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Contrast sensitivity from infancy to adulthood and its impact on selected eye diseases

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HIGHLIGHTS

Contrast sensitivity is a more sensitive and better indicator of eye diseases than visual acuity and should be a standard element of functional vision testing.

ABSTRACT

Contrast sensitivity is a key visual function that develops rapidly during infancy and plays a significant role in everyday visual activities. Unlike visual acuity, contrast sensitivity often deteriorates earlier and may remain reduced despite normal visual acuity. This review outlines the developmental trajectory of contrast perception and highlights its clinical importance in selected eye diseases such as glaucoma, age-related macular degeneration, and amblyopia. The article also emphasizes the importance of including contrast sensitivity testing in standard ophthalmic examinations.

Key words: contrast sensitivity, visual development, amblyopia, glaucoma, age-related macular degeneration

INTRODUCTION

Contrast sensitivity assessment plays a crucial but frequently overlooked role in evaluating visual function. Physically, the word 'contrast' refers to differences in luminance and colour, whereas perceptually, it describes the perception of these differences. Contrast sensitivity (CS) plays a key role in the process of vision: distinguishing objects from the background, detecting texture, colour, movement, shape, and depth. CS is defined as a function (CSF), which represents the ability to see differences between objects with varying contrast levels. It measures the limit of object vision in low contrast conditions [1].

Specifically, it is the inverse of the contrast sensitivity threshold, the minimal detectable difference in luminance (L) between dark and light gratings. CS depends on the absolute value of the stimulus, the spatial frequency (scale and size) of gratings, and potential changes in temporal stimulus.

In the context of the ability to detect colour differences, one can refer to luminance and chromatic contrasts. CS is calculated as the difference between maximal and minimal luminance using the following formula:

$$\frac{\text{Lmax} - \text{Lmin}}{\text{Lmax} + \text{Lmin}}$$

Contrast sensitivity can also be calculated as 1/contrast threshold, the level at which contrast can just be perceived. To express contrast in percentage terms, this indicator must be multiplied by 100%. The contrast of black print on a white background is close to 100%, but in everyday life, identifying objects often requires distinguishing low-contrast elements, which may be near zero. Thus, visual acuity (VA) is a fundamentally different measurement, defined as the ability to detect and distinguish periodically arranged objects, and is typically assessed under high-contrast conditions, almost always, using black symbols on a white background, which does not reflect natural viewing situations. It is expressed by the Snellen formula as shown below [2].

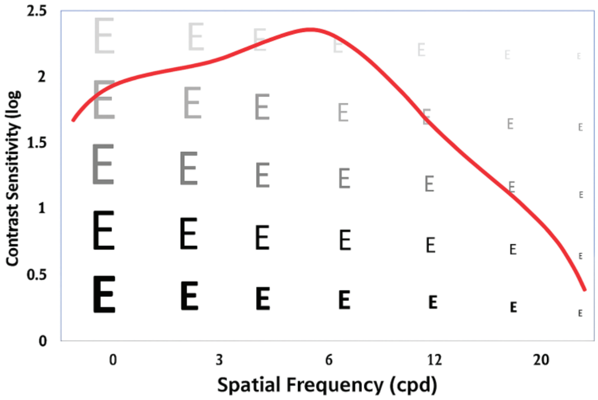
$$\text{Vision acuity} = \frac{\text{L (viewing distance used in meters)}}{\text{D (distance from which optotype has size of 5 s of arc)}}$$

While standard visual acuity charts measure the ability to recognise high-contrast symbols, contrast sensitivity tests assess the ability to detect much subtler differences between light and dark targets. Visual acuity is determined using the smallest symbols the patient can identify, whereas contrast sensitivity is measured with stimuli of the same size but with progressively decreasing contrast. Typically, contrast sensitivity deteriorates earlier than visual acuity. Occasionally, the opposite occurs: resolution remains normal while CS is reduced. Therefore, CS testing is considered to be as important as, or even more important than, VA testing. In clinical practice, CS measurements are valuable for vision screening, diagnosing eye diseases, assessing and monitoring visual function, and predicting visual impairments [3]. There are many charts designed for CS testing that should be used in routine examinations, for example: Pelli-Robson, Vistech, Arden, and Cambridge charts.

Normal eyes have a CS score of at least 2.0 log at spatial frequencies of 6 cpd [4] as shown in figure 1.

FIGURE 1

Contrast sensitivity function in a normal eye. Source [5].



The development of contrast sensitivity in infants and adults, as well as the influence of the visual system on contrast detection in individuals with selected visual impairments, represents a particularly interesting issue that will be discussed in more detail in the following sections of the article.

