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Visual development in human infants: Binding features, surfaces, and objects

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The development of visual binding in humans has been investigated with psychophysical tasks assessing the extent to which young infants achieve perceptual completion of partly occluded objects. These experiments lead to two conclusions. First, neonates are capable of figure–ground segregation, but do not perceive the unity of a centre-occluded object; the ability to perceive object unity emerges over the first several postnatal months. Second, by 4 months, infants rely on a range of Gestalt visual information in perceiving unity, including common motion, alignment, and good form. This developmental pattern is thought to be built on the ability to detect, and then utilize, appropriate visual information in support of the binding of features into surfaces and objects. Evidence from changes in infant attention, computational modelling, and developmental neurophysiology is cited that is consistent with this view.

The visual environment is a complex arrangement of object surfaces that are only partly visible at any given point in space and time because of the ubiquity of occlusion: Surfaces near to the observer in the optic array often overlap those that are more distant. Despite this complexity, however, an observer with a mature visual system is able to perceive surfaces as belonging to coherent entities with distinct boundaries at various distances, and not as a collection of fragments that undergo continual changes in appearance. Moreover, we are able to join separate surfaces into unified percepts of objects that maintain distinct attributes and identities over spatiotemporal transformations. Only under limited circumstances, such as reported in challenging search experiments that may bear little resemblance to real-world perceptual tasks (e.g., Treisman &

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Schmidt, 1982), or in observers with cortical damage (e.g., Goodale, Milner, Jakobson, & Carey, 1991), do veridical object percepts routinely fail to obtain in adults.

These remarkable achievements have often been described as the visual system's solution to the "binding problem" (Roskies, 1999). This term encompasses a variety of perceptual phenomena, including integration of intermodal stimuli, consolidation of visual information that is extended over space and time, conjoining such object features as colour and shape, and perception of the unity of partly occluded objects. In the present paper, I discuss insights that can be brought to bear on the binding problem from developmental studies using psychophysical methods with human infants between birth and 4 postnatal months of age. The experiments employ an "object unity" task, which incorporates two complementary processes: *unit formation*, or perception of the connectedness of edges across a spatial gap, and *surface segregation*, or detection of relative depth of two or more visible surfaces. I also discuss theoretical implications and speculation concerning the emergence of veridical object percepts across infancy. To anticipate, there is no current evidence in favour of the hypothesis that infants are born with mature object perception skills. However, such skills develop rapidly over the first few postnatal months. Mechanisms of the development of unit formation may include improvements in attentional skills and utilization of appropriate visual information, accompanied by cortical maturation.

INFANTS' PERCEPTION OF OBJECT UNITY

Figure 1A depicts a "rod-and-box" display consisting of a center-occluded object whose visible ends, protruding from behind a box, are aligned and undergo common lateral translation. Kellman and Spelke (1983) used this display, and others, to explore the conditions under which 4-month-olds would perceive the unity of the rod parts. They used a *habituation* paradigm in which an infant was first presented with the rod-and-box display until looking declined to a preset criterion. After reaching habituation, infants viewed two test displays, a complete rod (Figure 1B) and a "broken" rod (Figure 1C), which contained a gap in the space formerly occupied by the box. Each test display matched the visible portions of the rod surfaces in the habituation display, but the infants looked longer at the broken rod. Given that infants often look longer at a posthabituation display that is relatively novel, rather than at a relatively familiar display (Bornstein, 1985), these results imply that the infants perceived the unity of the rod parts in the habituation stimulus. Infants in a control condition viewed a rod-and-box display whose constituent parts were arranged so as to preclude unity percepts, and subsequently exhibited no consistent test display preference. This result mitigates against the likelihood of an inherent

