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Contour integration by 6-month-old infants: Discrimination of distinct contour shapes

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Abstract

Previous research has indicated that the ability to integrate individual elements in the presence of noise is immature in 3-month-old infants. The present study extended the developmental timeline by investigating 6-month-olds' ability to integrate individual elements into whole contours through an assessment of their capability to discriminate circle and square contours constructed from oriented Gabor patches via a newly designed cueing paradigm for infants. If infants discriminate the centrally-presented contour cues, then their eye movements would correctly anticipate subsequent target presentation at a rate greater than chance. The results indicated that infants integrated the contours and discriminated the different shapes, but, consistent with past research, this ability is still fairly immature at this age, tolerating limited amount of noise.

Keywords: Infants; Contour integration; Shape discrimination; Eye movements; Visual cueing; Visual development

1. Introduction

The essence of our coherent picture of our visual world consists, not of colors or edges, but of objects and their inter-relations. This coherent picture consequently relies on the perception of the shapes and contours that define those objects. That is, the items in our world that contain meaning and function are objects and, consequently, it is the goal of our perceptual systems to delineate the shapes and contours that define those objects. This is also certainly true of infants for whom many objects are novel and are in the initial stages of building a knowledge base and a coherent picture of their world.

1.1. Object perception and good continuation

A critical step in the perceptual processing of objects and their recognition, presumably in development as well, is thought to be the extraction of information about their boundaries and contours in the presence of surrounding perceptual information or noise. In order for contour extraction to occur and a coherent shape to be perceived, the contour is thought to be defined by certain principles, such as good continuation. The principle of good continuation (Koffka, 1935) states that if individually oriented elements are aligned or organized collinearly, our visual system perceives these separate elements as belonging together (forming a contour). The principle of good continuation may underlie the ability to perceive illusory contours and a unified object that is partially hidden by an occluder (Kellman & Shipley, 1991; Kellman, Yin, & Shipley, 1998; Wouterlood & Boselie, 1992) – perceptual capacities that have been shown to exist in infancy.

Thus, like adults, there is evidence that indicates infants possess a sensitivity to good continuation. For example, research suggests that 3- to 4-month-old infants correctly assign contours to the appropriate shape figure when two shapes overlap (Quinn, Brown, & Streppa, 1997) and interpret occluded objects as whole (e.g. Johnson, Bremner,

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Slater, & Mason, 2000; Kellman & Spelke, 1983; Kellman, Spelke, & Short, 1986; Slater et al., 1990). Furthermore, by 4 months of age, infants perceive dynamic (Curran, Braddick, Atkinson, Wattam-Bell, & Andrew, 1999) and perhaps even static (Kavsek, 2002) illusory contour figures. Nevertheless, these combined research findings have been based mainly on stimuli that do not require the integration of individual elements in the presence of background noise. Considering that rarely, if ever, are object contours perceived in isolation without surrounding background noise, it is therefore necessary to assess the detection of contours in the presence of noise in order to be able to judge the *efficiency* of the visual integration system (Kovács, Kozma, Fehér, & Benedek, 1999).

1.2. Contour Integration

The ability to use good continuation as a guiding principle in the integration of individual elements into perceptually detectable contours has been well documented in children and adults (Field, Hayes, & Hess, 1993; Kovács, 1996; Kovács & Julesz, 1993; Kovács et al., 1999; Saarinen & Levi, 1999). Integration and detection of contours have been tested by Kovács and colleagues by displaying individually oriented Gabor patches aligned in the shape of a contour (Kovács, 1996; Kovács & Julesz, 1993; Kovács et al., 1999) embedded in background noise (randomly oriented Gabor patches). Using these types of Gabor-patch displays, adults were shown to find closed contours as more salient than open contours (Kovács & Julesz, 1993; Pettet, McKee, & Grzywacz, 1998; Saarinen & Levi, 1999). However, the relation between contour continuity, which may be a local property, and the saliency of closed vs open contours, which are defined globally, has been controversial (e.g. Tversky, Geisler, & Perry, 2004). Nevertheless, neurophysiologically, Gabor patches are regarded as rough physical estimates of the receptive field characteristics of orientation-selective simple cells in the primary visual cortex (V1) (Kovács et al., 1999). Thus, the capacity to perceptually integrate Gabor-defined contours in the presence of background noise is thought to rely on spatial interactions of orientation-selective neurons in V1 in order to connect the individual elements (Burkhalter, Bernardo, & Charles, 1993; Hess & Field, 1999; White, Coppola, & Fitzpatrick, 2001). In particular, there exist horizontal connections between similarly orientation-tuned neurons, each of which code for adjacent spatial locations in the visual field (Gilbert, Das, Ito, Kapadia, & Westheimer, 1996; Gilbert & Wiesel, 1983; White et al., 2001). The integration of long-range comparisons between the local filters, consequently, can become impeded by the inclusion of surrounding random oriented Gabor patch noise.

In terms of development, Kovács et al. (1999) argued that, though the horizontal connections in V1 are in place as early as 4 months of age (Burkhalter et al., 1993), the functioning of these connections in support of contour integration is not fully developed until adolescence.[1] Using noise density ratio (spacing of the elements in the background divided by the spacing of the elements in the contour) as an index of contour detection sensitivity, Kovács et al. (1999) reported that children between 5 and 6 years of age have a threshold of $D = 0.84$, whereas adults' threshold was reported to be $D = 0.67$ (the lower the number, the denser the background noise). These data suggest there is considerable development in contour detection that occurs throughout early development into adolescence. Slow maturation of the primary visual cortex (V1) may be responsible for delayed contour integration abilities found in humans (Burkhalter et al., 1993; Kovács, 1996) with full functionality requiring the proper visual input experience (Kovács, Polat, Norcia, Pennefather, & Chandna, 2000). Consequently, adult-like thresholds are not achieved until adolescence (Kovács et al., 1999).

Though contour integration in the presence of noise is developmentally delayed, there exists little research on the initial stages of contour integration development. There appear to be only two studies that have investigated the detection of contours using oriented Gabor elements with infants (Gerhardstein, Kovacs, Ditre, & Feher, 2004; Norcia et al., 2005). Each study employed very different methodologies for testing infants; nevertheless, similar conclusions were reached. In the Gerhardstein et al. (2004) study, an operant conditioning paradigm was used in which 3-month-old infants kicked to move an overhead mobile that consisted of cards displaying either a Gabor patch-defined closed circle contour embedded in noise or the noise alone. Infants were tested 24 h after training for discrimination of the other display. The results indicated that infants could discriminate the two patterns, but only when the noise level was at $D = 0.9$ and not when it was at $D = 0.8$. This finding indicates that 3-month-olds' abilities to detect contours amidst background noise is considerably limited relative to older children and adults (see Kovács et al., 1999). The Gerhardstein et al. study, however, because it only assessed 3-month-olds, leaves a wide age gap in our understanding of the development of contour integration mechanisms.