DEVELOPMENT OF CONTRAST PERCEPTION DURING INFANCY

Knowledge about the development of contrast perception and contrast sensitivity from birth to adulthood provides important insights into the mechanisms influencing the maturation of visual functions. Establishing reference criteria for healthy children and those with visual deficits, such as amblyopia, is of great importance in clinical practice [6]. Studies addressing this issue during the first year of an infant's life reveal certain differences, yet consistently demonstrate a significant increase in overall contrast sensitivity during the first months of life. Various methods are used to measure contrast sensitivity, most commonly fixation cards or paddles, such as the Hiding Heidi test, visual evoked potential (VEP) testing, and techniques based on assessing eye movements during fixation on a target. The period around the second month of life has been identified as critical, as this is likely when visual mechanisms responsible for differentiating objects with varying contrast begin to form. Similarly, Banks [7] observed a marked increase in CS between the first and second months, particularly at high spatial frequencies, and noted a transient period of developmental inhibition between the second and third months.

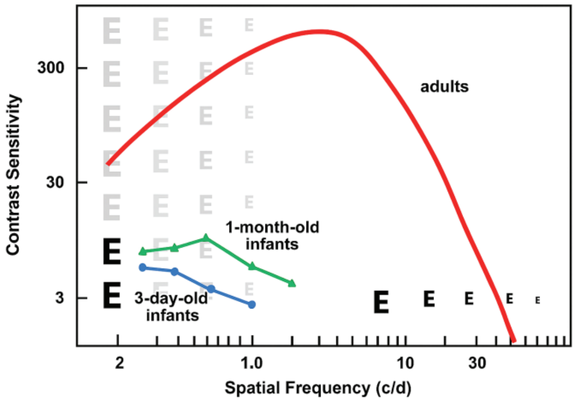
One of the earliest studies, conducted by Atkinson et al. [8], showed that at the fifth month and again between the eighth and twelfth months, there is another rapid quantitative and qualitative shift in CS development. Norcia et al. [9] further noted that CS development varies depending on spatial frequency and age, measuring 5 cpd at one month, 16.3 cpd at eight months, and averaging 31.9 cpd in adults. Unlike Banks [7], Norcia et al. [9] reported that for low spatial frequencies, CS develops rapidly between the second and ninth week and remains stable until the thirtieth week. The first behavioural measurements of CS in newborns during the first month of life were conducted by Brown et al. [10] and aligned with earlier VEP-based findings. These results showed that contrast perception for square-wave gratings of 0.1 and 0.06 deg, assessed using a fixation-and-following procedure, was significantly lower than in adults. The mean threshold for newborns was 0.50 for 0.10 deg and slightly higher for horizontal gratings. Braddick and Atkinson [11] emphasised that VEPs indicate contrast-related signals reach the infant's visual cortex, yet neurons may not respond to them. Nevertheless, CS measured in VEP tests changes over time. Although infants show limitations in contrast perception related to luminance, texture, background, and eye movements, even two-month-old infants can detect aligned, collinear contours.

Research on colour contrast perception from birth to six months, using chromatic and luminance patterns, has shown that responses are minimal until the fifth week. However, they are consistently stronger for luminance processed via the magnocellular pathway, compared to the parvocellular pathway, which mainly processes colour [12]. Furthermore, twin studies on infant contrast detection by Dobkins, Bosworth, and McCleery [13] demonstrated that the parvocellular pathway is generally more closely linked to visual perception and CS. While its development is genetically influenced, it is also shaped by environmental factors, such as growing up in a colour-rich environment. CSF measurements have proven highly sensitive for assessing visual function, which has also been confirmed in studies on children with cortical visual impairment (CVI). It has been shown that CVI has a markedly negative effect on CS development [14].

In summary, newborns exhibit a significant overall deficit in contrast perception compared to adults, with a critical developmental window occurring within the first three months of life and steadily improving with age, as illustrated in figure 2.

FIGURE 2

Contrast sensitivity function for adults, 1-month-old infants, and newborns. Source [5].



Decreased CS in infancy can be explained by the immaturity of the fovea, along with the development of accommodation and attention span [9]. In later childhood, CS develops less rapidly, and according to Dekker et al. [6], by the twelfth year of life it is approximately 90% better than in the fourth.

