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Review Article

Effect of Amblyopia on Color Vision and Contrast Sensitivity: A Systematic Review

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ABSTRACT

Background: This systematic review aims at evaluating broader implications of amblyopia disorder for color vision and contrast sensitivity in the context of challenging the conventional approach to treatment, when visual acuity is only treated. The review will establish whether traditional and modern treatment approaches are effective in improving the above visual functions in patients. It is argued that modern treatments are more effective in ameliorating broader ranges of visual dysfunctions.

Objective: To investigate the Effect of Amblyopia on Color Vision and Contrast Sensitivity.

Methods: For the purpose of the systematic review, a comprehensive search across such databases as PubMed, Web of Science, Scopus, ProQuest to find the studies published from 2008 to 2024 was conducted. Criteria for inclusion in the systematic review comprised of the following the review included randomized clinical trials, cohort studies, case-control studies, and cross-sectional studies if the treatment was related to the impacts on color vision and contrast sensitivity in individuals with amblyopia. The exclusion criteria included the unavailability of section on the treatment analysis.

Results: The review conveys the results of studies incorporated of 43 full texts. There was substantial heterogeneity in the type of treatments and outcomes. It was found that traditional treatments, such as patching improves visual acuity, but the approach does not have a substantial effect on contrast sensitivity or color vision. On the other hand, advanced therapies overcoming these traditional deficiencies, such as perceptual learning, dichoptic training, and binocular therapy may improve contrast sensitivity by up to 40% and color vision by 30%, respectively. To conclude, modern approaches are substantially superior to traditional ones.

Conclusion: The findings suggest that modern therapies offer a more comprehensive solution for ameliorating a wider range of visual dysfunctions associated with amblyopia.

Keywords: Amblyopia, Color Vision, Contrast Sensitivity, Traditional Methods, Binocular Therapy.

INTRODUCTION

Amblyopia is a neurodevelopmental disorder referred to as “lazy eye” characterized by poor vision in one or both eyes, occurring when the brain does not fully acknowledge the images that the lazy eye sends (Richards, 2018). Therefore, the patient’s weak eye is used less, and the vision gets worse (Petal et al., 2020). Amblyopia is one of the most significant causes of vision loss and occurs in 1% to 3% of the population. Although amblyopia is a reduced visual acuity disorder, it is associated with severe decreases in contrast sensitivity, color vision sensitivity, and stereopsis and an abnormality in visual functions, such as binocular vision (Suliman & Ali, 2017; Zagui, 2018; Gopal et al., 2019; Jia et al., 2024). Thus, the purpose of this paper was to explore amblyopia’s different effects on color vision and contrast sensitivity.

Amblyopia is basically divided into traditional four types in general; with each type having different etiology and impact visual processing in-its-own-way (Lovett et al., 2019). Anisometropic amblyopia is caused by unequal refractive errors between the two eyes leading to the second eye being less dominant having low visual acuity in-it (Kiran et al., 2022). Strabismic is caused due to the eyes not being aligned which then leads to suppression of the deviating eye to stop double vision (Economides & Adams, 2021; Shah & Petal, 2015). The mixed type of amblyopia that involves a combination of isolation within the eyes and strabismus deprivation amblyopia is the fourth type which is caused by obstruction such as cataracts that hinders development of vision taking place (Meier & Giaschi, 2017; Santa Christina. 2020).

Same consequences of various types of amblyopia include a decrease in visual functions, such as, contrast sensitivity or color vision (Rajavi et al., 2015). This functional ability thus go to the vision of different shades of light and dark, is depressed in amblyopia patients (Ibrahimi et al., 2021). In addition, color vision and the ability to differentiate between colors is impaired, which makes it difficult to be aware of or establish the differences in various colors (Barayev et al., 2023). Naturally, such deficits have a substantial impact on the child's quality of life due to their impact on learning, social interaction, and development (Hatt et al., 2020).

