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Measuring the Behavioral Effects of Intraocular Scatter

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TITLE:
Measuring the Behavioral Effects of Intraocular Scatter

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KEYWORDS:
Vision, intraocular scatter, optics, glare, recognition acuity, halometer, light-scatter, point-spread function

SUMMARY:
In this protocol, we outline the conceptual design elements and structural development of a glare acuity apparatus. Additionally, the design of a device for measuring positive dysphotopsia (halos, spokes) and two-point light thresholds is described.

ABSTRACT:
Intraocular scatter, with its associated functional manifestations, is a leading cause of automotive accidents and a significant biomarker of covert and overt ocular disease (e.g., diseases of the cornea and lens). Nearly all current methods of measuring the behavioral consequences of light scatter, however, suffer from various limitations mostly reflecting a lack of construct and content validity: to wit, the measures do not adequately reflect real world conditions (e.g., artificial light vs. sunlight) or everyday tasks (e.g., recognition under visually demanding conditions).

This protocol describes two novel, ecologically valid methods of measuring the behavioral effects of intraocular scatter by quantifying scatter geometry and visual recognition under glare conditions. The former was measured by assessing the diameter of halos and spokes that resulted from a bright point source. Light spread (essentially, the point spread function determined using Rayleigh criteria) was quantified by determining the minimum perceivable distance between two small points of broad-band light. The latter was done based on the identification of letters formed using apertures through which bright light was shone.

INTRODUCTION:
Glare is commonly defined as a degradation of optical clarity resulting from intraocular scatter within the ocular media. This scatter distorts the image's representation on the retina and produces a disrupted depiction of the visual scene. Most major accidents related to glare happen due to daytime intraocular scatter caused by the sun[1]. This origin means that time of day and season (solar position) are significant variables as well as the age of the driver[2,3]. Given the

importance of glare as an issue of safety, there have been several methodological studies focused on (mostly commercial) devices for testing individual and group differences[4]. Often, this manifests as bright lights (typically halogens or fluorescents) surrounding an acuity chart or gratings. Depending on the characteristics of the individual (e.g., ocular pigmentation, lens density)[5], the abutting lights cause a veiling luminance that degrades performance. At first blush, these tasks would seem to have high face validity. As illustrated in **Figure 1A,B**, increasing scatter does directly veil objects, and the available tests do capture variance attributable to the intensity of the glare source and personal characteristics. However, the tests have several drawbacks[6] and leave many important aspects of scatter unassessed. The first, and most obvious, is simply that the most common glare source in everyday life is the sun.

Scatter within the eye has a complex dependence on wavelength that is compounded by age and ocular pigmentation[7]. To the degree a test deviates from this natural source, its ability to predict visual function in those circumstances may be limited. Common tests use white light-emitting diodes (LEDs) or side-mounted halogens. In an early study of 2,422 European drivers, van den Berg et al. noted that scattering within the eye and visual acuity were relatively independent predictors of the quality of a subject's vision (scatter and acuity were not correlated)[4]. In the real world, however, glare often comes directly from the object being viewed. The glare source may come from above (e.g., the sun) or the side (e.g., car headlights), but the veiling luminance is directly in the line of sight. In this study, the researchers attempted to address both these issues by selecting a light source that closely matched noon-day sunlight (**Figure 2**), and designing a task that was based on recognition (not simply detection) and where task and light stress were, simultaneously, in the direct line of sight of the viewer.

In addition to veiling luminance reducing visual acuity (scatter along the sight line), many conditions influence the actual geometry of scatter within the eye (i.e., not just forward light scatter within the macula) and degrade vision. This is described by the common appearance of halos and spokes (or when sufficiently debilitating, positive dysphotopsia (PDP) (for examples, see **Figure 3**). PDP is a common side effect in individuals who have had LASIK corrective surgery[8] in addition to those with cataracts (often referred to clinically as "intolerable" PDP[9]—this demographic includes roughly half of the population aged 70 years and over). PDP is often not corrected by cataract surgery as the surgery itself creates inhomogeneities in the cornea, the seating of the implant within the lens capsule is imperfect, and many lens designs, while addressing some issues such as presbyopia, create others such as spoking and halos. For example, Buckhurst et al. showed that intraocular scatter was the same between differing clear intraocular lens (IOL) designs, but that multifocal lenses created significant PDP[10].

