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Chapter 4

Glare and Ocular Diseases

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Additional information is available at the end of the chapter

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Abstract

Glare is the result of veiling luminance from the different light sources we are exposed to in our everyday lives. The luminance from glare can cause problems ranging from the discomfort of our eyes to vision loss. All individuals are affected by glare issues but those problems are intensified in patients living with ocular diseases. Therefore, understanding the effects of glare is applicable to elucidating visual function and pathology. This makes glare testing highly necessary in both clinic and research. However, there are many components involved in glare testing that makes attaining valid results difficult. This is evident in the flaws of current glare devices and the lack of a standardization of measuring glare. Despite the insufficiency of most glare devices, evaluating those weaknesses can potentially lead to a better understanding of glare and glare testing.

Keywords: glare, disability glare, cataract, glaucoma, macular degeneration, stereopsis, corneal diseases, keratoconus, glare testing, glare devices, contrast sensitivity, visual acuity, mesopic, photopic

1. Introduction

Our eyes are exposed to numerous light sources and at various intensities such as the rays from the sun or light from the headlights of driving cars. When we visually experience a veiling luminance from any light source it is a phenomenon known as glare. There are different types of glare: disability glare, discomfort glare, dazzling glare, and scotomatic glare [1]. We commonly experience discomfort glare when the intensity of the light source causes an uneasiness or annoyance on our eyes. Furthermore, we also regularly encounter disability glare. Disability glare is the scattering of light that enters our eyes that leads to visual impairment. Since disability glare directly affects our visual ability, it has been a focus of research, which particularly is important in an aging population and various disease states.

Light is focused to the retina to receive visual information of the world around us. Thus, the transmittance of light is integral to how we visually function. To this accord, the human visual system is finely tuned to allow the maximum amount of light transmission to the retina with least scatter. The retinal anatomy is also tuned to decreased sensitivity to shorter wavelength light and the retinal pigment epithelium and macular pigment allows the absorbance of stray light. However, disability glare interrupts the direction of light to the eye thereby interfering with the way we see [2]. This is especially debilitating, and the effects of glare are worsened in those who suffer from ocular pathologies. The many layers and components of the eye is involved in directing and processing light and cues to interpret our surrounding. Thus, a disease that impacts any part of the eye can exasperate disability glare decreasing the ability to see and perform daily activities such as driving.

The impact of disability glare makes it an important visual function to measure. However, currently there is no standardized way to measure glare [3]. There are both commercial and self-made device that hope to address this problem. However, more evaluation will be necessary to solidify their validity for research and clinical use. As a result, much of disability glare in visual function and pathology is still under research.

2. Pathological conditions

2.1. Corneal diseases

The major function of the cornea is to direct and refract light to the retina as well as provide structural support to the eyeball. Thus, preserving transparency and corneal shape is highly important in visual function [4, 5]. In various corneal diseases, the cornea is damaged through inflammation, swelling, and dystrophy [6]. The transparency of the cornea is the function of tight controls on water content, diameter of the collagen fibrils, and the spacing between the fibrils. The collagen fibrils have a diameter of 27–35 nm and the distances between fibrils are 41.4–60 nm [7]. The precise pattern of the collagen fibrils enables efficient light transmittance with minimal scattering or absorbance in a healthy eye. Any increase or decrease in the distance between the fibrils will compromise the transmittance of light [7].

Corneal edema is one example of a condition that disrupts the uniformity of these fibrils. The increased water content that results in edema changes the distance between fibrils, and thus can affect the overall transparency of the cornea. Reduced transparency, as we know, induces scattering when light enters the eye. Furthermore, scarring of cornea or deposits in the cornea can lead to the scattering of light as well. Post-surgical scarring is known to decrease vision and increase glare [8]. Additionally, certain medications like amiodarone causes cornea verticillata or deposits in the cornea that leads to the scattering of light rays [9].

Moreover, the type of light scatter that occurs can either be backwards or forward light scatter, depending on the angle of deviation light enters the eye. In backward light scatter, the scattering of light causes less light to reach the retina. While in forward light scatter, the scattering of light causes a luminance over the retinal image.

Reduced transparency that leads to increased reflection and scatter of light can potentially cause disability glare. The disability glare along with diffraction and high-order aberration attribute to distorted retinal image, and thus impaired visual function. Components of vision such as contrast sensitivity can be hampered and if scattering is severe can lead to a deficit in visual acuity [4]. Therefore, those with corneal aberrations and abnormalities experience intensified forms of disability glare as well as reduced contrast sensitivity and visual acuity.

Keratoconus is a corneal dystrophy that leads to the progressive thinning of the center of cornea. Corneal thinning causes the center to protrude outward resulting in a cone shape cornea. Those with keratoconus can experience blurred vision as well as sensitivity to light [6]. Being reactive to light can make individuals with this corneal disease vulnerable to disability glare. Jinabhi and colleagues surveyed forward light scatter and visual function in subjects with mild to moderate keratoconus with no corneal scarring or history of ocular surgeries [10]. In the study, keratoconic and normal ocular healthy subjects underwent contrast sensitivity testing and glare testing to evaluate their visual function. The subjects with keratoconus exhibited lower contrast sensitivity than normal ocular subjects in testing. These results agreed with previous studies done and suggested contrast sensitivity was commonly compromised in keratoconus. Furthermore, keratoconic subjects also presented with intraocular scatter that resembled the increased scattering found in older populations or to those with early cataracts. Greater light scatter makes an individual with keratoconus more susceptible to disability glare [10]. More evidence of glare sensitivity in keratoconus could be found in a study done by Mäntyjärvi and Latinen. These researchers measured contrast sensitivity under glare conditions in keratoconic and ocular healthy subjects. The Pelli-Robson chart was used to measure contrast sensitivity. The chart contained letters of decreasing contrast that provided a quick and accessible way to measure contrast sensitivity [11]. The subjects were asked to read the Pelli-Robson chart under glare illuminance provided by the BAT. Then contrast sensitivity performance with and without glare was compared. The results of the comparison demonstrated that subjects with keratoconus experienced greater contrast sensitivity loss when tested under glare conditions than normal subjects [10]. Visual impairments being significantly greater in keratoconic subjects advocates the need for disability glare testing in measuring visual function. Disability glare performance can distinguish between normal individuals and those with ocular pathologies. Thus, in the case of corneal disease, disability glare can be a helpful diagnostic tool and could be a potential method of monitoring the disease progression. NEI VFQ (REF) or similar survey techniques can be used in conjunction to assist in evaluation of quality of vision and may be used in assessing glare related problems (**Figure 1**).

