

## ARTICLE

# Infant color perception: Insight into perceptual development

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**Abstract**

A remarkable amount of perceptual development occurs in the first year after birth. In this article, we spotlight the case of color perception. We outline how within just 6 months, infants go from very limited detection of color as newborns to a more sophisticated perception of color that enables them to make sense of objects and the world around them. We summarize the evidence that by 6 months, infants can perceive the dimensions of color and categorize it, and have at least rudimentary mechanisms to keep color perceptually constant despite variation in illumination. In addition, infants' sensitivity to color relates to statistical regularities of color in natural scenes. We illustrate the contribution of these findings to understanding the development of perceptual skills such as discrimination, categorization, and constancy. We also discuss the relevance of the findings for broader questions about perceptual development and identify directions for research.

**KEYWORDS**

color, infants, perception

## INTRODUCTION

Decades of research have charted the visual and perceptual development of infants, revealing remarkable perceptual abilities that provide insight into the nature of perception and human development in general (e.g., Johnson, 2011; Maurer & Werker, 2014). In this article, we discuss color perception, focusing mainly on the first 6 months after birth. Color is a rich tool for understanding how infants move from the basic sensation of a stimulus to a perceptual representation that is useful for understanding and interacting with the world around them. The neurobiology, sensory mechanisms, and perceptual processes involved in mature color vision and perception are well understood since they have been the focus of major interdisciplinary research (e.g., Conway

et al., 2010). Color is a pervasive aspect of visual experience; it is used as a cue for a range of tasks, such as communicating as well as perceiving objects, scenes, and faces, and it has a role in many other aspects of cognition, such as aesthetics (e.g., Elliot et al., 2015). Moreover, color can be precisely quantified and controlled as an experimental stimulus.

In this article, we summarize for those working in child development key findings on infant color perception, providing examples of relevant and contemporary studies. By bringing together for the first time findings on multiple aspects of infant color perception, we illustrate how research on this issue helps build a picture of infants' perceptual skills, and how it also addresses issues of broader relevance to the field of perceptual development. Regarding the generalizability of the research

**Abbreviations:** fMRI, functional magnetic resonance imaging; ISM, interdimensional salience mapping; MLCM, maximum likelihood conjoint measurement; WEIRD, western, educated, industrialized, rich, democratic.

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we discuss here, the studies have been conducted almost exclusively with infants from western, educated, industrialized, rich, democratic (WEIRD) populations (Henrich et al., 2010), such as the United States, the United Kingdom, Europe, and Japan, and the sociodemographic data of samples are rarely reported. We end the article with a discussion on the implications of this limitation.

## INFANTS' COLOR VISION

Contrary to the common view that infants see only in black and white, even neonates can detect some color. However, neonates' color vision is poor: Colored stimuli need to be highly saturated, relatively large, and of a certain hue (e.g., red) to be detected (e.g., Adams et al., 1994). In one study, more than 75% of neonates oriented to large patches of highly saturated red when it was shown on a grey background, while more than 80% failed to orient to a blue patch under the same conditions (Adams et al., 1994). This poor detection of color is likely due to both retinal and cortical immaturity in newborns; the cone photoreceptors that enable the sensation of color are not yet as elongated or densely organized as the cones of a mature retina (e.g., Yuodelis & Hendrickson, 1986).

Color vision in humans is typically underpinned by three types of cone photoreceptors, with spectral sensitivities that peak at long (L-cones, reddish light), medium (M-cones, greenish light), and short wavelengths (S-cones, bluish light). Signals from these cones are combined into two retino-geniculate mechanisms: the so-called *red-green* and *blue-yellow* cone-opponent channels. Converging evidence from studies using psychophysical methods and visual evoked potentials suggests that infants' red-green color mechanism develops first, and the blue-yellow mechanism develops around 4 to 8 weeks later, with infants being *trichromatic* (both cone-opponent mechanisms are active) by 3 months (see Teller, 1998, for a review). Even when infants become trichromatic, their ability to detect desaturated (less intense) colors is still relatively poor: Saturation thresholds do not reach adult levels until late adolescence (Knoblauch et al., 2001). These findings on color support the proposal that visual discrimination takes a long time to mature; visual acuity also does not reach adult levels until 7 years and global motion matures at age 12 (e.g., see Maurer, 2017).