CONTRAST SENSITIVITY IN ADULTS

The visual system in adults facilitates contrast perception thanks to the appropriate organization of receptive fields, cone density, and central and peripheral vision capability [1]. Under normal conditions, it should be no less than 2.0 log [4]. On the retinal level, there are ganglion cells characterized by high selectivity and sensitivity to contrast. Thanks to lateral inhibition, they are capable of adjusting their responses from their center to the surrounding receptive fields. A key role is played by two mentioned pathways: the parvocellular retinogeniculate pathway (P) and the magnocellular retinogeniculate pathway (M). The P pathway mediates perception of high spatial frequencies, responds well to low temporal frequencies, and has low sensitivity to contrast. In contrast, the M pathway mediates perception of low spatial frequencies, responds to high temporal frequencies, and has high sensitivity to contrast [15]. Electrophysiological studies have proven the existence of a third, middle temporal (MT) pathway [16], described as V5 – the fifth visual cortex. CSF is sensitive to dispersion, aberration, and luminance, and is altered in many diseases, including cataract, glaucoma, optic neuritis, diabetes, multiple sclerosis, keratoconus, amblyopia, and refractive disorders [3]. The influence of three diseases on contrast perception: glaucoma, age-related macular degeneration (AMD), and amblyopia is discussed in the following section.

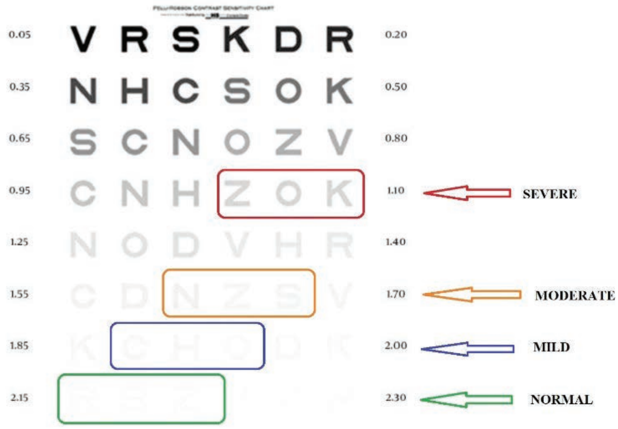
CONTRAST PERCEPTION IN GLAUCOMA

Contrast sensitivity in glaucoma is impaired and gradually deteriorates, affecting such visual functions as visual acuity, dark adaptation, and the detection of patterns and moving objects [17]. It has a tremendous impact on those patients' quality of life. Moreover, Keurten et al. [18] conducted a study showing a connection between loss of CS and reduced retinal blood flow in patients with normal-tension glaucoma. As the disease is one of the most common causes of blindness worldwide, early diagnosis plays a key role. Standard examination in glaucoma is based on tonometry, funduscopy, and perimetry. However, as noted by Thacur et al. [19], perimetry is not sufficient as a diagnostic criterion in the early stage of glaucoma because CS also changes. Thus, CS should serve as an additional diagnostic criterion due to its high sensitivity.

Richman et al. [20] reported that CS loss is more closely related to glaucomatous damage than bilateral loss of the visual field. Significantly, CSF disorders may be visible long before damage to the retinal nerve fiber layer and before a decrease in VA. These findings led to the development of the Spaeth–Richman Contrast Sensitivity Test, which measures CS in both the central and peripheral visual fields. Further studies have confirmed the high practicality of this test [21]. Changes in CS in glaucoma correlate with alterations in the central visual field [22], particularly in the fovea, which disrupt visual function [23] and may affect macular thickness [24]. Moreover, changes in CSF in glaucoma include loss of both luminance and chromatic vision. This can result in a total reduction of colour contrast measured in the peripheral retina [25]. Shafer [4] reported that in severe glaucoma, contrast sensitivity may be reduced by half to 1.0 log. CS worsens as glaucoma progresses. The relationship between disease stage and CS, compared with the normal eye, illustrated in figure 3.

FIGURE 3

Contrast sensitivity across glaucoma stages compared with a normal eye. Source [5].



