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Chapter 5

THE DEVELOPMENT OF OBJECT RECOGNITION THROUGH INFANCY

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ABSTRACT

Research over the past half-century has advanced our understanding of the human visual system's robust ability to recognize objects in a scene. Despite this progress, however, the human object recognition system is still not well understood. It is well accepted that one source of the visual system's robust performance is the presence of top-down knowledge in humans. This top-down knowledge comes from prior experience with the environment, and is used to make inferences about the three-dimensional (3D) world from often impoverished two-dimensional information. The focus of this review is to discuss the manner by which the visual system recognizes objects when there is no or little top-down knowledge, as may be the case early in development. Motion cues may play an especially critical role in these conditions where knowledge is limited: It is well documented that infants are attracted to moving objects, and they appear to be able to use motion information to form veridical interpretations of the world. In contrast, infants show more difficulty using static featural information (e.g., color) to accurately interpret a visual scene, but multiple different types of information begin to be used as development progresses. Static featural information is frequently unreliable, often leading to ambiguous object parsing prior to the availability top-down information, while motion information, however, is not as prone to ambiguous interpretation because the motion vector signature of a moving object is highly predictive of its 3D structure. The reliability of motion cues may explain why infants develop sensitivity to moving stimuli early in development. It is clear that motion serves as a primary means by which infants develop their concepts of objects. The earlier maturation of brain pathways associated with the processing of moving stimuli (i.e., the dorsal stream) further supports the possible bootstrapping role of motion in visual development. Other dorsal stream processing such

as that of color and texture, however, may come to play a greater role in object processing as development progresses. Top-down knowledge gradually becomes available with experience derived from various object properties along with the later maturation of more anterior brain structures. As a result of these developmental progressions, infants and young children improve in their ability to recognize objects in the absence of motion (e.g., in static photographs). This chapter will review and discuss the nature of this progression in the development of object recognition.

INTRODUCTION

The perception of objects as meaningful units is a primary goal of visual perception in adults. Object perception includes both object recognition, the process of matching a current object percept to one previously experienced, and object identification or categorization, the ability to associate a label with a previously unseen object. This collection of skills is fed by a powerful and redundant set of underlying processes. The developmental path along which these processes emerge has been the focus of active research over the past few decades and it is the focus of this essay.

The transformation that occurs over the course of visual development is profound: The visual abilities of a newborn are far from the powerful set of visual skills possessed by older infants, children and adults. However, this simple set of initial skills appears well-suited to the needs of the infant. The earliest skills available to the infant are those clearly adaptive for survival or those that regulate early exposure to visual content, thereby supplying the system with meaningful visual experience that will eventually facilitate object perception. For example, the visual system appears to be initially most sensitive to motion. Motion sensitivity in neonates supports collision detection and avoidance. Later on in development, motion-based information gives rise to the perception of object unity, figure/ground segmentation, and shape-from-motion computation. Despite producing a form of vision that is severely limited in many aspects, the premature visual system of infants is characterized by practicality and providence: As Hainline (1998) notes, “visually normal infants have the level of visual functioning that is required for the things that infants need to do.” (p. 9)

The fully developed visual system is itself not completely understood at this time, making investigations into how this system evolves over the course of development an immense challenge. It is clear that adult vision does not simply switch on at one specific point in infancy: Processing skills associated with basic features of shape (e.g., line segments, color, motion) unfold during development in a specific sequence. The ability to use these fundamental elements (e.g., simple line orientation) to construct more complex percepts of shape (e.g., angles or vertices) becomes possible only after the requisite biological mechanisms have sufficiently matured to permit detection of the visually lower level features. However, it is difficult to pinpoint the specific set of events responsible for any given newly-acquired function in an infant. A developmental cognitive neuroscience context in which physiological data are expressly tied to behavioral performance can inform both behavioral and physiological theories of development and enable a more accurate determination of the events responsible for a function. However, identifying these correspondences is an arduous task. The point at which a neurodevelopmental milestone is achieved is seldom an unambiguous clue as to what preceding process or processes gave rise to it. Furthermore, the

earliest age at which we can observe a particular skill in infancy does not identify the actual age of emergence of that ability. In order to provide a definitive account of visual development, it is critical to isolate the limiting constraint that precludes a certain skill from emerging at an earlier point. The set of possible contributing factors includes those events that are temporally linked to the ability in question. This typically includes a myriad of biological refinements occurring at various levels of the visual pathways and the simultaneous appearance of several other newly observable skills. Thus, the findings presented in the current discussion are not meant to provide a conclusive description of development, but are instead offered as important pieces of evidence that guide the ongoing investigation.

As the conclusions arising from behavioral or neuroscientific perspectives are tenuous, a strong cognitive model of object processing is needed to provide the framework for interpreting the findings. A definitive model has yet to be developed, and an active area of vision research is devoted to developing theoretical representations that can accurately depict the processes of the visual system responsible for object perception. Major models of object recognition are described in the following section, and then a brief overview of the trends of visual development is provided. The remainder of the chapter discusses research relating to changes across development in aspects of the visual system that are associated with object processing.

THE PROCESS OF OBJECT PERCEPTION IN ADULTS

We frame our review of development of the set of skills underlying object perception in humans by first briefly describing several perspectives on object recognition. This description is necessarily brief; space limitations preclude a more extensive discussion. For a more complete description followed by an alternative characterization of the visual system, see Churchland, Ramachandran, and Sejnowski (1994). Object recognition begins at the retina, which detects the visual world as points of light. The early stages of vision use these points to construct (or extract) small line segments, which are in turn used to construct/construe progressively larger or more complex elements such as contours, object vertices and edges, and surfaces. It is at this point that most theories suggest that contours and surfaces belonging to individual objects must be grouped together and isolated, or *segmented* from the overall scene being perceived (the object's background), a process known as "figure-ground segmentation." The bundle of elements collectively labeled as the "figure" is then identified.

Importantly, the segmentation process depends on the ability to separate elements differing in depth within the scene. This task presents a challenge because no direct cues to depth are contained within the retinal image. The notion of the impoverished stimulus is a common theme in all of perception; specifically in vision, the two-dimensional image reflected on the retina is an under-specified representation of the three-dimensional world. Nearly all accounts of object perception assert that the visual system must impose organizing assumptions on the impoverished incoming information available from the eye. The Gestalt school (Koffka, 1935) first codified these assumptions as a list of organizational principles, including common fate (correlated motion), good continuation (co-linearity), proximity, and similarity, and these principles are seen by most current researchers as fundamental to the organization of perception. At least one recent account (Peterson, 1994), however, argues that

in addition to a set of organizational rules, prior knowledge (i.e., top-down information) about an object may also inform segmentation, potentially allowing for faster and more robust segmentation. The role of top-down information is somewhat controversial in visual processing in general, but it is a useful concept in several contexts. The theme of the integration of top-down and bottom-up processes is a recurring one in visual perception, and one with extensive implications for development.

The task of re-creating, extracting, or inferring depth information from the perceived (2D) scene is centrally involved in the figure-ground decision. Depth information is highly useful in assisting with segmenting objects from a scene, and thus the ability to perceive depth is an important component of the overall object perception process. A large set of depth cues, from motion-based to static (learned) and binocular cues are available to the adult observer. The development of sensitivity to these cues and the onset of the ability to use them has been an important aspect of research into the development of object perception. Not only the figure-ground process, but also perception of the internal structure of objects, is assisted by the ability to process information for depth, and thus various findings on the ontogenetic emergence of depth perception skills is included in the review below.

The most explicit proposal regarding the early stages of the process of extracting object elements from a scene and then identifying them is the adult object perception theory of Marr (1982), though multiple theoretical accounts of adult object perception exist. These theories diverge from the point of object segmentation on, taking subsequent processing in a particular direction dictated by the hypothesized end-stage representation. Parenthetically, many or all of these theories tend to assume that some unmentioned process has already solved the figure-ground problem, and only address the process of object perception from this point on. These accounts differ in their view of the importance of specific types of information for shape: Structural descriptions, such as those offered by Marr (1980), Biederman (1987); (see also Stankiewicz and Hummel, 2002; Pentland, 1989) and others argue for the existence of an abstracted representation that requires the extraction of low-level or basic features differing substantially from the information immediately available in the proximal stimulus striking the eye. These theories imply a substantial amount of post-retinal processing, and depend to a greater or lesser extent on the ability to extract information regarding relative depth of surfaces, edges of objects, and other low-level features. Other approaches (Edelman & Bulthoff, 1993; Ullman, 1998; Tarr & Pinker, 1991) suggest that the system stores something closer to the retinal image, and tend to require less in the way of depth information as a component of the representation (but note that none suggest that the visual system stores a literal replication of the retinal image). Biederman's (1987) theory, in particular, was created in part to reduce or eliminate the need for sophisticated depth information, and relies on detection of 2D features that are visible in most or all views of an object. Even in this case, however, an implicit assumption exists that the observer possesses the prior knowledge needed to interpret the depth relationships implied by pairs of local vertices and edges. Stankiewicz (2002) offers a cogent discussion of the debate between these two perspectives. In regards to the goals of development, the various theories argue for different representations, but few offer any insight into the ontogenetic path to the adult system. Several of the theoretical perspectives have clear developmental implications, however, including the idea that perception will improve along with the ability to perceive and process both the object features (e.g., edges, vertices, surfaces) and depth information needed to construct an object percept.

These theories do not, in general, assert that only one type of information will serve to construct the representation. It is universally acknowledged that adults can use multiple basic information sources (motion, luminance, contrast) to perceive objects, and this is one basis for a widely-accepted argument that there are multiple paths to object perception. Object contours, for example, can be extracted from motion information alone (see the section on motion, below), from luminance information, or from one of the other types of information used by the Gestalt principles (e.g., co-linearity) in the absence of any other type of organizing data (see the section on contour detection, below). The fact that there are multiple redundant paths to object perception allows for a robust system, but this has implications for development. Because these mechanisms depend on different physiological sub-areas of the visual system, they do not begin functioning at the same time or develop at the same rate. Behavioral data can suggest (or constrain) speculation about the underlying neurophysiology, and conversely, explorations into the underlying physiological development can inform the sequence along which behavioral capabilities will emerge and mature.

EARLY BIOLOGICAL DEVELOPMENT OF THE VISUAL SYSTEM

The visual system undergoes vast structural transformation over the first several months of life. The current findings regarding visual system development and the emergence of object recognition processes have revealed a number of common developmental trends, several of which are clearly rooted in processes of biological maturation. Here, we describe some of the most relevant biologically-based trends related to object processing.

