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The Development of Color Perception and Cognition

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color, perception, cognition, development, infancy, childhood

Abstract

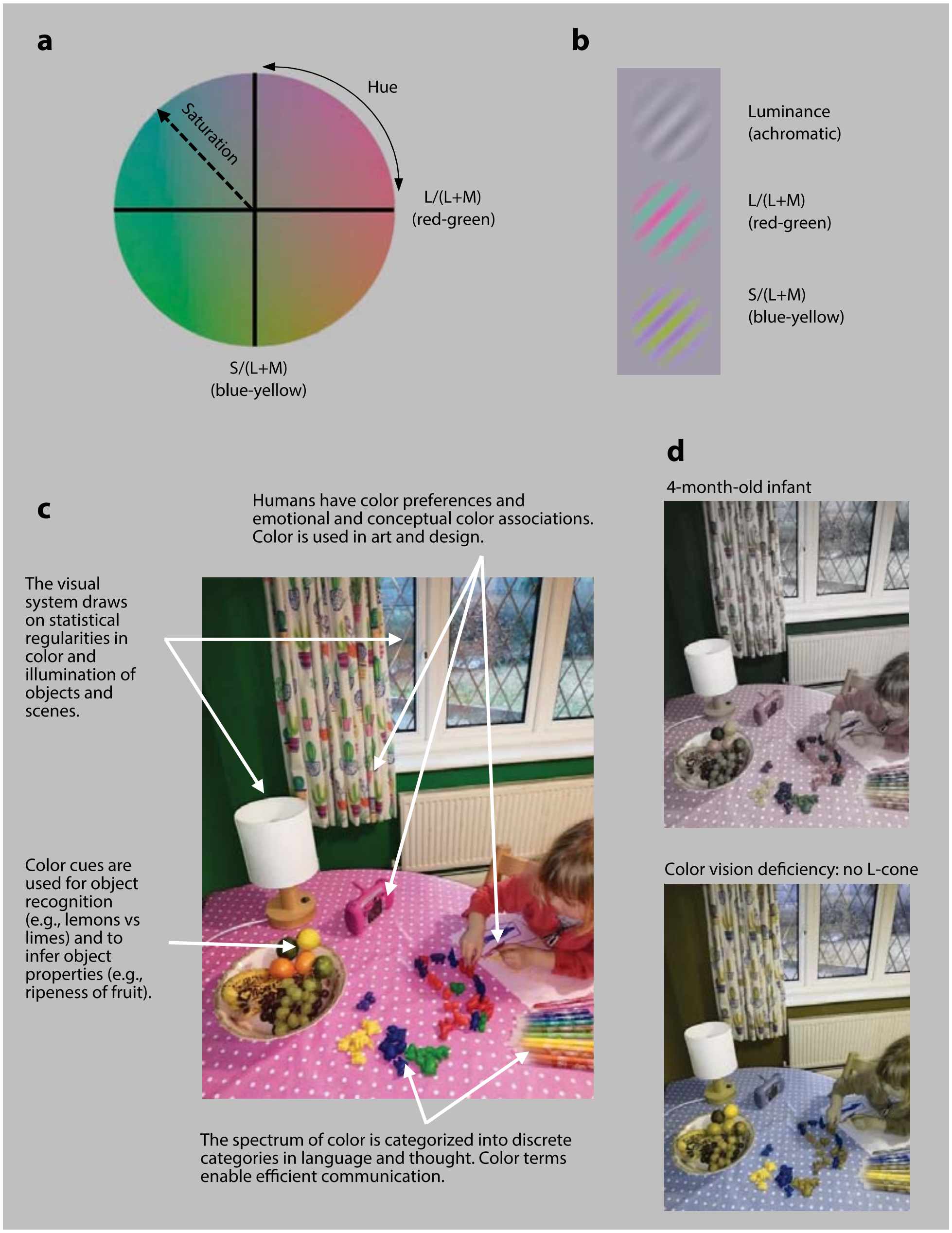
Color is a pervasive feature of our psychological experience, having a role in many aspects of human mind and behavior such as basic vision, scene perception, object recognition, aesthetics, and communication. Understanding how humans encode, perceive, talk about, and use color has been a major interdisciplinary effort. Here, we present the current state of knowledge on how color perception and cognition develop. We cover the development of various aspects of the psychological experience of color, ranging from low-level color vision to perceptual mechanisms such as color constancy to phenomena such as color naming and color preference. We also identify neurodiversity in the development of color perception and cognition and implications for clinical and educational contexts. We discuss the theoretical implications of the research for understanding mature color perception and cognition, for identifying the principles of perceptual and cognitive development, and for fostering a broader debate in the psychological sciences.

Contents

1. INTRODUCTION

1.1. Color Perception and Its Relevance to Psychology

Color is a ubiquitous feature of our psychological experience. The human visual system constructs a perceptual experience of color from wavelengths of light reflected or emitted from the objects and surfaces around us (see **Figure 1**). Color provides a key signal for basic vision. For example, it is a useful cue for object perception and cognition: It enables us to distinguish between objects of similar shape and aids the visual segmentation of objects from their backgrounds and the recognition of visual scenes (e.g., Gegenfurtner & Rieger 2000). Color holds useful information about the properties of objects and scenes (e.g., Osorio & Vorobyev 1996). For example, we use color to know when fruit is ripe to eat and when meat is cooked. The color of the sky tells us about the time of day and the weather, and the color of the trees tells us about the season that we are in. Color provides a signal about people's internal states—the blush of someone's cheeks tells us if they are embarrassed or aroused, whereas the pallor of someone's skin can indicate poor health (e.g., Stephen et al. 2009). Color terms enable us to be descriptive and communicate efficiently (e.g., Conway et al. 2020). Color is also strongly associative, with different colors having reliable associations with emotions (e.g., joyful yellow; Jonauskaite et al. 2019), and abstract concepts (e.g., Tham et al. 2020). This enables color to be used in symbols and signage (e.g., red for stop, green for go) as well as in marketing and design to communicate abstract concepts such as romance and environmentalism (e.g., Schloss et al. 2018b). Color also contributes to aesthetics and our appreciation of art (e.g., Nascimento et al. 2021), and humans have reliable preferences for some colors (e.g., blue) over others (e.g., chartreuse; e.g., Palmer & Schloss 2010). Finally, color informs the other senses, with the color of food contributing to how it tastes (e.g., Spence 2015) and the color of a room's illumination contributing to its perceived temperature (e.g., Huebner et al. 2016). Given the importance of color for so many aspects of human mind and behavior, understanding how humans encode, perceive, talk about, respond to, and use color has been a major interdisciplinary research effort.