2.2. Glaucoma

Glaucoma is globally the second most common cause of blindness and it affects over – millions worldwide and is a very large socio-economic burden to the health care system [12]. The risk of glaucoma increases with increase age and elevated intraocular pressure is a major risk factor in glaucoma. Lowering intraocular pressure remains the only proven alterable risk factor that has shown to slow down the disease progression. Although, the exact pathogenesis in glaucoma remains to be identified, glaucoma leads to progressive damage to the to the optic nerve fiber

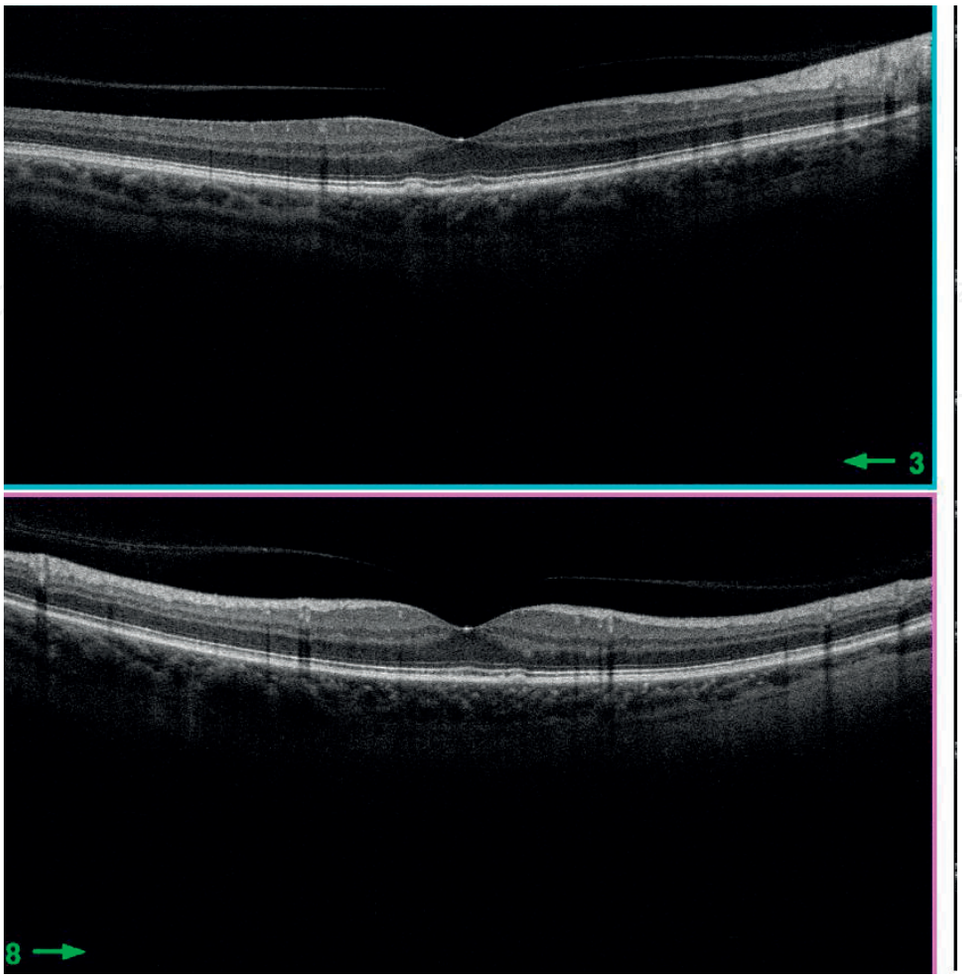

Figure 1. An optical coherence tomography image from a patient with early age-related macular degeneration. The drusen bodies are visible in the retinal pigment epithelium.

layer and changes in visual field that is in part associated to the level of intraocular pressure. If left unmanaged, glaucoma leads to progressive vision loss and blindness [12, 13].

Glaucoma affects several aspects of an individual's daily activities and task. Nelson and colleagues had articulated five major areas of difficulties in individuals with glaucoma. These difficulties include: (1) near vision issues, (2) peripheral vision issues, (3) dark adaptation and glare, (4) personal care and (5) household tasks, and outdoor mobility [14]. Their study measured both visual function and self-reported visual impairments. Subjects underwent multiple functional vision tests to assess the full spectrum of their visual capacity. The tests carried out included: Humphrey Visual Field Analyzer for visual field, Critical Flicker Frequency, Brightness Acuity Test (BAT) for disability glare, Goldmann-Weekers Dark Adaptometer for dark adaptation, Frisby Stereotest for stereopsis, and Farnsworth desaturated D-15 color test for color discrimination [14]. When comparing the results of the functional vision test to the self-reported impairments of the subject, there was a strong correlation between those two measures. Among the functional vision tests, disability glare testing done by the BAT best accounted for the difficulties the subjects reported. Nelson et al. also showed

that disability glare had one of the strongest relationship with the severity of visual field loss [14]. This relationship suggest that progression of glaucoma will be likely accompanied by increasing disability glare. Furthermore, the outcomes of this study affirm disability glare as a concerning visual impairment of glaucoma. In addition, the observed correlation between disability glare and visual field loss can potentially explain the components of the visual system that is involved in glare tolerance. This can in turn further the understanding of overall visual function.

As it is apparent that glaucoma patients suffer from disability glare, they found this impairment most concerning when driving. In surveying the value of various activities, glaucoma patients rate driving as highly important to maintaining their independence [15]. And so, understanding the impairments glaucoma patients face when driving is essential to addressing the concerns and preserving the quality of life for these individuals. Janz and colleagues surveyed open-angle glaucoma drivers and non-drivers about the types of visual problems they encounter during driving at a 6-month and a 54-month period. These surveys were also accompanied by ophthalmologic examinations. From the surveys and examinations, increasing visual field loss accounted for the differences between subjects who stayed drivers and subjects who became nondrivers because of their declining vision [15]. Thus, it can be inferred that those who are still drivers only had mild to moderate visual field loss. Despite little visual field loss, those drivers still reported many visual complications. One of the highest complaints from the drivers were tasks involving glare, which was said to be more troubling than visual search, peripheral vision, or visual processing speed which showed a lot of variation. Glare was a consistent issue among glaucoma drivers. Furthermore, glare was noted as one of the first issues subjects recognized when they first began to struggle with driving [15]. The study presents the driving challenges faced by glaucoma patients due to their sensitivity to disability glare. As mentioned earlier, driving is deemed as an important task to glaucoma patients to sustain autonomy. Therefore, assessing and managing disability glare is imperative to treating the visual impairments experienced by these individuals. Furthermore, since glare is one of the first detectable visual problems, disability glare test can potentially be utilized as a tool to identify the progression or worsening of a glaucoma in a patient. Though it is important to note that in the current state, it may be able to identify progression of the disease but may not give idea of the localization of the retinal damage in this disease. It will be interesting to evaluate the glare tolerance in various quadrants to see if the quantification of glare in specific locations is more sensitive than the non-specific glare tolerance testing.

2.3. Cataracts

The lens is a specialized structure that relies on its transparency, high refractive index, and curved surface to project clear images to the retina. Most of the lens comprises of concentric elongated fibers covered with an epithelium on its anterior surface. The epithelium along with the superficial fiber cells secrete an elastic extracellular matrix that encases the lens in what is known as the capsule [1]. Below the capsule, at the equator of the epithelium is where new fiber cells arise and differentiate [2]. The newer fiber cells constitute the periphery of the lens, named the cortex [1]. While the center of the lens is comprised of older fiber cells, some

originating from embryonic and fetal development, known as the nucleus [1]. Maintaining the transparency of the lens depends on the integrity of the arrangement of these fiber cells. However, as we age, oxidative damage and protein instability can accumulate, forming opacity in the lens and disrupting vision.