Additional support for the functioning of contour detection mechanisms in early infancy is illustrated by a recent study examining 2- to 5- and 6- to 13-month-old infants' ability to detect oriented textures and contours using a visual evoked potential (VEP) paradigm (Norcia et al., 2005). Results indicated significant VEP responses among the younger group for the transition between a coherent texture and an array of randomly oriented Gabors that

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[1] Though Burkhalter et al. (1993) did find that long-range projections in layer 2/3 emerge at 4 months, they found that they neuroanatomically resembled those at birth and do not become adult-like until 15 months of age. Consequently, anatomical maturation occurs somewhere between 4 and 15 months of age, but the relation between of anatomical maturation and functional maturation is, of course, not clear.

were not present when the same local changes occurred between two randomly oriented arrays. Thus, a sensitivity to overall orientation differences in the Gabor patch textures is present in infants as young as 2 months of age. In addition, results revealed that 6- to 13-month-olds exhibited significant VEP responses to the transition between pinwheel and circular oriented Gabor patch pattern, indicating that the contour detection mechanism is functioning by 6 months. Unfortunately, the younger age group was not tested with the contour stimuli so whether they detect contours could not be determined. Since this study did not test the discrimination of different shaped contours in the presence of noise and the Gerhardstein et al. (2004) study was limited to 3-month-olds, questions persist as to the development of infants' ability to integrate information amidst noise. For example, what are the noise density thresholds at which 6-month-olds are capable of contour integration? And, can infants integrate and discriminate between different shaped contours in the presence of noise?

1.3. The present study

Though previous infant studies have suggested the presence of a contour integration mechanism (Gerhardstein et al., 2004; Norcia et al., 2005), they were detection studies where the infants could have based their responding on the presence or non-presence of the contour stimuli. Neither, therefore, asked if infants could discriminate two distinctly different contour shapes in the presence of different densities of noise. Typically, in the assessment of infants' perceptual capacities, whether they can discriminate between different patterns serves as an indicator of the functioning of that capacity (e.g. Adler & Haith, 2003; Bertenthal, Campos, & Haith, 1980; Cohen, Gelber, & Lazar, 1971; Colombo, Mitchell, Coldren, & Atwater, 1990; Fagan, 1970; Yonas, Arterberry, & Granrud, 1987). Thus, to further understand the developmental trends in infants' ability to integrate individual elements into whole contours, this study not only assessed 6-month-olds' ability to integrate and detect but also whether they could discriminate oriented Gabor patches that formed either circle or square contours in the presence of background noise created by randomly oriented Gabor patches.

2. Experiment 1: Discrimination of contours

Past research of infants' perceptual discrimination abilities have typically used various forms of the habituation and novelty-preference paradigms (Cohen, 1972; Colombo et al., 1990; Fagan, 1970; Fantz, 1964; Salapatek, 1975). These paradigms, however, have been periodically criticized for their limitations (e.g. Hunter & Ames, 1988; Thomas & Gilmore, 2004). In the present study, we introduce a new paradigm for investigating infants' perceptual discrimination that is a modification of the Visual Expectation Paradigm (VExP; Haith, Hazan, & Goodman, 1988). In the VExP, infants typically view pictures that predictably alternate on the left and right sides of a computer screen and infants' anticipatory eye movements to the next picture (made before picture onset) in the sequence is measured (Adler & Haith, 2003; Haith et al., 1988; Haith & McCarty, 1990; Wentworth & Haith, 1992). In the current paradigm, which we call the Visual Expectation Cueing Paradigm (VExCP), rather than viewing pictures that predictably alternate on the screen, infants view to-be-discriminated stimulus cues presented randomly in the center of the screen, each of which predict a target stimulus appearing on either the left or right side of the screen. If infants can discriminate between the center cues, then they will correctly anticipate the future location of the target, based on the cue type-target location association, at a rate greater than chance. If not, then infants' anticipations to the targets will be random and correct at a rate not greater than chance. The first experiment, consequently, tested whether or not infants could discriminate a circle from square contour without the presence of background noise.

2.1. Methods

2.1.1. Participants

Twenty-two 6-month-old infants, recruited from a mailing list supplied by a Toronto-area company (Z Retail Marketing Inc., Toronto, Canada) and all of whom came from middle social economic status (SES) backgrounds, participated in the first experiment. The data from 6 infants was discarded due to crying ($n = 2$), inattentiveness (i.e., disinterested or looked at their hands or other parts of the visual field or provided data on less than 65% of the pictures; $n = 3$), and experimenter error ($n = 1$). Consequently, data from 16 infants (10 males, 6 females) who ranged in age from 163 to 206 days ($M = 180.3$, $SD = 11.1$) were included in the analysis. The infants were of Caucasian ($n = 7$), African ($n = 1$), Hispanic ($n = 2$), Asian ($n = 2$), and Other ($n = 4$) ethnic backgrounds. Infants were all born at full term, in good health, with no apparent visual, neurological or other abnormalities. Informed consent was obtained from the parent of each infant.

2.1.2. Stimuli and apparatus

The cue and target stimuli were computer-generated graphic images and all subtended a 4.5° visual angle. The cue stimuli were circle and square contours made up of Gabor patches and the target stimulus was a computer-generated graphic image of a colored-striped square (see Fig. 1). Each Gabor patch was constructed by applying a 0.54° Gaussian to a grating with a cycle of 0.27° that had a contrast level of 80% and was isoluminant with the background. The stimuli were presented on a 19-inch LCD color monitor with 1024 × 768 pixel resolution, a refresh rate of 75 Hz, and an 8 bit/pixel gray scale. The contour spacing was set to 12 lambdas, and the positioning of the contours was randomly selected for each trial, with the

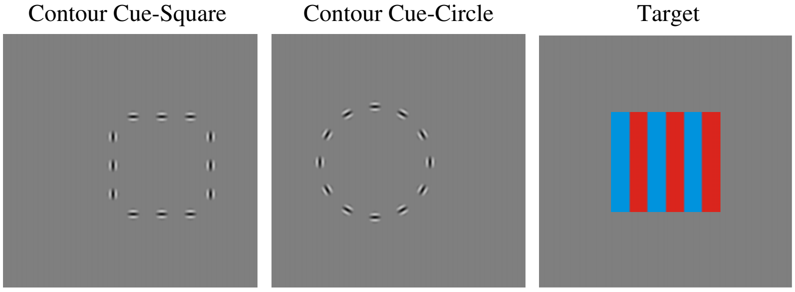

Fig. 1. Examples of the Gabor patch contours that served as cues and the target used in Experiment 1 for both the predictable and random conditions. D = no noise.

constraint that contours fell within a ±5° window around visual center. The target stimulus consisted of six alternating blue and red stripes and was presented 5° to either the left or right of visual center.

