the simultaneous representation of two objects due to the very long duration of looking at a single object.

3-month-old infants again showed a significant dishabituation to the novel conjunction, which is consistent with the previous reports that 3-month-old or older infants can discriminate novel compounds of shape and color (Cohen 1973; Bushnell and Roder 1985; Mundy 1985; Burnham and Vignes 1988). At the end of 2 months, infants begin to show repetitive saccades between two objects, which indicates that they perceive the stimuli as two distinct objects, and change their focus of attention between the two objects. The overt shift of attention and the good discrimination performance suggest a mechanism that selects an object's location and binds the features at that place into a unified object percept in an adult-like manner (Treisman and Gelade 1980).

The decline in performance at 4 months of age coincides with the decrease in the number of the repetitive saccades between the two objects. Since most 4-month-old infants glance at the stimulus without overt shift of attention between the objects and quickly lose interest in it, they may fail to detect changes in the conjunction of shape and color.

The U-shaped appearance, disappearance, and reappearance of behavior is observed in a number of aspects of early development. Previous reports of a U-shaped change of behavior in reaching and walking (Bower 1976; Butterworth 1989; Thelen and Smith 1994), audio–motor integration (Muir et al 1989), face perception (Morton and Johnson 1991), speech perception (Stager and Werker 1997), and cognition (Karmiloff-Smith 1992) have implied that functional reorganization may occur during periods with poorer performance. From a dynamical-systems point of view (Thelen and Smith 1994), spontaneous increase and decrease in fluctuation of dynamical states imply that a transition occurs. It is important to use the same stimuli and experimental procedure with different age groups to reveal some transitions in development. The spontaneous change in fluctuation of looking behaviors at 2 months of age in our study suggests that a transition of perceptual state may occur at this age.

Note that we are not able to rule out the possibility that 2-month-olds and 4-month-olds show discrimination of novel conjunctions of features when different stimuli or experimental procedures are used. Thus, there is a possibility that feature binding is available to infants very early and is present in all ages. Yet, our results showed that there is a drastic difference in oculomotor behaviors between 1-month-olds and 3-month-olds, both of who showed the same good performance with feature binding, and that it may reflect the way that the visual system organizes attributes and their conjunction. More study is needed to determine whether the changes in looking behaviors are directly related to the feature-binding processing or simply reflect attention processing.

Finally, we would like to speculate on the relationship between infant behavioral changes in our experiment and brain development. The good performance of 1-month-old infants may be attributed to subcortical systems controlling orienting responses which crudely define 'where' an object is located (Bronson 1974), and a part of the parvocellular pathway analyzing shape and color of objects. Early functioning of the occipital cortex was shown in a brain-imaging study (Yamada et al 1997). Behavioral studies also suggested that the parvocellular pathway, which processes 'what' information such as shape and color, may be operational earlier than the magnocellular pathway, which processes 'where' information (Johnson 1990; Atkinson 1992). The obligatory attention of 2-month-old infants may be related to a change in the locus of processing of spatial information from subcortical to cortical systems. Note that a neurological patient with parietal – occipital lesions showed specific difficulty with binding simultaneously presented features to the correct object (Friedman-Hill et al 1995). Moreover, the good performance in feature integration and the emergence of selective attention at 3 months of age suggest that integration of the parvocellular and magnocellular pathways may begin at this age. Colombo (1995) also suggested emergence of the magnocellular-pathway function somewhere between 2 and 4 months of age on the basis of orienting behaviors of young infants. These speculations are open to future studies using brain-imaging techniques.

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