(*Caption appears on following page*)

Figure 1 (*Figure appears on preceding page*)

The sensory, perceptual and cognitive components of color. (*a*) A version of the MacLeod-Boynton chromaticity diagram with the cone-opponent red-green and blue-yellow axes of color vision that correspond to the retinogeniculate neural pathways. Saturation increases with increasing distance from the central gray, and hue varies by moving around the circumference of the circle. (*b*) Grating stimuli that, if calibrated, would isolate the luminance, red-green, and blue-yellow neural pathways. (*c*) Photo illustrating the many ways in which color contributes to human perception and cognition. (*d*) Approximate simulation of how the colors in the photo in panel *c* are expected to appear to a 4-month-old given reduced saturation sensitivity (based on saturation thresholds taken from Knoblauch et al. 2001) (*top* of the panel) and to an observer with color vision deficiency who lacks L-cones (using Vischeck, developed by B. Dougherty and A. Wade at Stanford University; **http://www.vischeck.com**) (*bottom* of the panel).

1.2. Why Investigate the Development of Color Perception and Cognition?

There are several reasons to investigate how color perception and cognition develop. First, a developmental approach can contribute to broader debates about the relative contribution of experience, learning, culture, and environment to perception and cognition in their mature form. For example, research on infant color categorization has contributed to debate about the extent to which color categories are arbitrarily constructed by language (e.g., Bornstein et al. 1976). Second, a developmental approach can provide insight into the processes that underpin perceptual and cognitive development such as discrimination, constancy, and statistical processing (e.g., Skelton et al. 2022b). Color can be used as a testing ground for understanding these processes, and comparisons with other domains can establish how domain general these processes are. Third, understanding how infants and children see color has the potential to provide insight into broader aspects of their minds and behaviors—for example, object reasoning (e.g., Káldy & Blaser 2009) and language acquisition (e.g., Wagner et al. 2013). Finally, the development of color perception has relevance to clinical, educational, and industrial contexts. For example, color perception is atypical in children with neurodevelopmental disorders (e.g., Franklin et al. 2010), congenital color vision deficiency (CVD, or color blindness) in children can present barriers in education (e.g., Torrents et al. 2011), and children's color perception has implications for design (e.g., Luo 2006).

2. COLOR VISION AND DISCRIMINATION

Color vision is the basic sensory process that underpins color perception and cognition. It is defined as the ability to discriminate the wavelengths of light reflected from surfaces on the basis of hue rather than brightness or intensity. The typical human observer is trichromatic: Their retina contains three types of cone photoreceptors, with spectral sensitivities peaking in the long (reddish), medium (greenish), and short (bluish) wavelengths. The signals from these cones are combined to yield two cone-opponent channels, one encoding colors from cherry to teal (often referred to as the red-green channel) and the other encoding colors ranging from violet to chartreuse (often referred to as the blue-yellow channel) (see **Figure 1**). These cone-opponent channels provide two independent neural pathways transmitting the chromatic information from the retina to the thalamus and visual cortex, where there are color-selective regions responsible for processing this chromatic information, and projecting to the ventral visual pathway (e.g., Conway et al. 2010). As the basic neurobiology of mature color vision is relatively well understood, investigating the development of color vision could provide insight into the development of the neural structures and pathways that underpin vision. As a result, there has been a concerted effort to understand the development of trichromatic color vision in infants (e.g., Teller 1998), and to identify changes in color discrimination across the life span (e.g., Knoblauch et al. 2001). Here, we summarize the main findings. We also examine the role of experience and consider the hypothesis that early experience in infancy shapes how color vision develops, determining color vision in its mature form (e.g., Laeng et al. 2007).

2.1. Development of Trichromatic Color Vision in Infancy

Several decades of neurobiological, electrophysiological, and psychophysical research provide evidence that trichromatic color vision is present by around 2–3 months of age, with certain color discriminations such as those that rely on red-green cone opponency appearing earlier (e.g., Teller 1998). Psychophysical studies, in particular the pioneering work of Davida Teller, have been pivotal in determining that infants have true color vision using chromatic neural pathways. These painstaking studies carefully manipulated the chromatic parameters of stimuli (e.g., Teller et al. 1978), established infant iso-luminance (equating the perceived intensities of stimuli to isolate chromatic differences; Pereverzeva et al. 2002), and measured how sensitive infants are to chromatic gratings (see **Figure 1**) with various spatial properties (the contrast sensitivity function) (e.g., Peterzell et al. 1995; see Teller 1998 for a review). Visual evoked potentials (VEPs), which measure electrophysiological changes over the occipital cortex in response to visual stimuli, have also identified the development of the chromatic and luminance neural pathways in infancy. For example, Crognale (2002) charts developmental changes in the VEPs to achromatic, red-green, and blue-yellow gratings, presenting data for individuals ranging from 1 week to 90 years of age. VEPs appear for red-green gratings around 4 weeks and for blue-yellow around 6–8 weeks. However, infants' VEP waveform is different from that of adults: There are rapid and complex changes in the waveform shape and latency of components over the first year of life, and by 12 months infants' chromatic VEPs have a positive negative complex rather than the negative positive complex of the adult waveform. The shape of the chromatic VEP waveform continues to change throughout childhood and is not adult-like until 12–14 years of age. Crognale (2002) considers that there is likely a cortical reason for these changes, as suggested by source localization of child evoked potentials in another study (Ossenblok et al. 1992). VEPs to achromatic gratings appear in their mature form at 12–15 weeks of age, pointing to more rapid maturation of luminance than chromatic neural pathways.

2.2. Color Discrimination Throughout the Life Span

Although trichromatic color vision is established by 2–3 months of age, sensitivity to color continues to improve throughout childhood and into adolescence. This protracted maturation of color vision is well established: It is seen in the VEP study outlined above (Crognale 2002) and confirmed in behavioral studies that have measured color discrimination across the life span (e.g., Knoblauch et al. 2001). However, the role of nonvisual factors for changes in performance should also be considered (Cranwell et al. 2015). One classic study (Knoblauch et al. 2001) employed preferential looking to estimate saturation thresholds (i.e., the lowest intensity of a color that can be detected against a gray) across the life span, testing infants as young as 3 months old and adults as old as 96 years of age. The stimulus was a set of colored bars set among luminance noise (patches of gray at multiple levels of luminance) paired with luminance noise only. Preferential looking (for infants) or pointing (for children and adults) to the colored stimulus was measured, and the saturation of the colored bars was adjusted to estimate chromatic thresholds for protan (L-cone), deutan (M-cone), and tritan (S-cone) discrimination. The wonderfully rich data point to continued improvement in color discrimination from infancy up until late adolescence, with saturation thresholds approximately halving (i.e., sensitivity improving) with every doubling of age until adolescence and thresholds increasing (i.e., sensitivity worsening) thereafter. There is also a hint that blue-yellow (S-cone) color discrimination may initially develop at a slower rate than red-green (L- or M-cone discrimination), which is supported by a study that finds that it is not until 10 years of age that red-green and blue-yellow color discrimination develop at a similar rate (e.g., Ling & Dain 2018). Other studies suggest a later age of maturation than proposed by Knoblauch and colleagues, with the age varying from 18 to 30 years across studies (e.g., Paramei & Oakley 2014). The decline in color discrimination post-maturation has also been investigated: During this ageing phase, thresholds increase at a rate of around 1% per year for red-green and 1.6% for blue-yellow discrimination over the rest of the life span (Barbur & Rodriguez-Carmona 2015).