Infants were laid supine in a specialized crib and viewed the stimuli on a monitor that was situated 48 cm overhead. Between the infant and the monitor was a 12 × 12 inch infrared-reflecting, visible-transmitting mirror that allowed the infant a completely unobstructed view through the mirror of the stimuli on the monitor. A remote, pan-tilt infrared eye tracking camera (Model 504, Applied Science Laboratories [www.a-s-l.com], Bedford, MA) using bright pupil technology, also placed overhead, recorded the participant's eye movements via reflection in the infrared mirror at a temporal resolution of 60 Hz (see Fig. 2). Infrared light emitted from diodes on the camera was reflected off the infrared mirror on to the infant and then back from the infant's retina through the pupil producing a backlit white pupil. In addition, the infrared light produced a point reflection from the corneal surface of the eye. The relation between the corneal reflection and the centroid of the backlit pupil was used to calculate, via proprietary ASL software, eye fixation position. The eye-tracker was calibrated by having the infant look at a stimulus (concentric squares that loom in and out) presented successively at known locations on either side of the screen. All subsequently recorded eye tracker values were filtered through the calibration file to produce measures of eye position data.

2.1.3. Procedure

The experimental session and timing of the stimuli was programmed in Presentation Version 9.0 (Neurobehavioral Systems, Albany, CA; http://www.neuro-bs.com) running on an IBM computer. The sequence of stimulus presentation was based on a cueing paradigm modified from the VExP (Haith et al., 1988) and is somewhat similar to a paradigm previously used to study infants' categorization abilities (McMurray & Aslin, 2004). The experiment was designed so that on each trial a circle or square contour was randomly presented in the visual center of the monitor. Which contour served as a cue for the subsequent presentation of a target either 5° to the right or left of visual center was counterbalanced across infants. Regardless, for each contour shape, its relation with a specific target location was predictable.

An experimental trial began with the presentation of a contour shape for 2000 ms followed by a cue-target interval of 500 ms during which the monitor was blank (see Fig. 3). The cue-target interval was followed by the appropriate

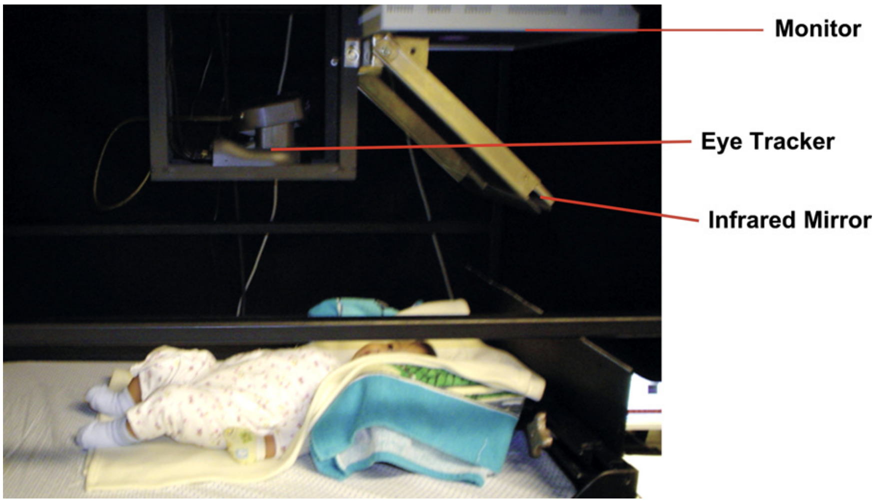

Fig. 2. Picture of the crib apparatus setup of the eye tracker, infrared mirror, and monitor on which the stimuli are presented.

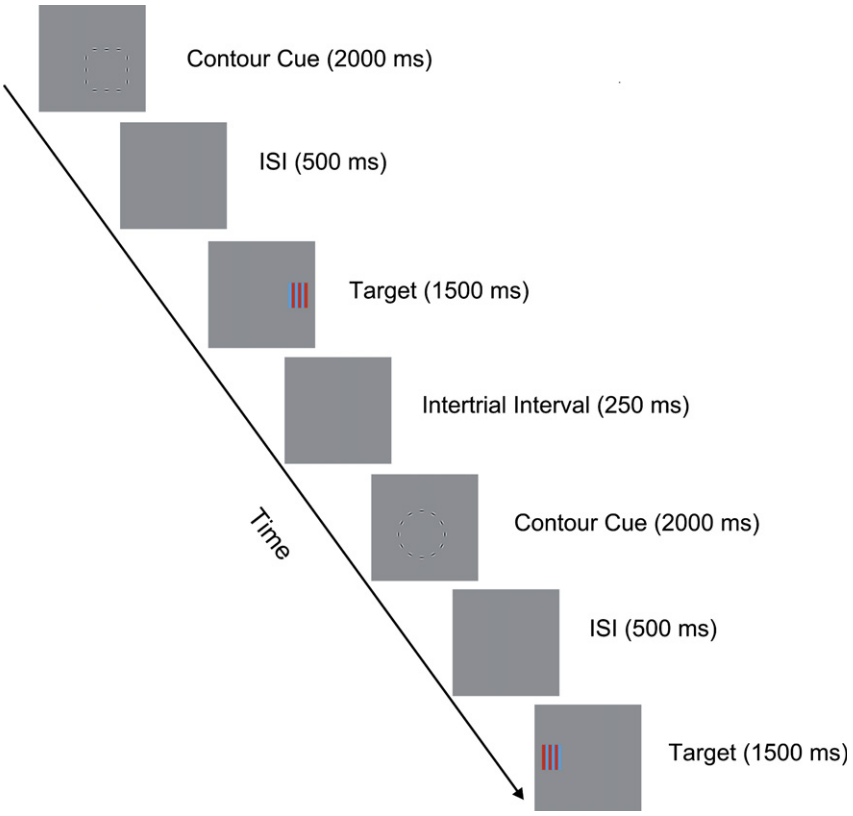

Fig. 3. Stimulus sequence of events over time. The infants were first presented with a contour image (circle or square) that acted as a cue to a target on either the right or left (dependent on the cue), so the target location was predictable based on the contour.

target (e.g. left side of the screen for circles, right side for squares), which appeared for 1500 ms. Finally, the trial ended with an inter-trial interval of 250 ms, after which the next trial began. In this and the next experiment, infants experienced a total of 60 trials, half of which consisted of a square contour cue and half of a circle contour cue.

Infants were randomly assigned to one of two conditions ($n = 8$). In the predictable condition, infants saw a stimulus sequence in which a contour shape cue predicted target location. In the random condition, the contour shapes did not predict target location such that infants were unable to form a consistent prediction about the location of the target on the basis of contour shape. This condition acted as a control for determining whether significant anticipatory responding in the predictable condition was due to discrimination of the contour shapes thereby detecting the contour shape-target location association rather than to random responding.