## PERCEPTUAL DIMENSIONS

Once infants are trichromatic around 3 months, they appear to use color information in ways that reflect higher-level perceptual processes. When do infants begin to perceptually represent color in terms of the perceptual dimensions of hue (roughly equivalent to the wavelength of the color, e.g., reddish and purplish), lightness (how

much light is in the color), and saturation (intensity) that describe mature color perception? Whether infants can extract a hue signal independent of the other color dimensions has been hard to demonstrate. In several preferential looking studies, researchers have identified *hue preference curves* in infancy, with infants from 3 months onward looking longest at bluish hues, a long time at reddish and purplish hues, and the least amount of time at yellow-greenish hues (e.g., Bornstein, 1975; Skelton & Franklin, 2020; Zemach et al., 2007). In psychophysical experiments, researchers demonstrated that these hue preference curves are best accounted for in terms of hue preference rather than detection thresholds, saturation, or brightness (Zemach et al., 2007), and modeling of these curves also suggests that luminance differences do not contribute (Brown & Lindsey, 2013). These findings suggest that 3-month-olds have moved beyond a simple sensation of wavelength to extracting the perceptual dimension of hue independent of the other dimensions of color. In adults, perceptual representations of color are thought to arise in the extrastriate visual cortex, downstream of the primary visual cortex, where neural representation is coded in terms of the sensory mechanisms (Brouwer & Heeger, 2009). The representation of hue by infants at around 3 months could indicate a shift in the development and organization of infants' visual cortex.

Many other questions arise about how the perceptual dimensions of color develop and how they come to govern the perceptual similarity of colors. Maximum likelihood conjoint measurement (MLCM) is a psychophysical method that quantifies the contribution of multiple dimensions of a stimulus to a behavior. Using signal detection theory, MLCM models how the probability of a choice between two stimuli is determined by covariation along multiple attributes of the stimuli (e.g., Ho et al., 2008). In a study that used MLCM, 6-month-olds' looking behavior to stimuli varying in chroma (roughly equivalent to saturation) and lightness was predicted most successfully by a sum of the contribution of these dimensions rather than an interaction between the two (Rogers et al., 2018). This is only a start at understanding the perceptual organization of color in infancy, but the MLCM provides a useful psychophysically controlled method for research on perceptual organization in infancy. Another promising method is interdimensional salience mapping (ISM), which uses forced-choice preferential looking to plot psychometric functions for salience of different dimensions, enabling the contribution of different attributes (e.g., size, shape, and hue) to infant cognition to be compared when perceptual salience is equated (e.g., Kaldy et al., 2006).

## COLOR CATEGORIZATION

In addition to being able to represent sensory color signals in terms of perceptual dimensions, by 4 months,

infants also appear to respond categorically to color. Converging evidence from multiple labs suggests that infants' recognition memory groups discriminable colors into five discrete color categories that correspond roughly to the basic color terms red, green, blue, yellow, and purple (e.g., Bornstein et al., 1976; see Maule & Franklin, 2019, for a review). To understand the nature and mechanisms of infants' categorical responding, a large-scale study mapped infant color categories onto color space using the novelty preference method (Skelton et al., 2017). Infants were familiarized to one hue and novelty preference was measured to another hue, sampling hue pairs around the hue circle. The pattern of novelty preferences revealed regions where hues were treated equivalently in infants' recognition memory despite being discriminable, while small hue differences in other regions elicited a novelty response. In other words, infants' pattern of response fulfilled the classic definition of categorization: Discriminably different stimuli were treated as equivalent.

Despite the converging evidence that infants' recognition memory for color is categorical, the claim that infants categorize color has been hotly debated, and poses a problem for the popular belief that color categories are entirely culturally constructed (see Maule & Franklin, 2019; Siuda-Krzywicka et al., 2019). However, the evidence for infant color categories is in keeping with a large body of research establishing that categorization is a key feature of infant perception and cognition, with young infants categorizing a range of stimuli, such as animals, faces, speech sounds, and objects (e.g., Westermann & Mareschal, 2012). Color provides an interesting example of infant categorization since there are no discernable features on which to base categorization (e.g., infant categorization of animals is achieved by computing the perceptual similarity of different visual features; Westermann & Mareschal, 2012). In fact, in the study mentioned earlier that mapped novelty preferences for hue, four of five infants' categorical distinctions were separated by the cardinal axes of cone-opponent color vision, identifying a contribution of sensory mechanisms (Skelton et al., 2017).

Infant color categorization has implications for understanding how categorization in infancy shapes lexical development. By mapping infant color categories (Skelton et al., 2017), infants' categorization shows striking similarity to the world's color lexicons. Although the ways different languages categorize color vary (e.g., some use one term to include blues and greens), commonalities also occur in color lexicons, with the world's color terms tending to be centered around particular points in color space (Regier et al., 2005). Infant color categories also cluster around these points, suggesting that the sensory mechanisms that parse infant categories may partially constrain the development of color lexicons (see Siuda-Krzywicka et al., 2019, for a critique of this theory).