The first halometer designed to precisely measure visual halos/spokes was described in 1924 by Robert Elliot. The device was essentially a lamp in a box with a small aperture and a slide rule (even earlier versions used drawings of the visual effects from candles). Several variations of that theme followed[9] until a device called the Aston Halometer finally reached the market. This device[10,11] is based on a bright white LED in the center of a tablet computer (subjects identify letters surrounding the tablet as they move centrifugally in 0.5° steps). As noted earlier, one challenge with this design is that white LEDs are not a great match for the sun. Another is simply that the source (a single LED) is not sufficiently bright to induce significant halos and glare spokes. The researchers imposed Bangeter occlusion foils (essentially a diffuser) to increase light scattering (and decrease specular reflections from the surface of the tablet). However, this risks confounding the source (i.e., much of the scatter then comes from the diffuser and not the inhomogeneities within the eye itself—the very variable that needs to be quantified). The redesign of the halometer has several features meant to address these issues. First, it uses broad-band xenon as a solar simulator[12] and uses the original aperture method introduced by Elliot with precision-centered calipers.

The light shield that forms the central aperture has the added advantage that it can be separated into two smaller apertures that can be slowly moved apart to measure light spread (essentially, a behaviorally derived point spread function; see **Figure 4**). This design has now been used in several recent studies to assess the optical characteristics of photochromic contact lenses[13]. Taken together, measuring the diameter of halos and spokes, the minimal distance between two point sources of light (light spread), and glare acuity, addresses not only **that** a patient suffers from glare using real world conditions, but also **how**. The behavioral effects of light scatter within the eye are not a unitary phenomenon[4,14,15]. Each of these variables explains a relatively unique aspect of the variance in visual function. Halos, for instance, result from forward light scatter arising primarily from the crystalline lens. Spokes (essentially ciliary corona) stem from diffraction and aberrations that arise from small particle scattering along the optical path[14,16].

PROTOCOL:

NOTE: The procedures outlined in the following protocol adhere to all institutional guidelines relating to human subject's research. This study was approved by the University of Georgia institutional review board, and the experimental procedures were conducted in accordance with Good Clinical Practice Guidelines and the ethical principles of the Declaration of Helsinki.

1. Constructing the glare acuity apparatus

NOTE: A conceptual drawing of the system is shown in **Figure 5**.

1.1 Begin with an optical table, and install a 1000 W xenon arc lamp with the associated power supply at the posterior end of the bench (see **a** of **Figure 5**).

NOTE: The best choice for an optical table is a breadboard with a grid of mounting holes, commonly, the M6 screw thread on a 25 mm grid. The minimum size necessary is ~91 cm x 122 cm. One limitation with these systems is that, if the light output is not constant (within and across sessions), small variations would be interpreted as variation in behavioral thresholds. Hence, make sure that the power supply is highly regulated with optical feedback sensors to ensure constant light output across experimental sessions and over time.

1.2 Install the first lens at a position that collimates the light from the source (see **b** of **Figure 5**), and introduce an optical element to remove heat within the optics generated by the intense light source (**Figure 5C**).

NOTE: All lenses within the system are plano-convex achromats with anti-reflection coating. The effective focal length is ~100 mm, and the diameter is ~5 cm (slightly larger than the exit aperture of the light source). Infrared filters could be used to remove heat, but they often intrude into the visible. A water bath is a nice alternative. In the current system, two optical flats enclosed a tube filled with water.

1.3 Introduce the next lens (see **d** of **Figure 5**) within the optical system to focus light to a small point on the 100 mm circular neutral density filter (see **e** of **Figure 5**), which attenuates light over a linear range of about 2 log units of optical density. Determine the nominal position of the filter using a digital readout coupled to a potentiometer (See **j** of **Figure 5**). Use a calibrated radiometer to determine the actual amount of light transmitted that corresponds to the circular filter's position and to periodically confirm that the overall energy within the system remains constant over the course of the experiment.

NOTE: As the filtering is done over a gradient, light needs to be focused to a fairly small area (4–9 mm^2) when passing through the circular filter (this position is also good for baffling using a small aperture that only passes the focused light).

1.3.1 Use a mechanical shutter or simply a blocking filter and holder to occlude the stimulus between trials (see **f** of **Figure 5**).

1.4 Add the next lens to the system, a collimating lens (see **g** of **Figure 5**), placed such that light expands to match the diameter of each letter aperture (10.16 cm), fully illuminating the optotype (7.62 cm).

1.5 Construct the letter apertures or purchase them as metal stencils: P, L, D, U, Z, E, T, and F (see **h** of **Figure 5**). Place the letter apertures in a circular rotator (to allow for easy alternation between letters) with spring-loaded tabs and divots to lock each letter in place so there is no movement of the wheel during the experiment.