These studies that have charted the development and ageing of color discrimination are valuable as they have established norms for color discrimination that can guide the diagnosis of color vision defects at various ages (see Section 5.1.1). The research also further contributes to our understanding of neural and visual development (and ageing) more broadly. It is currently unclear whether the relatively poor color discrimination of young children hampers their ability to use color as a cue for identifying objects and their properties, and what kind of real-world color cues (such as the blushing of skin) might be missed.

2.3. Plasticity, Sensitive Periods, and Early Experience

One important question about the development of color perception is the extent to which it is shaped by experience. It is well established that there are time windows during development when plasticity is greatest and when experience is essential for normal visual development (a critical period; e.g., Hensch 2005) or influences visual development but is not essential for it (a sensitive period; e.g., Knudsen 2004). However, whether similar experience-dependent processes govern the development of color perception is less clear. In support of the argument that experience does matter, one study (Sugita 2004) finds that rearing infant monkeys in a room illuminated only by monochromatic lights (i.e., lights composed of one wavelength) for 1 year led to long-term disruption to judgments of color similarity and color constancy (i.e., the ability to keep color perceptually constant under illumination changes; see Section 3.1). However, studies of human adults who had congenital cataracts appear to suggest that a period of visual deprivation in infancy caused by cataracts does not lead to long-term deficits in color vision. For example, patients who had congenital cataracts removed relatively late in childhood could identify the odd element within an array based on color (McKyton et al. 2015), and performance on a basic test of color discrimination also appeared normal (Pitchaimuthu et al. 2019). Although this may suggest that color vision is robust to the effects of early deprivation, it is possible that deficits would be revealed with a more sensitive probing of the various aspects of color perception.

Premature infants have additional visual experience relative to infants born full term, and comparing the visual abilities of premature and full-term infants matched on age since conception can identify whether this additional visual experience matters for visual development (e.g., Jandó et al. 2012, Peña et al. 2014). For the case of color, Dobkins and Bosworth have assessed chromatic and luminance sensitivity in infants born full term or premature (Bosworth & Dobkins 2009, 2013). In one study, chromatic sensitivity was enhanced by an extra 4–10 weeks of experience, and luminance sensitivity was enhanced by an extra 6–10 weeks (Bosworth & Dobkins 2013). Another study found that factors related to experience (such as postnatal age) affected chromatic sensitivity more than luminance sensitivity, for which factors unrelated to visual experience, such as infants' gestational length, were more important (Dobkins et al. 2009).

2.4. Tuning In to Chromatic Scene Statistics?

Comparisons of infants raised in different environments have shown that in the first year of life infant perception narrows to become specialist in the types of stimuli (e.g., types of language, faces, music) that the infant has experienced (e.g., Maurer & Werker 2014). This phenomenon of perceptual narrowing raises the question of whether color vision and perception also tune to early experience. Some tentative support for this idea comes from the comparison of the color vision of Norwegian adults born above or below the Arctic Circle (e.g., Laeng et al. 2007). Adults born above the Arctic Circle who would have early experience of the purplish twilight of winter *mørketid* (when the sun does not rise above the horizon for several months) had better discrimination of purples and poorer discrimination of greens than adults born below the Arctic Circle. Adults born above the Arctic Circle also had overall poorer color discrimination if born in the autumn than if born in the summer. This study provides tantalizing evidence that color vision tunes into the colors of the environment during early development, leading to specialized color vision in the long term. Evidence consistent with that hypothesis comes from a psychophysical study that finds that at 4–6 months of age infant color vision is aligned with the distribution of chromaticities in the environment (Skelton et al. 2022a). Both adults and 4- to 6-month-old infants have poorest saturation sensitivity for the chromaticities that have the greatest variation in saturation in natural scenes (blue and yellow-orange hues), and an efficient encoding account for this effect has been proposed (Bosten et al. 2015, Skelton et al. 2022a) (see Simoncelli & Olshausen 2001 for more on efficient encoding; see Section 4.2.1 for more on cultural effects on color perception). These effects at just 4–6 months of age either point to evolutionary tuning or suggest that infant color vision tunes in to the chromatic and illumination scene statistics of environments in the first few months of life. Comparing the color vision of infants born in environments with different chromatic and illumination scene statistics (e.g., above versus below the Arctic Circle, or lush versus arid environments) would clarify whether the effect is due to early tuning.

3. USING COLOR AS A CUE FOR OBJECT PERCEPTION AND COGNITION

As outlined in Section 1, color is a useful perceptual cue for object and scene perception and cognition. Here, we review what is known about how this ability develops, starting with the perceptual process of color constancy.

3.1. The Development of Color Constancy

The adult visual system is remarkably good at keeping the color appearance of surfaces perceptually constant or inferring constancy under changing illumination: We perceive a banana as yellow even under bluish light. This color constancy enables color to be a useful cue for identifying objects and their properties (e.g., Smithson 2005). Color constancy has been attributed to perceptual mechanisms such as adaptation and simultaneous contrast, the use of perceptual cues such as specular highlights (bright spots of light on glossy objects), a daylight prior, and higher-level cues such as object color knowledge (see Witzel & Gegenfurtner 2018 for a review). However, the relative contribution of these elements to mature color constancy in the real world is still being unraveled.

Developmental studies of color constancy may provide insight into the mechanisms of color constancy, and they could be informative for developing artificial intelligence systems that can learn color constancy or for identifying how the visual system learns to draw on low- and high-level properties of objects, scenes, and their illumination (e.g., Wedge-Roberts et al. 2022). Research suggests that even young infants from around 4 months of age have rudimentary color constancy (e.g., Yang et al. 2013) but that color constancy continues to develop and mature throughout childhood (e.g., Wedge-Roberts et al. 2022). The evidence for color constancy in infancy comes from four studies that use the habituation/novelty preference method (Chien et al. 2006, Dannemiller 1989, Dannemiller & Hanko 1987, Yang et al. 2013). These studies each attempted to measure infants' sensitivity to illumination changes using either physical surfaces and real illuminations (Chien et al. 2006, Dannemiller & Hanko 1987) or simulated illumination changes using computer-rendered stimuli (Dannemiller 1989, Yang et al. 2013). If infants are color constant, their visual systems should discount the effect of illumination changes on surfaces, and so they would show familiarity (i.e., no novelty preference) to the same surface despite a change in illumination but a novelty preference when the color of the surface is changed. These studies have shown that by 4–5 months of age, infants appear to already have some color constancy (Dannemiller 1989, Dannemiller & Hanko 1987, Yang et al. 2013) as well as lightness constancy (Chien et al. 2006), whereas color constancy is not evident at 9 weeks (Dannemiller 1989).