2.1.4. Data reduction and analysis

The raw digital data recorded by the eye tracker was imported into a MATLAB toolbox called ILAB (Gitelman, 2002) for subsequent analysis. The ILAB toolbox software allowed analysis of eye movements, separating out and displaying individually the horizontal and vertical components of the eye movement, on a trial-by-trial basis. Moreover, ILAB provided a means by which to display the scan path of the eye on a trial by-trial basis and thereby determine whether or not the eye first fixated the contour cue and the nature of the eye movement (direction and distance) relative to the stimuli.

In order for an eye movement to be included in the final data sample, it needed to meet a number of criteria. First, because the critical question was whether infants could discriminate the contour cues and then guide their anticipations accordingly, the infants were required to be fixating on the contour "cue" stimulus before the target was presented. Second, in order for an eye movement to be counted as anticipatory it needed to occur after the offset of the contour cue until the first 133 ms after onset of the target. This latency value was chosen as the anticipation cut-off because it has been previously determined that 6-month-olds cannot make eye movements in reaction to the onset of stimulus faster than 133 ms (Canfield, Smith, Brezsnyak, & Snow, 1997). If the eye movement occurred 133 ms after picture onset until picture offset, it was considered reactive in nature and its latency was determined. Third, in order for an infant's data to be included in the final sample, they must have looked at the stimulus on a minimum of 65% of the trials or 39 of the 60 trials (e.g. Adler & Haith, 2003; Adler & Orprecio, 2006). Finally, the eye movement to the target had to trace a path that was more than 50% of the distance between the contour cue and the target. This was assessed by analysis of the infant' scan path compared to the image. The 50% criterion has been used in previous studies using infants' eye movements (e.g. Adler & Haith, 2003; Adler & Orprecio, 2006) and is typically taken as an indication that the eye movement was intentional and not random.

Infants' eye movement data was analyzed in terms of three dependent measures. First, a total anticipation measure was calculated by taking the percentage of all valid eye movements that were made to the targets that were anticipations (correct or incorrect). Next, a correct anticipation measure was analyzed in terms of the *percent* of all anticipations that correctly localized target locations. Finally, a median reactive latencies measure was calculated for all eye movements that occurred to the target after its onset.

2.2. Results and discussion

2.2.1. Total anticipations

To ensure that any differences for correct anticipations between the predictable and random conditions was not due to differences in total anticipations, a 2×2 analysis of variance (ANOVA) was performed on the percent of total anticipations, with condition (predictable, random) as the between factor and contour cue shape (circle, square) as the within factor. Neither of the main effects (condition: $F(1,28) = 0.762$, *ns*; shape: $F(1,28) = 0.51$, *ns*) nor the interaction of condition with shape ($F(1,28) = 2.66$, *ns*) for total anticipations were significant (see Fig. 4). This indicates that the total number of anticipations, regardless of whether they were correct or incorrect, did not differ as a function of the predictability of the cue-target relation or the cue's shape (see Fig. 4). Consequently, any observed difference in correct anticipations as a function of predictability could not be due to differences in total anticipations.

2.2.2. Correct anticipations

To assess whether infants could discriminate between the contour cue shapes and thereby detect the predictability of the cue-target association, the percent of their anticipations that were to the correct target was measured. If infants could discriminate between the contour shapes, then infants in the predictable condition should exhibit anticipations that are correct greater than 50% (chance) of the time due to detection of the cue-target association. Infants in the random condition, however, should exhibit anticipations that are correct at only chance level or no more than 50% of the time due to the lack of a cue-target association.

A 2×2 analysis of variance (ANOVA) was performed on the percent of correct anticipations, with condition (predictable, random) as the between factor and contour shape (circle, square) as the within factor. There was a significant main effect of condition, $F(1,28) = 5.62$, $p < .05$ (see Fig. 5), indicating that infants in the predictable condition ($M = 74.3\%$, $SE = 6.1$) made more correct anticipations than infants in the random condition ($M = 53.7\%$, $SE = 6.1$). This suggests that infants discriminated the contour cue shapes, which allowed them to detect the cue-target association when it was predictable. There was no main effect of contour shape ($F(1,28) = .735$, *ns*) nor a significant interaction ($F(1,28) = .360$, *ns*), indicating that correct anticipations after each cue shape were similar overall and as a function of condition.

Although the preceding analysis indicated that infants in the predictable condition exhibited more correct anticipations than infants in the random condition, it did not assess whether either group exhibited correct anticipations at a rate greater than chance – a finding necessary for the demonstration of the ability to discriminate between the contour shapes. To this end, the mean correct anticipations of infants in each condition was compared to 50% or chance responding. Overall, collapsed across both contour shapes, a one-sample t-test revealed that infants in the predictable condition made correct anticipations at a rate greater than chance, $t(15) = 5.23$, $p < .001$, whereas infants

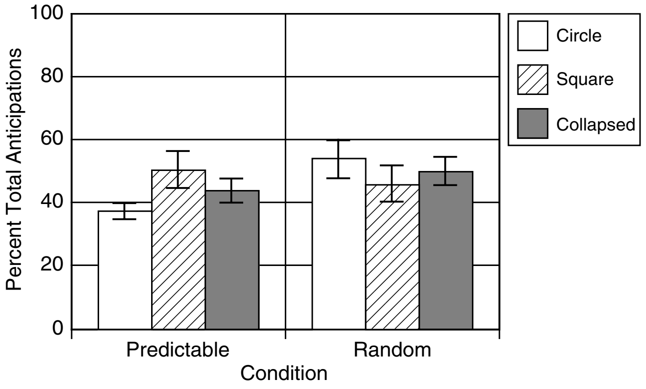

Fig. 4. This figure represents the mean percent of total anticipations (regardless of whether they were correct or incorrect) that infants made to the targets based on the contour cues in both the predictable and random conditions in Experiment 1. Error bars represent ±1 standard error of the mean.