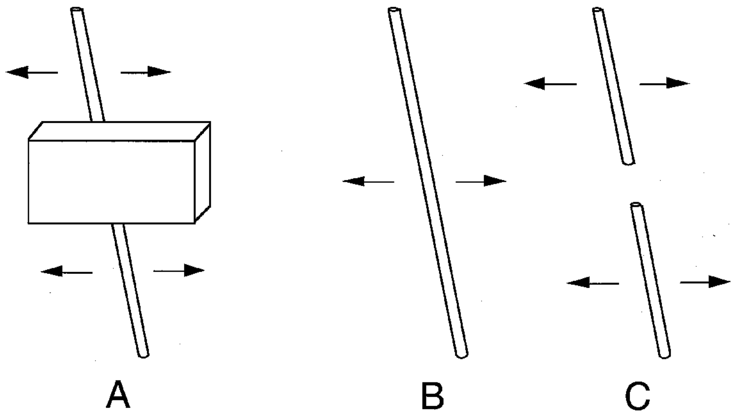

Figure 1. Displays employed in past research to investigate young infants' perception of partly occluded objects (adapted from Kellman & Spelke, 1983). **A:** A partly occluded rod moves relative to a stationary occluder. **B:** Complete rod. **C:** Broken rod. After habituation to A, infants often show a preference for C relative to B, indicating perception of the rod's unity in A.

preference for the broken rod that could account for the outcome of the unified-object condition.

Since the original studies, research on perception of object unity has taken two directions. The first is a series of explorations of the visual information used by infants to achieve unit formation in partly occluded object displays. The second consists of investigations of the origins of unit formation in infancy. Each is discussed in turn.

HOW DO INFANTS ACHIEVE UNIT FORMATION?

Kellman and Spelke (1983) reported robust unit formation when 4-month-olds viewed rod-and-box displays in which the rod parts underwent common motion relative to a stationary occluder. In contrast, however, 4-month-olds do not appear to perceive the unity of static partly occluded surfaces, nor surfaces that move along with the occluder. Kellman and Spelke posited that young infants are not able to take advantage of the full range of available visual cues when engaged in perceptual tasks, such as perception of object unity. Rather, infants were assumed to rely exclusively on the common motion of the rod parts, failing to use other cues such the rod parts' collinearity, the similarity of their surfaces, and so on. In Gestalt terms, then, young infants appear sensitive to common fate, but not good continuation, good form, or symmetry. In contrast, older infants and adults utilize these latter cues, as well as motion, to perceive unity (cf. Craton, 1996).

To account for these results, Kellman (1996) delineated a two-process account of development of perception of object unity. The first process was denoted *edge-insensitive* (EI) and was proposed to be the only process available to infants younger than 6 months. The EI process specifies object unity by relying on motion, but not other cues such as the orientation of edges as they intersect with the occluder and the configuration or appearance of the partly occluded surfaces. The second process was denoted *edge-sensitive* (ES) and was proposed to become available to infants older than 6 months. The ES process exploits a range of cues, including edge orientation and surface configuration. Under the ES process, object unity will be perceived if the visible edges are *relatable* (i.e., if they were to be extended behind the occluder, they would meet at an obtuse angle; see Kellman & Shipley, 1991). Given that the ES process is unavailable to young infants, they would not be capable of unity perception based on visual information other than motion.

A wealth of recent evidence is inconsistent with this view, and indicates that young infants utilize several Gestalt cues, in addition to common motion, in perceiving object unity. Johnson and Aslin (1996) began these more recent investigations by testing the Kellman (1996) prediction that 4-month-olds would perceive unity in any display in which two visible rod parts undergo common motion. We observed infants in four conditions, using computer-generated displays, as well as control conditions to rule out the likelihood of any inherent test display preference. (The control conditions consisted of displays in which rod surfaces did not move together behind the occluder.) The first group of infants viewed a rod-and-box display (Figure 2A) against a textured background (a grid of dots), and subsequently exhibited a consistent, statistically reliable posthabituation preference for the broken rod. This result replicates the original findings of Kellman and Spelke (1983) in its suggestion that the infants perceived the unity of the rod parts during habituation. The second group of infants viewed a rod-and-box display against a solid black background with no texture elements, and showed no reliable posthabituation preference. The next experiment used a *misaligned* rod display (against a textured background) in which the rod parts were not aligned, but were relatable, according to the Kellman and Shipley (1991) criteria for edge relatability (Figure 2B). These infants showed no test display preference. A fourth group of infants viewed a *nonaligned* rod display (against a textured background) in which the rod parts were neither aligned nor relatable (Figure 2C). These infants preferred the *complete* rod during test. In none of the four accompanying control conditions was there a consistent test display preference. On the logic that posthabituation looking times reflect novelty preferences, this pattern of results suggests that the infants in the first condition perceived the unity of the partly occluded rod. In contrast, percepts in the second and third conditions appear to have been indeterminate, and infants in the fourth condition seem to have perceived the rod parts as disjoint objects. Taken together, these findings indicate that unity perception does not appear to be driven exclusively by common motion, because common motion was available in all four displays. Rather,