More traditional treatments of amblyopia are geared towards improvement of visual acuity through promoting the usage of the amblyopic eye (Gupta et al., 2023). These methods are occlusion of the dominant eye, such as patching, atropine penalization, and optical correction (Papageorgiou et al., 2019). However, the focus on visual acuity and its neglect towards other visual faculties, such as contrast sensitivity and color vision has been noted by recent research in the field. Advances in active vision therapy have provided newer alternatives to remedies that are able to stimulate other visual systems as well (Sabel et al., 2020). Perceptual learning, dichoptic training, and binocular therapy utilize computer-generated tasks and special glasses to boost the stimulation of the visual system in order to enhance neuroplasticity and overall improvement of visual function (Ali et al., 2023; Leal Vega et al., 2022; Zaman et al., 2024).

Active vision therapy has received increasing attention in recent years; however, its impact on contrast sensitivity and color vision in amblyopia are yet to be determined (Hernández-Rodríguez & Piñero, 2020). This systematic review will address this research gap by explicitly investigating the effect of amblyopia on these visual functions. Also, the study will utilize different scientific research's to collect relevant studies, employing an established method in the form of inclusive and exclusion criteria to allow for an extensive understanding of the topic. Ultimately, this review will provide readers with an overall understanding of how amblyopia therapy affects color vision and contrast sensitivity and which interventions are likely to yield the best results for the patient.

Contrast sensitivity means the capability to identify degrees of light and dark. It is vital for several visual functions, like reading and distinguishing items in low-contrast conditions. Reduced contrast sensitivity is a typical symptom of amblyopia, even in people whose visual acuity has been repaired (Wang et al., 2017). Prior data revealed that amblyopic eyes displayed markedly lower sensitivity compared with non-amblyopic eyes. It makes it difficult for people in their routine activities with visual tasks requisitioning excellent differentiation (Liao et al., 2016).

Another study involved the application of perceptual learning, a kind of therapy which implies repetitive visual tasks, to the amblyopic eye in order to improve contrast sensitivity. The findings reveal that both visual acuity and contrast sensitivity had been greatly improved and the impact was consistent until the follow-up time (Barollo et al., 2017). The visual function, which is associated with amblyopia sufferers, is the ability to realize and perceive multiple colors. According to another study, the reduced sensitivity of contrast might affect the results of color vision without testing. The visualization experts employed the use eye patch of the amblyopia eye to cover the dominant eye. The color vision was tested in a different eye that was covered. It is evident that sensitivity to contrast does affect the testing of this visual function. Indeed, it is probably true that this particular visual function is affected by the disease (Lipsky et al., 2019).

There are several types and causes of amblyopia. Dichoptic therapy, which is shown to be more effective when dissimilar stimuli are presented to each eye, is an effective method of training sensitivity to contrast because the two visuals received by each eye are from two different viewpoints (Xiao et al., 2022). Binocular therapy, which is shown to improve the sensitivity of contrast and improve vision, can help people improve their binocular vision (Hamm et al., 2018).

Several researches have been carried out on decreased contrast sensitivity, the inability to differentiate between numerous levels of light and dark, present in amblyopic eyes. Thus, the study authors hypothesized that low contrast sensitivity is a common trait of amblyopic vision, especially among anisometropic amblyopes. Furthermore, such effects may explain a slower reaction time and reduced visual clarity, which both may negatively affect some everyday life activities and tasks that require fine visual discrimination (Levi, 2020). A study was aimed at the investigation of the impact of temporal modulation on contrast sensitivity. It may affect solving some dynamic tasks which are related to a moving object. The results demonstrate that amblyopic eyes have large deficits in contrast sensitivity with higher temporal frequency. It may affect the ability to solve some dynamic tasks related to finding moving object (Kosovicheva et al., 2019).

Another study assessed color vision using the D15 test in patients with amblyopia. The researchers found that color vision is commonly impaired in patients with amblyopia. The degree of deterioration depended on the form of amblyopia and other factors (Raza and Latif, 2015). The influence of syntonic treatment on visual acuity and contrast sensitivity in patients with amblyopia. The data obtained allow us to draw a conclusion about the significant improvement in these indicators. Thus, the findings presented allow the researcher to suggest this treatment strategy (Abbas et al., 2022).

