Interhemispheric integration of visual concepts in infancy

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Abstract

Abstraction often requires appropriate integration of more concrete representations. During development, the more specific or localized representations may arise first. Here we study the special case of integration of visual representations from the left and right hemispheres during infancy. We present failures of interhemispheric integration in two domains, form perception and approximate number, in infants ranging from 8 to 18 months of age. In Experiment 1, infants succeeded in representing equality of two shapes only when both shapes were presented in the same visual hemifield. In Experiment 2, infants represented 16 when shown 16 dots in one hemifield but not when shown 8 dots in each hemifield. We argue that interhemispheric integration poses a particular and unusually late-resolved challenge in infant vision.

Keywords: visual invariance; interhemispheric integration; corpus callosum; split-brain; approximate number system

Introduction

Any latent cause in the world can lead to myriad patterns of observations. Recognizing an object in the visual world requires achieving invariance over transformations–including translations, rotations, scaling, and lighting changes–that can drastically affect its retinal projection. Similarly, understanding more abstract concepts often requires recognizing the identity or shared causes of superficially disparate manifestations: three voices, three bears, or three hugs; perceptual causality or statistical covariance; a frown and a raised voice. Assuming that in some cases these specific "views" may be represented before the more general concepts, how do infants integrate these distinct representations?

Newborns have already been demonstrated to have several forms of visual invariance such as size constancy (Slater, Mattock, & Brown, 1990) and recognition of invariant positional relations (Antell & Caron, 1985; Milewski, 1979), although these progress with visual experience during the first year (McKenzie, Tootell, & Day, 1980; Granrud, 2006; Gliga & Dehaene-Lambertz, 2007). Visual adaptation and aftereffects suggest that high-level visual concepts including approximate number (Ross & Burr, 2010) and facial identity (Webster & Maclin, 1999) may pose similar learning challenges, as they are first represented by spatially localized detectors. Split-brain patients likewise provide dramatic evidence for distinct spatially localized representations of high-level visual concepts (for review see Gazzaniga, 2005).

Regardless of the exact computations involved, the relationships among localized detectors need to be learned or refined to produce integrated representations. We propose to study the special case of integration of visual concepts from the left and right hemispheres. Late myelination of the corpus callosum, which connects the two cereberal hemispheres (Yakovlev & Lecours, 1967), its continued development through adolescence (Giedd et al., 1999; Salamy, 1978), and the separate critical period for the corpus callosum to affect visual development (Elberger, 1984) make this plausibly challenging in early childhood. Indeed, interhemispheric transfer of a visual rule learned in a single hemisphere does not occur spontaneously before 4 months of age (de Schonen & Bry, 1987), and children under 24 months have difficulty integrating information about shape across hemispheres (Liegeois, Bentejac, & de Schonen, 2000). However, this effect is specific to face stimuli; the operant conditioning task introduced additional demands; and the bilateral and unilateral presentations differed in visual angle from the fovea, allowing several alternative explanations of the apparent failure.

We first sought to confirm infants' difficulty comparing shapes from opposite visual hemifields. In Experiment 1, we attempted to familiarize infants with matching shapes either unilaterally or bilaterally by briefly presenting matching pairs of shapes while infants fixated on a small video. This familiarization period was designed to affect their preference for looking at matching shapes, which we measured before and after familiarization.

Experiment 1: Is a square on the left the same shape as a square on the right?

Methods

Participants Infant subjects were recruited at the Boston Children's Museum and parents provided informed consent to participate. 48 infants between 8 and 14 months of age (mean age 11 months 2 days) participated in this study. An additional 33 infants were excluded due to fussiness, inattention, or experimenter error.

Procedure Each infant sat on a parent's lap for the duration of the study, 1.5 m from a large monitor used to display all stimuli. Subjects were videorecorded using a camera positioned directly above the monitor. The experimenters were positioned behind the monitor, hidden from the view of the infant, and monitored the infant using a webcam positioned above the monitor while controlling the progression of the study using Psychtoolbox extensions (Brainard, 1997) in

MATLAB (Natick, MA).