There are many questions about how infant constancy compares to constancy in its mature form and what perceptual cues infants draw on. The novelty preference method is a blunt instrument for asking these questions, since infants sometimes prefer to look at the familiar stimulus during a test depending on the amount of familiarization, and a lack of novelty preference does not indicate that the familiar stimulus is perceived as visually identical to the novel one (e.g., Houston-Price & Nakai 2004). Studies that simulate illumination change by changing the chromaticity of a computer-rendered background stimulus are also clouded by lack of clarity on whether infants actually perceive this as an illumination change. In adult color constancy studies, the adult can be instructed that the illumination is changing in the task instructions, and adults can be directed to find the stimulus that is cut from the same card as the original one; however, such instructions cannot be given to infants [see Witzel & Gegenfurtner (2018), who argue that even adults may fail to perceive the change in background as a change in illumination]. These methodological challenges make further probing of the mechanisms underlying infant color constancy difficult.

The methods that are used to measure color constancy in adults can be gamified to make them suitable to use with young children from around 2 years of age. Rogers et al. (2020) devised a color matching game to measure color constancy in which children were required to match printed colored stimuli (cut in the shape of sweaters) with two cardboard bears under different illuminations. Rogers and colleagues found that at 2–4 years of age some children had color constancy approximating adults' performance on the task, but other children had very poor color constancy. Another study asked 3- to 5-year-old children to assign a set of colored stimuli (cut from the Munsell card) to color groups based on color terms, and children repeated the task under different room illuminations (Witzel et al. 2021). The way in which children grouped the colors varied only to a small extent under different illuminations. Both of these studies found a relationship between children's color term knowledge and their degree of color constancy, potentially flagging the importance of color constancy for cognitive development or vice versa (see Section 4.1.2 on color naming for further discussion).

Color constancy has also been measured in older children, at 6–11 years of age, in a series of carefully controlled experiments using an object selection task that involved helping a dragon find his favorite colored sweet under different illuminations (Wedge-Roberts et al. 2022). In two experiments that used 2D and 3D computer-rendered stimuli, color constancy surprisingly weakened between the ages of 6 and 11, and children had better color constancy than adults. However, in a third experiment with a small sample of children ($N = 15$), color constancy was better in adults than in children when tested with rendered matte and glossy objects under daylight and non-daylight illuminations (Wedge-Roberts 2021). There was no consistent evidence for a daylight prior in color constancy that would get stronger with development, and there was tentative evidence that children's color constancy is not helped by specular highlights (bright spots of light on glossy objects) as it is in adults. However, it is unclear whether the developmental differences are due to children's use of different cues for color constancy than adults or to differences between children and adults in interpreting the computer-rendered stimuli, illuminations, and tasks.

Another question is the extent to which the development of color constancy depends on common perceptual systems that enable other types of perceptual constancy to develop. Color constancy appears to have a similar developmental trajectory to other types of perceptual constancy, such as size and shape constancy. For example, there is converging evidence that young infants have rudimentary size constancy (e.g., Granrud 2006), and at large viewing distances this still appears to be developing at 9 years (e.g., Granrud & Schmechel 2006). For the case of size constancy, evidence has pointed to the need for children to develop reasoning abilities so that they can use a deliberate strategy to help their perceptual estimates (Granrud 2009). The roles of reasoning and deliberate strategies and of object knowledge in color constancy in children remain to be probed. Direct comparisons of the development of perceptual constancy across domains (e.g., size, shape, and color) might prove useful.

3.2. Using Color for Object Cognition

How object representations develop in infancy and beyond has been a major focus of developmental science. Research has also asked about the role of color in object individuation (e.g., Wilcox 1999), identification (e.g., Káldy & Leslie 2003), and generalization (e.g., Samuelson & Horst 2008), pitting color against other attributes of objects such as shape, size, location, and luminance. Wilcox and colleagues find that 11-month-old infants use color to individuate objects several months later than shape or pattern (e.g., Wilcox 1999), but that if color is made functionally relevant in the experimental task, then infants can use color cues several months earlier (e.g., Wilcox & Chapa 2004). Káldy & Leslie (2003), using an object occlusion task, show that 9-month-old infants can use shape but not color to identify two objects and track the objects' changing location behind occlusion. However, they also argue that such effects could be due to the particular selected shapes (e.g., circle and square) being more perceptually different than the selected colors (e.g., yellow and green), and the effects do not necessarily indicate that one type of information is more important to object identification than the other. An elegant solution to this underappreciated issue is provided by the development of the psychophysical interdimensional salience mapping (ISM) method for equating infants' perceptual salience of stimulus differences across object feature types (Káldy & Blaser 2009). This method uses forced-choice preferential looking to plot psychometric functions for salience changes on different dimensions. Káldy & Blaser showed that when salience changes were equated in this way, 9-month-old infants could identify objects on the basis of shape and color but not luminance. They argued that infants use color before luminance because in the real world color is more diagnostic of objects than luminance (see **Figure 1*c***).

It has been argued that toddlers are less likely to generalize labels to novel objects on the basis of color than on the basis of shape (the so-called shape bias; e.g., Samuelson & Horst 2008), although other research indicates that children access color information when processing words (e.g., Johnson et al. 2011, Mani et al. 2013). For example, after hearing a word (e.g., strawberry), 2-year-olds orient more quickly to the image of an object that has the same color as the spoken word (e.g., red cup) than to the image of an object of an unrelated color (e.g., blue chair), indicating that children at this age process the color of the spoken object (Johnson et al. 2011). However, even though this demonstrates object color knowledge by 2 years of age, semantic knowledge still appears to be stronger at this age: On hearing a word (e.g., banana), 2-year-olds orient faster to a semantic match (e.g., cookie) than to a color match (e.g., yellow cup) (Mani et al. 2013), again potentially suggesting that color is less prominent than other object properties. There is limited research on the age at which object color knowledge emerges. Color is diagnostic of certain objects: Objects such as food, natural objects (e.g., leaves), or faces have a typical (canonical) color. One study finds that 6-month-olds look longer at typically than at atypically colored faces and fruit, suggesting that object color knowledge may start to develop in early infancy (Kimura et al. 2010). However, an unpublished study failed to find a preference (in 5- and 8-month-olds) for naturally colored faces over digitally manipulated green, purple, and blue faces equated in saturation, and infant hue preferences were the same when colored stimuli were faces or scrambled faces (Clifford et al. 2014).

In the real world, changes in the color of objects can also be indicative of the properties of the objects: Meat changes color when it is cooked, leaves change color with the seasons, fruit changes color when it ripens, and skin changes color when someone is aroused or ill. In fact, it has been proposed that the need to be able to register changes in the color of skin or the ripeness of fruit provided the basis for trichromatic color vision to evolve (e.g., Changizi et al. 2006, Osorio & Vorobyev 1996). The development of the ability to use object color changes to infer the properties of objects is a topic for further research. In the real world, the color of objects also has statistical regularities. For example, an analysis of the color of a database of real-world images found that objects were more frequently warm colored (e.g., red) and the backgrounds were more frequently cool colored (e.g., blue), potentially making warm colors more communicable than cool ones (Gibson et al. 2017). Research considering when such statistical regularities in the color of objects feed into the development of object perception and cognition could be fruitful.