One important point to be taken from our understanding of the structural organization of neural mechanisms is that it does appear that to some degree the visual signal encoded in the cortex is roughly organized according to information type. For instance, form, color, and motion may follow separate, parallel pathways from the retina on their way to the higher visual areas. The specialization of processes based on information type fosters the concept of distinct visual “modules,” or mechanisms responsible for processing specific features of objects. Infant data suggest that the average ages associated with the emergence of perceptual abilities varies according to type of visual information. Specifically, motion processing abilities can be observed at earlier ages than processes related to other visual features. In support of these behavioral findings, it has been established that the specific pathway implicated in motion processing (called the *magnocellular/dorsal* pathway) becomes functional prior to the channel responsible for processing form and color (the *parvocellular/ventral* pathway) (Hickey & Peduzzi, 1987; see also Schneider, 1969). The majority of connections from the parvocellular pathway project along the ventral stream to area V4 and the inferotemporal (IT) cortex, areas critical to color and shape processing. The majority of magnocellular input is routed along the dorsal stream to the V5/MT motion areas and the posterior parietal cortex. The ventral stream, sometimes labeled the “what” stream, is associated with visual cues such as object form and color, and is capable of processing information in high spatial resolution. The dorsal or “where” stream processes information in lower resolution and is linked to motion processing, saccade-launching and representation of spatial location (Ungerleider & Mishkin, 1982). Although this description represents a vastly oversimplified model of visual processing, it highlights the roles of some of the more relevant

brain regions in maintaining the distinction between these two major categories of information pertinent to object perception.

One early influential account of development posits that a gradual transition from subcortical to cortical dominance is a defining characteristic of early development. This view holds that the majority of visual processing is initially carried out by structures within the evolutionarily older subcortical areas, before the more sophisticated higher-level cortical pathways acquire functionality. The distinction between cortical and subcortical dominance has important implications for the cognitive developmental stages culminating in object recognition. Understandably, physiological research on adult vision is primarily concerned with the complex, highly specialized operations of the cortex, the brain's intricately folded surface layer which is responsible for high-level cognitive functions. However, visual perception involves extensive cross-talk between these areas and various subcortical regions. Subcortical areas may be of particular importance early in life, because development of cortical pathways lags behind subcortical development. The degree to which cortical activation impacts early vision is, however, a matter of contention. Although the majority of retinal outputs project to the LGN, several retinal projections follow other paths from the eye, including subcortical areas. Most of these areas also receive additional input from the eye through another waystation, the ventral lateral geniculate nuclei, and these paths are clearly involved in eye movement control and other functions (Fuchs, Kaneko, & Scudder, 1985). Thus, substantial subcortical information is available to the eyes. For example, some retinal outputs project to the pretectum and superior colliculus (SC) within the midbrain, which regulate reflexive eye and head movements (see figure 1). These "pre-loaded" response mechanisms may play a critical role in dictating which visual elements constitute our earliest visual experiences (see the section on visual search, below). However, evidence continues to surface that suggests that the notion of a cortical shift is an inadequate/flawed depiction of development, examples of which are presented throughout this chapter.

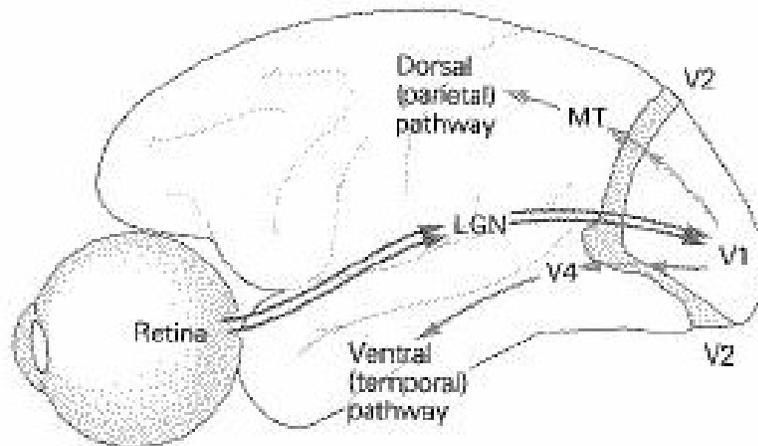


Figure 1. Overview of the cortical and subcortical structures involved in visual processing.

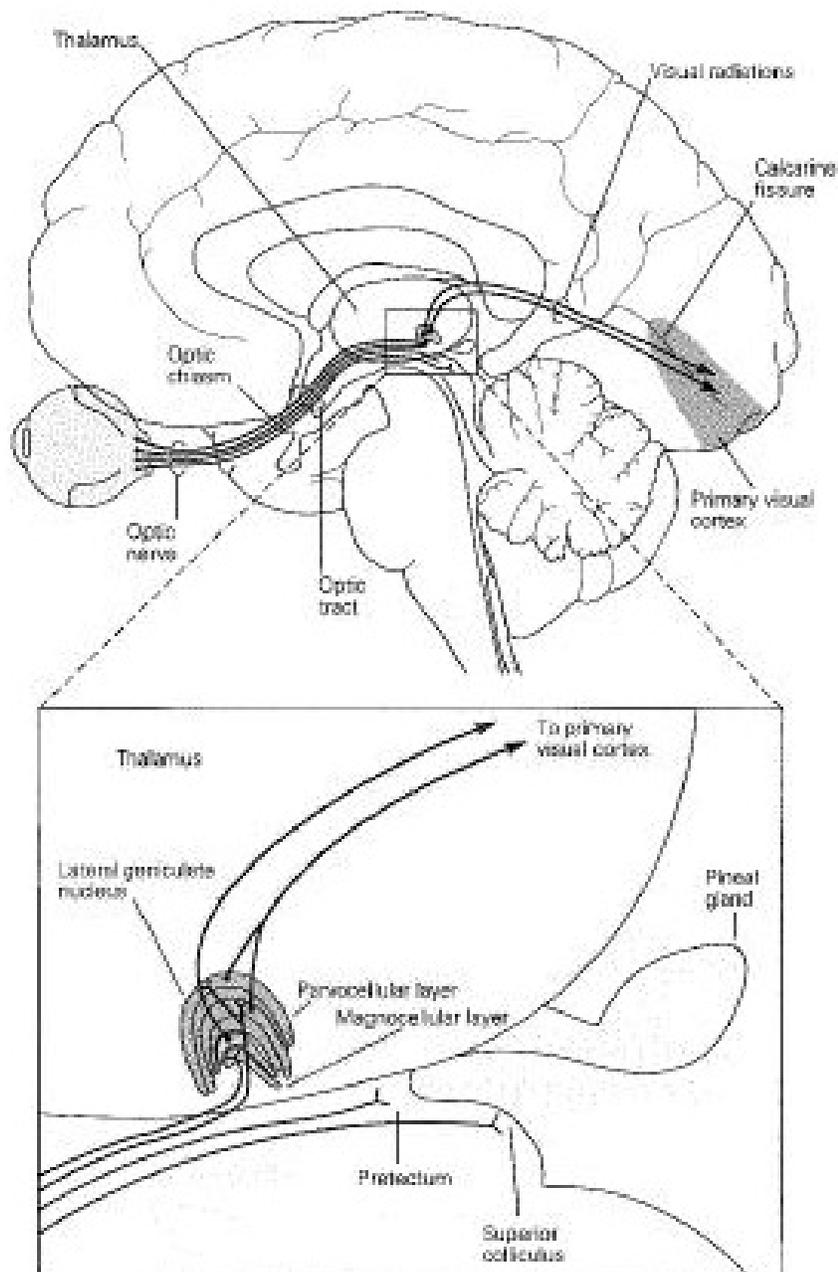


Figure 2. Diagram of the major processing channels in the human visual system, showing the dorsal (“where”) and ventral (“what”) streams (see text for explanation).

A vital feature of the visual system is its hierarchical arrangement, so that cells in the earliest stages of the process respond to a broad range of visual input. Progressively deeper layers contain cells that are increasingly specialized, responding only to a particular combination of features. This allows information to be represented with increasing levels of complexity as it proceeds to the higher visual areas. Cells are generally responsive to stimulation in only one small area of the retina; this area is called the cell’s receptive field.

Many cells in the last layer of the retina instantiate a center-surround organization; that is, they respond in one direction (e.g., positively) to stimulation in a small central area within their receptive field, and in the other direction to stimulation in a slightly larger surrounding area (e.g., negatively). The initial layers of visual cortex, however, appear to house cells that respond to specific properties beyond a simple center-surround organization typical of retinal cells. These properties include orientation sensitivity (for example, a vertically oriented line), motion in a particular direction, form, stereo sensitivity, color, and others. The implications for early development of object processing skills are clear. Considering the fact that early vision is limited to the perception of basic features in isolation rather than unified, complex percepts, such as objects, we can identify the extent to which the visual pathways are functional at a given point in development by tracking the emergence of perceptual abilities that imply the influence of higher visual areas.

Finally, visual experience plays a key role in shaping the visual system. A surge of synaptic growth and axonal myelination can be observed in the visual cortex over the first few months of life (Rakic, Bourgeois, Eckenhoff, Zecevic, & Goldman-Rakic, 1986), suggesting a possible “learning” mechanism that is driven by repeated exposure to specific types of visual input. This may offer insight into how the initial reliance on motion-based cues for several fundamental elements of object perception later gives way to proficiency with static-based cues.

Motion

Motion, above all other elements in a visual scene, is critical to visual development in its earliest stages. It is responsible for directing reflexive eye movements in newborn infants, driving their earliest experiences with visual information. Motion analysis also plays a central role in avoiding collision with quickly-approaching objects and maintaining posture and balance. Over the first few months of life, infants must rely on motion as the primary source of information about object properties. The presence of motion affords young infants the opportunity to develop rudimentary representations of spatial depth, object boundaries, and three-dimensional form before they can master the use of or even detect the presence of other types of cues in the scene. Investigating how the system responds to motion in early development also affords the means for advancing what we know about specific neurodevelopmental events in early infancy by linking them to what we observe behaviorally at various points in development. In the mature system, the MT/V5 area of the cortex is the primary region associated with motion processing. Two major pathways feed into the MT area: a more direct subcortical route implicated in the control of eye movements, and a somewhat protracted route that ascends through intermediate cortical regions, such as V1. The cortical route is distinctly related to the motion-based processing of object primitives. So, although both may respond to motion in the broad sense, it should be emphasized that the subcortical route must not be interpreted as a precursor to the cortical route. The two appear to involve separate mechanisms of motion analysis, serving fairly unrelated functions initially, but they are clearly related in the sense that subcortical orienting allows for the relevant information to be picked up by the cortical motion pathway.