The procedure consisted of (1) a baseline test of looking-time to matching and non-matching pairs of shapes; (2) a familiarization period showing only matching shapes; and (3) a final test of looking-time to matching and non-matching pairs of shapes. Because the procedures for baseline and final tests were identical we first address the familiarization period.

Familiarization The familiarization period was intended to familiarize infants with the concept of two matching shapes if possible. Images of matching shapes were flashed for 280 ms each only while the infant was looking at a small, attractive "fixation video," which continued to play throughout familiarization[1]. Infants' attention to the monitor was maintained by switching among two fixation videos and three pieces of music as necessary. The familiarization period ended when the infant looked away after being shown at least 100 images of matching shapes at a maximum rate of one per second. Example sequences for each condition are shown in Figure 1. Images were shown in random order with none presented more than twice to any infant and no overlap between the shapes used for familiarization and testing.

In the 'bilateral' condition, the images of matching shapes were on opposite sides of the fixation video, at one and two units from fixation (the position of the more distant shape was consistent within subjects and counterbalanced). In the 'unilateral–peripheral' condition, both matching shapes were on one side of the central fixation video (side consistent within subjects and counterbalanced), at distances of one and two units from the fixation video as in the bilateral condition. In the 'unilateral–distance' condition, the fixation video was shifted towards one side (consistent within subjects and counterbalanced) of the monitor to accommodate the placement of both shapes on one side of fixation at a distance of three units from each other. We predicted that infants would only recognize the identity of the two shapes when they were presented unilaterally, whereas familiarization would not lead to a representation of "matching shapes" when shapes were in opposite hemifields.

Looking time tests Parents closed their eyes during the looking-time measurements to avoid inadvertent bias. Each test consisted of four trials[2] (images shown in Figure 2). Before each trial, the infant's attention was attracted to the monitor by a chime and a colorful spinning ball, displayed at the center of the monitor. Once the child looked at the monitor, a static image of a pair of shapes was displayed and remained on the screen until the child looked away for at least 1 second.

The set of images used for the baseline test was counterbalanced and the opposite set was used at the final test. The order of presentation was counterbalanced such that half of

[1] Pilot data established that a coder blind to condition could correctly identify the location of the fixation video from the infant's gaze as a basic manipulation check.

[2] An additional two trials were performed at the end of each testing period but not analyzed, in order to demonstrate the testing procedure to parents.

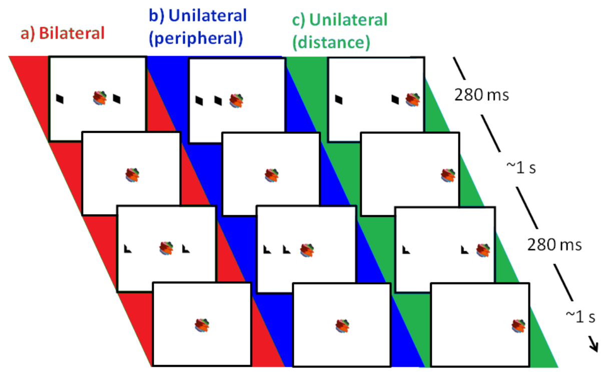

Figure 1: Familiarization with matching shapes. (a) Bilateral condition: one shape on either side of fixation, at distances of one and two units. (b) Unilateral condition, matched to the bilateral for peripherality of shapes since they were also at one and two units from fixation. (c) Unilateral condition, matched for distance (three units) between shapes.