Color is important not just for the perception of objects; in adults, color appears to be also important at both the encoding and retrieval stages when recognizing scenes (Gegenfurtner & Rieger 2000, Gegenfurtner et al. 1998), and scene category identification is fastest when scenes are presented in their natural colors (Oliva & Schyns 2000, Wichmann et al. 2002). There has been little developmental investigation of this topic. Skelton et al.'s (2022b) investigation of infants' saturation thresholds, outlined in Section 2.4, potentially suggests that infants tune into the chromatic properties of scenes. Another unpublished study conducted by Skelton and colleagues further suggests that young infants are sensitive at least to the chromatic properties of scenes, finding that 6-month-olds' looking preference for urban compared to rural scenes can be predicted by a number of low-level spatial and chromatic features of the scene (Skelton et al. 2021). However, the age at which infants are able to draw on the color information in a scene to encode and recognize scenes is currently an open question.

4. CATEGORIZATION, LANGUAGE, AND AESTHETICS

As outlined earlier, color is more than a simple perceptual cue for identifying objects and their properties: Color infiltrates our language and communication, and it invokes an emotional and aesthetic response. Here we review what is known about the development of these aspects of our experience of color.

4.1. The Development of Color Categorization and Naming

Although there are millions of discriminable colors (e.g., Linhares et al. 2004), when we communicate about color we group these colors into a discrete number of categories and use color terms to refer to these categories (e.g., red, green, blue). There have been decades of interdisciplinary debate about whether color categories and their lexicons are arbitrarily linguistically constructed or there are biological constraints or other factors determining how colors are grouped and named (Lindsey & Brown 2021). Investigation of the world's color lexicons has revealed striking variation in how languages talk about color: Some languages have only a few basic color terms, whereas others have 11 or more (e.g., Kay et al. 2009). However, despite this variation, commonalities across color lexicons have also been identified, and it is now commonly accepted that color categorization is not an arbitrary process (see Lindsey & Brown 2021 for a review). Here we outline developmental research that has asked questions about how color categories develop and how children learn the words for color categories. We illustrate that this research contributes to the debate about the origin and nature of color categories and to our understanding of how infants and children categorize information and learn terms for categories more generally.

4.1.1. Infant color categorization. One hotly debated question about the development of color categorization has been whether or not infants can categorize color before they have learnt the words for color. Bornstein and colleagues' classic studies were the first to claim that infants categorize color (e.g., Bornstein et al. 1976). These studies presented infants repeatedly with a monochromatic light composed of one wavelength so that they habituated to it (i.e., their looking time decreased) and then recorded how long the infants looked at light of a novel wavelength. Infants only dishabituated to the novel light (i.e., increased their looking) when it was from a different lexical category than the habituated light (e.g., green and blue) but not when it was from the same lexical category (e.g., both green). Bornstein and colleagues interpreted these findings as evidence that infants categorize the continuum of wavelength into blue, red, green, and yellow categories.

Since Bornstein and colleagues' work, there has been much debate about the existence of infant color categories. Stimulus limitations in those classic studies were identified (e.g., Davies & Franklin 2002), and a number of subsequent studies have attempted to replicate and extend the work using stimuli and color spaces that address those limitations. These studies have also used a range of methods, such as eye-movement search tasks (e.g., Franklin et al. 2005), event-related potentials (Clifford et al. 2009), and functional near infrared spectroscopy (f-NIRS) (Yang et al. 2016), to attempt to probe the nature of infants' categorical responses. We refer the reader to Maule & Franklin (2019) for a detailed overview of these studies, their limitations, and a nuanced debate about whether infant color categories affect infant color perception or memory. The overall message of Maule & Franklin's review is that there is substantial evidence that infants' recognition memory responds to color in a categorical manner.

Skelton et al. (2017) further investigated the nature of infant color categories with a large-scale infant study that mapped infant color categories onto the stimulus array used in a survey of the world's color lexicons (World Color Survey; Kay et al. 2009). Using a method similar to that of Bornstein's original studies, Skelton and colleagues found that infants' response parsed the continuum of hue into five categories: red, green, blue, yellow, and purple. Skelton and colleagues then used this infant color category map to establish the extent to which it followed the common pattern of categorization across the world's color lexicons. The centers of lexical color categories (category centroids) across the world's color lexicons tend to cluster around particular points in color space (Regier et al. 2005), and Skelton and colleagues' quantitative analyses found that infant color categories were also organized around these hues. This similarity was used to argue that infant color categorization and the commonality across color lexicons could be partly determined by similar processes. Further analyses of infants' responses suggested that the categorical distinctions infants make can be accounted for by early color representation in retinogeniculate pathways, providing support for a biological account of infant color categorization. That account has been challenged based on the claim that early color representation cannot neatly account for lexical color categories in adults (e.g., Siuda-Krzywicka et al. 2019); yet it is plausible for infant color categorization to be biologically determined, whereas color lexicons are determined by a mix of biological, cultural, and linguistic forces. The link between infant color categories and color lexicons deserves further investigation.

4.1.2. Learning color terms. Although infants appear to coarsely categorize color, children have the challenge of learning the words for the color lexicon of their own language and culture. It has been commonly argued that children find this process of color term learning difficult and that color terms are harder for children to learn than other abstract terms (e.g., Kowalski & Zimiles 2006, Sandhofer & Smith 1999). The age of color term acquisition has come down over time, with children now typically being able to point to and name the best (focal) examples of the basic color terms by around 3 years of age (Pitchford & Mullen 2002). However, despite this reduction in age, a body of work has considered color term acquisition to be atypically effortful and has investigated the reasons for this (e.g., Rice 1980). One common proposal is that children find it difficult to abstract the property of color and to know that color is the object property that is being labeled (e.g., Kowalski & Zimiles 2006). However, Wagner et al.'s (2013) study of color naming has strongly challenged this proposal. Wagner and colleagues carefully considered the nature of children's errors before they were able to point to and name a term correctly. They found that even before children succeeded in accurate comprehension and production of a color term, their pattern of errors was systematic and indicated some understanding of the terms and the categorical structure of color. For example, children's errors at this stage were commonly directed at similar colors (e.g., red was named as pink). Contrary to the hypothesis that children who do not know color terms have a problem with abstracting color, Wagner and colleagues argued that these children can abstract color and respond to it in a meaningful way; they are just working out the color category boundaries of their own language. Further support for the hypothesis that children have an understanding of color terms before they pass on to formal comprehension and production tasks comes from eye tracking and parental reports (Forbes & Plunkett 2020, Wagner et al. 2018). Wagner et al. (2018) found that children as young as 23 months of age were showing some color term comprehension with these measures. Forbes and colleagues also found that even infants as young as 19 months of age could reliably look at the correctly colored object following an instruction to look at the object with a given color term (Forbes & Plunkett 2019).