The precocious nature of infants’ motion responsiveness is often offered as evidence that the subcortical system dominates vision before cortical mechanisms become fully functional.

However, it should be noted that this account does not deny that there is some amount of motion sensitivity present in the neonatal cortex, whose influence on early behavior is currently undetermined. Most of the relevant behavioral research on motion processing in neonates is based on observed eye movements. Although newborns are able to track the path of a moving object, relative to adults, their eye movements tend to be inaccurate and slightly delayed (Aslin, 1981). Furthermore, if the stimulus is presented to only one eye at a time, they will only track an object if its motion is nasal-ward. Such signature characteristics of early visual orienting imply a subcortically-regulated orienting mechanism, because they correspond to qualities associated with the SC. The qualities of SC, particularly spatial attention, have been shown to mediate the control of both pursuit and saccadic eye movements in human adults (Adler, Bala, & Krauzlis, 2002) and monkeys (Krauzlis, Liston, & Carello, 2004).

Over the first few months of life, the action of the visual system undergoes considerable transformation, especially in regard to its response to motion. There exist a number of behavioral findings that may signal the gradual emergence of cortically-based mechanisms involved in motion processing. After one month of age, infants begin to demonstrate obligatory attention, or “sticky fixations,” (Hood, 1993; Milewski, 1976), meaning they are slow to saccade away from a stimulus once it has been fixated. Johnson (1990) proposed that this may reflect the introduction of a cortical mechanism responsible for inhibiting activity in the SC. At around two months of age, smooth pursuit is achieved and sensitivity to coherent motion emerges (Johnson 1990). Johnson suggested that these developments may imply the influence of MT. At 3-5 months, the directional asymmetry of monocular tracking is attenuated (Norcia, Tyler, & Hamer, 1990), further indicating that a cortical shift is underway. A final piece of evidence for the early influence of cortical mechanisms comes from Haith and colleagues (Adler & Haith, 2003; Adler, Haith, Arehart, & Lanthier, 2008; Haith, Hazan, & Goodman, 1988; Wentworth & Haith, 1992), who have found that by 3 months, and perhaps at 2 months, infants exhibit anticipatory eye movements to predictable events. That is, infants are presented with a sequence of stimulus events that alternate either predictability or randomly between two spatial locations. Infants quickly learn the spatial sequence and exhibit anticipatory eye movements to the future location of events prior to their onset (e.g., Haith et al., 1988). Additional studies have indicated that infants are capable of learning and exhibiting anticipations to events with more complex spatial sequences than simple alternation (Canfield & Haith, 1991). A recent study has also indicated that 3-month-olds exhibit anticipatory eye movements to events with predictable timing (Adler et al., 2008), the processing of which is also thought to rely on cortical mechanisms, particularly the supplementary motor area, basal ganglia, and premotor cortex (Harrington, Haaland, & Knight, 1998; Ivry, 1997; Rubia et al., 1998). Relevant to object perception, infants have also been shown to demonstrate greater anticipatory eye movements to events with predictable color content (e.g., every event is red and green) or ‘what’ information (Adler & Haith, 2003) – information presumably processed by the ‘ventral’ cortical stream that also processes form information, as described earlier. These anticipatory eye movements have been shown to be controlled by the cortical frontal and supplementary eye fields (FEF and SEF) in adults and monkeys (Schall & Boucher, 2007). The combination of the fact that young infants exhibit anticipatory eye movements in the first place and the type of information to which the anticipations can be generated suggests that cortical mechanisms are influencing behavior at 3 months and perhaps as young as 2 months of age.

The ability to perceive direction is a basic skill needed to make functional use of motion cues, and one with which humans are not innately endowed. Visual-evoked potential (VEP) studies of direction reversal sensitivity have identified the ability to discriminate the direction of motion at 7-8 weeks and habituation studies indicate a similar time frame of 6-8 weeks. The emergence of directional sensitivity at this point in development is believed to be linked to the maturation of cortical pathways projecting to the MT area (Wattam-Bell, 1996). Infants are initially sensitive only to direction of motion within a narrow range of velocities, but this range expands rapidly up until 20 weeks of age (Aslin & Shea, 1990). Impressively, the upper limit of velocity of a rotating object is around 5 degrees/s at 2.5 months but by 3 months this value reaches 20 degrees/s (Wattam-Bell, 1991). According to Banton and Bertenthal (1996) this period of accelerated progress in motion sensitivity may reflect the development of complex motion detectors in the MST area activated by directionally sensitive cells in MT.

The findings discussed above show that motion information is available to infants at an early age, and that this information is of primary importance to overall visual perception at an ontogenetically early point. Direct questions regarding perception of shape from motion in infants have also been investigated by multiple researchers, and these data suggest that motion-based information is in fact an early source of information about objects. One type of motion fundamental to object processing is relative motion, which allows the system to extract local object information based on its movement against a static background. For example, when an object rotates, the retinal image of its surface will transform as one object region disappears from view and a new previously obscured region appears. This information can be employed in the process of figure-ground segmentation. Granrud et al. (1984) found that infants are sensitive to boundaries defined by accretion and deletion of texture early in development. A landmark study by Yonas, Craton, and Thompson (1987) tested 4-month-olds in a "transfer-across-depth-cues" procedure (Yonas & Pick, 1975). Infants were familiarized to a flat wireframe triangle with 3 internal lines extending from each vertex to the center, or with a 3D wireframe pyramid. Each object was presented rotating in depth behind a rear-projection screen, so that only a 2D projection of the rotating object was visible. The two different objects produced highly distinctive dynamic projections on the screen. Following habituation to one of the two projections, infants were presented with both objects, depicted as (stationary) binocular disparity stimuli that unambiguously depicted the 2D triangle and the 3D pyramid. Disparity-sensitive infants were able to distinguish the novel shape from the shape that they had seen during habituation, demonstrating clearly that they had established a 3D representation of the shape, abstracted away from the specific motion-based cues that depicted the shape during encoding. This test is unambiguous, in that the training and test use distinct information sources; there is no disparity information in the training session, and there is no motion information in the test session. The age of onset of binocular disparity, however (approx. 4 months), means that this study cannot be held up as a potential developmental starting point for this ability. Arterberry and Yonas (2000) produced an earlier demarcation point for the developmental onset of this ability, by depicting a shape using only motion information. Their stimulus was a cloud of dots that, when set into motion rotating about the vertical axis, depicted either a whole cube or a cube with a "bite" out of one corner. This type of stimulus eliminates the possibility that other types of (non-motion-based) information for shape are available; when the dots that form the stimulus are static, no shape is visible, even to adult observers. Following a habituation period, infants were tested with both the novel and the familiar stimuli, and showed a novelty preference, indicating

discrimination. Note that there was a negligible delay between the end of habituation and test, so little memory demand was present in this task. Thus, this finding pertains only to a short-term memory for objects, but is one of the earliest demonstrations of a functional channel for shape perception in infancy.

Optic Flow

Another category of motion relevant to object processing is uniform motion, in which global elements in the visual field are seen in synchronous motion. Optic flow, a type of uniform motion, provides us with feedback about the nature of our own movements and trajectory as well as that of surrounding objects. As we move through the environment, object surfaces deform in a manner specific to the path of our own motion, making optic flow a reliable cue for object form. However, before shape perception abilities are attained, optic flow analysis serves another crucial purpose to the infant: avoiding collision with objects by responding to optical expansion cues. Optical expansion may be the earliest used source of motion information. This cue, which many researchers include in the general category of optic flow information, has been shown to be used for collision detection by infants as young as 4-6 weeks (Nanez, 1988; Yonas, Pettersen, & Lockman, 1979), prior to the point at which luminance edges appear to be detectible. A behavioral response to optical expansion has been demonstrated in infants only 3 days old. Jouen, Lepecq, Gapenne, and Bertenthal (2000) investigated 3-day old infants' head movements in response to backward flow of varying velocities. They measured the pressure exerted as infants leaned back when exposed to the stimuli, and found that the amount of pressure applied in head movements correlated directly with the velocity of the stimulus. The early use of optic flow cues appears to be a critical adaptation allowing neonates to respond quickly to moving objects that may pose a threat by making postural adjustments. Another test of optic flow (Bertenthal & Bai, 1989) indicated that 5-month-olds are sensitive to the cue of (global) peripheral optical flow for postural sway, which is typically induced by self-motion, but do not show compensation when peripheral flow is pitted against other (non-visual) information, such as vestibular and mechanical input (Bertenthal & Bai, 1989). Thus the use of this information appears to be present early in development, but is clearly immature (although this immaturity may stem from the ontogenetic state of muscles needed for postural control and not from perceptual immaturity). It is important to note that five months may not be the ontogenetic starting point for sensitivity to this information; the test has not been attempted with younger infants. Other cues from optic flow, including motion perspective, have also been found to drive perception of depth ordering in a scene early in life (for a review of this research, see Arterberry, Craton, & Yonas, 1993).

Perception of Biological Motion in Infants

The vast majority of infants will receive substantial exposure to many examples of biological motion within the first few months of life. This information can be isolated in what is known as point-light display, which shows only a set of dots in motion. The motion signature of, for example, a person walking, in which the dots are attached to the person's joints, is specific, so much so that adult observers can discriminate gender, action, and even certain familiar individuals from brief displays of biological motion alone (Johansson, 1977; Cutting & Proffitt, 1982). Bertenthal, Haith, and Campos (1983) used point light displays to test 3- and 5-month-olds' perception of biological motion; infants at both ages showed a clear

ability to discriminate between an upright and inverted walker display. They also confirmed that the collection of (correctly related) moving dots was the basis of the discrimination by pairing the upright walker with a randomly relocated set of dots from the walker, indicating that the motion relative to the walker was responsible, and not the overall motion difference, in the upright/inverted test. Bertenthal and Davis (1988) demonstrated that 3-month-olds, but not 5- or 7-month-olds will discriminate between a standard point light walker display and one that is out of phase (the relational motion is disrupted in a particular manner), when the standard and phase-shifted displays are inverted. This suggests that top-down knowledge regarding walking is impacting the interpretation at 5, but not at 3 months. This conclusion was supported by a finding from Pinto and Bertenthal (1993) that 5-month-olds appear to become sensitive to a general category of “upright locomotion” following a short period of exposure to multiple types of upright locomotion (walking, marching, walking while waving), and look longer at inverted walkers, while 3-month-olds showed no sensitivity to inverted walker displays in this test. Thus, some level of learning (and categorization) appears to be engendered by this type of information early in development.