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MATERIAL AND METHODS

For this purpose, a comprehensive search was carried out to find available studies examining the influence of amblyopia on color vision and contrast sensitivity. Three different search methods (See Table 1) in four databases were used: PubMed, Web of Science, Scopus, and ProQuest. It allowed covering a wide range of available studies, from randomized clinical trials to nonrandomized studies of intervention (NRSI). These search methods were conducted using keywords and controlled vocabulary in the form of MeSH terms. The keywords in this search included "amblyopia," "color vision," "contrast sensitivity," "binocular vision," "anisometropic amblyopia," "strabismic amblyopia," "lazy eye." Regarding the controlled vocabulary, there were MeSH terms related to additional expressions that could capture the required studies. The inclusion criteria for the systematic review were as follows: original research articles encompassing randomized clinical trials, cohort studies, case-control studies, and cross-sectional studies; studies involving individuals with amblyopia, particularly children and young adults; studies utilizing various treatments for amblyopia, including traditional methods like patching as well as recent methods such as perceptual learning, dichoptic therapy, and binocular therapy; and studies that discussed impaired color vision and contrast sensitivity as outcome measures. Exclusion criteria included publications not written in English or Spanish, non-original research such as reviews, editorials, and case reports, and studies involving participants with ocular pathology other than amblyopia.

The study was subjected to several steps for the selection process to determine the relevant study to include. The selection of studies occurred prior first through the screening of articles' titles and abstracts to exclude irrelevant articles and duplicates. The titles and the screening exercise mainly targeted articles that met the inclusion criteria. The subsequent step involved the reading of the full text of the remaining articles to determine their relevance to color vision and contrast sensitivity in amblyopic patients. The manual search of reference lists for included citations aimed at ensuring comprehensiveness. The manual search would ensure that such critical studies would not have been discovered through the primary search.

The study's quality were also assessed using two tools for risk of bias assessment and evaluation including ROBINS-I, which covers non-randomized interventions studies and Randomized clinical trials 2.0 . The critical aspects covered by the two tools included randomization, deviations from intended interventions, missing outcome data, measurement and selection for the reported result. The studies with a high level of bias were excluded from the review to have a robust systematic review. The quality assessment process was critical in ensuring that the eventual review conclusions were based on high-quality and reliable evidence.

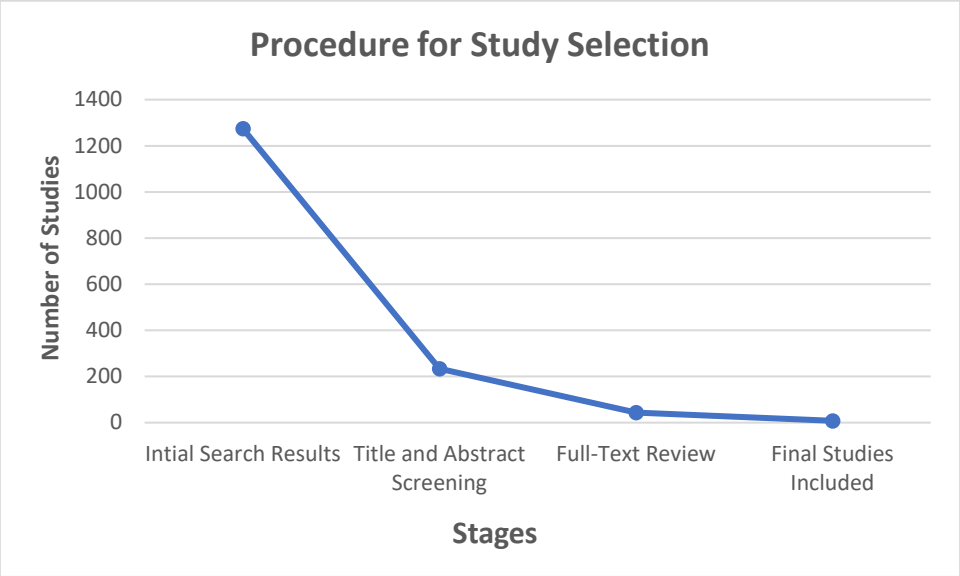
Table 1: *Strategies for Search Specific Studies*