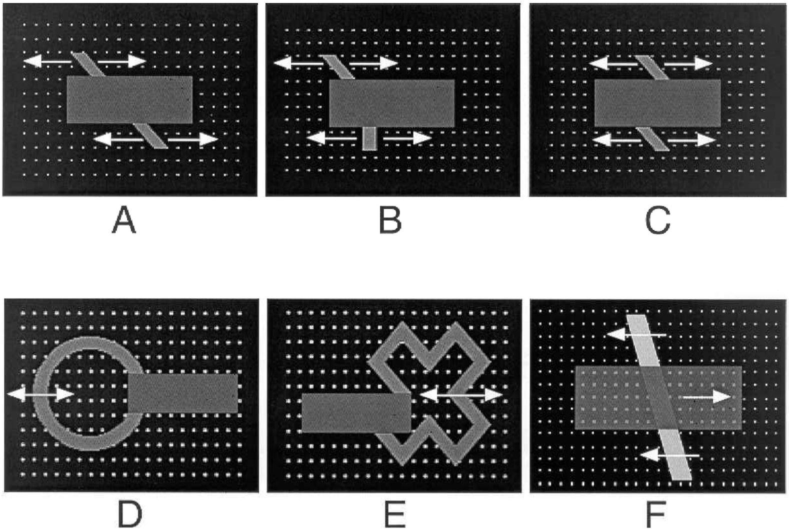

Figure 2. Displays employed to investigate the role of edge orientation, object form, and surface appearance in young infants' object perception. **A:** Rod parts are aligned across the occluder. **B:** Rod parts are not aligned, but are relatable (if extended, they would meet behind the occluder). **C:** Rod parts are neither aligned nor relatable. Four-month-old infants perceive unity only in A, underscoring the importance of edge alignment to unit formation. **D and E:** Edges at the rod/box intersections are not aligned, but good form supports perception of object unity. **F**: The box appears transparent under some conditions to 4-month-olds, suggesting that surface appearance aids in perceptual segregation. (A–C: adapted from Johnson & Aslin, 1996; D–E: adapted from Johnson, Bremner, Slater, & Mason, 2000. F: adapted from Johnson & Aslin, 2000.)

other cues, such as edge orientation and the presence of background texture, also support young infants' perception of object unity. Further experiments have revealed that good form supports unit formation (Figures 2D and 2E; Johnson et al., 2000), and that young infants perceive transparency in some displays, suggesting that the infants bound together surfaces with different reflectance characteristics in segregating the display into a translucent and an opaque layer (Figure 2F; Johnson & Aslin, 2000). (See also Craton, 1996; Johnson & Aslin, 1998; Jusczyk, Johnson, Spelke, & Kennedy, 1999; Needham, 1998.)

To account for these results, I have proposed a *threshold model* (Johnson 1997, 2000; Johnson & Aslin, 1996), positing that young infants' veridical surface segregation relies on several subprocesses, rather than a single cue (such as motion). If any of these subprocesses are disrupted, veridical object perception may be precluded. Nakayama and colleagues (Nakayama, He, & Shimojo, 1996; Nakayama & Shimojo, 1990; Nakayama, Shimojo, & Silverman, 1989) noted that in order to segregate surfaces in an occlusion display, the observer must determine in which depth plane each surface resides (a process called *depth placement*), and determine which contours in the scene belong with which objects (*contour ownership*). Depth placement relies on depth cues, and accretion and deletion of background texture, for example, aids perceptual segregation of the rod and box surfaces into their constituent depth planes. Contour ownership may rely on edge alignment, and when rod edges are nonaligned, infants appear to perceive them as belonging to separate objects, as if the contours of the rod ended at the box, unless additional information is available from good form. These results suggest that veridical object perception depends upon both the *sufficiency* of visual information and the *efficiency* of perceptual and/or cognitive skills, and that unit formation and surface segregation are multiply determined by independent sources of information. Unit formation and surface segregation, on this account, proceeds from an initial analysis of individual feature elements (cf. Marr, 1982): edge orientations, surface intersections (e.g., T-, L-, and X-junctions), and surface motions. From here, a viewer-centred description of relative distances of surfaces is constructed, incorporating additional information from disparity and other depth information (e.g., accretion and deletion of texture). Finally, an object-centred representation of the visual environment is realized, incorporating complete "object permanence" (Piaget, 1954). As described in the next section, the surface description does not appear to be available to human infants until several months after birth, and mature object-centred representations take longer still.