SENSITIVITY TO ORIENTATION

As discussed previously, the development of infants’ visual skills is frequently seen as a process of constructing complex percepts from basic, more sensory-level information. The perception of orientation information is another developing ability in the early visual system that may inform investigations into the time course of cortical functionality. The findings of Hood, Atkinson, Braddick, and Wattam-Bell (1992) suggest that visual cortical processes operate to some degree at an earlier point in development than previously thought (at or shortly after birth). Hood et al. (1992) suggest that the first cortical mechanism to become available during development of visual perception is orientation sensitivity (see discussion of visual system, above) in the primary visual cortex. This is an important ‘marker’ in development because orientation-selective neurons are found in cortical regions only, meaning that the demonstration of this behavioral skill is a confirmation of the functioning of a cortical visual pathway, at least to some intermediate level. A suggestion that orientation-selective mechanisms are present at birth, but are immature is based on the finding that infants at 6 weeks postnatal can discriminate between a grating pattern (black and white stripes) shifting orientation at 3 cycles per second (from slanting left to slanting right and back) and a grating pattern that is only shifting phase (the black and white stripes reversing, but not changing orientation). Infants at 6 weeks cannot, however, make this same discrimination if the orientation is cycling 8 times per second (adults have no problem with this task at all), showing that even motion perception is clearly immature at this early stage in development. In keeping with the indications of early motion sensitivity, discussed above, it should be noted that these stimuli are in motion; static orientation differences do not appear to be detectable by infants at this age.

An example of how the perception of form begins to emerge from the perception of basic features (such orientation) is provided in a seminal study by Cohen and Younger (1984), later replicated by Slater, Mattock, Brown, and Bremner, (1991). They found evidence for a shift in form perception occurring sometime after the age of six postnatal weeks. In their study

they habituated infants to either a 45 or 135 degree angle. During testing infants were exposed to stimuli that were different in terms of their line orientation, angle, or both the line orientation and the size of the angle (Figure 3). They found that initially, infants (at about 6 weeks of age) appear to perceive only absolute line orientations, such that rotating an angle (formed from a vertical and horizontal line) by 45 degrees in the picture plane produced a form that the infant did not recognize. A few weeks later (by about 14 weeks), however, infants were able to perceive that the same angle was present following the rotation. They found that prior to 6 weeks infants processed the object as if it were two separate lines. Additionally, after 14 weeks infants were able to detect changes in the size of the angle. This means that sometime after 14 weeks infants are able to recognize that there is a relationship between two differently oriented lines, which forms the angle. This study was one of the first demonstrations of the nascent ability for form abstraction in young infants.

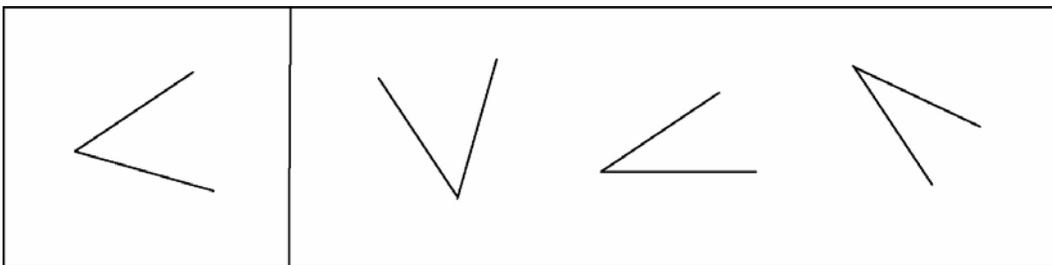


Figure 3. Example of the line segment stimuli used by Cohen and Younger (1984) and later by Slater, Mattock, Brown and Bremner (1991).

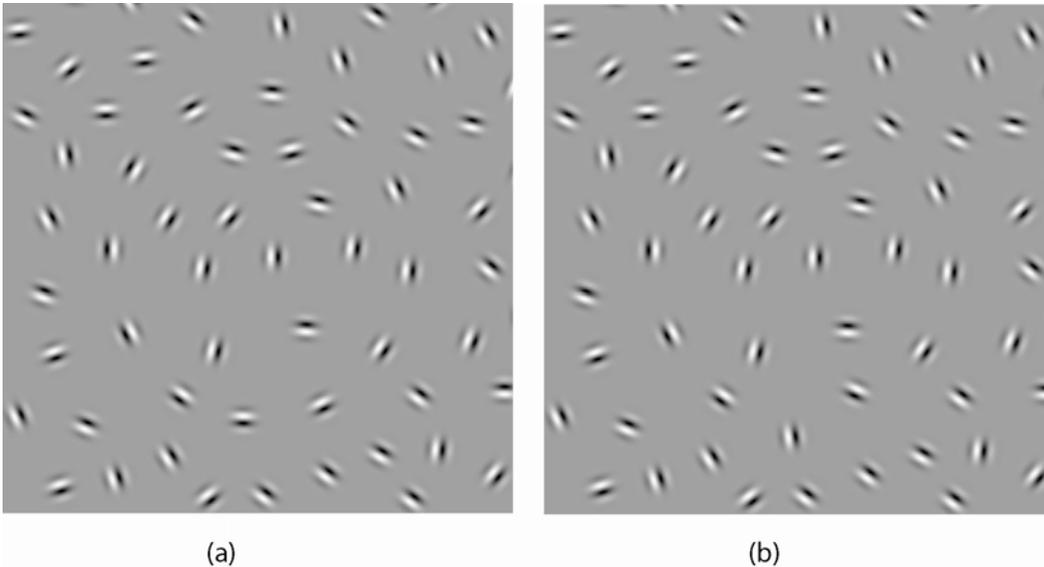


Figure 4. Example of Gabor patch stimuli. (A) open contour embedded in noise, (B) closed contour embedded in noise.

The overall implication of these findings (Hood et al., 1992; Cohen & Younger, 1984; Slater et al., 1991) is that infants younger than about 8-10 weeks respond preferentially to the lower level features of an object (features like basic line orientation). These features are present in and can be detected directly from the retinal image. Object characteristics such as form (the angle in the Cohen and Younger study) are much less salient prior to this age. The development of orientation-sensitive vision is an important precursor to the development of more complex visual skills such as contour detection, which we discuss next. It is important to note, however, that orientation sensitivity and contour detection do not necessarily develop linearly, and in fact may develop in parallel to some extent.

CONTOUR DETECTION

Contour detection, the process of identifying object surfaces, is achieved by applying basic rules of perceptual organization to the individual line segments comprising object edges. For example, the basic Gestalt principles such as co-linearity and proximity (Koffka, 1935) give rise to the more complex construct known as closure, which allows for the representation of a unified border around the object surface. The contour detection mechanism operates by taking advantage of the ubiquity of orientation similarity between adjacent and nearly adjacent points for distinct objects in natural scenes (Geisler, Perry, Super, & Gallogly, 2001). The ability to perceive objects by this account depends upon the capacity to segment a scene into the distinct sets of edges and surfaces, a process usually termed “figure-ground segmentation.” Closure may serve as the basis for figure-ground segmentation (and indeed, may be essential for shape representation, (Kovács, Fehér, & Julesz, 1998). To investigate this conjecture about the role of closure in object recognition, well-controlled stimuli, called Gabor patches (Figure.4) are used. Gabor patches are designed to control for differences at the local feature level (in terms of color, luminance, contrast), but differ at the level of the global contour (Field, Hayes, & Hess, 1993; 2000; Pettet, Mckee, & Grzywacz, 1998; Kovacs & Julesz, 1993). Tests using displays of contours rendered from co-aligned Gabor patches in arrays at varying noise levels reveal that adult observers can detect such contours in large amounts of noise, and sensitivity to the contour roughly doubles when the contour is closed as opposed to open (Kovacs & Julesz, 1993; Pettet et al., 1998). Kovacs (1996) labeled this increase in sensitivity the “closure superiority” effect. Pettet et al. (1998) demonstrated further that there are limits to the extent of line curvature that can be tolerated by this system. In particular, Pettet et al. reported that changes in co-linearity of greater than about 30 degrees resulted in a substantial drop in detection performance, a finding in agreement with other data (Field et al., 1993) also showing that adult detection of contours depicted using Gabor patches is limited. Field et al. used a method in which random variability between neighboring patches was introduced, and found that adult vision tolerated this variance up to a limit, beyond which performance rapidly declined.

The findings of Pettet et al. (1998) and Field et al. (1993), among many others, suggest that a mechanism implementing global contour detection exists in the visual system, and that this mechanism acts to somehow pass excitatory messages between neighboring cells with similar orientation preferences. This mechanism must necessarily span distances far beyond the extent of the local receptive fields in primary visual cortex. A mechanism for this

exchange of excitation was first proposed some time ago, and it is now generally accepted that horizontal or lateral interconnections between neurons of the primary visual cortex are responsible for spanning the distances beyond local receptive fields and linking together local line segments that share the same (or similar) orientations (e.g., vertical to vertical) (Ts'o, Gilbert, & Weisel, 1983; Rockland & Lund, 1982; Le Vay, 1988). Successful contour detection, therefore, may depend on the number and length of these lateral connections. The importance of contour-based parsing is that it may provide the means by which adjacent (and perhaps even distant) points in the visual field are integrated into features (edges, vertices) that are then integrated into a coherent and complete representation of an object (Altmann, Bühlhoff, & Kourtzi, 2003; Kovacs & Julesz, 1994). The physiological underpinnings of this mechanism have been demonstrated by Kapadia, Ito, Gilbert, and Westheimer (1995), who used single-unit (neuron) recordings in awake monkeys to determine cell responses. Their display (see figure 5) included line segments, sized so that each corresponded to exactly one cell's classical receptive field. These segments were presented in one of three contexts: in isolation, within a field of randomly oriented segments, or as part of contour formed from multiple co-aligned segments. A cell stimulated by a line segment did not respond differently when it was presented in isolation or as part of a co-aligned contour, but elicited depressed responding when it was presented along with multiple randomly aligned segments. According to the classical account of local receptive field architecture, which posits that cells respond only on the basis of information within their receptive field, there should be no difference in response across these three stimulus presentation conditions. These findings demonstrate that cells can be influenced by stimulation from outside of their classic receptive fields.