Cataracts is a disease cause by an opacification or cloudiness of the lens in the eye. The disease affects certain components of the lens, thus understanding the anatomy of the lens is important to pathophysiology of cataracts. There are various types of cataracts, but age-related cataract can be mainly divided into one of three types cortical, nuclear, and posterior capsular. Although, mixed type with features of three cataract types cortical, nuclear and posterior sub capsular are not uncommon. Each type has its own pathophysiology, anatomical differences and prevalence in the population [16]. Nuclear cataracts affect the oldest fiber cells of the lens which are the those formed in embryonic and fetal life. Evidence supports that nuclear cataracts arise due to the accumulation of reactive oxidative species that disrupt the normal protein and lipid components of fiber cells in the nucleus. The resulting cataracts causes patient to experience increase light scatter [17, 18]. However, cortical cataracts occur in matured fiber cells that arise later in life which lie closer to the surface of the lens. The progression of the cortical cataract encircles the outer circumference of the lens. The damages due to cortical cataract is much greater than that of nuclear cataract, the effects [17, 18]. On the other hand, posterior subscapular cataracts take place at the posterior surface of the lens where the cells just below the capsule are swollen. Since, the pathology of posterior subscapular cataracts is at the optical axis, visual function particularly reading tasks are greatly compromised. Furthermore, swelling of the posterior fiber cells impairs visual function even more by increasing the scattering of light [17, 18]. Clinically the cataract that causes the most glare related disability is the posterior subcapsular cataract. This is due two reasons (1) the entrance angle of the peripheral light rays is more oblique than central light rays and (2) the area that the posterior capsule cataract covers is also greater compared to nuclear cataract. Clinically in age related cataract we see mixed type of cataracts that has features that combine the nuclear, cortical and to some extent posterior subcapsular cataract.

The light is refracted through the lens before reaching the retina to be processed, and any sort of opacity that disrupts light transmittance can increase light scatter particularly if the opacity is large and spread throughout the lens. Being prone to disability glare, makes glare one of the biggest visual complaints and impairments experienced by those suffering from cataracts. Glare devices have an integral part in the research behind cataracts and currently, a large basis of literature is focused on the effects of disability glare on cataracts and how to accurately assess these visual challenges. Most glare devices available are geared toward cataract testing with the purpose of mimicking visual problems in real life in a clinical setting with the additional purpose of evaluating, monitoring and treatment of the disease state [2].

Clinically, cataracts are commonly evaluated by visual acuity charts which poses some problems. Visual acuity testing optotypes are at 100% contrast with black letters on white background and do not simulate real life scenario. In many cases, patients with cataract will have good visual acuities meeting legal standards of driving but still report experiencing visual

impairments while driving, difficulties in dimly lit environments and especially with disability glare [19]. Thus, the purpose of disability glare devices and testing methods is to provide additional information and insight that cannot be given with visual acuity testing.

There is evidence that supports that those with cataracts often experience a decrease in contrast sensitivity when compared to the age-match ocular healthy groups without cataract [20]. The contrast sensitivity loss in patients with cataract is even more pronounced under glare luminance [21]. Furthermore, cataract patients also have lower contrast sensitivity in mesopic conditions [1]. This becomes an issue when driving at night because that activity integrates mesopic light levels, contrast sensitivity, and the presence of glare. Thus, patients with cataract frequently complain of debilitating problems related to driving at night, under foggy, or rainy conditions, particularly with the addition of glare from incoming headlights [22]. Thus, as an importance of safety and the quality of life issue for those with cataracts, disability glare testing that accurately measures the challenges of night time driving is necessary. Disability glare in the daytime can also present visual impairments. Glare during the day predominantly originates from incoming rays of the sun. Unlike nighttime glare, daylight glare can be more accurately measured under photopic conditions [23].

There are numerous devices available that intend to simulate glare under the various conditions such as night, foggy, or rainy conditions, however, glare devices are not yet standardized [2]. Thus, the foundation on how to measure disability on those with cataracts have not been set. Though, the present literature already provided some insight to the impairments of cataracts. Research continues to find a valid, repeatable, and reproducible method for testing the disability glare.

Overall it is shown that glare induces a significant loss in visual function and individuals with cataract have further decline in visual acuity and contrast sensitivity in a range conditions with glare.

2.4. Macular degeneration

Centered at the retina is the macula which is highly packed with cone photoreceptors, and xanthophyll pigments that give it a darken appearance [24]. The macula is responsible for the majority of our photopic visual acuity, despite only comprising of less than 4% of the retinal space [24]. A disease known as age-related macular degeneration causes a gradual breakdown of these photoreceptors in the macula as well as changes in the retinal pigment. These damages lead to a decline in central vision [24]. Age-related macular degeneration (AMD) is divided into non-exudative (dry AMD) and exudative type (wet AMD). Early stages of dry AMD symptoms may go unnoticed, but patients slowly experience vision loss and can ultimately be converted to the wet AMD [25]. Some of the symptoms of AMD includes: decrease vision, blurry vision, metamorphopsia, and central scotomas [25].

As mentioned previously, the macula is comprised of xanthophyll pigments, specifically lutein and zeaxanthin. The role of these pigments is thought to have protective effects on the macula, as this is an area vital to visual function. Lutein and zeaxanthin are believed to filter some of

the harmful short-wave length blue light [24, 25]. Additionally, these pigments can also act as antioxidants to tackle free radicals and eradicate reactive oxygen species that damage the photoreceptors of the macula. Furthermore, lutein and zeaxanthin has shown to absorb straylight which can decrease the amount of harmful light entering the retina and possibly lower glare. The protective properties of these pigments led researchers to believe that increasing these pigmentations could potentially improve visual function.

One of the visual functions believed to be improved is disability glare and glare recovery. Stringham and Hammond looked at the relationship between disability glare and macular pigments. They measured macular pigment optical density (MPOD) of their subjects and compared that to their disability glare scores. The disability glare score was attained by measuring the level of illuminance from Maxwellian-View optical system that is high enough to induce disability glare when viewing sinusoidal gratings at 100% contrast [26]. From this test, the disability glare scores calculated showed a strong correlation to the macular pigment density. The researchers attributed the lower disability glare when there is a greater pigment density to the filtering effect of macular pigments. This was supported by the lack of correlation they showed between disability glare scores and macular pigment density when the glare source excluded the wavelengths of light that macular pigments are believed to filter [26]. These results provide compelling evidence for the involvement of the macula in disability glare. Disability glare is most associated with issues involving the optical media of the eye like the cornea and lens. However, as research has shown, the effects of disability glare can also be mediated by macular pigment. This provides more insight to visual function as well as the visual impairments that result from ocular diseases.

In additional studies, Stringham and Hammond recruited normal subjects who were given daily a 500-mg tablet that contained 10 mg of lutein and 2 mg of zeaxanthin over a 6 months period [27]. The research recruited 40 participants consisting of 23 women and 17 men. The subjects were assessed at 1,2,4 and 6-month period where their disability glare, photostress recovery, and macular pigment optical density (MPOD) were measured. As the researchers had done previously, disability glare was tested by utilizing the by the Maxwellian-view optical system to determine the illuminance level sufficient to cause visual impairment. All the subjects except for two had shown increase MPOD at the end of 6 months. The study subject also displayed reduced disability glare compared to baseline, tolerating greater veiling lights before any effects to their vision. On average, the participants tolerated 58% more glare ($p < 0.0001$) [27]. These results proposed a correlation between MPOD and tolerance to disability glare. This was further supported by the two subjects who did not experience any changes. These subjects that did not show an improvement in the MPOD also did not show an increased tolerance to glare. The researchers inferred that the macular pigment reduce glare disability by acting similarly to a yellow filter that cuts out short wavelength light and decreases veiling luminance [27].