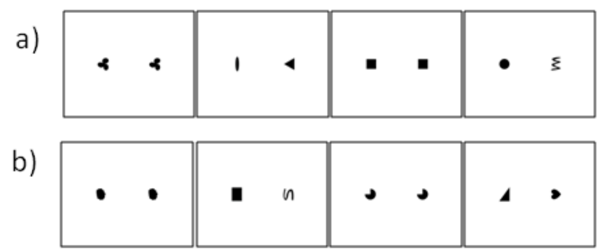

Figure 2: Pairs of matching and non-matching shapes used for baseline and test displays. (a) Test set A, (b) Test set B.

the infants saw a matching pair first (order 1, 2, 3, 4, 5, 6) and half saw a nonmatching pair first (in order 2, 1, 4, 3, 6, 5); an infant who saw a matching pair first at the baseline test also saw a matching pair first at the final test.

Video coding Two coders blind to experimental condition recorded looking times until the first continuous 1-second lookaway for each trial during the baseline and final tests using SuperCoder (Hollich, 2005) or VCode (Hagedorn, Hailpern, & Karahalios, 2008). The looking times recorded by the two coders were averaged. A preference score for non-matching shapes was computed for each subject by dividing the sum of the looking times to nonmatching pairs (trials 1 and 3 or 2 and 4) by the sum of the looking times to all four pairs (trials 1-4). Preference scores thus ranged from 0 to 1 with a score of 0.5 indicating equal looking times to matching and non-matching pairs.

A shift in preference towards nonmatching shapes was computed for each subject by subtracting the baseline from the final preference score; a positive shift indicated that the preference for nonmatching shapes increased over the course of familiarization. Our goal was to assess the impact of familiarization on the infant's preference for matching shapes.

If he or she represented this concept, the preference would shift due to familiarity, leading to greater differences between baseline and test measurements in the unilateral conditions.

Results

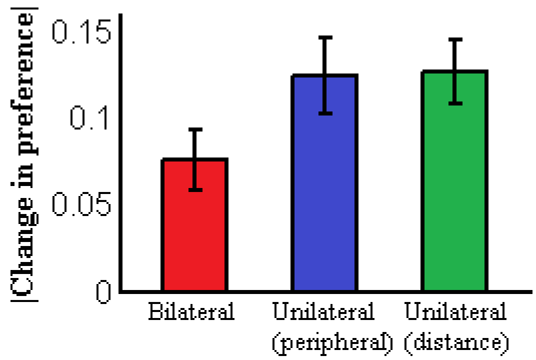

Figure 3: Mean absolute value of the change in preference for non-matching shapes between baseline and final looking time tests, +/- s.e.m. N=16 per condition.

Our primary finding was that, as predicted, the absolute value of the shift in preference was greater in the unilateral conditions than in the bilateral condition (Wilcoxon signed rank test, one-tailed, $p < 0.05$). This greater variance indicated a larger absolute effect of familiarization on preferences in the unilateral condition.

To better understand the nature of the preferences potentially induced by familiarization, we also evaluated the correlation between subjects' age and shift in preference. The shift in preference was correlated with age in the unilateral conditions ($r = 0.46$, $p < 0.01$, Spearman rank correlation) but not in the bilateral condition ($r = 0.07, p > 0.5$, Spearman rank correlation). In the unilateral conditions, younger infants showed familiarity preferences whereas older infants showed novelty preferences, as shown in Figure 4.