A pattern of early synaptic development described by Burkhalter, Bernardo, and Charles (1993) can account for much of the behavioral evidence for the emergence of contour detection in infancy. Burkhalter et al. (1993) found that orientation-selective connections form in two stages. Shorter connections, which appear to serve a primarily inhibitory function (Polat & Sagi, 1993), begin developing prenatally and appear to begin functioning in the perinatal period. Longer-range connections do not appear until after birth and may not reach adult-level density until sometime after the end of the first year. If long-range horizontal connections implement the contour integration system, then young infants should show little or no ability to detect contours rendered using Gabor patches. Gerhardstein, Kovacs, Ditre, and Feher (2004) tested 3- to 4-month-old infants using Gabor patch stimuli in an operant training task, which provides the infants an extended training exposure of 30-40 minutes to the stimulus. Infants were trained to kick to move a mobile that was attached to one foot. This procedure induces infants to produce elevated kicking when the training mobile, or a mobile that is not perceptibly different from the training mobile, is presented to the infant. When a perceptibly different mobile is presented, however, infants will withhold kicking. Even very small differences will result in kick rate reductions following training in this procedure (Adler, Gerhardstein, & Rovee-Collier, 1998). A set of randomly-oriented Gabor patches were displayed on the sides of the individual placards that made up the training mobile. Following training, a test mobile displaying a contour of co-aligned Gabor patches in visual noise consisting of randomly-oriented Gabor patches was shown to the infant. Kicking behavior indicated that infants could detect the contour, but at a level of sensitivity substantially below that of adults. Further, there was no evidence of a closure superiority effect; infants' detection of open and closed contours was equally bad (recall that closed contours facilitate adult detection substantially). This finding suggests that horizontal

connections in layer 2 and 3 of the visual cortex are functioning, but are by no means equivalent to the mature adult system at this age. Additionally, this finding is consistent with Burkhalter's report that the lateral interconnections that may underlie this perceptual capacity are far from mature at this age.

More recently, Baker, Tse, Gerhardstein, and Adler (2008) followed up the Gerhardstein et al. (2004) finding by using an eye-tracking method with the newly designed Visual Expectation Cueing Paradigm and Gabor-patch stimuli to test 6-month-olds' ability to detect and discriminate shapes (a square and a circle) rendered using Gabor patch contours. They found that although 6-month-olds could detect the square and circle contours, little behavioral improvement in sensitivity to detect the contours relative to 3-month-olds' performance was seen under conditions of even moderate noise. This finding is important because it occurs during a period of infancy during which Burkhalter et al. (1993) reported significant increases in arborization of lateral connections. Thus, if arborization underlies development of the mechanism for contour detection, then the findings of Baker et al. suggest that improvements in behavioral performance lag behind maturation of the underlying physiology.

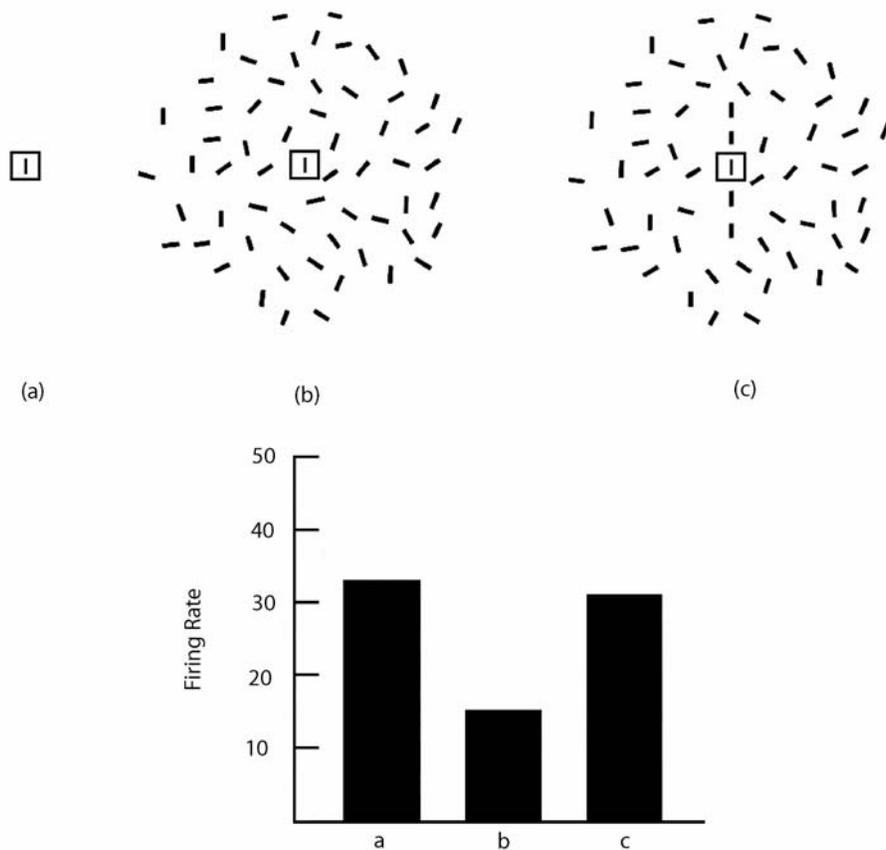


Figure 5. After Kapadia et al. (1995). Stimuli include a single bar (A), an isolated bar in a field of noise (B) and a bar as part of a contour in noise (C). The graph reflects responses of the same cell in the context of each of the three conditions.

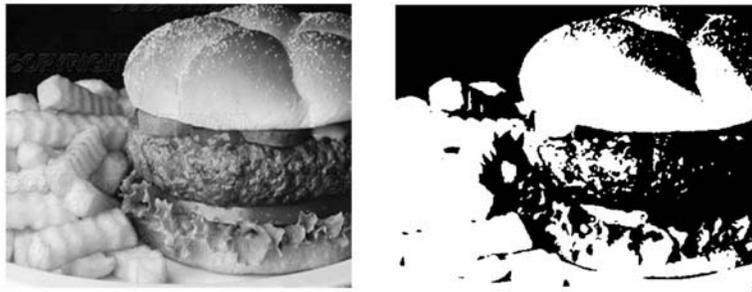


Figure 6. An example Mooney image (A) and the corresponding photograph (B) from which the Mooney image was made.

The ontogenetic emergence and development of the capacity to detect contours defined by co-linearity (aligned contour segments) and from those contours, closed regions, may be a critical precursor to the development of an effective system for performing figure-ground segmentation. While motion alone (without form, or edge information) can give rise to a percept of a closed region, if there is no information about internal edges or other local features, only a very limited figure percept will be available to the infant visual system. Thus, if the developmental account suggested by the anatomical findings of Burkhalter et al. and supported by Gerhardstein et al. and Baker et al. is correct, visual segmentation in infants, young children, and possibly even older children is likely to be qualitatively poorer than that of adults.

A study by Kovacs, Kozma, Feher, and Benedek (1999) supports this idea. These researchers tested children 5-10 years of age for sensitivity to open and closed contours using stimuli similar to those of Gerhardstein et al. (2004). They used a card task [a variant of a test developed by Kovacs and Julesz (1993)] and found that children as old as ten years showed less sensitivity to both types of figures (open and closed) than adults, suggesting that the mature capacity to perceive contours and segment an object from a scene may not be present until sometime into adolescence. A second suggestion of a prolonged developmental path for contour and closure detection comes from a recent study by Yoon, Winawer, Witthoft, and Markman (2007), who used a set of images called Mooney images (see Figure 6) first defined by Mooney (1957). Mooney images are distorted by increasing the contrast of photographs to produce images that contain no hue, texture, or shading information. Yoon et al. found that adults performed substantially better than preschool-aged children with these images overall, and most strikingly, after being shown the undistorted (original) photos, adults could easily point to the major objects in the Mooney image, but the children could not. This is similar to a previous result by Kovács and Eisenberg (2005), and suggests that children, even at this relatively late point in development, do not possess the adult-level capacity to parse images based on partial or poor information. Remember, however, that Baker et al. (2008) did demonstrate that 6-month-olds were able to discriminate between square and circle Gabor patch contours even when embedded in background noise, suggesting that a rudimentary ability for figure-ground segmentation likely exists early in development, so this story is likely to be more complex than described here. Regardless, tests of this nature demonstrate that, while performance under ideal conditions suggests the presence of a relatively mature

visual system by the start of school (five years or so), the system appears to undergo substantial further development after this age.

COLOR PERCEPTION

Development of Color Vision

Color vision is the ability to discriminate stimuli on the basis of their spectral composition (Brown, 1990). Color vision develops much later than most basic visual abilities and can be influenced by gender. That is, color vision in male infants develops later than in female infants. Aslin and Lathrop (2008) suggest that for most infants, color vision has matured by 4 months. The process, by which color vision develops, however, is highly contested. Brown (1990) lists several theories about how infant color vision develops. Among these theories is the idea that infants have fewer than the three color-sensitive photoreceptors (i.e. cones) available to the adult system. The opposing (and generally accepted) view suggests that infants are born with three immature, partially formed color photoreceptors, and that limited color awareness, discrimination and color use as a means of object identification are the result of immaturity in the cones and the color processing pathways.

As color information moves beyond the sensory apparatus, it encounters two distinct color processing channels in the brain that do not develop in parallel. The red/green pathway is available first and supports input from two of the three photoreceptors. The tritan pathway develops later than the red/green pathway and is primarily responsible for integrating information streaming from the three photoreceptor types but is also involved in the perception of yellow-green, and various shades of purple. Teller (1998) found that when 2 month old infants had to detect a color field surrounded by white, infants only successfully fixated red, orange, blue-green, and blue, and failed to discriminate yellow-green and what Teller described as mid-purple, with saturation values in a moderate range. Maximal saturation of a color enables 2 month old infants to discriminate white from the tritan channel colors (yellow-green, and mid purple). The requirement that the colors be highly saturated suggests that the tritan channel is immature at 2 months, as level of saturation is essentially a measure of the intensity of hue.