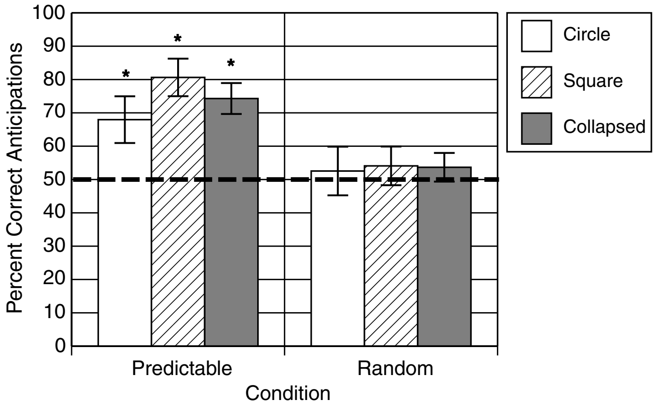

Fig. 5. This figure represents the mean percent of correct anticipations that infants made to the targets based on the contour cues in both the predictable and random conditions in Experiment 1. The dashed line represents chance performance (i.e. 50% correct). Asterisks indicate correct anticipations that were significantly greater than 50% or chance performance. Error bars represent ±1 standard error of the mean.

in the random condition did not, $t(15) = 0.51$, *ns* (see Fig. 5). Further t-tests on correct anticipations after each contour cue shape revealed that infants in the predictable condition made correct anticipations at a rate greater than chance both after circle contours, $t(7) = 2.56$, $p < .05$, and after square contours, $t(7) = 5.44$ $p < .01$ (see Fig. 5). Infants in the random condition, however, made correct anticipations at a rate no different than would be expected by chance after both contours (circle: $t(7) = 0.01$, *ns*; square: $t(7) = 0.04$, *ns*). These findings indicate that infants discriminated between the contour shapes, thereby detecting the contour cue-target location association when it was predictable and the lack of a contour cue-target location association when it was not predictable.

2.2.3. Reactive latencies

To determine the effect of predictability of the cue shape-target location association on reactive latencies, a 2×2 analysis of variance (ANOVA) was performed on median reactive latencies, with condition (predictable, random) as the between factor and contour shape (circle, square) as the within factor. This analysis revealed a significant main effect of condition, $F(1,28) = 8.21$, $p < .01$, indicating that infants' median latencies were slower for the predictable condition ($M = 434.3$ ms, $SE = 30.4$) than the random condition ($M = 310.9$ ms, $SE = 30.4$; see Fig. 6). The main effect of contour shape, however, was not significant ($F(1,28) = .513$, *ns*) nor was the interaction of condition and contour shape ($F(1,28) = .662$, *ns*), indicating that mean reactive latencies to the target after each cue shape were similar overall and as function of predictability.

The findings from this experiment indicate that 6-month-old infants are able to integrate individual elements into unique contour shapes in the absence of noise. They were then able to discriminate the unique square and circle contour shapes. This discrimination provided the basis for infants detecting the predictable cue shape-target location association in the predictable condition and the random, unpredictable cue shape-target location association in the random condition. On a secondary note, these results also demonstrate the validity of the VExCP as a viable methodology for assessing contour integration and discrimination in young infants, in particular, and perceptual processing and discrimination, in general.

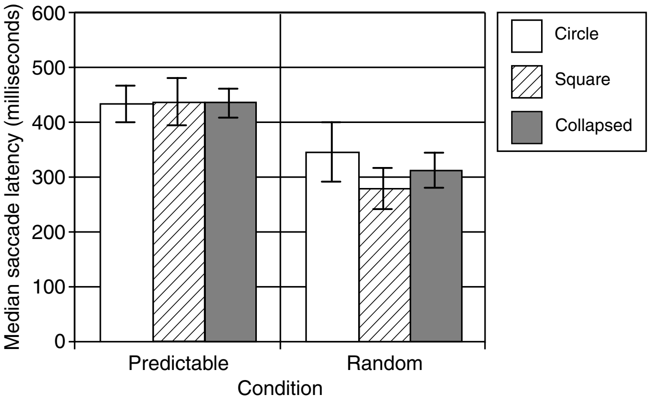

Fig. 6. Infants' median reactive latencies to the targets for both conditions in Experiment 1. The three bars represent reactive latencies for circles, squares, and circle and square averaged. Error bars represent ±1 standard error of the mean.

3. Experiment 2: Discrimination of contours in the presence of noise

Although the first experiment demonstrated that 6-month-old infants can integrate and discriminate the circle and square contours, it failed to assess whether they could do so when the contours were embedded in noise. Studies have revealed that infants can detect and discriminate contours in the presence of noise, but this ability is immature (Gerhardstein et al., 2004; Kovács et al., 1999; Norcia et al., 2005). In the second experiment, to add to developmental trends, 6-month-olds' ability to integrate and discriminate circle and square contours in the presence of random-oriented Gabor patch noise was examined. In addition, the level of noise was manipulated in order to assess the sensitivity of 6-month-olds' contour integration (e.g. Kovács et al., 1999) relative to the other points on the developmental continuum.

3.1. Methods

3.1.1. Participants

Infants were recruited in the same manner as Experiment 1. Forty-one 6-month-old infants, from middle social economic status (SES) backgrounds, participated in the first experiment. The data from 17 infants was discarded due to crying ($n = 7$), inattentiveness (i.e., disinterested or looked at their hands or other parts of the visual field or provided data on less than 65% of the pictures; $n = 4$), equipment or software error ($n = 5$), and experimenter error ($n = 1$). Consequently, data from 24 infants (13 males, 11 females) who ranged in age from 166 to 204 days ($M = 185.8$, $SD = 12.2$) were included in the analysis. The infants who participated in this experiment were of Caucasian ($n = 18$), Hispanic ($n = 1$), Asian ($n = 2$), Polynesian ($n = 1$), and Other ($n = 2$) ethnic backgrounds. Infants were all born at full term, in good health, with no apparent visual, neurological or other abnormalities.

3.1.2. Stimuli, apparatus and procedure

The apparatus and procedure were identical to what was used in Experiment 1. The only difference was that the contour cue shapes defined by the oriented Gabor patches, rather than being presented on a blank background as in Experiment 1, were presented embedded in background noise consisting of randomly oriented Gabor patches (see Fig. 7). Infants were initially tested with contour cue shapes with a noise density of 1.0. If infants were able to discriminate the contour shapes with a noise density level of 1.0, then an independent group of infants was tested with con-

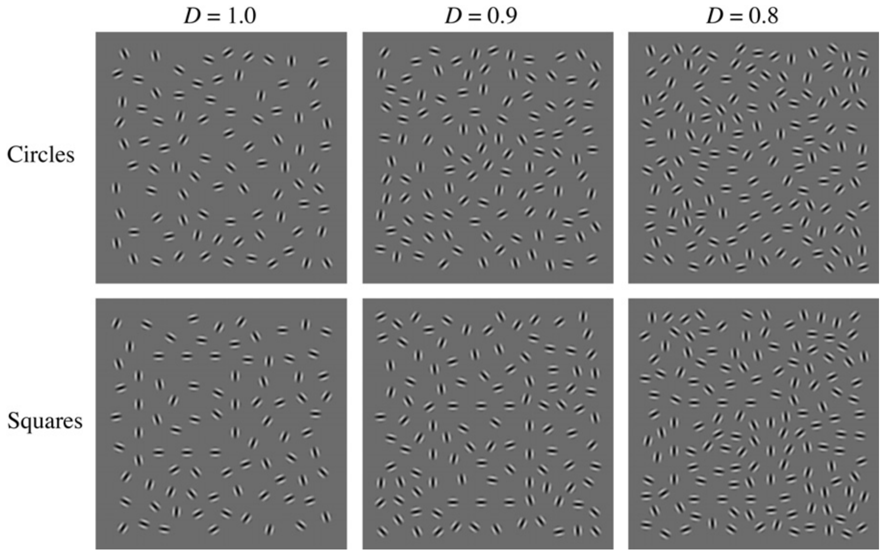

Fig. 7. Examples of the Gabor patch-defined circle and square contours and the different noise densities used in Experiment 2.

tours shapes with a noise density that was decreased by 0.1. Testing of subsequent groups of infants with noise density that was decreased by 0.1 was continued until a noise density was found at which infants could not discriminate the contours. Infants, consequently, were assigned to one of three experimental groups ($n = 8$) that were defined by the noise density level of the contour cues.