From the relationship between macular pigment and disability glare, we speculate that the disability glare experienced by those suffering with macular degeneration can be partially due to the reducing level of MPOD. Moreover, knowing that MPOD can be supplemented and increased leaves possibility to improve the visual function of those with AMD, especially in the visual impairment of disability glare.

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3. Allied visual functions

3.1. Issues involved in glare testing

Disability glare plays an impairing role in many ocular pathologies such as the ones previously mentioned [2]. Thus, glare testing is not only valuable to understanding visual function, but it can also serve as a tool to evaluate the efficacy of treatments and surgeries of ocular diseases as well.

Though obvious that disability glare affects visual function, it still under study of what component of vision is most impaired by glare. Vision involves visual acuity, contrast sensitivity, stereopsis and many other components that can potentially be impaired by glare. Disability glare is commonly evaluated by either visual acuity or contrast sensitivity [28] (**Figure 2**). However, disability glare has shown to influence those aspects of vision differently, and so are important factors to consider when testing glare. Furthermore, glare is also tested under various light conditions such as photopic and mesopic. This is to mimic the changing luminance from day to night. Disability glare effects also varies from different light conditions; thus, presenting its own specific challenges in each light level [29]. Since glare testing is highly specific, appropriate variables must be incorporated for reliable and interpretable results.

Knowing the role of glare in visual function, proper glare testing methodology and devices are important. There are many components involved in glare testing some of which are the type of stimuli, glare source, and conditions. These factors play a role in the effectiveness of measuring disability glare and creating a real-world simulation. The capability of a glare testing method or device depends mainly on three criteria: discriminative ability, reliability, and validity [28]. Since glare methods and devices vary on the components they incorporate, so do their performance on the criteria mentioned. However, most current devices do fail to meet all three criteria, and thus there is still no standard way to measure glare. While there is a lack of standardization, there are a number commercial machines that are utilized in clinics and research [28]. Some of these devices are potentially valuable assessment tools but further research is necessary to evaluate their validity. However, there are many self-made devices created by researchers to address the glare test problem. Those have also shown good discriminative and repeatability. Despite positive findings, these devices and methods are still new and require much more additional research to assess their accuracy and validity.

3.1.1. Stereopsis

Stereopsis is the visual function of depth perception in a 3D world. The visual system integrates binocular disparity to interpret the placement of objects in space. Primarily a binocular visual function, good and balanced acuity of both eyes are necessary for proper depth perception [30].

As with some visual functions, stereopsis has shown to decrease with age even when visual acuity is still good. It is speculated that the decline in stereopsis is due to changes the eye undergoes with aging. The refractive and ocular motor system that can change with age can

Figure 2. Brightness acuity test (BAT) commonly utilized as a glare source for glare testing. Elliot et al. [28].

also influence stereopsis [30]. Alongside other visual functions such as contrast sensitivity and mesopic vision, disability glare has also shown to worsen with age [31]. Seeing a potential link, researchers considered the relationship between disability glare and stereopsis and whether they can predict the performance of one another. Schneck and colleagues measured coarse stereopsis and several other visual functions including disability glare in a population of individuals older than 58 years of age [31]. Disability glare was measured using a low contrast vision chart and a glare source. Further details of the disability glare testing were not given. These visual function tests were then analyzed on its relation to stereopsis. The results demonstrated that those who exhibited good visual function which included performing well on the

disability glare test were also those with good stereopsis. Similarly, when the visual function was low, their stereopsis performance was significantly lowered as well [32]. However, since the research grouped disability glare with other visual components in the analysis, there is no convincing evidence of a direct relationship with stereopsis. The inference that can be made is that an individual with healthy visual function should have both stereopsis and tolerance to disability glare intact.

Despite some correlational evidence, current literature does not show a strong relationship between stereopsis and disability glare. Though they are commonly assessed in visual function, stereopsis may not provide further insight to the effects of disability glare. Thus, glare testing seldom utilizes stereopsis as a measurement of visual performance.

3.1.2. Visual acuity versus contrast sensitivity

Glare testing consists of evaluating visual function under glare conditions. The most commonly used basis to determine visual function is contrast sensitivity and visual acuity [28] (**Figure 3**). The information provided by visual acuity and contrast sensitivity are utilized to determine severity of pathology, the need for ocular surgeries, and evaluate treatments. However, both these measurements convey different information, and so it becomes necessary to assess the validity of visual acuity and contrast sensitivity in evaluating glare. Furthermore, understanding how these measurements influence glare testing, it can provide us with further insight to what glare devices and testing techniques will ensue the most credible results.

Visual acuity is a familiar assessment done clinically using a chart with high contrast letters such as in the Snellen Chart or using symbols such as the Landolt C. The patient is asked to read the row of letters in assorted sizes at a set distance [33]. The smallest optotype the patient can read corresponds to their visual acuity [34]. Visual acuity has been shown to be a valuable tool to correct refractive errors. However, visual acuity has not been as effective in assessing target identification and detection [35]. Furthermore, the black letters on a white background found in visual acuity charts are not representative of the type of objects and conditions that are observed in day to day life. This is where visual acuity falls short of accurately portraying the visual difficulties one can experience in reality.

A less prevalent clinical evaluation is contrast sensitivity where varying levels of contrast is presented in the form of sinusoidal gratings, symbols, or letters. Much of contrast testing is done using sinusoidal gratings which has various phases, frequency, and contrast. The spatial frequency of the gratings correlates with sizes of realistic objects encountered in everyday settings. Low spatial frequencies have larger gratings, therefore is analogous to viewing larger objects. While higher spatial frequencies have smaller gratings, and thus analogous to viewing smaller objects [35]. Testing for contrast evaluates the various brightness and shades of gray commonly observed in real life.

Visual acuity and contrast sensitivity can provide overlapping visual information. Measuring visual function using high contrast and small letters in visual acuity is comparable to high contrast and high frequency optotypes in contrast sensitivity. However, contrast sensitivity has the advantage of incorporating a range of spatial frequencies, specifically low spatial

Figure 3. The Pelli-Robson chart tests varying levels of contrast but only at low spatial frequency. Image courtesy of Clement Clarke International Ltd. Elliot et al. [28].

frequencies which visual acuity lacks. Additionally, contrast sensitivity also supplies information on low contrast sensitivity which is often vision involved with nighttime [35].