Color Constancy

One critical feature of the visual system is the ability to accommodate inconsistencies in the environment in order to form a consistent and unified object percept despite the environmental inconsistencies. The relevant skill in color perception is known as color constancy. Color constancy is the ability to make a correct identification or discrimination under conditions where the lighting (or other environmental factors) may influence the appearance of the stimuli as it exists in the environment. Dannemiller and Hanko (1987) tested color constancy using a habituation procedure. They presented infants with a colored display illuminated by one of two light sources. When infants were presented with this same display but the light source changed (in this case the test lighting had a bluish tint) infants

younger than 4 months treated the test display as if it contained a novel color. After 4 months infants did not recover to the condition with the novel lighting, suggesting that the infants understood that the surface color did not change when the source of lighting changed. A later study by Dannemiller (1989) used simulated sunlight as a source of illumination and was able to confirm that infants at 4 months show color constancy.

The Role of Color in Object Recognition

Much of the early work of color vision in infancy focused on the onset of color vision (Bornstein, 1975a; Bornstein, 1975b; Teller, 1998). More recent areas of investigation (Wilcox, 1999; Wilcox & Chapa, 2004) have focused on the functional development of color vision and its relationship to object identification and recognition. Wilcox (1999) suggests that color is a surface feature and can be used by older infants (11.5 months) to determine how many objects are involved in an occlusion event. Using an event monitoring paradigm, Wilcox tested infants' sensitivity to a variety of object features (size, shape, pattern, and color). Sensitivity to these features was tested by presenting infants with a stimulus that moved back and forth behind an occluder. This stimulus either remained the same when emerging from occlusion or it emerged as a different color. Infants' perception of the continuity of the occluded object was determined by their looking time. If the infants perceived the object as one unified object then their looking time would remain low, however if they perceived the event as involving two separate and distinct objects then they would look at the novel object for longer than the familiar object. Wilcox found that infants at 11.5 months were able to individuate the object on the basis of color, but infants at 7.5 months were not. Seven and a half month-old infants were only able to individuate the objects involved in the occlusion event based on the patterns on the object. The general finding of this study suggests that infants use form features (e.g., size and shape) to identify the number of objects involved in an occlusion event earlier in development than surface features (e.g., texture, pattern, and color). Interestingly, a later study by Wilcox and Chapa (2004) found that it is possible to get infants as young as 7.5 months to use color information in an object individuation task during an occlusion event if the infant has been primed to preferentially attend to color rather than pattern or form information. Another interesting finding related to the use of color in object recognition is presented by Adler and Haith (2003). They found evidence of infants as young as 3 months using color information as a basis for forming expectations about future events. In their eye-tracking study infants were presented with a spatially alternating sequence, which had variable color combinations on one side, whereas the other side had an invariant color combination (e.g., invariant side was always red/green or blue/yellow). They found that infants exhibited greater number of anticipatory eye movements to the color invariant side than to the color varied side, indicating that the infants formed a content expectation for the color information that appeared on the invariant side. That infants formed an expectation for the specific color information was substantiated in a subsequent experiment in which infants' anticipatory eye movements were disrupted by the presentation of a novel color combination but only when it was presented on the invariant side but not when it was presented on the varied side. In total this is an important finding because it suggests that around 3 months of age infants begin to use color to facilitate the perception and processing of objects and events.

Color vision is among the latest basic visual skills to develop. Sensitivity to motion, orientation-selective mechanisms, size and shape constancy all develop within a few weeks or months after birth. Color, however, is not functionally developed until around 4 months and is not used until the very end of the first year of life. Taken together the findings presented in this section lead to the idea that color is less reliable than other (form based) information when used in object identification. This is because color information is a surface characteristic of an object, and surface characteristics have less definitional power than form characteristics. Thus the primary role of color in object identification may be to act as a feature which helps to define a particular instance of an object rather than define the type of object itself.

Visual Search and the Detection of Features

As noted above, young infants preferentially respond to the lower level or more basic features that define objects. Theories of perceptual processing have proposed that an initial stage of processing decomposes objects into these basic features and a later stage selectively focuses processing resources to individual items for the purpose of binding the features into a unified object percept and for object recognition (Julesz, 1981; Treisman & Gelade, 1980; Biederman, 1987). The basic perceptual features that have been identified include elongated blobs, orientations, width and length, size, color, motion, and elongated blob terminators—a list that agrees well with the properties that physiological evidence suggests are processed by the early visual cortex (Deco, Pollatos, & Zihl, 2002; Livingstone, Hubel, & Recording, 2003). The primary behavioral assessment of these stages comes from visual search paradigms. These paradigms have been used to demonstrate attentional pop-out (consistent detection time as array set size increases) when an item in a visual array differs from the other items in one of the basic features. They have also been used to demonstrate attention-requiring search (increasing detection time as array set size increases) when the item does not differ in just one feature (Treisman, 1988; Wolfe, Butcher, Lee, & Hyle, 2003).

Developmentally, because the basic object features are thought to be perceptually primitive and processed early in the visual system, they should be processed by infants as well. Consequently, attempts have been made to assess pop-out and visual search of some primitive features that can be detected in infancy. Infant visual search studies, using preferential-looking, novelty-preference, and the mobile conjugate reinforcement paradigms, have suggested that preattentive processing and pop-out of some of the basic object features occurs by 3 months of age. The basic object features for which pop-out and visual search have been demonstrated include orientation (Atkinson & Braddick, 1992), size (Sireteanu & Rieth, 1992), terminators (Adler & Rovee-Collier, 1994; Rovee-Collier, Hankins, & Bhatt, 1992), and motion (Dannemiller & Nagata, 1995). These studies and others suggest the functioning of the early stage of processing of objects' basic features early in development. Unfortunately they suffer glaring methodological weaknesses that limit the validity of their interpretations. In particular, these infant studies do not assess the functioning of the early feature processing stage on the appropriate time scale (minutes rather than the appropriate milliseconds) nor do any of them measure detection time as a function of different array set sizes – a key requirement for determining pop-out and the functioning of the early object feature processing stage.

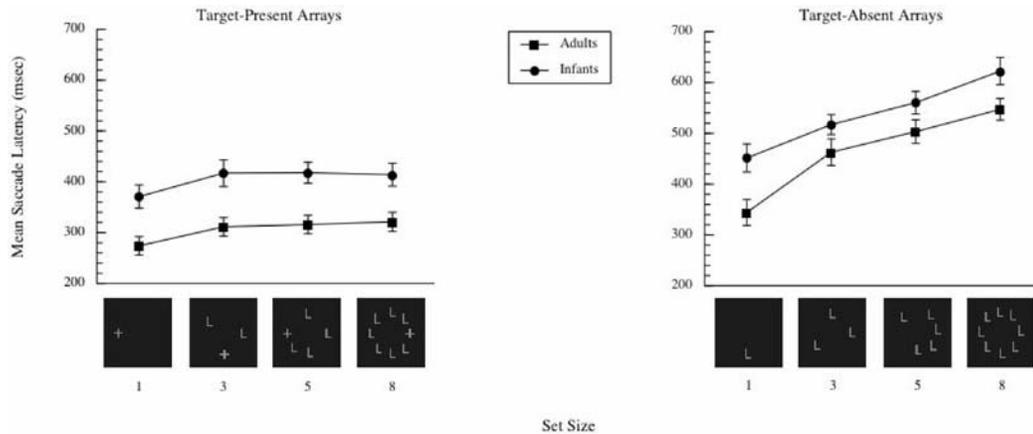


Figure 7. Example stimuli and results from Adler and Orprecia (2006).

To overcome these weaknesses, Adler and Orprecia (2006) designed an eye-tracking paradigm in which the latency of infants' eye movements are measured as they look to visual search arrays that have different set sizes. Specifically, Adler and Orprecia presented 3-month-old infants with visual arrays in which the pop-out target (+) was either present or absent amongst distracter items (L's) and had set sizes of 1, 3, 5, and 8 items (Figure 7). The + was a pop-out target because it contains more terminator features than L and also contains the line crossing feature (identified by Julesz (1984), as a basic feature). Results indicated that infants' saccade latencies remained unchanged in the target-present conditions as set size increased from 1 to 3, 5, and 8 items, whereas their saccade latencies increased linearly in the target-absent conditions as set size increased (Figure 7). This pattern was identical to that found with adults with the exception that adults had faster latencies across all conditions. These findings clearly demonstrate that the object feature processing stage is functioning early in development. Furthermore, the Adler and Orprecia findings indicate that eye movement latencies are a more accurate measure for assessing these processing mechanisms in infants, which can be used to determine the developmental trends in the processing of various object features.

The second processing stage involves binding object features into a unified object percept. This has not been systematically studied in early development, with one exception. Typically, the binding stage is assessed by the search for an item defined by a unique conjunction of features, rather than a single unique feature. This requires the binding of features to form a unique, unified object percept. In the visual search paradigm, the time required to detect a conjunction of features increases as set size increases. In one infant study, Bhatt, Bertin, and Gilbert (1999) used the novelty-preference paradigm to compare the ability of 5.5-month-old infants to detect a target item (red X's) embedded in a surrounding array of different (distractor) items (blue X's and green O's). Overall they found that infants exhibited a novelty preference when the embedded target item was defined by a single unique feature (e.g. red X among blue X's) but not when it was defined by a conjunction of features (e.g., red X among blue X's and green O's) This finding suggests that 5.5-month-old infants do not yet have the capacity to bind object features to form a unified object percept. Gerhardstein and Rovee-Collier (2002), however, have demonstrated the functioning of this capacity in 12- to 36-month-olds. Unfortunately, the Bhatt et al. study, which used a novelty-preference

paradigm, suffers from the same weaknesses as other similar studies (as noted above) and, consequently, a full description of the development in the functioning of the second processing stage, in which features are bound into a unified object percept, awaits future eye tracking studies.

Binocular (Stereo) Vision

The fact that human vision uses two eyes enables the detection of what is called stereo disparity, defined as the difference between the images captured by each eye from the same area in space. The amount of disparity between the two images can be used to infer depth information regarding that an object or area of the scene. The adult visual system uses this information, through a system of disparity-sensitive cortical cells, to encode depth information about the visual world. Note that this is one of two sources of “real” depth information; the other is movement of the visual scene resulting from motion of the observer’s head. That source of information relies on feedback from subcortical systems that control head motion. The stereo system appears to be primarily driven, as noted above, by cortical cells.