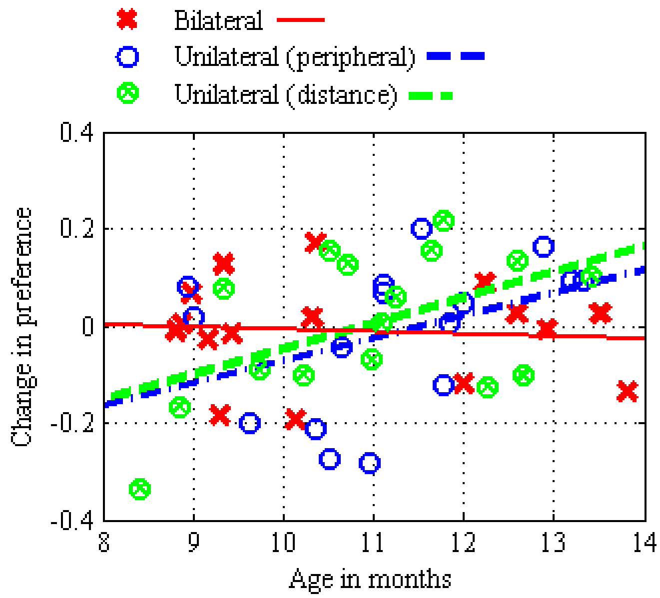

Figure 4: Difference in preference for non-matching shapes between baseline and final test periods. A positive difference indicates a greater preference for non-matching shapes at final test. Lines show least-squares linear fits for each condition.

Discussion

These findings suggest that infants shown identical shapes in each hemifield did not represent the visual stimuli as pairs of matching shapes; infants who saw the same images within a single hemifield did. Successfully inducing familiarity with matching shapes between the baseline and final measurements of preference would increase the average absolute change in preference by adding a systematic shift to any random variation. We found this increase when both shapes were presented in one visual hemifield, indicating that the consistent relationship between the two shapes was more readily represented. This is in contrast to the bilateral field advantage adults exhibit when comparing visual stimuli (Sereno & Kosslyn, 1991; Kraft et al., 2005).

Abundant evidence shows that the quality of the representation constructed by an infant affects the preference expressed for familiar stimuli. Younger infants (Hunter, Ames, & Koopman, 1983), more complex stimuli (Kidd, Piantadosi, & Aslin, 2012), and less familiarization time (Houston-Price & Nakai, 2004; Richards, 1997; Roder, Bushneil, & Sasseville, 2000; Rose, Gottfried, Melloy-Carminar, & Bridger, 1982) can all lead to familiarity rather than novelty preferences (for a review see Aslin, 2007). A constant amount of familiarization as performed in Experiment 1 would therefore be expected to induce a shift from familiarity to novelty preference with age. This is exactly what we found in the unilateral conditions, in support of the interpretation that the increased variance in change in preference was due to a true familiarity with the concept of "matching shapes." In contrast, the preference shifts between baseline and final testing of infants in the bilateral condition showed no such systematicity, confirming that the shifts we did observe could be attributed to random variation between two consecutive measurements.

The age trend observed does not indicate a change in interhemispheric integration over the age range studied; rather, we are assuming that when shown matching shapes in one hemifield all infants represent "matching shapes" but express this familiarity differently with age. Over the age range studied, we observed no evidence for a comparable representation of "matching shapes" when the shapes were presented in opposite hemifields. The condition difference cannot be attributed to differences in peripherality of or distance between the matching shapes, since we observed comparable trends when matching either for how peripheral and how distant from each other the matching shapes were.

The question remains of whether infants in the bilateral condition simultaneously perceive two clear but incomparable shapes, or have separate experiences of seeing each shape as two separate people might. Experiment 2 addresses perceptual integration more directly in the case of approximate numerical representations by familiarizing infants with 16 dots either all in one visual hemifield (16+0) or split evenly between the two hemifields (8+8). We directly predict the representation that would result from a failure to integrate information: infants in the 8+8 condition will represent 8, whereas infants in the 16+0 condition will represent 16[3]. We also expect that younger infants will express these representations via familiarity preferences whereas older infants will show novelty preferences. That is, we expect that infants in the 8+8 condition will start off showing a familiarity preference for 8 and shift to a novelty preference for 16, whereas infants in the 16+0 condition will start off showing a familiarity preference for 16 and shift to a novelty preference for 8.

Experiment 2: Does 8 on the left plus 8 on the right look like 16?

Participants Infant subjects were recruited at the Boston Children's Museum and parents provided informed consent to participate. 36 infants between 12 and 19 months of age (mean age 15 months 12 days) participated in this study.[4] An additional 12 infants were excluded due to fussiness, inattention, or experimenter error.