## COLOR CONSTANCY AND OBJECT PERCEPTION

One of the computational challenges of using color in object perception is that the illumination of our environment is highly variable: Light changes throughout the day, from room to room, and from inside to outside. This varying illumination means that the composition of wavelengths reflected from surfaces (the spectra) also changes. For example, the light reflected off a yellow banana under a bluish light has a different spectrum than that of the same banana under a reddish light. The human visual system can compensate for this variation in illumination through a process called *color constancy* (e.g., Brainard et al., 2006). In several studies that used habituation and novelty preference methods, from 3 months, infants did not appear to perceive the color of a stimulus as novel when the illumination changed (e.g., Dannemiller, 1989; Yang et al., 2013). This suggests that young infants have at least rudimentary mechanisms of color constancy. However, the extent to which infants' color constancy relies on the same mechanisms as mature color constancy is unclear. Other developmental work suggests that color constancy is still maturing at 2 to 4 years (e.g., Rogers et al., 2020). Other forms of perceptual constancy such as size, shape, and lightness constancy are also present by at least 6 months (e.g., Granrud, 2006), and work that compares developmental trajectories across domains could provide insight into the role of domain-general perceptual and cognitive mechanisms, such as adaptation and object knowledge.

Another process related to the perception of object color is the association of objects with their typical color. In one study, 6-month-olds looked longer at objects when they were typically rather than atypically colored (e.g., they looked longer at a yellow banana than a blue one; Kimura et al., 2010). However, in an unpublished study, researchers failed to find that infants look longer at typically colored faces than at digitally manipulated and equally saturated green, purple, and blue faces; infants' color preferences were the same whether the stimulus was a face or a scrambled face (Clifford et al., 2014).

Further work is needed to clarify when infants start to associate color with objects. Studies with older infants suggest that color is initially a less attended cue than cues such as shape and size when reasoning about, individuating, or identifying objects (e.g., Wilcox, 1999), although we need more studies using ISM that equate the perceptual salience of stimuli when comparing across different kinds of attributes (e.g., Kaldy et al., 2006). More research in this area will help us understand what information infants draw on when learning to perceive, think, and talk about objects in the world around them.

## CHROMATIC SCENE STATISTICS

The presence of at least a rudimentary form of color constancy indicates that 3-month-olds' perceptual systems are at least on some level registering the illumination of their environments. Several studies suggest that adult color perception is specialized and calibrated to natural illumination and the statistical regularities of color in natural scenes (chromatic scene statistics, e.g., Bosten et al., 2015). For example, adults' sensitivity to color aligns with a line in a cone-opponent color space that connects colors that appear blue and yellow, where measurements of natural daylight fall (Mollon, 2006), and along which the distribution of chromaticities in natural scenes is elongated (e.g., see Bosten et al., 2015). Adults have the least amount of sensitivity on a discrimination task (highest saturation thresholds) for blue and yellow hues that have a wider range of saturations in natural scenes than for other hues (e.g., Bosten et al., 2015), and this reduced sensitivity cannot be explained by cone-opponent mechanisms. In a psychophysical investigation of infants' saturation thresholds for different hues, infants' saturation sensitivity was similarly aligned with this blue–yellow color appearance axis at just 4 months (Bosten et al., 2016); this is the earliest demonstration that the infant visual system is aligned with natural scene statistics. One study presents tentative evidence that 9-month-olds are sensitive to the texture statistics of natural scenes (e.g., Balas & Woods, 2014), while another suggests that children's vision is not optimally sensitive to spatial scene statistics until age 10 (Elleberg et al., 2012). The efficient coding framework proposes that our visual systems are optimized to encode the statistical regularities of natural scenes (e.g., Simoncelli & Olshausen, 2001). The finding that infant color vision is aligned with chromatic natural scene statistics at just 4 months (Bosten et al., 2016) points to optimization on an evolutionary time scale, or suggests that infant color vision tunes to the statistics of the environment in the first few months after birth.