3.2. Results and discussion

3.2.1. Total anticipations

To determine that there were no differences in the percent of total anticipations (whether correct or not) for the different noise density groups, a 3×2 ANOVA was conducted with noise density ($D = 1.0$, 0.9, and 0.8) as the between factor and contour cue shape (circle, square) as the within factor. There was a main effect of noise density on the total anticipations, $F(2, 42) = 5.221$, $p < .01$. A pairwise comparison with Bonferroni adjustment to the alpha level revealed that significantly more total anticipations were made by infants in the $D = 0.8$ condition ($M = 50.0\%$, $SE = 3.48$) than in the $D = 0.9$ condition ($M = 34.13\%$, $SE = 3.48$), $p < .01$ (see Fig. 8). There were no differences, however, in the total anticipations made by infants in these two conditions ($D = 0.8$ and 0.9) and those made by infants in the $D = 1.0$ condition. Thus, there was no systematic effect of noise density level on infants' total anticipations that could potentially affect the exhibition of correct anticipations.[2]

3.2.2. Correct anticipations

To assess whether infants could discriminate between the contour cue shapes when they were embedded in background noise and thereby detect the predictability of the cue-target association, a 3×2 analysis of variance (ANOVA) was performed on the percent of correct anticipations, with noise density ($D = 1.0$, 0.9, and 0.8) as the between factor and contour cue shape (circle, square) as the within factor. The main effect of noise density was not significant, $F(2, 42) = 2.49$, *ns* (see Fig. 9), indicating that the percent of correct anticipations did not differ as a function of noise density. Further, there was no main effect of contour shape ($F(1, 42) = .103$, *ns*) nor a significant interaction ($F(2, 42) = .310$, *ns*), indicating that correct anticipations after each cue shape were similar overall and as function of noise density.

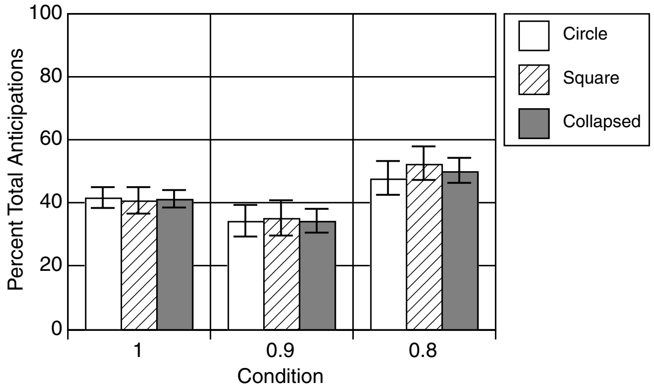

Fig. 8. This figure represents the mean percent of total anticipations (regardless of whether they were correct or incorrect) that infants made to the targets based on the contour cues with the different noise densities in Experiment 2. Error bars represent ±1 standard error of the mean.

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[2] That there was no systematic relation between total anticipations and correct anticipations across the noise conditions was confirmed by separate correlations for each condition comparing infants' total anticipations to their correct anticipations. These correlations indicated that there was no significant relation for noise densities of 1.0 ($r = -0.045$, $p = .869$), 0.9 ($r = -0.042$, $p = .877$), or 0.8 ($r = -0.312$, $p = .240$).

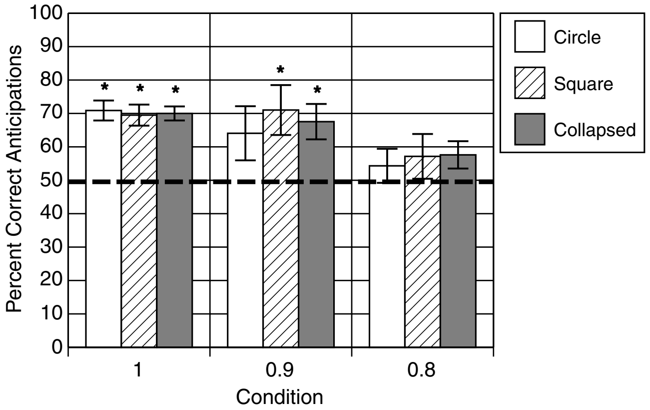

Fig. 9. Infants' percent correct anticipations made to targets as a function of noise density and contour cue shape in Experiment 2. The dashed line indicates chance performance (50%). Asterisks indicate correct anticipations that were significantly above 50% or chance performance. Error bars represent ±1 standard error of the mean.

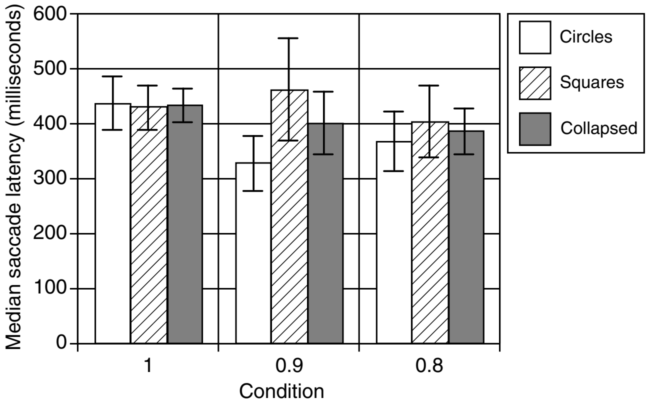

Fig. 10. Infants' median reactive latencies to the targets for the three noise density conditions in Experiment 2. The three bars in each condition represent reactive latencies for circles, squares, and collapsed across both. Error bars represent ±1 standard error of the mean.