NOTE: The letter apertures were approximately 15 mm x 6 mm x 25 mm (~0.17°), and were chosen because they are classic Sloan optotypes and approximately the same size. In this system, luminance measured at the letter aperture was 4000 lux; 40 lux when measured at the plane of the eye.

1.6 Next, baffle the system such that subjects can only see the back-illuminated letter apertures (e.g., the intense light coming out of an "E"). For instance, place the optics of the system in one room with the subject in an adjoining room. Position a hole within the doorway adjoining the rooms and align it so that subjects cannot see the experimenter or stray light. Should the participant be unable to hear the experimenter's instructions, add an intercom system.

1.7 To ensure that the position of the eye relative to the visual system is fairly precise, create some form of head and chin rest assembly—use a rubber eye cup mounted on a black tube (both mounted on a movable cart). As done in this protocol, add a mount behind the tube to allow for the use of trial lenses to correct for refractive error using standardized lenses (i.e., no tinting).

NOTE: The use of trial lenses will also allow for the use of a glass "blank" to ensure that the optical effects of those who did not require refractive correction match those who required refractive corrective optics (see **i** of **Figure 5**).

1.7.1 Additionally, ensure the viewing station is secured so that it does not move between subjects. Use a laser level to ensure alignment of the eye piece with the optics (7 m from the plane of the eye).

2. Measurement of glare recognition acuity

NOTE: At the beginning of an experimental session, it is confirmed that all optical elements within the system are aligned, light intensity (with no attenuation) is correct, and the subject's eye is in the proper position. The task is then explained to the subject (letter identification), and the stimuli are presented in random order at differing levels of intensity. The goal is to find the highest intensity at which a subject can still correctly identify individual letters (with the actual threshold defined probabilistically at 75% correct detection, 6 correct out of 8).

2.1 Use the method of limits (to get close to the threshold) and then constant stimuli to obtain a precise value of the subject's glare recognition acuity threshold.

NOTE: There are more accurate psychophysical methods available (signal detection, forced choice), but this method was used based on the number of measures and time constraints.

2.2 Use a random letter generator to organize the letters on the wheel into a unique, random order. Use letters for the apertures that are commonly found in other recognition tasks (e.g., Snellen chart, Sloan letters).

NOTE: The letters used in the present method were P, L, D, U, Z, E, T, and F.

2.3 Before beginning the protocol, explain the nature of the experimental task by showing the subject suprathreshold stimuli. Ensure the subject is aware the task is fairly simple: can the letter be seen or not? Run enough trials to generate a psychometric function that allows derivation of an accurate probabilistic threshold.

3. Constructing the halometer device

3.1 Utilize the same steps 1.1–1.2 in setting up the optics table for these measures. Make sure the light from the source illuminates the back of the light shield over a sufficient space (13–14 cm) to allow a separation of the two points.

3.2 Install the light shield, and ensure that it serves as a baffle by blocking most of the light coming from the light source so that the subject just sees the light coming from the aperture and contains a small (~4 mm) aperture for the halo/spoke measures. Affix a digital micrometer to the back of the light shield to be used to measure the physical separation of the two light points.

NOTE: The aperture must be produced by two abutting and movable apertures (2 mm each), and the shield must contain a collapsible baffle such that, as the apertures are moved apart, the baffle occludes light from passing between them.

3.3 To maintain consistency with this protocol, ensure that the light output measured at the light shield is 10 cd/m^2.

3.4 In accordance with the schematic (**Figure 2**)[13], place the centering calipers in the space between the light shield and the subjects stabilized head position (a simple chin and forehead rest). Make sure the jaws of the caliper are aligned with the 4 mm aperture and ~13–14 cm in height.

NOTE: It is helpful to put some reflective material on the subject side so that they can be clearly seen. The jaws move equally from the center, and their position is indicated by a Vernier scale.

3.5 To maintain consistency with the setup used in this protocol, verify the light shield is ~100 cm and the calipers are ~60 cm from the plane of the subject's eye.

3.6. When making the two-point measures, use a long focal length lens. Determine the exact placement of this final lens based on the focal length and the distance from the light shield and the plane of the subject's eye. Remove this lens when doing the halo/spoke measures.

NOTE: A 200 mm achromatic plano-convex lens 18 cm from the plane of the eye was used in this setup (this places the eye in the focusing beam, but not at the focusing plane, the eye is anterior to the final focal point). This is used because individuals with very good acuity and low scatter can often see two abutting small points of light even when very close. The focusing lens will cause the points to overlap and magnify the distance necessary to distinguish two points.