There has been debate as to which measurement more accurately pertains to disability glare in real life situations. Increasing evidence in literature has shown that contrast sensitivity is a better predictor and more discriminative of disability glare in those with ocular pathologies than visual acuity. Those with cataracts often complain of visual impairments but measurements of their visual acuities meet normal standards. Hence, visual acuity may not be sufficient to identify problems caused by glare. Additionally, valuable information on visual function can be extracted by contrast sensitivity testing. A comparison study done by Elliot et al. looked at both the predictability of visual acuity and contrast sensitivity in subjects with early cataracts [36]. Since contrast sensitivity comprises of multiple factors, contrast was measured at high and low spatial frequencies. LogMAR charts with different contrasts was

used to the measure the contrast sensitivity. In an age-matched evaluation of normal and cataract subjects, high spatial frequency contrast sensitivity showed the most visual impairments in subjects with early cataracts than low spatial frequency and visual acuity. An example of contrast sensitivity testing in low spatial frequency is the use of the Pelli-Robson chart. As this study has shown, low spatial frequency does not provide additional information or have good discriminative ability. This is further supported by another study completed by Elliot and his colleague, Bullimore. In their study, the Pelli-Robson chart in conjunction with the glare source from the BAT also showed poor discriminative ability. The researchers also believed this was attributed to the low spatial frequency of the Pelli-Robson chart [28, 36].

Furthermore, Abrahamsson et al. carried out a studied that assessed the sensitivity of visual acuity and contrast sensitivity to reflecting pathological differences under glare testing. Abrahamsson et al. was introducing a new methodology and device to test for glare [21]. The device had a point light source and used sinusoidal gratings as a measure of contrast sensitivity. The study used a glare score to analyze visual function between subject groups. The glare score was determined by using the lowest contrast visible to the subject. Once calculated, cataract and normal age-matched subjects were compared. Additionally, their visual acuity was also tested separately. By using contrast sensitivity as the basis of visual function, the glare device attained a disability glare score that correlated with the opacity of the lens in cataract patients. However, visual acuity showed a low correlation with the disability glare score, indicating that visual acuity may not be sensitive enough to detect changes in opacity [21]. These results suggest that contrast sensitivity tests can reflect subtle physiological changes. This can be beneficial to monitoring the progression of a disease and allow intervention before late stages. Also, contrast sensitivity can potentially lead to earlier detection of ocular pathologies.

While discrimination is necessary in glare testing, reliability is also highly important in attaining meaningful results. In the study done by Abrahamsson mentioned previously, the reliability of their glare device which used contrast sensitivity was good [21]. However, keep in mind that their retest was done on a small number of subjects and so further testing is necessary. While visual acuity tests have shown little discriminative ability, Elliot and Bullimore found glare testing that used visual acuity displayed high reliability. This is a potential positive in utilizing visual acuity in glare testing. The Berkeley Glare Test and the Regan charts using the BAT (Brightness Acuity Test) as the glare source are examples of glare tests using visual acuity [28]. In that same study, the evaluation of glare devices, Vistech and Miller-Nadler Glare Tester, which utilized contrast sensitivity demonstrated low reliability [28]. However, both those devices also exhibited little discriminative ability. Hence, the problem may reside in the design of the device and less so on contrast sensitivity. Moreover, the reliability of both visual acuity and contrast sensitivity is still not clear and their reliability needs to be further examined to determine its effectiveness in evaluating glare.

3.1.3. Lighting conditions

The measurements of visual function for disability glare are important considerations. However, it is also necessary to keep in mind that both visual acuity and contrast sensitivity perform differently depending on lighting conditions. Thus, one must consider the luminance

levels used during disability glare testing and how that relays to realistic encounters in everyday situations.

Contrast sensitivity performance in photopic conditions do not always correlate with mesopic conditions. Hertenstein et al. compared contrast sensitivity under both photopic and mesopic conditions [37]. Individuals recruited for the research comprised of normal, cataract patients, and glaucoma patients. The study utilized a glare testing device known as the Mesotest for the mesopic condition while using two different visual acuity test, Freiburg Acuity and Contrast Sensitivity Test (FrACT) and the Mars Letter Contrast Sensitivity Test for the photopic condition. Furthermore, the three testing methods were also retested to assure the reliability of the results. Overall, the study demonstrated that high mesopic contrast sensitivity score correlated with high photopic contrast sensitivity score. That correlation was also true when the subjects had low photopic contrast sensitivity score and low mesopic scores. However, high photopic contrast sensitivity score did not show the same predictability because individuals with those scores had various mesopic contrast sensitivity scores [37]. This suggest that to fully understand the visual impairments of disability glare, glare must be tested in different light conditions. Disability glare is present in everyday life at various light settings and so testing in many conditions provides more applicable knowledge of impairments patients face daily. As research has shown, visual performance differs depending on lighting and one condition cannot completely predict the results of another. However, testing under mesopic conditions may provide more information about visual function because a high score correlated to good vision in both light levels.

In patients with ocular pathologies and older drivers, concerns associated with disability glare often comes from difficulty driving at night. Realistic visual problems cannot always be accurately tested in clinical examination because visual acuity only tests visual function with high contrast and in photopics conditions. A study done by Kimlin and colleagues demonstrates this flaw by assessing the predictability of visual tests on the driving performance of its subjects [38]. These subjects had little to no ocular pathologies but had trouble night time driving. The subjects were put through driving obstacles to monitor their driving performance during night time. The subjects were also tested under photopic conditions for both visual acuity and contrast sensitivity. Then, they were tested under mesopic conditions for visual acuity and contrast sensitivity as well as glare testing. The study revealed that out of all the test results, high contrast visual acuity provided the least information about driving performance. In turn, glare and mesopic conditions were better predictors and accounted for more of the driving variations in the subjects [38]. Thus, a major visual problem like night time driving cannot be captured by typical clinical settings. Visual acuity and photopic conditions cannot provide information adequate in assessing all visual complaints. Thus, proper measurements of disability glare should be done in a lighting condition that most accurately addresses the visual complaint of interest.

In addition, mesopic conditions mimic those of night time illuminance as well as fog. While it has been shown that visual acuity decreases during mesopic conditions, central vision is less important and the ability to discriminate contrast becomes more necessary [39]. Thus, the effects of disability glare on contrast sensitivity during mesopic conditions can be more clinically valuable and applicable to daily life.

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4. Instruments and tests for glare

4.1. CSV-1000E

One widely known clinical tool to measure disability glare is the CSV-1000E from Vector Vision. This device measures disability glare using contrast sensitivity at spatial frequencies ranging from low to high. The spatial frequencies are measured using sinusoidal gratings at varying levels of contrast. The CSV-1000E has a backlit illumination of 85 cd/m^2 which can be used for glare testing under photopic conditions. The device can measure in mesopic conditions as well with the use of neutral density filters which lowers illuminance to 3 cd/m^2, the FDA recommended setting for mesopic measurements [40] (**Figure 4**).

The test consists of eight levels of contrast for each spatial frequency. There are eight columns consisting of two circles each, one which contains the sinusoidal gratings. The subject is tasked with identifying which of the two circles contain the grating for each of the columns. The responses are recorded and converted to a logarithmic scale.

Since the CSV-1000E can test in both photopic and mesopic conditions at various spatial frequencies, it has a variety of useful applications in a clinical setting. Shandiz et al. demonstrated the use of the CSV-1000E in individuals with different types of cataracts and different levels of severity. The CSV-1000E was sensitive enough to display a correlation between the subject's performance on contrast sensitivity and their level of lens opacity [41]. Since the CSV-1000E is a discriminative test that reflect ocular pathologies, it can be valuable in tracking the progression of a disease such as cataracts.