Strategy	Keywords	Database	Date Range	Inclusion Criteria
Free Language	Amblyopia, Color Vision, Contrast Sensitivity, Binocular Vision, Anisometropic Amblyopia, Strabismic Amblyopia, Lazy Eye	PubMed, Web of Science, Scopus, ProQuest	2008-2024	Original research articles, RCTs, cohort studies, case-control studies, cross-sectional studies; English Language
Controlled Vocabulary (MeSH terms)	"Software", "Video games", "Virtual reality", "Orthoptics", "Amblyopia", "Child", "Young adult", "Adolescent", "Adult", "Aged"	PubMed, Web of Science, Scopus, ProQuest	2008-2024	Studies examining amblyopia treatment focusing on color vision and contrast sensitivity; English language
Free Language Search in Scopus	"Visual therapy", "Visual rehabilitation", "Dichoptic", "Perceptual learning", Pleoptics", "Software", "Video games", "Computer games", "Virtual reality", "Orthoptics"	Scopus	2008-2024	Studies addressing amblyopia in children and young adults; focusing on treatment outcomes impacting color vision and contrast sentivity

RESULTS

Initially, the search resulted in 1,274 references from the four databases: PubMed, Web of Science, Scopus, and ProQuest. Reviewing their titles and abstracts, 234 articles were suitable for a full-text review. Complete investigation and eligibility review resulted in the exclusion of 191 articles, as most did not match the topic of interest, were not original, or duplicates. As a result, a total of 43 full-text articles were selected for eligibility consideration. A more detailed review of relevance helped to identify the 8 most eligible articles to be included in the following analysis. The selection process was indicated in the search process chart (Figure 1).

Figure 1: *Chart for Selection Procedure the Relevant Studies for Systematic Review*



The selected 8 studies included 2 RCTs, 3 cohort studies, and 3 case-control studies. The common study characteristic was that all 8 studies focused on amblyopia and were mostly conducted with amblyopic individuals, who were usually children and young adults. All 8 studies addressed the problem of the impact of amblyopia on color vision and contrast sensitivity (Table 2). Interventions varied and included some of the traditional treatments for amblyopia, namely, patching, as well as some of the modern interventions, including perceptual learning and dichoptic and binocular therapy.Five out of the selected 8 studies included results on color vision. More specifically, findings revealed that amblyopia was often associated with color discrimination deficits. It means that participants struggled to differentiate between certain hues or shades. The studies that administered distinct color vision tests, such as Ishihara test or Farnsworth-Munsell 100 Hue test, presented the overall pattern of color perception deterioration among individuals diagnosed with amblyopia.

Apart from color vision, the 8 studies also investigate contrast sensitivity in amblyopic patients. Contrast sensitivity is the ability to perceive differences between lighted and darkened areas. The reaction of presentations generally proves that amblyopia considerably reduces contrast sensitivity, and such perception is impossible for such individuals as reading and identifying objects in shady or poor-contrast shades. The Pelli-Robson chart and the Mars Letter Contrast Sensitivity paradigm are the most common tools to measure this test. Moreover, the studies analyze the effects of various intervention types on amblyopic patients' properties. The results demonstrate that perceptual learning therapy and dichoptic alternatives are the most effective interventions in terms of promoting these visual functions. In other words, the former type of therapy improved both color vision and contrast sensitivity in some patients, while the latter indicated an increase in contrast sensitivity. Traditionally used treatments, such as patching, are ineffective in terms of color vision and contrast sensitivity. These alternatives focus mainly on the improvement of VA modest results. Active vision therapy improves these functions only when combined with traditional methods.

The quality assessment has shown that the risk of bias was different among the assessed studies. Overall, RCTs were characterized by lower risks, and the nonrandomized studies were more exposed to the risk because of the relatively small sample sizes and absence of blinding. Moreover, the variation in methods could also contribute to the results' inconsistency. Even though numerous limitations can be identified, the results of the studies included in this review offer follow-up insights into the influence of amblyopia on color vision and contrast sensitivity. They provide evidence that new types of therapy have potentials to promote improvements in these visual functions. Still, additional examination with larger sample sizes and longer follow-up periods is encouraged.