HOW DOES PERCEPTION OF OBJECT UNITY DEVELOP IN HUMAN INFANTS?

Kellman and Spelke (1983) interpreted 4-month-olds' success at object unity tasks as evidence for object perception skills that were functional at birth: "Humans may begin life with the notion that the environment is composed of things that are coherent, that move as units independently of each other, and that tend to persist, maintaining their coherence and boundaries as they move" (p. 521). When newborn infants were tested using similar procedures, however, these infants responded during test with the *opposite* looking time pattern than 4-month-olds: A significant preference for the complete rod (Slater et al., 1990). Concurrent experiments controlled for competing interpretations of the neonates' responses (e.g., familiarity rather than novelty preferences, an inability to detect each of the visible surfaces or segregate figure from ground, and so on), leading Slater et al. to conclude that these infants did not perceive object unity. Rather, neonates appeared to perceive disjoint rod surfaces in the rod-and-box display.

These two findings point to the time between birth and 4 months as the period during which veridical responses to object occlusion emerge. In an initial attempt to pin down more precisely the time course of development of unit formation, we found that 2-month-olds exhibited no preference for either a broken or complete rod test display after habituation to a rod-and-box display (Johnson & Náñez, 1995), suggesting that 2 months of age represents a time of transition from perception of disjoint objects in the display (the neonates' response) to unit formation (the 4-month-olds' response). Recall, however, the stipulations of the threshold model: It might have been that we supplied insufficient visual information to support unit formation in a population that might be expected to have relatively inefficient perceptual skills. This hypothesis was tested by presenting 2-month-old infants with rod-and-box displays in which more of the rod was visible as it moved back and forth, either by reducing box height, or by incorporating strategically placed gaps in the box (Johnson & Aslin, 1995). In each condition, the infants showed a consistent posthabituation preference for the broken rod relative to the complete rod, implying perception object unity during habituation. (Control groups did not exhibit this preference.) Thus perception of object unity may be a skill that, although fragile in its earliest form, is available to even very young infants if given adequate perceptual support (cf. Kawataba, Gyoba, Inoue, & Ohtsubo, 1999).

The Johnson and Aslin (1995) finding of perception of object unity in 2-month-olds raises an important question: Might neonates also perceive object unity, if given additional perceptual support? This possibility was investigated by Slater, Johnson, Brown, and Badenoch (1996), who presented neonates rod-and-box displays that were richer in visual information for surface segregation, relative to the display employed by Slater et al. (1990): Reduced occluder height, increased separation in depth between the rod and box, background texture (to increase the salience of the depth differences between surfaces), and so on. Even with this additional information, however, the neonates did not appear to respond to object unity: They showed a clear and reliable posthabituation preference for the complete rod, relative to the broken rod.

MECHANISMS OF DEVELOPMENT

To summarize the evidence to date on development of perception of object unity, neonates appear to perceive a partly occluded object as comprised of disjoint surfaces, implying that at birth, humans may experience what Piaget (1952, 1954) called a "sensory tableaux", or a mosaic of disconnected, fragmented shapes. The process of binding these fragments into coherent, segregated surfaces and objects develops rapidly such that incipient unit formation emerges by 2 months, and by 4 months, infants utilize a range of visual information in object perception tasks, including orientation, motion, shape, depth, texture, and colour (Johnson, 2000).

It is clear, then, that unit formation and surface segregation skills develop rapidly in the human infant with the onset of visual experience. At present there is no single developmental account that encompasses the entire range of evidence, but the threshold model holds promise in identifying important theoretical links to other approaches that might help explain the emergence of these skills. The heart of the model is the contention that improvements in information-processing proficiency underlie development of the ability to bind features into coherent surface and object percepts. This contention is supported by recent evidence from studies of infant eye movements, connectionist modelling, and developmental neurophysiology, presented in the next section.