While the CSV-1000E has shown some discriminative ability, one report has shown the device is unreliable. Kelly et al. looked at the repeatability of the CSV-1000E in children and adults. The results indicated that the CSV-1000E has poor reliability. The reliability only improved in

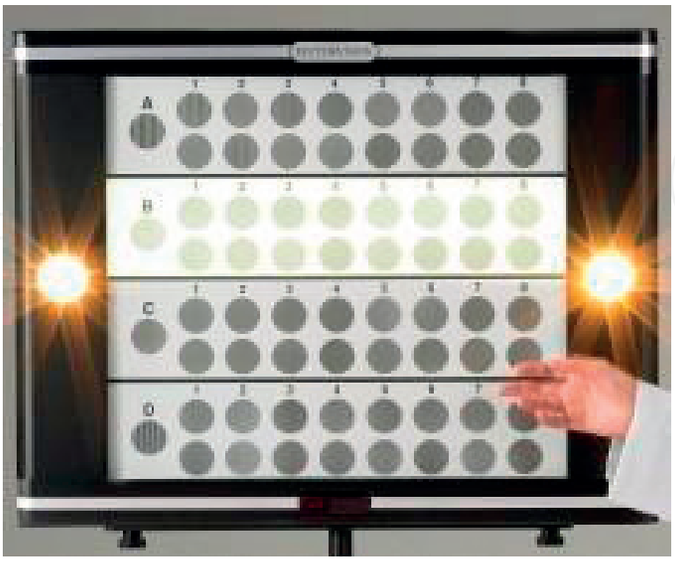

Figure 4. CSV-1000E used for glare testing at varying luminance and contrast sensitivity at different spatial frequencies. Image courtesy of VectorVision [40].

the case of maintaining the same experimenter, but even so the reliability was still low [42]. Some issues with the study was it involved both children and adults and the groups were too small to perform a reliable sub-analysis.

Examining the reliability of the CSV-1000E with a subject of pool of glaucoma patients, the investigators found the device and testing to be reliable. The reliability was calculated as the coefficient of repeatability (COR) which was on average .191 which was lower when compared to another known glare test, the Miller-Nadler Glare Tester (COR = 0.36) [43]. The study tested the effectiveness of a beta-blocker therapy on the contrast sensitivity of open angle glaucoma and looked at the reliability of CSV-1000E. The CSV-1000E was able to detect the changes in visual function from the beta-blocker treatment which can suggest good discriminative sensitivity [43]. Furthermore, based on repeatability the results supported that CSV-1000E can be a clinically reliable tool.

The CSV-1000E is a clinically versatile device as it can measure disability glare in various conditions. The device has also shown discriminative ability in detecting the changes in state of those with cataracts and glaucoma. However, the repeatability of the test remains uncertain and so further assessment of the CSV-1000E with a large sample size will be necessary for understanding its suitability in glare testing.

4.2. Halometer

Disability glare while causing a veil of light over the visual object, can also create an illuminated ring in our viewpoint which is known as a halo. The halo can be quantified by its disk radius and be used as a mean to measure disability glare. In a study conducted by Palomo-Alvarez et al., it was demonstrated that in comparison to straylight and corrected visual distance acuity (CVDA), disk halo radius was more discriminatively sensitive at detecting differences between normal and cataract subjects under glare conditions [44]. Thus, disk halo radius can be a valuable diagnostic tool to measure disability glare in clinics. One of the current tools for measuring halos are halometers. There are several models of halometers which are adopted by researchers to fit their studies. However, the foundational principals of the different halometers for evaluating disability glare are very similar.

The halometer test mainly entails a point light source at the center of the testing screen which varies in intensity depending on the device and study. The optotype used can be illuminated with a green or red light to monitor the effects of wavelength on light scattering. The protocol usually comprises of the subject moving the optotype either away or to the light source until it is just no longer visible or just visible depending on the specific instructions. The distant from the light to the object is then measured and analyzed as the disk radius halo which correlates with the amount of disability glare experienced.

In a study performed by Babizhayev et al., the halometer was used to assess individuals with cataracts [45] (**Figure 5**). Additionally, the performance of the Halometer was compared to other clinical tools such as visual acuity measurements and digitized opacity representations of the lens to determine the validity of the test. The digitized representations were done with retro-illumination photography that was digitally analyzed for light scattering and absorption.

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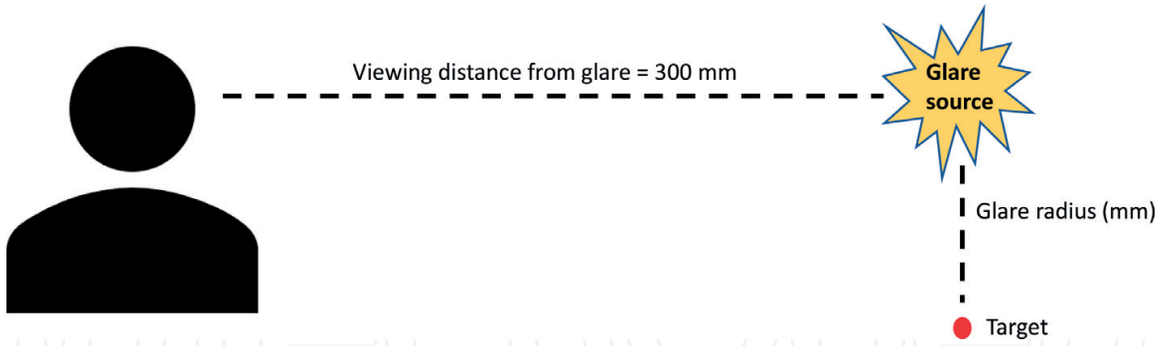

Figure 5. Schematic of the Halometer glare device utilized by Babizhayev and colleagues to measure intraocular light scatter in subjects with cataracts. Babizhayev et al. [45].

The halometer showed significant correlation between the visual acuity and the digitized opacity measurements. The results indicate that this glare test can contribute additional knowledge to visual function in relation to cataracts. Furthermore, the repeatability of the halometer was also assessed. The halometer performed with high repeatability of about 0.998 with test and retest occurring 1 week apart [45]. The halometer being both discriminative and reliable can be a beneficial and useful addition to clinical evaluation of patients.

Another modification of the halometer utilized an iPad application and an LED point light source. The halometer is known as the Aston Halometer [46] (**Figure 6**). The study subjects were tested monocularly with the use the Bangerter occlusion foil to induce disability glare. The target, presented at four different Weber contrast levels, was moved from the LED light source in eight different directions. The subject was to identify when the target was just visible from the light source and the distance, being the halo disk radius, was measured and analyzed. The performance of the Halometer was compared to the straylight meter which had been shown to be an accurate measurement of straylight and correlated to the amount of disability glare. The Halometer showed sensitivity to lower contrast letter and had high repeatability during testing which makes for a promising device [46]. However, the device was only tested on normal subjects without ocular pathologies. Therefore, while there is evidence in the Halometer's sensitivity to varying levels of contrast in normal subjects, the study did not provide insight to glare in ocular pathologies such cataract and glaucoma. Since the population of those living with ocular pathologies struggle with disability glare, a glare device needs to demonstrate discriminative ability in disease such as cataracts, glaucoma, and corneal disease.