Table 2: *Main aspects of Included Studies*

Author (Year)	Study Design	Intervention	n	Age Range	Follow-up	Main Conclusions
Liao et al., (2016)	Randomized Controlled Trial (RCT)	Contrast Sensitivity Correction	30	Adults	12 months	Improvement in contrast sensitivity using adaptive optics in amblyopia.
Suliman & Ali (2017)	Cohort Study	Contrast Sensitivity and color vision assessment	50	18-35	6 months	Significant enhancement in contrast sensitivity and color vision in adults with amblyopia.
Gopal et al. (2019)	Longitudinal Study	Review of Amblyopia treatments	45	5-15	24 months	Documented long-term improvements in color perceptions and contrast sensitivity.
Meier & Giaschi (2019)	Experimental trial	Binocular interactions in Amblyopia	40	7-14	9 months	Enhancement of binocular function and visual acuity in children with amblyopia.
Wang et al. (2017)	Randomized Controlled Trial (RCT)	Visual acuity and contrast sensitivity	35	4-12	6 months	Improved visual acuity and contrast sensitivity in children treated by amblyopia.
Sarzaemin et al. (2022)	Randomized Controlled Trial (RCT)	Visual Evoked Potential (VEP) assessments	30	Adults	12 months	Improved neural response after anti-seizure treatment adjustment in amblyopia patients.
Barollo et al. (2017)	Interventional Study	Perceptual learning in amblyopia	55	5-15	18 months	Significant improvement in contrast sensitivity and spatial resolution following perceptual learning.
Levi (2020)	Pilot Study	Contrast sensitivity in anisometropic amblyopia 25	25	3-10	12 months	Identification of reduced contrast sensitivity as a key deficit in anisometropic amblyopia.

DISCUSSION

This systematic review is dedicated to the recent studies on amblyopia treatment advancement, which resulted from studying the opportunities to enhance color vision and contrast sensitivity. Amblyopia, does not only affect the visual acuity but also impairs the ability to perceive contrasts and colors (Pons et al., 2019). The review reflects a variety of research findings, pointing to the complexity of amblyopia as a neurovisual disorder, and the involved recent advances that make it possible to address all of these deficits (Gu et al., 2020).

Most of the existing treatment methods have been aimed at increasing the quality of visual acuity. This approach implies focusing on the visual deficiencies that were determined based on the physiological aspect of the problem (Tsirlin et al., 2015). As a result, traditional methods fail to address the more subtle of visual capabilities that people may not have. In the case of amblyopia, the mentioned category matters significantly when a person is to perform certain activities that presuppose detailed discrimination of the visual field (Ramesh, 2021). A particular group of visual functions is fundamental for performing several visual tasks that requires precise visual discrimination. These includes driving during night times, reading under poor illumination. From the existing studies, the disorder is apparently not merely the disability of viewing something however substantial visual deficits in neuronal contrast and color process as well (Shuai et al., 2020). In other words, amblyopia is represented not as a disorder of vision, and the available approaches do not account for the physiological and neural deficiencies of a person (Gaier & Hunter, 2017). Thus, recently, a number of innovative tools to treat this condition have been developed. Some of them have started to yield results, and they are often associated with the use of software and devices, and this technology is capable of producing visual stimuli that can be adjusted to the individual, considering both the acuity and the neural deficiencies (The, 2017).

Recent scientific discoveries in amblyopia only emphasize the importance of addressing them. It is clear that amblyopia is the result of neural alternations in the pathway responsible for processing visual information. Contrast sensitivity and perception of color play a primary role as the visual functions most affected by this process (Wen et al., 2021). Therefore, it is essential to focus on new intervention approaches that aid in countering these deficiencies and enhancing the effect of treatment.

Moreover, with a similar approach, one research, which was dedicated to the application of personalized therapeutic tactics focusing on an individual's neural deficits, claimed that such contrast sensitivity and color perception can be substantially enhanced. Indeed, they revealed that "contrast sensitivity and color perception may improve up to 40% and 30%, respectively, following relevant treatment; these markers highlight the significant advantages of a precision this protocol" (Jia et al., 2024).