Eye movements

It seems probable that at least part of the differences in performance on the object unity task across the first few months after birth is rooted in improvements in attentional skills: The more proficient infants become at information pickup, the more likely it is that they will be able to detect and utilize that information in perceptual tasks. Recording of eye movements can serve as an important tool to investigate this possibility. To date, however, there have been no reports in the literature of infants' scanning of moving objects, and few reports of longitudinal investigations of changes in individual infants' eye movement patterns (see Bronson, 1994, 1997). Johnson and Johnson (in press) recorded scanning patterns in thirteen 2- and 3.5-month-old infants engaged in free viewing of partly occluded rod displays. We predicted that 3.5-month-olds, relative to 2-month-olds, would scan more often in the rod's vicinity, more often on both visible rod parts, and less often in uninformative regions of the display. Several noteworthy findings emerged. First, as predicted, older infants produced a higher proportion of fixations per second than did younger infants. Second, older infants scanned more extensively (across the display), whereas younger infants scanned less often in the vicinity of the bottom rod part (see Figure 3). Younger infants' fixations in the bottom part of the display were more frequent, however, with longer display times. We did not obtain evidence concerning the infants' perception of object unity in this study, but these results

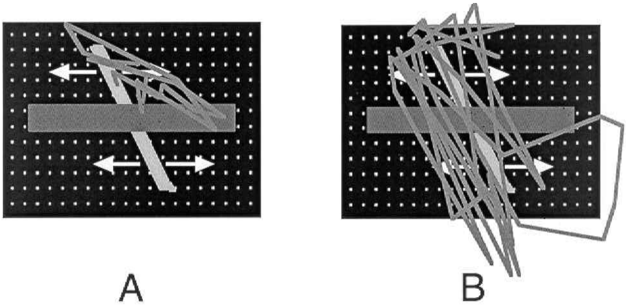

Figure 3. **A:** Example of a younger infant's eye movement pattern when viewing an occlusion display; scanning is limited, perhaps restricting pickup of relevant information in support of visual binding. **B:** Example of an older infant's scanning, which is more extensive, suggestive of superior information pickup.

indicate that the period in infancy during which unit formation undergoes rapid improvement is accompanied by important advances in scanning efficiency.

Connectionist modelling

Mareschal and Johnson (1999, in press) devised computational models of the development of perception of object unity. These models were programmed with standard connectionist architectures (i.e., input, hidden, and output layers) using backpropagation as a training algorithm, and endowed with sensitivity to visual information that has been found to influence infants' perception of object unity (object orientation, motion, and accretion and deletion of background texture). They were then presented with input that represented partly occluded object displays in which rod parts moved back and forth behind an occluder, and emerged from either side. That is, the rod was both fully and partly visible during each excursion across the display. The models were also equipped with a transient memory, such that after a rod became occluded, a trace of its now-hidden portion remained. After varying amounts of exposure to a subset of the possible occlusion events, the models were tested for perception of object unity while presented with events in which the rod parts did not emerge from behind the occluder. The results were positive: The models reliably perceived unity in most of the test events. The extent to which the models learned, and learning efficiency, were highly dependent on the training environment—which events were presented during training (i.e., which cues were made available), and how long training was allowed. Surface binding, then, arose from an initial perceptual sensitivity combined with transient memory and experience viewing objects that became occluded and again fully visible.

Developmental neurophysiology

Recent speculation concerning the visual system's ability to bind perceptual features has centred on the role of synchronized oscillatory firing patterns across neural assemblies (e.g., Singer, 1993, 1994; Singer & Gray, 1995). Binding is achieved when attention towards an object activates constellations of feature detectors throughout the visual system. Individual stimuli will tend to activate unique cell assemblies, with the global activity of assemblies' subcomponents functioning to bind together stimulus attributes. The "glue" that binds together unique object representations is the synchrony of neuronal discharges. In humans, this binding process appears largely nonfunctional at birth. A potential bottleneck in this process, therefore, might be rooted in limitations in synchronization of neural groupings. Notably, young infants' cortical discharges are characterized by a relatively high degree of neural "noise" or incoherence that impedes efficient neural transduction, and may restrict, for example, contrast sensitivity and other low-level visual functions (Skoczenski & Aslin, 1995; Skoczenski & Norcia, 1998). There is every reason to believe that more sophisticated perceptual functions, such as unit formation and surface segregation, are also compromised. Cell circuitries in infants analogous to those in adults, therefore, may be engaged to some extent by a particular display, yet the totality could be insufficient to activate appropriate responses to object properties. This suggestion is consistent with the tenets of the threshold model in stressing the necessity of sufficiency of visual information to achieve veridical percepts.