Procedure Infants were positioned as in Experiment 1. The procedure consisted of (1) a familiarization period showing images of 16 dots and (2) a final test of looking-time to images of 16 and of 8 dots.

Familiarization All infants were familiarized with images of 16 dots while looking at the "fixation video" on a large monitor as in Experiment 1. In the 'bilateral' condition, 8 dots appeared on one side of the fixation video and 8 dots on the other side. In the 'unilateral' condition, the same images were used but the fixation video was shifted to either the left or right side. The side of fixation was counterbalanced between infants, so that each infant was familiarized with 16 dots in one consistent hemifield. Example sequences for each condition are shown in Figure 5. We expected that this familiarization would induce familiarity with 16 dots in the 16+0 condition but with 8 dots in the 8+8 condition.

Looking time tests Looking time to a series of six images, alternating between 16 and 8 dots as shown in the examples in Figure 6, was measured as in Experiment 1. The density and dot size were matched to those of the familiarization images.

[3]We assume that infants can represent and distinguish these quantities since since 6-month-old infants succeed (Xu & Spelke, 2000) with sufficiently long presentations (Wood & Spelke, 2005).

[4]An additional 3 infants under 12 months were tested and did not show clear familiarity preferences; however, their inclusion does not change any of the qualitative findings reported here.

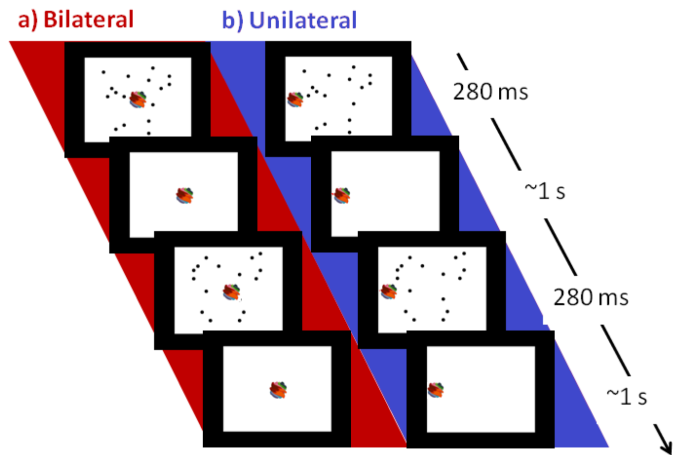

Figure 5: Familiarization with 16 dots. (a) Bilateral (8+8) condition: 8 dots on either side of fixation. (b) Unilateral (16+0) condition, with all dots in one hemifield.

The order of presentation was consistent across all subjects to reduce variance associated with decreasing looking time over the six trials.

Figure 6: Test displays of 8 and 16 dots used in Experiment 2.

Video coding Two coders blind to experimental condition recorded looking times as in Experiment 1. The looking times to the 2nd through 5th trials were used to compute a preference score for 8-dot pictures as a proportion of the total looking time during these trials[5]

Results

As predicted, the correlation of preference for 8 dots with age was greater in the unilateral (16+0) than in the bilateral (8+8) condition (permutation test on Spearman rank correlations, $p < 0.01$). In the unilateral condition infants showed a shift towards prefering 8 dots with age ($r = 0.70$, $p < 0.005$) and in the bilateral condition they showed no significant shift overall ($r = -0.08$, $p = .3$). However, preferences in the bilateral condition showed a significant positive quadratic trend (permutation test, $p < 0.05$) indicating the possibility of two shifts in preference: first from preferring 8 to preferring 16, and then back to preferring 8–like infants in the unilateral condition–as infants neared 18 months.

[5]The first trial was not included in the analysis because of the large variance in interest in the first static image displayed.