Another study also used the Aston halometer to measure disability. They did so to evaluate night time driving in older adults with minimal pathologies including cataracts, glaucoma, and corneal pathology [38]. The subjects recruited was put through a driving obstacle to monitor their driving performance. Then mesopic conditions as well as glare testing was measured to see whether the visual testing is an accurate predictor of the subject's driving. While the test showed that the Aston halometer was a better predictor than photopic high contrast visual acuity (HCVA) testing, it was not a better predictor than mesopic high contrast visual acuity testing [38]. This suggest that the Aston halometer may need other improvements to increase sensitivity and further studies will be necessary to assess the validity of the halometer.

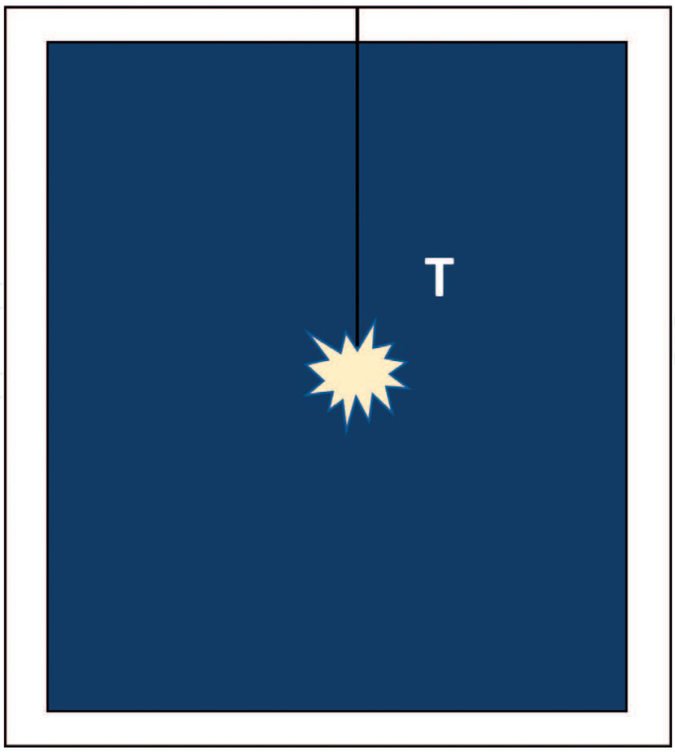

Figure 6. Schematic of the Aston Halometer designed on the iPad with an LED light source and target optotype controlled by iPhone. Buckhurst et al. [46].

4.3. Berkeley glare test

The Berkeley Glare Test has long been used for glare testing in clinic and research. The Berkeley Glare test measures visual acuity optotypes and different contrast levels under glare conditions [47]. A chart of varying levels of contrast is placed in the device, behind the opal Plexiglas screen which has a back illumination of 85 cd/m^2. The device has three levels of glare, being 300, 800, and 3000 cd/m^2. The creators of the Berkeley Glare test, Bailey and Bullimore, tested the technique on young and older ocular healthy adults [47]. Older adults were categorized as healthy if no ocular pathologies were present and their nuclear sclerosis score was grade 1 and under. The subjects were tested under four conditions which were no glare, and the three glare illuminations mentioned earlier. The chart used in the Berkeley Glare Test can vary and be chosen to meet specific needs. Visual function at high contrast was measured using the Bailey-Lovie Chart, a letter chart that assessed visual acuity. Low contrast visual function was also measured by using a letter chart that was at a Michaelson 10% contrast. The subjects were scored on a basis of a disability glare index (DGI) which was the difference in the number of letters the subject can see in the no glare versus glare conditions. Bailey and Bullimore's testing results showed that subjects with early nuclear sclerosis had a higher reduction in disability glare in comparison to visual acuity. The data also reflected subtle changes in lens opacity in the subject's DGI score before those changes could be detected by visual acuity testing [47]. The significant difference between DGI scores suggested that the Berkeley Glare test was more sensitive to physiological changes when assessing for contrast sensitivity than visual acuity [47]. This also noted the importance of using contrast sensitivity

over visual acuity in the case of the Berkeley Glare Test to produce more sensitive and accurate results. Furthermore, the Berkeley Glare Test also presented versatility as a glare device because the charts can be changed to test a wider range of visual function. This is potentially helpful in ocular diseases such as cataracts to evaluate different visual impairments in various settings. The Berkeley Glare Test also presented good discriminative ability as it can differentiate between those with early signs of nuclear sclerosis and normal subjects.

Further evaluation of the validity of the Berkeley Glare Test was done by Elliot and colleagues in a study where different glare tests were also observed [28]. The test was utilized with a low contrast (Weber 15%) Bailey-Lovie chart with a back illumination of 80 cd/m^2 and the glare setting was set to 750 cd/m^2 illumination. The Berkeley Glare Test displayed good repeatability but did not perform as well as the Regan chart and BAT (Brightness Acuity Test) as the glare source in reliability. The Berkeley Glare Test also exhibited good discriminative ability between normal and cataract patients. However, the study did disclaim that the subjects were referred to the ophthalmologist's office due to discrepancies in visual acuity. Since visual acuity in these subjects were already low, it can be expected that visual impairments were apparent enough to be easily detected by most tests. And so, these results did not further support the discriminative ability of the Berkeley Glare Test. The Berkeley Glare Test also fulfilled the three criteria of a vision test outlined by the American Academy of Ophthalmology (AAO). The criteria include: a force-choice protocol, test target follows a uniform logarithmic progression, multiple trials should be done at each level of acuity or contrast [28]. The Berkeley Glare Test's performance as outlined by the AAO criteria is both reliable and discriminative test. Therefore, the Berkeley Glare test can potentially be a strong foundation as both a research and clinical tool.

In another instance, a research study utilized the Berkley Glare Test to evaluate nighttime driving and disability glare. The study compared the Berkeley Glare Test to the Aston Glare Test in predicting night time driving performance. The Berkeley Glare Test did not show any significant correlation in driving performance while the Aston Glare Test displayed significant correlations [38]. This may suggest that while the Berkeley Glare Test can produce valid results, newer glare devices are surpassing it in sensitivity and leaves room for improvement in the test itself.

4.4. EpiGlare tester

In another glare test, known as the EpiGlare tester, the inventors developed a glare testing device that has the validity and discriminative disability to detect vision loss caused by glare. Epitropoulos and colleagues assessed the changes in corrected distance visual acuity (CDVA) in cataract and normal subjects under glare conditions [48]. The EpiGlare tester is a LED light emitting device that can be attached to a phoropter. There are four LED lights placed evenly around the aperture of the device. Under induced glare conditions, the subjects are asked to read off an EDTRS chart to assess their CDVA. The study also incorporated a Functional Vision Questionnaire that assessed the subjects driving and glare experiences. An additional question was asked after glare testing on how closely the test resembled their glare problems while nighttime driving (**Figure 7**).

Figure 7. EpiGlare tester designed by Dr. Alice Epitropoulos can be easily attached to phoropter for clinical use. Image courtesy of good-Lite. Epitropoulos et al. [48].