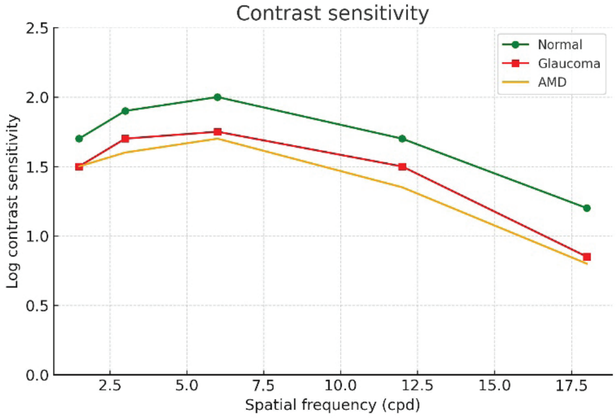
CONTRAST PERCEPTION IN AGE-RELATED MACULAR DEGENERATION

Alongside glaucoma, AMD is one of the most common eye diseases leading to permanent visual impairment. With aging, a progressive decrease in CS is observed, which may decline from a normal CS score to 1.7 log. It has been shown that CS disorders, similarly to decreased VA, are an important factor affecting the quality of life in AMD patients [26]. Notably, CS deterioration occurs faster than VA deterioration, which can be extremely useful for earlier diagnosis. Ridder et al. [27] reported that CS deficits become more pronounced in intermediate AMD under low-light conditions. However, CSF measurements alone are not sufficient for detecting early AMD. Ou et al. [28] confirmed the association between reduced contrast sensitivity in both intermediate and advanced AMD under photopic and mesopic conditions that is, in both standard and low luminance. In the case of CS for first- and second-order stimuli, a lack of gender correlation was reported, but age correlations for CS were confirmed [29]. Furthermore, they demonstrated those stimuli differ in their susceptibility to neurophysiological changes in the elderly, with deterioration in second-order stimuli occurring earlier, yet progressing more slowly. In addition, Keane et al. [30] highlighted the utility of OCT, noting a significant correlation between increased total subretinal tissue and decreased CS in patients with neovascular AMD. This is consistent with findings showing that patients with AMD exhibit cone function impairment at short wavelengths and deficits in colour vision particularly for black, blue, and yellow which especially affect those with wet AMD [31].

In summary, the reduction in CS observed in both AMD and glaucoma is comparable, averaging about 12% lower than in healthy individuals, as shown in figure 4.

FIGURE 4

Contrast sensitivity in glaucoma and age-related macular degeneration compared with a normal eye. Source [5].



CONTRAST PERCEPTION IN AMBLYOPIA

Amblyopia, apart from strabismus, is a common visual impairment affecting 2–5% of the population and resulting in multiple visual deficits [32]. The reduction in CS in amblyopia is evident in both mesopic and scotopic conditions across various spatial frequencies, reaching up 25% of norm. Studies have shown a significant relationship between the severity of amblyopia and the reduction in CSF [33]. According to Dorr et al. [32], contrast sensitivity function in amblyopia was particularly impaired at medium and high spatial frequencies and to a greater extent in strabismus. Moreover, CS dysfunction in amblyopia persists despite achieving normative visual acuity, with the parvocellular (P) pathway, as demonstrated by Wang et al. [34], proving resistant to treatment. Similarly, Chatzistefanou et al. [35] demonstrated that in strabismic amblyopia, CSF remains markedly reduced in both treated and untreated patients with normal acuity. CS deficits have also been observed in anisometropic amblyopia associated with myopia, which consistent with earlier research on hypermetropic amblyopia showed a reduced CSF level for medium and high spatial frequencies [36]. Furthermore, Kosovicheva et al. [37] emphasised that although CSF is impaired in amblyopia, the temporal contrast sensitivity function (TCSF) and temporal aspects of contrast sensitivity remain preserved, but only at low spatial frequencies, meaning that threshold sensitivity in this range is often maintained. This selective preservation may explain why patients can still detect large, high-contrast objects, yet face difficulties in visually demanding environments with low or variable contrast.

Reduced contrast sensitivity in amblyopia contributes to so-called vision learning disorders (VLD), which include, among others, slower reading speed and difficulty distinguishing figure from background. This hinders school learning and may affect a child's motivation. In addition, CS deficits impair spatial orientation, for example, during sports activities. Importantly, even after amblyopia has been treated, CS impairment may persist, reducing the quality of visual functioning and, consequently, quality of life. Therefore, it is particularly important in children with amblyopia that visual function assessment also includes contrast sensitivity testing, as it provides a more accurate prediction of functional vision potential and greater diagnostic sensitivity [38].

CONCLUSION

A reduction in contrast sensitivity is a frequent consequence of various eye diseases and can have a substantial impact on visual function and overall quality of life. Consequently, the assessment of visual performance should extend beyond standard visual acuity measurements. Including contrast sensitivity evaluation provides a more comprehensive understanding of how patients see and function in daily life. It may also serve as a sensitive indicator of early visual dysfunction, enabling detection of problems that are not yet apparent in visual acuity testing. Therefore, contrast sensitivity assessment should become a routine element of ophthalmic examinations. The Pelli-Robson chart, which is widely available and relatively inexpensive, is well suited for clinical use and should be a standard tool in every ophthalmology clinic.

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