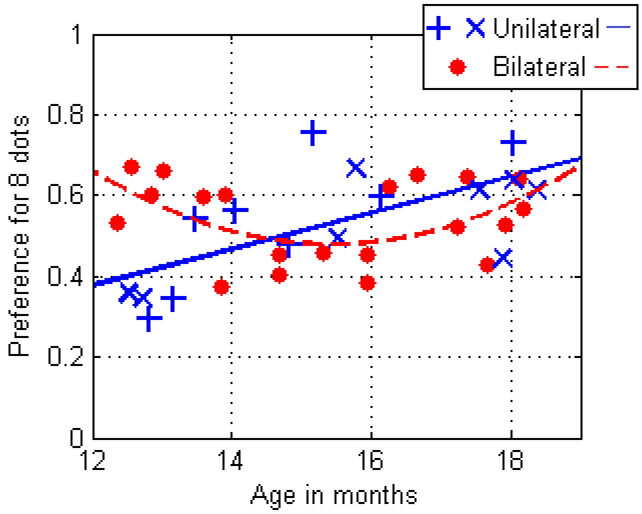

Figure 7: Preferences at test for images with 8 dots rather than 16 dots. In the unilateral condition, 'x' represents an infant shown the 16 dots on the left and '+' an infant shown the 16 dots on the right. Curves show a linear fit for the unilateral condition and a quadratic fit for the bilateral condition.

Discussion

These results are consistent with the possibility that whether infants see 16 dots as 16 dots depends on whether the dots are presented to a single hemisphere. In the unilateral condition, we predicted the observed trend from a familiarity preference for 16 in to a novelty preference for 8 in older infants. In the bilateral condition, we predicted that infants would represent 8 dots (twice), expressed as a familiarity preference in younger infants shifting to a novelty preference in older infants. If, after this first shift, infants began to integrate the two numerosities and represent 'approximately 16', this preference would shift again to a novelty preference for 8 dots, as observed. We hypothesize two orthogonal age trends comprising the quadratic trend observed in the bilateral condition: a shift from familiarity to novelty preference that reflects the mode of expression of a stable representation, and later a change in the representation itself.

An increase with age in the precision of numerical representation could explain the age trend in the unilateral condition, but not the difference in correlation between conditions. Whereas a hypothetical decreasing impact with age of peripherality on underestimation of numerosity, demonstrated in adults (Valsecchi, Toscani, & Gegenfurtner, 2013), could potentially explain this difference, it cannot account for the quadratic trend in the bilateral condition.

Because of infants' demonstrated capacities for flexible combination of numerosities, we expect that the primary use of single-hemifield numerosity estimates–without an additional deficit in integration–would not lead to the observed pattern of results. Not only can infants predict the results of dynamic addition and subtraction events over large approximate numbers (McCrink & Wynn, 2004) but they readily represent and compare multiple simultaneously presented numerosities (Xu & Garcia, 2008; Gweon, Tenenbaum, & Schulz, 2010). However, previous work has not directly addressed whether infants can represent nested or overlapping numerosities (e.g., the number of balls and the number of red balls) in addition to disjoint numerosities (the number of red balls and the number of yellow balls). This limitation be explored using standard psychophysical techniques in adults and free-viewing presentations with infants and children.

General discussion

Experiments 1 and 2 demonstrate deficits in processing of bilateral visual stimuli late in development, with consistent age trends observed in two distinct domains: form perception and approximate number.

There are several challenges that could prevent infants from achieving representations of a stimulus covering the entire visual field. We focus here on the integration of putative single-hemifield representations, but early failure to perceive or remember the content of both hemifields–for instance, due to exclusive allocation of attention to one hemifield at a time–could also explain the results presented here. Adult data makes an attentional explanation unlikely without substantial developmental change in the structure of attentional resources, as adults are actually *more* able to maintain spatially separated attentional foci in different hemispheres (Malinowski, Fuchs, & Müller, 2007) and may indeed use independent resources for object tracking in each hemifield (Alvarez & Cavanagh, 2005). Nevertheless, it will be important to establish whether both sides of the briefly presented stimuli are seen and processed.

Additional open questions include the developmental trajectory of interhemispheric integration and the specificity of these findings to vision rather than more abstract lateralized representations.

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