A second consideration is the likelihood that veridical object percepts are limited by deficiencies in horizontal and vertical connectivities within and between areas of the immature visual system. Burkhalter (1993; Burkhalter, Bernardo, & Charles, 1993), for example, reported that vertical connections within V1 and V2 begin to develop prenatally, perhaps supporting analysis of local features in visual scenes with the onset of visual experience. Horizontal connections within cortical layers, in contrast, show a much more protracted developmental trajectory, and were sparse even in a 4-month-old. Connections between areas V1 and V2 also mature during this period. Along with the construction of new circuitries arising from these connections is extensive pruning of existing synapses, a process that likewise requires months (or longer) to reach maturity (Huttenlocher & de Courten, 1987). This developmental sequence is consistent with the ontogeny of perception of object unity after birth that we have observed, which would seem to require integration of information across the visual field, and therefore coordination across local circuitries in visual cortex.

RELATIONS TO OTHER EXTANT EVIDENCE

Evidence on the development of visual binding sketched out in the previous sections dovetails well with other current evidence and accounts of feature binding and perceptual segregation. First, Sireteanu (2000) described a programmatic series of experiments exploring infants' segregation of stimuli from texture differences (e.g., variations in orientation or density of individual line segments). The earliest evidence for texture-based segregation in these experiments was 2 months, but improvements continued to be observed over the first several years in children tested for detection of texture differences in more complex patterns. Second, Kovács (2000) presented findings from experiments that investigated contour integration in stimuli consisting of Gabor elements that were oriented either randomly or along a path. Gabor elements are small patches of alternating black and white that are presented against a gray background. These elements match receptive field properties of orientation-selective simple cells in V1, and are thus well-suited to probing the interactions of low-level visual mechanisms (in the present case, to perceive a continuous path specified by the alignment of the elements). Kovács did not report evidence from infants, but observed marked improvement in performance in children from 5 to 14 years, suggesting that integration of information across the visual field is characterized by a protracted developmental profile. Both Sireteanu and Kovács discussed their findings in terms of maturation of long-range cortical interactions (e.g., horizontal connections in layers 2 and 3 of V1), an account consistent with the evidence on perception of object unity in infancy outlined previously.

Finally, Hummel and Biederman (1992) devised a connectionist model of object recognition that instantiated many of the principles outlined previously in the progression from figure–ground segregation to binding features into coherent object percepts. This model was equipped with banks of feature detectors composing the input layer, and subsequent layers that combined the resulting computations (such as local connectivities and discontinuities) into object parts (known as geons), and eventually matched the perceived collection of geons to a series of stored templates to arrive at an ultimate description of the object. The model used temporal synchrony as the binding mechanism: Individual cells, tuned to local line orientations, fired together to form "fast enabling links" capable of detecting longer contours. The goal of the model was to explore object recognition, rather than simply object perception, and therefore contained more sophisticated mechanisms (such as stored representations of geons and templates of complete objects) than required by an account of the development of visual binding. Nevertheless, this approach shares much in spirit with developmental considerations. Biederman (1996) has suggested that object recognition proceeds in children in analogous fashion to categorization and word learning: By the acquisition of a "vocabulary" of objects. The first entries into this vocabulary will be relatively simple, or "entry-level" objects (analogous to entry-level, or basic, categorization), followed by more complex objects. Notably, the Hummel and Biederman model of object recognition contains built-in representations of geons and objects. Future connectionist models of the development of object recognition must account for how these representations come to exist in the first place.

CONCLUSIONS

The evidence recounted in this paper supports a view of the development of visual binding that stresses the importance of both *experience-independent* and *experience-dependent* mechanisms. The experience-independent mechanisms are evinced by an assemblage of visual functions at birth, such as attention towards contour and motion (Slater, 1995), and figure–ground segregation (Slater et al., 1990). Experience-dependent developmental mechanisms involve processes such as changes in synaptic strengths and increased synchronization of the firing of neurons in various visual areas in response to environmental stimulation (Bailey & Kandel, 1995; Shatz, 1992). These two kinds of mechanism may combine in their contributions to the shaping of the visual system during infancy, because edges and motion provide critical information for surface segregation, and both kinds of cue are central to young infants' (and adults') unit formation.

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