3.7. Use a white reflectance standard placed at the eye and a telescoping spectral radiometer to measure spectral light output, both radiometrically and photometrically, to ensure that the visible spectrum has the desired characteristics (in this case, simulated sunlight, **Figure 2**). To monitor energy output more often and with a highly sensitive detector, use a regular radiometer with a silicon-based photo-head.

NOTE: Such light output measuring devices will yield both the spectral shape of the curve and photometric values (measured in the same position at the eye itself).

4. Glare geometry

NOTE: Prior to testing, subjects were provided examples of the appearance of halos and starbursts in natural scenes (see **Figure 3**).

4.1 Once the subject is aligned, move the jaws of the caliper until it just surrounds the halo, and then until it is just at the outer circumference of the starbursts or spokes. Obtain the threshold by averaging the spread from both directions (from in to out and out to in).

4.2 When beginning the two-point measures, ensure maximal proximity of the two 2 mm apertures; note that the stimulus will appear as a single, bright point of light. Slowly move the two apertures apart, quantifying the distance by the back-facing digital micrometer, centered on the apertures. From the "zero point," (abutting apertures) ask the subjects to indicate when the spread from each light point does not overlap (usually one direction works well here).

4.3 As some error can be encountered if the subject becomes misaligned with the system, utilize a small-bore camera (with infrared) to ensure the eye always stays in correct position.

REPRESENTATIVE RESULTS:

For the glare acuity measures, 20 young subjects (average age = 19 years, standard deviation (SD) = 1 year) with good acuity were tested. The results shown in **Figure 6** indicate the variation in the number of letters seen at one relatively bright intensity level. Another approach to analyzing the data would be to use the correct identification to generate a psychometric function with threshold defined as 6 identifications out of 8 (the energy at 75% correct identification). As shown in **Figure 6**, there is wide variation present even when testing healthy young subjects.

Data from the halos and spokes measures are shown in **Figure 7A,B** and are from a different sample of 23 young subjects (average age = 20 years, SD = 4 years). Both samples were recruited from the student population at the University of Georgia. All these subjects had good acuity (20/20) and/or were corrected with clear contact lenses. The minimum distance (mm) required to resolve two points of light as distinct (the two-point thresholds here) was also measured. These data are shown in **Figure 8**.

As seen in the **Figure 6**, **Figure 7**, and **Figure 8**, despite the sample being so homogeneous (composed of relatively young healthy observers with good vision), there was wide variation in the behavioral measures of scatter. This suggests that standard clinical measures of visual function (e.g., acuity) fail to quantify many visual attributes that likely impact visual performance under real world conditions.

FIGURE AND TABLE LEGENDS:

Figure 1: Two nighttime driving scenarios. (**A**) Minimal intraocular scatter from the car headlights with the pedestrian in the road clearly visible. (**B**) High intraocular scatter from the car headlights, obscuring the pedestrian in the road.

Figure 2: Graph representing the spectral distribution of midday sunlight (red), the xenon arc

lamp light source (black), and a high-bright white LED source (blue). Abbreviation: LED = light-emitting diode.

Figure 3: Examples of PDP symptoms: spokes (far left), halos (left), and starbursts (right) and of 2-point light scatter (far right).

Figure 4: Semantic representation of the point-spread function and visual illustration of car headlights. Relative energy on y-axis and visual angle on x-axis; visual illustration of how the separation between two bright points of light (headlights) is a behavioral measure of its width.

Figure 5: A conceptual drawing of the glare acuity system. The components include (a) a xenon light source, (b) collimating lens, (c) water bath, (d) focusing lens, (e) circular filter (100 mm neutral density filter), (f) filter holder, (g) lens, (h) letter apertures in circular rotating wheel, (i) refraction correction (trial lenses), (j) digital readout of circular filter potentiometer. Abbreviations: CL = collimating lens; FL = focusing lens; L = lens; TL = trial lenses.

Figure 6: A column chart showing the number of letters each subject was able to identify when the luminance of the stimulus was held at a bright constant (absolute energy, 16,392 cd/m^2).

Figure 7: A column chart showing the individual differences in a sample of 23 young, healthy observers. (**A**) Halo diameter. (**B**) Starburst/spoke distance.

Figure 8: A column chart showing the minimal distance where two small points of light did not overlap (two-point thresholds).