## THE ROLE OF EXPERIENCE

The possibility that infant color vision tunes into the chromatic and illumination scene statistics of the environment in the first few months after birth relates to a broader debate about the role of experience in perceptual development (e.g., Maurer, 2017). Research with premature infants (who have more visual experience than infants matched for gestational age) suggests that experience enhances chromatic sensitivity and does so more than for luminance (e.g., Bosworth & Dobkins, 2009). Whether there are sensitive periods in infancy when experience shapes the development of color perception for later in life is unclear. In support of this notion, infant macaques who experienced only monochromatic

input for nearly a year after birth failed to develop color constancy or typical color judgments (Sugita, 2004). Contrary to this notion, adults who had congenital cataracts removed in early development appeared to show typical color judgments and discrimination later in life (e.g., Pitchaimuthu et al., 2019). One explanation is that the nature and extent of the deprivation matter. Alternatively, sensitive periods may exist only for specific aspects of color perception and certain types of discrimination. A more detailed examination of the effect of congenital cataracts in infancy on the development of different aspects of color perception (e.g., perceptual organization, constancy, use of color in object, and scene perception) is warranted.

A study of Norwegian adults born above and below the Arctic Circle provides further evidence for sensitive periods in infant color perception (Laeng et al., 2007). Participants' latitude of birth and hence their amount of exposure to natural daylight in early infancy predicted subtle differences in adults' color discrimination. Adults born above the Arctic Circle who would have had early experience of the purplish twilight of *mørketid* (when the sun does not rise above the horizon for several months) could discriminate purple hues more effectively and greener hues less effectively than adults born below the Arctic Circle. In addition, those born above the Arctic Circle in the autumn had overall poorer sensitivity to color than those born above the Arctic Circle in the summer. The type of chromatic input early in infancy appears to have determined color discrimination abilities later in life. This finding could also support the hypothesis that the alignment of infant color vision with the blue–yellow axis by 4 months is due to early tuning. Research that compares the color perception of infants and children raised in visual environments that differ in their chromatic scene statistics and illumination can help clarify the time scales of these effects and the perceptual processes at play. Such studies would contribute to our understanding of how experience and sensitive periods in infancy shape perceptual development (e.g., Knudsen, 2004); they could be considered alongside phenomena such as perceptual narrowing, where perception of social stimuli (e.g., faces, speech, and music) is shaped by the types of stimuli experienced in the first year after birth (e.g., Maurer & Werker, 2014).

## DIRECTIONS FOR RESEARCH

Many questions about infant color perception remain. We understand little about the cortical representation of color in infancy. A few studies using event-related potentials or functional near-infrared spectroscopy have attempted to probe this topic (e.g., Yang et al., 2016), but inferences about cortical representation have been limited by the constraints of the methods. Recent breakthroughs in infant functional magnetic resonance



imaging (fMRI), which have revealed category-specific regions of ventral visual pathway in infants younger than 1 year old (Kosakowski et al., 2021), present exciting possibilities for identifying how the representation of color in the cortex changes in infancy. In adults, fMRI studies have characterized color-selective regions of the ventral visual cortex, as well as regions involved in other aspects of color perception (e.g., Conway et al., 2010). Conducting equivalent fMRI studies with infants could have broader implications for understanding when and how different regions of the brain become specialized for different functions and how this is guided by experience (e.g., Kosakowski et al., 2021).

Another direction for research is using color as a tool to probe the role of top-down and predictive processing in infants' perception. In adults, expectations about the color of objects are thought to affect the appearance of color (e.g., Hansen et al., 2006), and once infants are aware of the color of objects, researchers have an opportunity to explore whether such top-down effects of object knowledge also occur in infant perception. Bayesian models of adult color perception, which combine a representation of prior sensory experience with current sensory input, have also been proposed (e.g., Brainard et al., 2006), and studies that attempt to apply Bayesian models to infants' color perception could contribute to our understanding of the role of Bayesian and predictive processing in infant perception (e.g., Emberson et al., 2017).

As noted earlier, most research on infants' color perception has been conducted with infants from WEIRD populations (Henrich et al., 2010). We anticipate that many of the findings we have discussed would be broadly generalizable to other samples. However, the finding that Norwegian adults' color discrimination is affected by season and latitude of birth (Laeng et al., 2007) reminds us that even low-level aspects of color vision can vary with environmental factors and experience. Researchers should aim to diversify the populations studied, both to improve the generalizability of the science and to further understand the role of experience in perceptual development.

## CONCLUSIONS

Collectively, the findings on infant color perception point to remarkably rapid visual and perceptual development in the first 6 months after birth. Infants are barely able to detect color as newborns, yet by 6 months, they show evidence of starting to perceptually organize, categorize, and keep color perceptually constant, and their sensitivity to color aligns with statistical regularities of natural scenes. Throughout this article, we have pointed to similar perceptual competencies for other types of perceptual stimuli, and the case of color contributes to understanding the more general development of perceptual skills. Further research on infant color perception

could also provide insight into broader questions about perceptual development, such as the role of sensitive periods, when brain regions become specialized regions for visual features and processes, and the role of top-down and predictive processing in infants' perception.

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