These recent studies on color term acquisition have also considered the factors that determine the speed at which color terms are learnt. Re-analysis of Wagner et al.'s (2013) color naming data found that three factors could account for whether or not terms were applied consistently (across objects of the same color) and precisely (not to other colors). The frequency with which children hear a given term in child-directed speech, the size of a term's color category, and the perceptual salience of the best example of a given term could account for the majority of the variance in Wagner et al.'s (2013) data (Yurovsky et al. 2015). Forbes & Plunkett's (2020) analysis of infant language surveys in 12 languages also identifies that the frequency of the color term in child-directed speech and the syllabic complexity (number of syllables) of a color term are predictors of the ease with which a term is learnt (Forbes & Plunkett 2020). These findings are important because these factors also affect the learning of concrete nouns, providing support for the hypothesis that color terms are not a special case: Color term acquisition is driven by the same mechanisms as the acquisition of other kinds of words.

Wagner et al.'s (2013) proposal that color term acquisition involves a "gradual inductive process" of learning the category boundaries of a given term points to the importance of investigating color term learning with stimulus sets that include both focal examples (e.g., category centroids) and poor examples (e.g., colors at the category boundaries) of color terms. Studies that have asked children to sort stimulus sets similar to those used in adult color naming research (e.g., World Color Survey) into groups based on color terms have revealed the gradual sharpening of color category boundaries (Bonnardel & Pitchford 2006, Raskin et al. 1983, Witzel et al. 2021). Recent cross-cultural studies of children's color naming using a set of 93 colors find that while input frequency and category size determine the rate of learning category centroids (as in Yurovsky et al. 2015), it is the inconsistency with which a color is named by adults that determines whether Japanese and German 3- and 5-year-olds name boundary colors accurately (Imai et al. 2020, Saji et al. 2020). These studies highlight the importance of considering color term acquisition as a process of category learning rather than a process of simply learning the names for the best examples of a term.

Another line of research has considered the effect that color term acquisition has on color perception. Research testing the Whorfian hypothesis that language affects perception has found that color category effects on perceptual tasks are lateralized to the language-dominant left hemisphere (e.g., Drivonikou et al. 2007, Gilbert et al. 2006). Developmental research has also found a switch in the hemispheric lateralization of the effect of color categories from the right hemisphere to the left hemisphere as color terms are learnt (Franklin et al. 2008a,b). However, these laterality studies suffer from the constraints of the split-field measure of hemispheric lateralization, and lateralization of color category effects in adults has been found to be unreliable across studies (Witzel & Gegenfurtner 2011), potentially due to the fact that factors such as spatial attention and expertise determine the pattern of lateralization. Nevertheless, there are other hints that learning color terms corresponds with changes in color perception. For example, as outlined in Section 3.1, Rogers et al.'s (2020) investigation of color constancy in preschoolers found a correlation between the number of color terms a child knows and the degree of their color constancy, although the direction of this relationship is unknown.

4.2. The Development of Color Preference

Decades of research have documented systematic and reliable adult color preferences: On average, adults from the United States and the United Kingdom like blue hues the most and yellow-green hues (particularly if dark) the least (Palmer & Schloss 2010, Taylor & Franklin 2012). There is also a smooth hue-preference curve for these adults, with preference steadily rising the bluer the hue. One account of color preference is ecological valence theory (Palmer & Schloss 2010), which proposes that adults like colors to the extent that those colors are associated with liked objects. In support of this theory, the valence of color-associated objects can account for up to 80% of the variance in US adults' color preference (although much less for other cultures; e.g., Yokosawa et al. 2016). Another approach has been to describe hue-preference curves in terms of weights on the cone-opponent mechanisms, potentially providing insight into the nature of the preference (Hurlbert & Ling 2007; see also Schloss et al. 2018a). Hurlbert & Ling's (2007) study of adult color preference found, for both British and Chinese adults, that women weighted the red-green cone-opponent mechanism more strongly than men, with a female bias towards reddish hues (see also Sorokowski et al. 2014). In their original work, they argued that this difference might be attributed to evolutionary sex differences in foraging behavior that bias women toward reddish hues: In other words, the difference would be biologically driven. Here, we summarize developmental studies that have investigated the origins of sex differences in color preference and hue preferences in infancy.

4.2.1. Children's color preferences and the development of sex differences. Like those of adults, children's color preferences are also reliable and systematic and vary with hue: Ling & Hurlbert (2011) identified that the hue-preference curves of 8- to 9- and 11- to 12-year-olds were highly similar to those of adults, with a few notable differences. One major focus of developmental color preference studies has been the question of whether sex differences are culturally constructed or biologically driven. Potentially in support of this, Ling & Hurlbert (2011) found that sex differences in color preference were amplified at the start of adolescence. However, other developmental work has favored cultural accounts of sex differences in color preference. For example, girls' preference for and boys' aversion to pink start to arise around 2.5 years of age, when sex-stereotyped behaviors also appear (LoBue & deLoache 2011). Sex differences in color preference are so strong around this age that they affect toy preference (Wong & Hines 2015), and some have argued that coding the gender of toys using color leads to gender differences in social and developmental outcomes (e.g., Orenstein 2011). In support of a cultural account of sex differences in color preference, sex differences are not found in 4- to 11-year-olds from three small-scale societies that are not strongly influenced by global industrialization (Davis et al. 2021; see also Taylor et al. 2013a for adult data).

4.2.2. Infant color preferences. Research on infants' visual preferences for color can also contribute to understanding color preferences in their mature form. Studies that have recorded how long infants look at patches of color when shown individually or in pairs have found that around 3–4 months of age, infants look longest at blues, a long time at reds and purples, and the least time at yellows and greens (e.g., Bornstein 1975, Skelton & Franklin 2020, Taylor et al. 2013b, Zemach et al. 2007); as for adults, their response follows a systematic hue-preference curve (e.g., Brown & Lindsey 2013). The nature of these early visual preferences has been examined, and psychophysical experiments have established that they are not determined by adult-like brightness or saturation differences, colorimetric purity, or infants' chromatic detection thresholds; rather, they are best accounted for by "spontaneous hue preference" (Zemach et al. 2007). Other work has shown that infants' color preferences, like adults', can be summarized in terms of weights on the cone-opponent axes (e.g., Taylor et al. 2013b), and infant color preferences from three studies have been effectively modeled with a cone-opponent model of color vision (Brown & Lindsey 2013). This modeling also found that infants' preferences were best explained when the luminance of the stimuli was not taken into account, providing compelling evidence that infants of this age are able to respond to colors on the basis of their hue, independent of their other perceptual dimensions (see also Rogers et al. 2018).

One question is the extent to which these early visual preferences for color relate to adults' aesthetic color preferences in their mature form. Infant looking preferences, of course, do not necessarily indicate that an infant likes something, and a number of processes are known to be related to how long an infant looks at a stimulus, such as novelty and complexity (Houston-Price & Nakai 2004). However, infants' visual preferences for color do bear a striking similarity to adults' aesthetic color responses. For example, how long a 4- to 6-month-old infant looks at different colors significantly correlates with adults' ratings of how much they like those same colors, with almost half of the variance shared between the two measures (Skelton & Franklin 2020). This striking similarity between adults' aesthetic color preferences and infants' visual preferences for colors raises the question of whether or not these two types of preference are driven by similar mechanisms. Both infant and adult preferences can be summarized by how colors activate cone-opponent mechanisms (e.g., Skelton & Franklin 2020), and one possibility is that the preferences of both groups have a similar sensory component. Color preferences may start in infancy as an early sensory bias for looking longer at some hues over others and then develop into aesthetic and hedonic preferences during development, when meaningful interactions with colored objects, concepts, and environments increase. As these aesthetic preferences develop, they are likely to be shaped by an individual's identity, experiences, and culture (e.g., Schloss et al. 2011).