From the data of 40 subjects with cataracts and 49 ocular healthy subjects, EpiGlare tester demonstrated that cataract subjects are more impaired by disability glare than normal subjects [43]. These findings support the discriminative ability of the EpiGlare tester to distinguish the visual loss between pathology and healthy vision. Furthermore, the questions asked during the testing provides additional evidence to the validity of the device. From all the subjects, 83% of the cataract subjects reported the device accurately simulated their difficulties nighttime driving [48]. The device was easy to utilize and incorporate in clinical settings. The attachment to phoropter increases repeatability of the glare tester because the device setup will be consistent. The study did not directly examine its reliability and thus further evaluation of the device is still necessary. However, the EpiGlare tester simple use can be advantageous in clinical settings with its discriminative sensitivity and convenience.

4.5. Ophthimus glare tester versus contrast sensitivity function glare test

While there can be many variations among glare devices, the core of what is required in glare testing is the same. Therefore, there are several present methods and devices that share similar set ups. Two of which are the Ophthimus Glare Tester (Hightech Vision) and the contrast sensitivity function (CSF) glare tester created by Abrahamsson and his colleagues [21, 49]. Both these models examine cataract and normal subjects as well as monitoring their visual performance with contrast sensitivity under glare conditions (**Figures 8** and **9**).

These devices employed similar setups by using a ring fluorescent tube as the glare source with the optotype presented in the middle. Both assessed contrast sensitivity; however, the Ophthimus Glare Test utilized the Landolt C with varying levels of contrast as its optotype [21]. The CSF Glare Tester, on the other hand, used sinusoidal gratings to measure contrast sensitivity with different contrast levels and spatial frequencies [49]. Furthermore, the type of glare sources differed, and the intensity of both glare sources were not disclosed. Hence, there is no basis to compare the two on illuminance.

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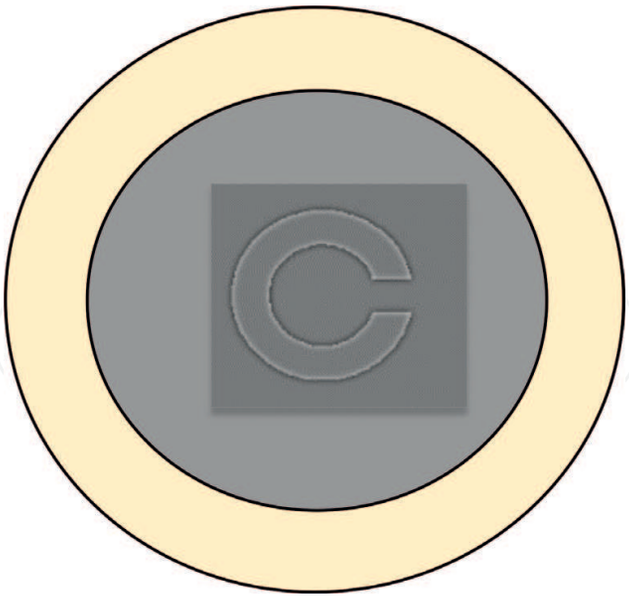

Figure 8. Schematic of the Ophthimus glare test with the ring light as the glare source and Landolt C at the center. Martin [49].

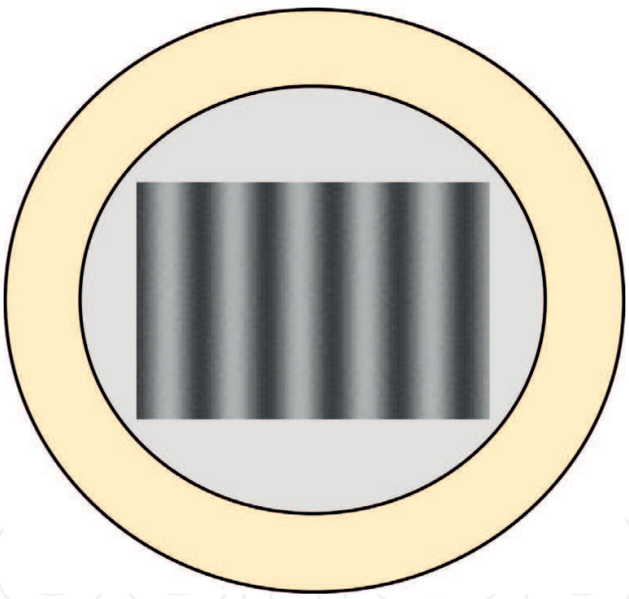

Figure 9. Schematic of Abrahamsson and Sjostrand glare device with a ring light as the glare source and sine wave contrast sensitivity in the center. Abrahamsson and Sjostrond [21].

When using the Landolt C, the protocol normally ensued a force choice answer. In the case of Ophthimus Glare Tester, the subjects were asked to report which direction the gap of the Landolt C was facing. This was done until the subject reached the lowest contrast in which the direction of the Landolt C could still be answered correctly [21]. This resembled the procedure of the CSF tester as the sinusoidal gratings were gradually increased to the contrast that was

barely visible to the subject under glare conditions. The task was done at all spatial frequencies [49]. Both glare test measured the lowest contrast level visible by the subject to determine their contrast sensitivity. These results were both used to calculate a glare score which was used to understand the visual function of the cataract subjects and ocular healthy subjects.

Their shared similarities in testing methods also yielded the same results where both glare tests displayed discriminative ability between cataract subjects and age-matched ocular healthy subjects. However, each study correlated their glare score with different measurements and so each drew their own specific inferences from their results. The Ophthimus Glare Tester study looked at cataract patients in preparation for cataract surgery. These individuals had normal visual acuity, but the results of the study showed their disability glare score to be significantly lower and they also reported visual complaints associated with glare. After the surgery, 24 out of 25 subjects had no self-reported glare problems but some of the subjects still displayed elevated glare sensitivity [21]. This supported the discriminative ability of the Ophthimus Glare Tester that the glare test could still distinguish between cataracts and ocular healthy individuals even after surgery when visual function improved. The validity of the Ophthimus Glare Tester's performance was supported by being relevant to the subjective visual complaints of the subjects as well as with the results of preoperative and postoperative surgery. The CSF glare tester, on the other hand, measured their scores against opacity levels of the cataract subjects. They demonstrated a correlation between the glare scores and the current pathology of each subject [49]. Hence, the validity that the CSF glare tester was based more so on physiological progress of the disease rather than subjective experiences. Both these glare tests exhibited strong discriminative findings but because the studies that utilized the tests based their results on different foundations, the information yielded by each glare testing device was distinctive. This also applied to the information each study provided about the effects of glare on cataracts even though the glare tests shared a number of similarities. And so more testing should be conducted to assess the comparative validity of these glare tests.

5. Conclusion

Functional vision deficits may occur in ocular healthy individuals and in individuals that have disease. It appears that glare testing can serve as a good indicator of visual function and may also be affected in disease states. As various new treatment modalities become available for age related macular degeneration, glaucoma and newer intraocular lens surgeries and laser refractive surgeries, treatment outcome may be better assessed using visual function tasks that are more difficult to perform and are more realistic of "real" world activities. To this accord a combination of glare testing with contrast discrimination may be well suited. The difficulties arise in lack of standardization of parameters or lack of existence of evaluation standards makes assessing of the glare tests very difficult. There is tremendous need for these standards setting and independent evaluation of these devices before a clinically acceptable standard can be obtained and accepted. It appears that although the glare testing shows huge promise it cannot be utilized clinically as a useful test and currently remains a technique useful for research arena.

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