As in Experiment 1, in order to determine whether infants were able to discriminate between the contour shapes embedded in noise with a given density level, their mean percent of correct anticipations in each noise density condition was compared to 50% or chance responding. Overall, collapsed across both contour shapes, a one-sample *t*-test revealed that infants in the 1.0 noise density condition made correct anticipations at a rate ($M = 70.19\%$, $SE = 2.23$) greater than chance, $t(15) = 9.57$, $p < .001$. Further *t*-tests on correct anticipations after each contour cue shape in the 1.0 noise density condition revealed that infants made correct anticipations at a rate greater than chance both after circle contours, $t(7) = 2.56$, $p < .05$, and after square contours, $t(7) = 5.44$, $p < .01$ (see Fig. 9). When the noise density was decreased to 0.9, infants still made correct anticipations, collapsed across contour shape, at a rate ($M = 67.54\%$, $SE = 5.39$) greater than chance, $t(15) = 3.25$, $p < .01$. This was also true for a noise density of 0.9 when assessing correct anticipations after the square contour shape, $t(7) = 2.81$, $p < .05$. After a circle contour shape with a noise density of 0.9, however, infants' correct anticipations were not significantly different than chance, $t(7) = 1.73$, *ns*; though they were correct at a rate clearly above 50% but were individually highly variable ($M = 64.0\%$, $SE = 6.87$; see white bar for the 0.9 condition in Fig. 9). Finally, when the noise density was decreased to 0.8, infants made correct anticipations, collapsed across contour shape, at a rate ($M = 57.60\%$, $SE = 4.09$) not different than would be expected by chance, $t(15) = 1.85$, *ns*. This result was true when looking at correct anticipations after each contour cue shape independently (circles: $t(7) = 1.57$, *ns*; squares: $t(7) = 1.05$, *ns*). Thus, these results indicate that infants discriminated between the contour shapes and exhibited correct anticipations greater than 50% (or by chance) when the noise density was 1.0 and 0.9. However, they failed to discriminate between the contours when the noise density was 0.8 and correctly anticipated target location only by chance.

3.2.3. Reactive latencies

As in Experiment 1, to determine the effect of noise density on reactive latencies, a 3×2 ANOVA was performed with noise density ($D = 1.0$, 0.9, and 0.8) as the between factor and contour shape (circle, square) as the within factor. This analysis revealed that neither the main effect of noise density, $F(2,42) = .304$, *ns*, nor contour shape, $F(1,42) = 1.29$, *ns*, were significant, indicating that infants' median latencies did not differ as a function of noise density level or the shape of the contour cue (see Fig. 10). Furthermore, the lack of an interaction of condition and contour shape ($F(2,42) = .790$, *ns*), indicated that there was no systematic difference in mean reactive latencies to the target after each contour cue shape as a function of noise density.

The findings from this experiment indicate that infants were able to integrate the individual Gabor elements into contour shapes when embedded in background noise and consequently discriminate between them, thereby detecting the predictable contour cue shape-target location association. Furthermore, the finding of contour integration by 6-month-olds when the noise density was 1.0 and 0.9 but not when it was 0.8 is consistent with previous findings with 3-month-olds (Gerhardstein et al., 2004) and supports the notion that contour integration in the presence of noise in early infancy is limited (Gerhardstein et al., 2004; Norcia et al., 2005).

4. General discussion

The purpose of this study was to extend our knowledge of the developmental trends regarding the capacity for the integration, detection and discrimination of contours in early infancy. Specifically, two questions guided the current research. The first question was: What is the noise density threshold at which 6-month-olds are capable of the integration and detection of contours in the presence of noise? The current findings indicated that the 6-month-olds' density threshold for detecting contours within background noise is approximately $D = 0.9$ and appears similar to that found for 3-month-olds (Gerhardstein et al., 2004). The second, and perhaps more important, question was: Can infants discriminate between different shaped contours in the presence of noise? This study highlighted the fact that not only were young infants able to integrate and detect the contours from within noise, they were able to discriminate between the contours when they had different shapes. This is developmentally a capability that would seem to be critical for infants' object perception and recognition if they rely on an early phase of contour detection.

4.1. Development of noise density threshold

Perceiving and recognizing shapes and objects in the real world requires that they first be detected from amidst surrounding perceptual information. Presumably this requires the early extraction of information about edge boundary assignment and contour description of the object in the presence of noise (Canny, 1986; Kovács & Julesz, 1993; Li, 1998; Malik, Belongie, Leung, & Shi, 2001). In order to gauge the efficiency of the contour integration and detection system, therefore, it is necessary to assess the detection of contours in the presence of noise (Kovács et al., 1999). To this end, Kovács et al. (1999) found that adults' threshold for detecting a contour within background noise was $D = 0.67$, whereas adolescents had a threshold that was similar at $D = 0.7$, indicating that their contour detection could tolerate an average spacing between the background elements that was 30–33% closer than the elements in the contours.

Developmentally, Kovács et al. (1999) reported that children between 5 and 6 years of age have a threshold of $D = 0.84$, indicating that the average spacing between the background elements was 16% closer than the contour elements, half the sensitivity in adults. Gerhardstein et al. (2004) have further demonstrated that contour detection sensitivity is even more immature early in infancy, in that 3-month-olds have a threshold of $D = 0.9$, indicating an average spacing between the background elements that was only 10% closer than the contour elements. Thus, young infants' contour detection mechanisms are only one-third as sensitive as an adults'.

In the current study, 6-month-olds were found to have a detection threshold of D between 0.8 and 0.9, which was similar to Gerhardstein et al.'s (2004) 3-month-olds' threshold. The suggestion is that infants' mechanisms responsible for integrating, detecting, or discriminating contours show little or no improvement between 3 and 6 months of age. However, considering that no noise densities between 0.8 and 0.9 were tested, an absolute developmental standstill cannot be concluded. It should be further noted that there were substantial methodological differences between the VExCP used in the present study and the mobile conjugate reinforcement paradigm used in Gerhardstein et al. In particular, the 6-month-olds had a few seconds of exposure to the contour stimuli whereas the 3-month-olds had several minutes of exposure over two days. Thus, the short exposure may have underestimated 6-month-olds' abilities relative to the long exposure provided to 3-month-olds. Nevertheless, other findings in the literature suggest that there is in fact a slow development of contour perception and that the lack of a difference between 3- and 6-month-olds cannot be attributed solely to methodological differences. The threshold reported for 5- to 6-year-olds, for instance, was 0.84 (Kovács et al., 1999), suggesting the protracted development extends well beyond infancy – consistent with the present findings. Furthermore, neurophysiological factors may underlie the protracted developmental pattern, as illustrated by the Norcia et al. (2005) study in which brain responses did not show differences between 2- and 5-months or between 6- and 13-month-olds in discriminating oriented Gabor textures. Considering that contour integration and detection is likely to occur early in the perceptual buildup of object representations and their recognition (Canny, 1986; Kovács & Julesz, 1993; Li, 1998; Malik et al., 2001), the apparent slow rate of developmental progression in infants' ability to detect contours might be a limiting factor in the development of infants' overall object perception and recognition.