Beyond the developmental work on color preferences for individual colors, we know little about whether color contributes to children's aesthetic appreciation of art as it does in adults (e.g., Nascimento et al. 2017) or even to the development of aesthetics generally (e.g., Krentz & Earl

2013). Further developmental work has the potential to shed light on the nature of aesthetics. Similarly, other than one study that identifies color–emotion associations at 3 years of age (Zentner 2001), there is little understanding of how these associations develop, and further developmental work could clarify how color–emotion associations are shaped by experience.

5. NEURODIVERSITY AND CLINICAL AND EDUCATIONAL IMPLICATIONS

Throughout this review we have charted the development of color perception and cognition for neuro-typical individuals with trichromatic color vision. However, there is also neurodiversity in this development. One source of individual difference comes from congenital CVD (commonly called color blindness). Here we review what is known about CVD in children, discuss the pediatric clinical tests available for diagnosis, and consider what impact CVD has on children's well-being and education. We also review the evidence that color perception and cognition are atypical in children with neurodevelopmental conditions, focusing mainly on the case of autism.

5.1. Color Vision Deficiency

CVD is the most common congenital visual disorder and affects around 8% of males and 0.4% of females (Birch 2012). Due to genetic polymorphism, either the spectral sensitivity of L-, M-, or S-cone photoreceptors is atypical (anomalous trichromacy) or a cone photoreceptor type is missing (dichromacy; see **Figure 1*d***). L- and M-cones are more commonly affected (red-green CVD).

5.1.1. Diagnosis of color vision deficiency in children. Screening for CVD in schools or by opticians is not routine in many countries, and in the United Kingdom around 80% of affected pupils starting secondary school (age 11–12) are unaware that they have CVD (Albany-Ward 2005). Tests used to diagnose CVD in adults (e.g., the gold-standard anomaloscope) are difficult for young children to complete, and nonvisual factors often cloud the interpretation of the results when testing children (Tang et al. 2022). A number of pediatric tests for CVD do exist (e.g., the Ishihara test for the unlettered; Ishihara & Ishihara 2016), yet many of these can also be difficult for young children, do not control for nonvisual factors, or lack sufficient data on sensitivity and specificity at various ages (see Tang et al. 2022, table 1). These pediatric tests for CVD are also often not kept at hand by opticians or are costly for teachers or parents to obtain. A new test, ColorSpot, aims to make pediatric CVD testing more readily available, child-friendly, and accurate (Tang et al. 2022). The test combines gamification and psychophysics and is designed as an iPad app using color calibrations for numerous iPad models. ColorSpot can be self-administered, is completed in around 5 minutes by children as young as 4 years old, and diagnoses the same children as the Ishihara for the unlettered while being more decisive about children who are unclassified by that test (Tang et al. 2022). The test is open access for research purposes (**https://osf.io/v5p2y/**) and may serve as a useful screening tool for research with children that involves color or as a measure of children's color discrimination.

5.1.2. Impact of color vision deficiency on children's daily life, education, and well-being. Although red-green color blindness is commonly interpreted as an inability to see red and green, it actually affects any color discriminations to which differences in redness or greenness contribute. For example, purple and blue are commonly confused by those with CVD, as these differ in redness. In adults, everyday tasks such as seeing the blush or pallor of skin, identifying whether meat is cooked, or pairing colored socks are affected, and adults with CVD commonly report problems in daily life related to their CVD (e.g., Tagarelli et al. 2004). In the case of children, education and the classroom are highly color coded: For example, color is used in teaching materials, to give feedback, in topics such as art, math, geography, and science (e.g., litmus paper) as well as in the color coding of sports teams (e.g., Mashige 2019). Suero et al. (2005) showed that CVD in preschoolers has a negative impact on their performance on standard classroom tasks (e.g., counting beads on a colored abacus or reproducing colored geometrical figures), and that teachers unaware of their diagnoses rate CVD preschoolers as poorer achievers. Another study found that 10% of exercises in math textbooks for 5- to 7-year-old Catalan children are inaccessible for observers with CVD (Torrents et al. 2011). Grassivaro Gallo et al. (2002) also found lower school achievement for CVD high school students compared to students without CVD.

A quality-of-life questionnaire developed for adults with CVD [the Colorblind Quality of Life (CBQoL); Barry et al. 2017] indicates that adults frequently experience emotional difficulties in relation to their difficulties with color, such as feeling anxious, depressed, or embarrassed. A pediatric version of the CBQoL would be useful to determine the extent of such emotional difficulties in children and adolescents with CVD. One large study of 8- to 11-year-olds found that the Child Behavior Checklist (Achenbach & Edelbrock 1983) identified greater behavioral and emotional difficulties in children with CVD compared to children without CVD (Thomas et al. 2018), although differences on the Strengths and Difficulties Questionnaire (Muris et al. 2003) at 8–11 years of age have not been found (Nithiyaananthan et al. 2020).

Another question for further research is whether early diagnosis and support help alleviate any of the impacts of CVD on quality of life. Although there is currently no available treatment for CVD, early diagnosis and support from teachers and parents could be beneficial. For children who have received a diagnosis, teaching materials can be made CVD-friendly with simple modifications (e.g., by making them gray scale or adding texture in place of color; e.g., Rubin et al. 2009). If children know why they are struggling with some tasks at school, this could also prevent the buildup of behavioral and emotional difficulties. A large-scale intervention study is needed that systematically evaluates the benefits of CVD diagnosis and subsequent support on the quality of life of children with CVD at different stages of development.

5.1.3. Color vision deficiency and perceptual development. Adults with CVD are surprisingly good at naming colors, particularly for highly saturated focal colors. One theory is that those with CVD learn strategies to compensate for their CVD, such as attending to lightness differences between colors (e.g., Lillo et al. 2014), although it is unclear when such strategies are learnt. An fMRI study also suggests that adults with anomalous trichromacy neurally compensate for the deficiency in their color signals, finding that the color signals in V2 and V3 of anomalous trichromats are boosted (Tregillus et al. 2021). It is unclear whether this neural compensation for CVD is learnt during development, when neural plasticity is heightened. Heightened visual plasticity in early development may also affect the efficacy of glasses that have been designed to boost color vision in anomalous trichromats (the lenses use notch filters that amplify differences in color; e.g., Werner et al. 2020). For example, if the perceptual effects of such lenses harness the plasticity of cortical color signals, then their effects could be potentially stronger if used early in development, when the visual system is more open to calibration. These proposals have not yet been tested.