The preceding discussion of developmental neuroanatomy makes clear that cortical functioning is poor at birth, so it is unsurprising that neonatal infants show no sensitivity to stereo disparity. Investigation of the ontogenetic onset of this ability is one of the most powerful demonstrations of the capacity of research in the developmental cognitive neuroscience of vision to clearly delineate an emergent ability and to connect this emergence to the maturation of an underlying cortical cell type. The first demonstration of the emergence of the ability to use disparity was provided by Fox, Aslin, Shea, and Dumais (1980), who showed, using a longitudinal design that the onset of binocular sensitivity occurs between 3-4 months of age. Shimojo, Bauer, O’Connell, and Held (1986), using a technique developed by Shimojo, Birch, Gwiazda, and Held (1984), presented infants with a vertically oriented grating to one eye, and a horizontally-oriented grating to the other eye. These stimuli were depicted using a disparity display, such that the two gratings were in different depth planes. Adult perception of this display is that the two gratings appear to be at different depths, with the intersections “twinkling”, or appearing and disappearing as the visual system attempts to resolve the conflicting depth information offered by stereo disparity at these points. This is referred to as binocular rivalry, and is a hallmark of functioning stereo fusion in vision.

Shimojo et al. (1986) found that infants younger than the apparent onset point for functional stereo disparity detection (about 4-5 months, similar to the report of Fox et al.) show a preference for an overlapping display. The display consisted of a horizontal grating presented to one eye, paired with a vertical grating presented to the other eye, with varying levels of disparity. This manipulation induces rivalry in an observer with functional stereopsis. The preference for an overlapping display presumably results from the combined percept of the two gratings, which is of a cross-hatched image. Such a display offers the infant a stimulus containing many “+” intersections which infants find attractive (Adler, 1997), if they do not perceive the disparity difference. This percept arises because development of ocular dominance columns is not well advanced, and cortical areas are likely receiving input from both eyes prior to this point in ontogeny (Held, 1993; Stryker & Harris, 1986). Shimojo et al. found that infants reveal, at about 4 months, a crossover in preference

from the rivalry-inducing gratings to a pair that, using functional stereo vision, would not induce rivalry. Johnson (1997) offers an extensive discussion of the neural changes that may underlie this shift, but it is clear that this shift marks the onset of sensitivity to binocular disparity. This finding is important because, as with previous examples, it reveals an ontogenetic point of onset for cortical neural functioning. It also offers a developmental marker for the onset of a reliable source of depth information that is not dependent upon reliable and sophisticated infant motor control, as is the case with motion parallax and vergence. This finding, however, does not indicate a higher-level cognitive understanding of the meaning of stereo disparity, merely that sensitivity to this cue is present.

Size Invariance

An apple viewed on a coffee table two feet away will project a much larger image on the eye than the same apple viewed at a distance of thirty feet in a supermarket. Adult observers effortlessly account for the retinal size difference in terms of distance, and do not ever suppose that the object has shrunk from one viewing situation to the other. This ability to perceive the distal (real-world) size of an object despite changes in proximal (retinal) size across different presentations is referred to as size constancy. Size constancy is a critical component of object perception. Changes in an object's retinal size usually occur as the result of changes in distance from an observer, and the adult observer's ability to perceive object size accurately has been clearly demonstrated to depend upon depth perception as well as knowledge of the object in question (Holway & Boring, 1941; Gregory, 1966). It is therefore not surprising that when Slater, Mattock, and Brown (1990) used a preferential looking method to test the impact of proximal and distal size changes, they found that neonates, with poor depth perception, showed a strong preference for changes in proximal (retinal) size. This result, which is the opposite of expected adult performance, is not adaptive, as a system that responds to such changes will perceive an object as having changed substantially every time it is presented at a different viewing distance. In a follow up experiment Slater et al. found, surprisingly, that neonates *are* able to detect changes in the distal size of an object. They presented infants with either a large or a small cube. During familiarization the distance from the viewer changed with each presentation of the cube. The distance was changes at each trial in an attempt to desensitize infants to the objects retinal size. Desensitization to retinal size would lead to the infants paying greater attention to the objects real (distal) size. These finding suggest that neonates possess some degree of size constancy, though determining whether a change is due to distal (real world) or proximal (projection, or view-specific) factors may require that infants posses some experience with size and distance changes in objects (Slater et al., 1990). Needham (1998) has also examined this issue, and the conclusion from both of these studies is that some nascent ability for size perception exists early on, but that the system is far from adult-like in infancy.

Object perception requires not only the ability to use depth information to determine distal size of objects currently being viewed, but also requires the capacity to encode and retrieve information regarding object size. Memory representations appear to store form and feature information differently, and this differential encoding influences the conditions under which this information can be retrieved. Gerhardstein, Adler, and Rovee-Collier, (2000) found (using the mobile conjugate reinforcement paradigm) that infants encode size as part of

an explicit memory representation. Infants operantly conditioned to kick to move a mobile displaying symbols of one size showed discrimination performance when tested with a mobile displaying symbols that were 33% larger or smaller than the training symbols. An interesting contrast to the findings presented in their first experiment was found in a follow-up experiment, which used a type of priming task called a memory reactivation. The memory reactivation paradigm requires that the infant learn to kick in order to move a mobile that is located above the infant's head, and then be allowed to forget that learning (at 3 months, forgetting to a demonstrable benchmark occurs in about 7 days or less, depending on the stimulus). Following forgetting, a reactivation (priming) treatment is administered, in which the infant is exposed to (in this case) a mobile displaying either the same size-symbol or a differently-sized symbol. Presentation of the training size is a control; this treatment will "reactivate", or reawaken the forgotten memory for training and elicit performance indicating full retention at test. The size-change reactivation treatment is the critical condition: If the infants' stored representation is insensitive to size, then a change to the size of the reactivation stimulus should not matter. Gerhardstein et al. found that a differently-sized object successfully reactivated the training memory for the original mobile objects. This is important because it presents a disassociation between implicit and explicit memory regarding differences in the encoding of size information. These findings are important because they provide support for the notion that infants, like adults, possess multiple functional memory systems. These systems map onto the adult explicit and implicit memory systems (Graf & Schacter, 1985; Rovee-Collier, Hayne, & Colombo, 2001) and, as with the adult systems, differ in terms of size sensitivity. Several reports (Gerhardstein et al., 2000; Cooper, 1992; Slater et al., 1990; Cooper, Schacter, Ballesteros, & Moore, 1992) suggest that the explicit memory system appears to be size-sensitive whereas the implicit memory system is not. This means that size is encoded as part of an explicit representation, but that the implicit memory representation is size-invariant. Developmentally, infants at the age of 3 months appear to be able to encode object memories both with and without size information, an ability that enables a more general use of object information than either type of representation alone.

Among the later skills to develop in size perception is the use of size information for object individuation, which is the task of determining the number of objects in a display when occlusion is involved. Wilcox (1999) used an occlusion task and found that there was a staggered onset of featural use for object individuation. The use of size information was tested by presenting infants with a display consisting of a stationary object that was partially hidden by an occluder. In some conditions the visible portions of the object were similar and in some conditions they were different in size. The infants were required to determine the number of objects hidden by the occluder (Needham, 1998; Needham & Baillargeon, 1998; Wilcox & Baillargeon, 1998 for detailed description of event monitoring tasks). Wilcox suggested that by 4-5 months, infants are able to use an object's size to perceptually delineate the number of distinct objects are involved in an occlusion event. Thus, size appears to be the first feature to be used, with use of shape information for determining object individuation coming later in the first year.

Finally, size information also plays an important role in the development of reaching behavior in young infants. Because size is encoded as part of an explicit memory representation, it is available to influence how an action towards an object is planned and executed. Newman, Atkinson, and Braddick (2001), for example, investigated infants'

development of reaching, and how this skill relates to objects in the external world, in particular, their size. Infants between 5 and 8 months will not consistently look at and reach for the same object. Often the looking preference is directed towards the larger object, whereas reaching is dictated by the objects grasp affordances. This means that infants will preferentially reach towards an object's that they could conceivably hold onto. After 8 months of age, an infant's looking and reaching behaviors become more consistent, with gaze being consistently directed towards the graspable object.

The accurate perception of an object's distal size is a critical precursor to perceiving more complex types of form information. Furthermore, the development of functional size perception affords infants the opportunity to learn what objects can be easily manipulated, and what objects can only be viewed. It is clear that the development of size-invariant perception is a crucial step in the development of robust and mature visual perception.

Object Unity

The perception of object unity, the ability to organize contours in a visual scene into discrete objects, relies upon the ability to accomplish perceptual or amodal completion. Perceptual completion, the act of grouping together discrete parts of a partially occluded object, has received substantial investigation in the context of development. Kellman and Spelke (1983) found that infants will correctly interpret what has come to be called a "rod and box" display as a complete unitary rod (although they do not 'see' a unitary rod) behind a stationary occluding box only if the rod is moving. Various other manipulations have been attempted, but as noted by Smith, Johnson, and Spelke (2003), motion appears to be a necessary (but not in all cases sufficient) component of the stimulus if infants are to succeed in this task. Johnson in particular has demonstrated (Johnson et al., 2003) that the width of an occluder is correlated with development. Older infants can successfully complete an object passing behind an occluder of a greater width. Below a certain age, infants appear to habituate to the display itself. This implies that they perceive the broken pieces and do not complete the rod behind the occluder. If, however, the width of the occluder is reduced, even infants at 2 months will show a preference for the full rod at test (Johnson & Aslin, 1995). Johnson and Náñez (1995) have demonstrated that 3D structure is not needed for this percept to arise; 4-month-olds demonstrated object unity when the stimulus was a 2D image of a moving rod occluded by a box. Johnson has attempted to both impair and improve the capacity of infants at one age or another to achieve object unity across occlusion, by changing the texture, co-alignment at the occluding contour, and other means (Johnson & Aslin, 1996; Smith et al., 2003). Johnson and Aslin (1995) found that when provided with enriched information, infants as young as 2 months can perceive object unity of an occluded object. In their study they presented infants with the traditional rod and box display, except that much more of the rod was visible due to a smaller occluder or the inclusion of a gap in the occluder. Jusczyk, Johnson, Spelke, and Kennedy (1999) successfully impaired older infants' ability to achieve object unity by eliminating motion from the display.

These tests show that many cues (co-alignment in particular) influence infants' perceptions, but one fundamental conclusion is supported: Infants need common motion of the exposed ends of the occluded object to achieve a percept of object unity in these occlusion-based tests. This agrees with the results of a control condition from Kellman and

Spelke's (1983) ground-breaking experiment, they tested infants with rod pieces that shared shape, color, or orientation but did not move. The infants showed no preference in these cases. Kellman and Spelke saw this preeminence of motion information as indicating that infants first established an object representation based solely on motion, and not on other types of information. Johnson's findings are not completely consistent with this position: he argues that both motion and the Gestalt principle of good continuation (or alignment) are both important to object unity perception in infants (e.g., Smith et al., 2003). Johnson has developed an alternative account that suggests that through development, infants become more flexible in regard to the type and amount of information they can use to complete a partially occluded object.