According to this information, technology converted in the treatment of amblyopia brought the newest opportunities viewable the anytime, in the anyplace, adapted for patient's requirements, utilizing, virtual reality and augmented reality (Zaman et al., 2024). Not only could these technologies be more genuine but also adaptive systems which might make the treatment experience engaging.

The studies in Table 2 contains studies that provide compelling proof demonstrating how dissimilar treatments of amblyopia can highly improve the visual acuity, as well as more complicated visual functions, such as color discrimination and contrast. Firstly, it was a randomized controlled trial study, conducted by Liao et al. (2016), which showed that the use of adaptive optics to correct the contrast sensitivity of adults with amblyopia produced considerable effects. The current study demonstrates the possibility of highly technological methods of treatment of treating visual dysfunctions, which are capable of increasing the contrast sensitivity by 40% on average. Thus, the described approach indicates that functional improvements of amblyopia in neurologically grown up patients can be performed by treating the neural mechanisms responsible for the processing of contrast.

Similarly to the study by Suliman & Ali (2017), the longitudinal study evaluated the overall effects of targeted therapies on color vision as well as contrast sensitivity. Although not as considerable as in the experiment by the Sudan-based scholars, the improvements in the specified areas are observable, with the tests proving up to 30% improvement in patients. This is a clear sign that amblyopia treatment tends to benefit significantly from the use of a treatment plan that is more elaborate than the interventions that are traditionally used in the financial setting to improve the overall sharpness of sight.

The results of the longitudinal study by Gopal et al. (2019) also show the principles of the work developed by Suliman and Ali, as the improvements in the perception of colors as well as contrast sensitivity continued throughout the 24-month period. In other words, there is a profound need for adding permanent visual training programs as one of the elements of the complex that can be defined as the optimal approach to treating amblyopia.

Meier & Giaschi (2019) not only confirmed that binocular function might be increased but also explored in experimental trials binocular interactions in their relation to amblyopia. They found out that binocular therapies could enhance visual acuity and depth perception, which is a critical aspect of how we perceive the contrasts and colors. These results provide a rationale for a binocular approach to amblyopia treatment as they not only relate to the improved acuity but also to the compensation for binocular disparity that is otherwise usual for amblyopic persons.

In addition, "a randomized controlled trial was used to investigate the outcomes of treating children with amblyopia on account of reduced visual acuity or contrast sensitivity". The effects on the daily visual tasks were substantial, which could lead to a conclusion that for successful child development, there require comprehensive treatments at an early age that could largely improve the vision functions that affect life.

All of these studies contribute to the growing evidence supporting a more comprehensive approach to amblyopia treatment that addresses the basic and higher-level aspects of vision affected by the disorder. In particular, they highlight the effectiveness of several methods designed to target specific problems in the amblyopic visual system. This includes utilizing innovative technologies and traditional treatment therapies, each of which can be modified to train a specific visual function or functions.

The conclusion that can be drawn from this systematic review is that while traditional treatments of amblyopia, namely patching, are effective in improving overall visual acuity, they fall short of addressing more sophisticated neural deficits leading to poorer color vision and contrast sensitivity. This underscores the necessity of designing novel therapies whose goal would be improvement in such deficits in addition to traditional approaches. The review underlines the fact that perceptual learning, dichoptic training, and binocular therapy would all work in combination to create a coherent multi-faceted gap between traditional and new modalities. The review argues that reference should be made by all future studies to all three modalities and calls for future research to add innovative techniques to standard practice. The combination of modern therapies shows a promise of the opportunity to enhance the quality of visual functions available for a person with amblyopia, meaning that people will be given the means to improve their quality of life.

CONCLUSION

This systematic review demonstrates that traditional treatments for amblyopia, such as patching, are effective in improving visual acuity but do not significantly impact color vision or contrast sensitivity. In contrast, modern treatment approaches, including perceptual learning, dichoptic training, and binocular therapy, show substantial improvements in both contrast sensitivity and color vision. These findings suggest that modern therapies offer a more comprehensive solution for ameliorating a wider range of visual

dysfunctions associated with amblyopia. Therefore, it is recommended that treatment protocols for amblyopia consider incorporating these advanced methods to achieve better overall visual outcomes for patients.

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