5.2. Neuro-Developmental Conditions

Individuals with neuro-developmental conditions and neuro-typical individuals are known to differ in many aspects of perception and cognition, including color (e.g., Simmons et al. 2009). In the case of attention-deficit/hyperactivity disorder (ADHD), blue-yellow discrimination appears reduced in adults and children (e.g., Uebel-von Sandersleben et al. 2017), and it has been proposed that lower levels of retinal dopamine in ADHD reduce the efficiency of short wavelength cones (e.g., Kim et al. 2014). The case of autism is outlined next.

Anecdotal reports of atypical color perception and cognition in autism are common, with reports of hypersensitivity to certain colors or obsessions and aversions for particular colors that govern daily life (e.g., Ludlow et al. 2014). For example, one case study identifies an autistic child whose color obsessions were so strong that he painted the family dog blue and only wore dark blue clothes, his bedroom was painted purple and black to try to alleviate stress, and he would only eat foods with little color (Ludlow et al. 2014). Despite the anecdotal evidence, there has not yet been a systematic investigation of the prevalence of color obsessions or atypical sensitivity to color, an explanation for why this affects some autistic individuals but not others, or an investigation of what underpins the phenomenon. It does appear, however, that various aspects of color perception and cognition are atypical in autism. Early studies that assessed children's performance when searching for, memorizing, sorting, making similarity judgments, or attending to large suprathreshold color differences pointed to atypical color perception in autistic children (e.g., Franklin et al. 2008c, Heaton et al. 2008). For example, children with autism performed more poorly at memorizing a colored target and searching for it compared to a control group of children without autism matched on nonverbal cognitive ability (Franklin et al. 2008c).

Chromatic discrimination in autistic children and adolescents also appears to be poorer relative to that in non-autistic individuals, both on the Farnsworth-Munsell 100 Hue Test, controlling for nonverbal ability (Franklin et al. 2010), and on tasks that measure chromatic thresholds for both red-green and blue-yellow discriminations (Cranwell et al. 2015, Franklin et al. 2010, Zachi et al. 2017) where performance is not predicted by IQ (Cranwell et al. 2015). Further evidence for atypical color discrimination comes from a VEP study that finds prolonged N1 latencies (a negative component of around 100 ms) to chromatic gratings in adolescents and adults with autism (Fujita et al. 2011). It is worth pointing out here that the difference in group chromatic thresholds, although significant, is small and may have limited importance for daily functioning (Franklin et al. 2010), and only a subset of autistic individuals (e.g., 30% in Zachi et al. 2017) perform outside of the "normal" range. In addition, discrimination of moving chromatic contrast is typical: Koh et al. (2010) find typical sensitivity to moving chromatic gratings in autistic adolescents, and siblings of autistic individuals even have heightened chromatic sensitivity under these conditions.

The findings on atypical color discrimination in autism have been used to inform models of perceptual and neural functioning in autism (e.g., Pellicano & Burr 2012). A series of studies that identified atypical perception of colored ensembles (Maule et al. 2017) but typical color adaptation (Maule et al. 2018) in adults with autism has also informed the theory that perceptual priors are attenuated in autism (Pellicano & Burr 2012); however, these color phenomena have not yet been investigated in children. Further work that more fully characterizes color perception and cognition in autistic children, identifying the source of individual variability and the neural basis of atypical performance, may be informative for understanding autism and perceptual development more generally.

6. CONCLUSION

As seen throughout this review, there has been a concerted effort to understand how infants and children perceive and think about color and to understand how such perception and cognition develop. We have seen how many aspects of color perception are present early in infancy in a rudimentary form. Trichromatic color vision is in place just a few months after birth (e.g., Teller 1998), and by 6 months of age infants have developed perceptual mechanisms, such as color constancy (e.g., Yang et al. 2013), that enable them to start to use color cues to perceive objects and scenes (e.g., Káldy & Blaser 2009). However, we have also seen that, despite these early competencies, color perception and cognition are slow to mature, and many aspects such as chromatic discrimination and color constancy do not mature until late childhood or adolescence (e.g., Knoblauch et al. 2001). The rudimentary processes in infancy and protracted maturation throughout childhood have the potential to provide insight into the neural basis of visual development as well as the relative contributions of biology, experience, culture, and environment to color perception and cognition. For example, the similarity of infants' early visual color preferences and color categories to common patterns of color preference and categorization in adults potentially suggests at least a partial sensory and biological basis for these phenomena in their mature form (e.g., Skelton & Franklin 2020, Skelton et al. 2017).

We have also seen how comparing the developmental trajectory of color perception and cognition to other perceptual traits can help identify the domain-general aspects of perceptual and cognitive development. For example, shape and color constancy have similar developmental trajectories, potentially pointing to common perceptual mechanisms. As for other perceptual domains, at least some aspects of color perception appear to be affected by and potentially tuned to early experience (e.g., Laeng et al. 2007). In addition, while color term acquisition was once thought of as a special case, it now appears that the factors that influence color term acquisition are similar to those that influence other types of word learning (e.g., Saji et al. 2020). However, other comparisons suggest that color cues may be more difficult for infants and children to draw on than perceptual cues such as shape—for instance, in the case of object perception and cognition (e.g., Wilcox 1999).

While the relative importance of color compared to other perceptual features can be debated, it is clear that color has an impact on how children perceive, think about, and interact with the world around them. We have seen that even in children as young as 2 years old, color preferences affect toy choice (e.g., Wong & Hines 2015), and autistic children can have strong color obsessions that govern what they eat and other aspects of daily life (e.g., Ludlow et al. 2014). Children with CVD are potentially disadvantaged in an education system in which color-coded teaching materials are inaccessible to them (e.g., Torrents et al. 2011). Finally, there is even some suggestion that a reduced ability to see color can affect children's well-being and emotional functioning (e.g., Thomas et al. 2018).

There have been notable advances in our understanding of the development of color perception and cognition, although there remain a number of key issues for future research (see the Future Issues section below). These future issues illustrate the potential for developmental color science to have implications beyond the topics of color and perceptual development. Further research on the development of color perception and cognition can contribute to a broad range of fundamental topics in psychology, such as the role of experience and environment in human development, the statistical basis of perception, the nature of cortical representation, and the factors that influence children's educational outcomes and well-being.

FUTURE ISSUES

1. What aspects of color perception tune to early experience, and what is the time course of any tuning? For example, does having congenital cataracts in infancy affect the long-term development of aspects of color perception, such as chromatic sensitivity at high spatial frequencies or color constancy? Do infants raised in different chromatic environments develop different patterns of hue sensitivity that can be predicted by the environmental differences in chromatic scene statistics?

2. When and how do infants and children draw on real-world color cues? For example, what statistical regularities in the colors of objects and natural scenes are infants and children sensitive to, and how are these used in object perception and cognition?
3. What changes in the cortical representation of color underpin the development of color perception and cognition? For example, are regions of the ventral visual cortex specialized for color in early infancy as in adulthood, or does this specialization develop with visual experience?
4. What is the impact of color on children's daily functioning, education, and well-being? For example, does CVD impact children's quality of life as it does in adults, and does early diagnosis of CVD make a difference to developmental outcomes?

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