The extraction of cues to depth (needed to parse the unity displays correctly) thus appears to require motion in infants below 4 months. At least one study, however, suggests that motion is not always needed at this age. Shuwairi, Albert, and Johnson (2007) familiarized 4-month-old infants to a single 2D drawing depicting a cube with the central region occluded. They were tested on two types of displays with the occluder removed: one which revealed an image that adults perceive as 'possible' and one that adults perceive as 'impossible' (depicting an object that normally does not occur in the 3D world—see Figure 8). Infants showed a preference for the less standard drawing, suggesting that they perceived it as novel. This occurred despite a lack of any explicit familiarization to either complete image. This finding suggest that 4-month-olds can, in the words of Shuwairi et al., "...make use of shape and vertex information, as well as interposition (occlusion) cues, to detect global inconsistencies in object structure." (p. 306) Shuwairi et al. (2007) also tested whether infants would still prefer to look at the impossible object if the available depth cues were based on contour geometry alone (no color or shading was present). Even in this situation, where the number of available cues was reduced, 4-month-olds still looked reliably longer at the non-standard object. These findings are seemingly at odds with the perspective of Yonas and his colleagues, who have shown in a large set of studies (Granrud, Yonas, & Pettersen, 1984; Yonas, Elieff, & Arterberry, 2002; Yonas & Arterberry, 1994; Bruggeman, Yonas, & Konczak, 2007) that infants tend under most circumstances to demonstrate (through reaching behaviors) a functional understanding of the meaning of depth cues only later (5-6 months) in development (and definitely after the age of onset of binocular vision). However, the looking behavior implies only that the infants can see a difference. If infants have, at this age, seen many cubes, they will have some level of familiarity to the "standard" cube, and might on that basis be expected to look longer at the non-standard cube. Thus, the findings of Shuwairi et al. imply only that the infants see a difference, not that they understand the difference. Overall the results of this study suggest that from an early age infants are sensitive to low-level feature configurations that form the basis of pictorial (i.e., static, or 2D) depth and form cues, but the reports of a need for motion in object unity perception and the body of work by Yonas and colleagues, among others, suggests that the cognitive interpretation needed to use these cues to correctly parse a 2D image is lacking until later in development.

Viewpoint Invariance

An important aspect of the adult capacity for object perception is the ability to identify an object from many (most) viewpoints. Marr (1982) suggested that this would be a primary goal

of any general-purpose vision system, and asserted that this is one of the hallmarks of the human visual system. Biederman (1987) theory was partly predicated on the premise of producing a viewpoint-invariant representation, but subsequent research (Biederman & Gerhardstein, 1993) made clear that a compromise solution was necessary, and suggested that, for many objects, several linked representations (or *descriptions*) would be needed to fully accommodate all of the different views that a particular object (in its normal environmental orientation) could present to an observer (upside down cars, for example, would not likely be represented and would present “accidental” views that would challenge the observer). Other adult theories (Edelman, 1993; Tarr, 1991; & Ullman, 2003) agree that the ability to recognize an object across changes in view (or in novel views) is central to adult object perception, but do not view the representation in the same manner. Instead, they typically argue that a larger collection of more viewpoint-specific representations are needed to adequately represent most objects, along with some means of matching any particular view to the set of stored views. Debate regarding the nature of the representation continues [and is not likely to be settled soon; see Stankiewicz, (2002), or Tjan and Legge (1998) for cogent discussions of the underlying issues].

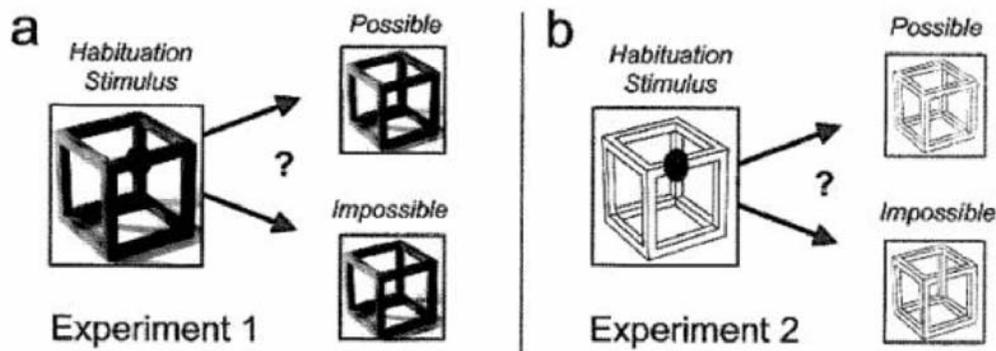


Figure 8. After Shuwairi et al. (2007). Standard (A) and nonstandard (B) versions of the cube stimulus.

The developmental perspective on this issue, however, is more directly focused on behavioral questions regarding performance at different points in development, and the factors that may influence such performance. A primary question regards the point at which infants show even the beginnings of an ability to recognize an object from a novel viewpoint. Kellman, (1984) examined infants' ability to accomplish viewpoint-invariant object perception by exposing 4-month-olds to either a set of static photos of an artificial object at constant steps of rotational change (15 or 60 degrees) about the X- and Z-axis or with a full motion video of the object in rotation about the same two axes (alternating) during familiarization. He then tested infants by pairing the familiar object and a novel object, both rotating about the (novel) Y-axis. Infants showed clear discrimination of the novel object only when familiarized with motion. Kellman and Short (1987) found further support for the argument that motion is necessary for young infants' formation of an abstract shape representation, reporting that 16- and 24-week-olds showed a capacity to generalize to a novel view after habituation to a moving observer (not the object), but only if the motion was

continuous. Kraebel and Gerhardstein (2006) examined this question by presenting (3D) objects in various ranges of motion during training, and then testing with a view clearly outside the training range. Infants in an operant learning procedure using a crib mobile (see Rovee-Collier, 1999; Sullivan, Rovee-Collier, & Tynes, 1979; Adler et al., 1998) demonstrated recognition of the novel view only when the multi-part 3D object was presented in a sufficiently wide range of training views. Infants tested with a novel view differing by 35° from one extreme of a highly restricted ($\pm 5^\circ$) training range performed as if the novel view were a novel object, and discriminated the novel view. Infants trained with an object that moved through a $\pm 22^\circ$ range showed recognition of the novel view differing by 35° viewpoint change at test. Kraebel, West, and Gerhardstein (2007) demonstrated that this was also the case when simpler, single-volume 3D objects were used as stimuli. These tests suggest that not only motion, but a minimum amount of motion, is necessary for the formation of a representation of shape in infants at 3-4 months sufficiently robust that it can be successfully matched to novel views of the object. Other tests (e.g., Ruff, 1982) have suggested that rotational motion is more difficult for infants to process than translational motion when infants are tested using novel views, but the stimuli (real 3D objects) and method (manipulation of the objects was permitted during familiarization) may have influenced this finding. See Kraebel (2007) for a discussion of the haptic-visual issues that may arise from this type of approach to familiarization.

Methodological issues aside, the suggestion from all of these investigations is that while some level of abstract shape representation is available early on, memory limitations and restrictions imposed by the type of information that can be processed [potentially, motion-based information is the only source that can be used early on, but (see Johnson & Shuwairi, 2008)] cause infants to be limited in their ability to generalize across viewpoint early in life. This observation is easily underscored by observing that in the tests above, any adult observer would have no problem generalizing from one view to another without any motion experience at all. The limitation on infants' ability to generalize across views is a serious hindrance, as any tendency to perceive novel views as novel objects will present serious problems in maintaining a consistent percept of objects in the world, unless they are constantly present in unoccluded form. Such restrictions do not well describe the regular visual world, and as discussed above, infant limitations on perception of object unity in the face of occlusion are significant, meaning that the nascent ability to perceive objects across the double challenges of occlusion and viewpoint change (which can result from self-occlusion as well as occlusion by another object, see Weinshall and Malik, 1995), limit the perceptual power of infants at this early point (3-6 months) in development.

SUMMARY

The preceding sections describe a set of processes that, while in some cases only loosely related, all impinge upon this larger process and therefore belong in a review of this topic. The lack of an immediate connection between some of the topics, as well as the inclusion of a developmental cognitive neuroscience perspective can make this endeavor more difficult, as both of these issues increase the complexity of the discussion. Thus, a general overview is usually difficult to achieve in the context of a research topic as large as object perception, but

this discussion has identified a set of overarching themes regarding development and object perception that are clearly supported by the research findings.

First, it should be clear that there is no unitary process called “object perception.” This skill is instead made up of many quasi-independent processes that the mature observer combines to achieve the goals of the perception/recognition system, but in the developmental realm, the point at which a particular skill (disparity detection, orientation sensitivity, object unity) emerges, and the rate at which the power of any of these individual abilities develops, can either limit the performance of the developing individual, if that particular skill presents a “bottleneck” for visual sensitivity or integration of information, or can represent the emergence of a new level of competence, as appears to be the case when binocular vision is joined with prior motion-based depth perception abilities, to produce the ability to perceive and correctly interpret static depth cues, as described by Yonas and colleagues.

Second, the utility of a cognitive neuroscience perspective in development should be clear. The connection between physiological development and behavioral performance is not always direct, as in the case of contour detection. In other examples, such as the emergence of binocular vision, however, a closer correspondence between the maturation of the physiological ability and the emergence of detectible behavioral performance is fairly clear. The continued use of these twin sources of information about development, combined to produce one (necessarily more complex, but also more informative) account of changes across development of a particular ability is impacting strongly both descriptive and also explanatory accounts of developmental changes in vision generally and in the area of object perception in particular.

Finally, the fact that the preceding discussion includes so many disparate topics strongly suggests the need for a theoretical account of object perception that can tie together the early portions of the process, in which fundamental elements (edges, vertices, depth information) are used to perform the figure-ground segmentation task and achieve object unity with the later processes of matching between the identified figure and a representation in memory. Indeed, research in the adult object perception/recognition community is clearly deficient in this regard, and the investigation of developmental skill and changes holds the potential not only to be informed by, but also to inform, general accounts of the process in the mature observer. The interplay between research on adult observers and research in the developmental arena with this topic is not often emphasized and has not historically been influential, but it appears that encouraging this type of approach may be mutually beneficial to attempts to achieve a more complete understanding at both levels.

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