4.2. Neural mechanisms, development, and contour detection

Neurophysiologically, integrating a set of oriented Gabor patches that obey good continuation that results in the detection of a unique contour shape is thought to be accomplished, even in the presence of background noise, by the spatial interaction of orientation-selective neurons in the V1 area of the primary visual cortex (Burkhalter et al., 1993; Hess & Field, 1999; White et al., 2001). More specifically, in V1 there exist horizontal connections between similarly orientation-tuned neurons, each of which code for adjacent spatial locations in the visual field (Gilbert et al., 1996; Gilbert & Wiesel, 1983; White et al., 2001). Research has indicated that the horizontal connections in V1 are functional fairly early in development (Burkhalter et al., 1993). However, post-mortem data showed that there are fewer horizontal connections during early development (Burkhalter et al., 1993), which could mean less integrative power between V1 receptors. As a consequence, consistent with the current study and others (Gerhardstein et al., 2004; Norcia et al., 2005), contour detection amidst noise is relatively poor in early development. During adolescence, the horizontal connections become more fully developed and functional (Kovács et al., 1999), due to the experience of significant visual input (Kovács et al., 2000). A slow trajectory for the development of contour detection in noise and the underlying neural mechanisms is supported by the findings across studies of a prolonged timetable for the improvement of the noise density threshold. Moreover, that there was apparently no or, at best potentially, only a small improvement in noise density threshold in the current study with 6-month-olds as compared to 3-month-olds (Gerhardstein et al., 2004) may be indicative of the slow progression of development in the neural mechanisms responsible for contour integration and detection.

4.3. Contour discrimination

Infants in the current study were easily able to discriminate between circle and square contours when there was no noise and when the noise density was $D = 1.0$. Considering the theoretical importance of contour detection for the perception and recognition of objects (Canny, 1986; Kovács & Julesz, 1993; Li, 1998; Malik et al., 2001), infants' capacity to discriminate contours might be a necessary requirement as they attempt to distinguish and recognize the variety of objects in their environment. When the noise density was $D = 0.9$, however, infants apparently had difficulty detecting the circle contour and discriminating it from the square contour; though their anticipations after the circle contour cue were correct 64% of the time – considerably better than chance performance. One explanation for this apparent lack of detection and discrimination of the circle contour when the noise density ratio was 0.9 might be related to the possibility that infants are not actually perceiving the entire contour.

The casual observer may notice that it is not necessary to perceive the entire contour in order to discriminate between the two contour shapes and thereby be able to predict the spatial location of the target. In particular, the square contour but not the circle contour was comprised of four collinear Gabor patches on each of its sides, which engender the Gestalt principle of collinearity to a greater degree than a circle contour (Koffka, 1935). Considering that recent research has suggested that different Gestalt principles become functional at different points in development (Quinn & Bhatt, 2006; Quinn, Bhatt, Brush, Grimes, & Sharpnack, 2002), collinearity may have a developmental advantage for the infants in the current study. Consequently, infants discriminate between the square and circle contours on the basis of the detection of the presence of collinear Gabors in the square rather than its entire contour shape. In turn, this may give infants an advantage in discriminating the square and not the circle (that has less collinearity) in the $D = 0.9$ condition.

In addition, one might have expected that the opposite effect would have happened (discrimination of the circle and not square at lower D levels) due to the circle being a completely closed contour (Kovács & Julesz, 1993) whereas the square is not because the Gabor patches are orthogonal at its vertices. Field et al. (1993) have reported that for adults contours with relatively large curvature angles (>60°) are more difficult to detect from within noise. In the current study, infants had to detect a circle with a curvature angle of 30°. Though what the curvature threshold is for infants is an empirical question, perhaps the curvature angle used in the present study was too large such that detection of the circle contour became more difficult with increasing noise density. Regardless, it is clear that infants did discriminate circle from squares on some perceptual level, even in the $D = 0.9$ condition.

The apparent failure to detect the circle contour in the 0.9 noise condition, whereas the square contour was detected, also provides support for the contention that infants in the 1.0 noise and the no noise conditions were discriminating both contour shapes. If the contour shape could not be detected then infants would have no basis to detect the contour shape cue-target relation and their anticipations after that contour shape would be correct at a rate not different from chance – as occurred in with the circle contour in the 0.9 noise condition. In contrast, if the contour shape was detected then infants would detect the contour shape cue-target relation and their anticipations would be correct at a rate greater than chance. Consequently, if both shapes were detected then they would have to be discriminated from each other in order for correct anticipations after each contour shape to be greater than chance – as occurred in the no noise conditions, 1.0 noise condition, and square contour in the 0.9 noise condition.

4.4. The visual expectation cueing paradigm

This study also represents the introduction and validation of a new paradigm for assessing the development of infants' perceptual capacities. This VExCP is a modification of the VExP developed by Haith and colleagues (e.g. Adler & Haith, 2003; Haith et al., 1988) and has similarities to the paradigm used by McMurray and Aslin (2004) to study infants' categorization capabilities. The VExCP has several benefits over conventional methods, such as novelty-preference and habituation, that are typically used to test perceptual processing in early development. Compared to novelty-preference and habitation, the VExCP does not require the infant to become "bored" (i.e. decrease in looking time to indicate learning). Furthermore, the results from the VExCP are unambiguous; with novelty-preference and habituation, in contrast, when there is no preference, no interpretation can be offered (e.g. Hunter & Ames, 1988). In terms of the paradigm used by McMurray and Aslin (2004), their stimuli contained motion and occlusion within the same display, thereby likely limiting the size and complexity of the stimulus that can be shown and the age of the infants with which it can be used – limitations that VExCP does not suffer. Though this is only a first study using the VExCP, its future utility for studying different aspects of perceptual development (e.g. Adler & Baker, 2006) appears promising.

5. Conclusion

The results from the two experiments in this study demonstrate that infants are able to discriminate circle and square contours made up of oriented Gabor patches, even in the presence of background noise. Consistent with past research (Gerhardstein et al., 2004), young infants' ability to perform this task in the presence of noise is immature compared to that of children and adults. The present results suggest that the noise density threshold for detecting closed contours for 6-month-olds is somewhere within the $D = 0.9–0.8$ range, higher than 5 and 6-year-olds' ($D = 0.84$) and adults' thresholds ($D = 0.67$) (Kovács et al., 1999), but similar to 3-month-olds' (Gerhardstein et al., 2004). With contour integration and detection considered as early perceptual processes in figure-ground segregation and object recognition, the slowness of contour detection mechanisms to improve may be a limiting factor in the development of object perception. The current cause for this protracted development is unknown, but is likely due to neural development. Future research is needed to better understand the functional maturity of the visual-spatial integration and object recognition systems.

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