DISCUSSION:

The visual consequences of intraocular scattering are often assessed as glare disability and discomfort[17,18]. These methods focus directly on the dysfunction and slight pain that accompanies intense light, but not on directly how it is disabling vision. The how is also important, however, because intraocular scatter does not only affect vision when it is intense. Even a low-intensity visual image (e.g., low luminance, low contrast targets) can be degraded by light scatter. The underlying optics[15] can be described by the Strehl ratio, point spread function, or diffusion index (largely independent of luminance). Another method, effective even at lower luminance (10 cd/m^2 in this setup), involves the measurement of the separation of two point sources of light. Individuals with a wider point spread function will require more separation before two small points of light will appear distinct. The Rayleigh criterion method of quantifying the spread of two small point light sources has a long history[19]. In the present case, this method was adapted to increase its ecological validity (e.g., by using white xenon that simulated noon-day sunlight).

Figure 5 shows a conceptual drawing of the glare acuity system. In essence, it begins with a bright white light source that simulates sunlight (xenon bulbs are typically a good choice, 1000 watts provide sufficient intensity). Light from the source is cooled with a water bath (transparent to visible light) and then manipulated by a series of lenses that carry light in focused and collimated beams. A circular neutral density filter attenuates the light that is then passed through lettershaped apertures. The subject sits at a fixed distance from the isolated stimulus (~7 m) and views the stimulus with one eye at a time (eye position fixed by an eye cup). What the subject sees is a series of letters that are themselves the glare source. When the light is too intense for a given subject, consistent correct identification is not possible. Glare acuity thresholds can be defined using any number of classic psychophysical techniques.

The basic design of the halometer is similar to the glare acuity device described above and can use the same light source (an intense xenon) and optical table[13]. The two elements that differ are the introduction of a light shield that contains small movable apertures and centering precision calipers. The aperture in the light shield is 4 mm in diameter and is backlit by the light source. The broad band light passing through this small hole creates a bright point source that spreads (the pattern determined by the optical characteristics of the observer, so for some, it spokes more, others have more diffuse haloing), and the calipers are used to measure this geometry. The 4 mm aperture in the light shield can be broken into two smaller apertures (2 mm each) that can be slowly moved apart until the spread of each is not overlapping. That distance (tracked by a micrometer on the light shield) is used as the behaviorally derived point spread function (two-point thresholds).

The diameters of the halo (diffuse light around the point source) and starburst (concentric rays radiating outward from the point source) were determined by using the method of limits (in ascending and descending modes). The researcher moved the jaws of the caliper (outward from the center) until the subject indicated that the guides just surrounded the halo or the starburst. When making the two-point measures, the two tiny abutting apertures are moved slowly apart (horizontally), and subjects indicate when the spread from each light point does not overlap (e.g., when they first perceive a small black space between the two points). A technical schematic of the system has been described by Hammond et al.[13].

Measuring the way that light scatters instructs the nature (and correction) of the problem. Starbursts (peripheral spokes), halos, and glare disability and discomfort all have individual characteristics. When the eye is compromised by aging, disease[9], or surgery[8], these optic phenomena also change in distinct ways. Halos, for example, are often seen as a relatively homogeneous veil, whereas starbursts tend to not be homogeneous and extend into the periphery. This pattern is demonstrated clearly by Hammond et al.[13].

These different patterns imply the need for different types of correction[7]. For example, macular pigments (yellow pigments concentrated in the macula) have been shown to be useful for correcting central glare (light veiling in the line of sight)[20]. However, as these pigments are only in and around the retinal fovea, they do not influence light scatter outside that area[21]. For this purpose, filtering in the more anterior portion of the eye is desirable such as with the use of tinted spectacles[22], contact lenses[13], or intraocular implants[23]. All things being equal, individuals with optimal glare acuity can discern letters at much higher intensities than those with poor glare acuity.

Past studies have also shown that measures of light scatter do not correlate well with more commonly measured metrics such as visual acuity[4]. This motivated the development of a light scatter method that was convolved directly with acuity judgements (analogous to a Snellen Chart). Previous methods were based on detection or resolution (e.g., seeing individual bars within gratings of varying frequency) as opposed to recognition. However, recognition acuity, like other forms, is dependent upon the contrast between two elements within an image. Light scatter can degrade that difference and was the dependent measure in the present glare acuity assessments. As shown by the empirical results of this young, largely homogeneous sample, all things equal, there are large individual differences in how light scatter effects visual function under real world conditions.

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DISCLOSURES:
The authors have nothing to disclose.

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Figure 1A

A

Figure 1B

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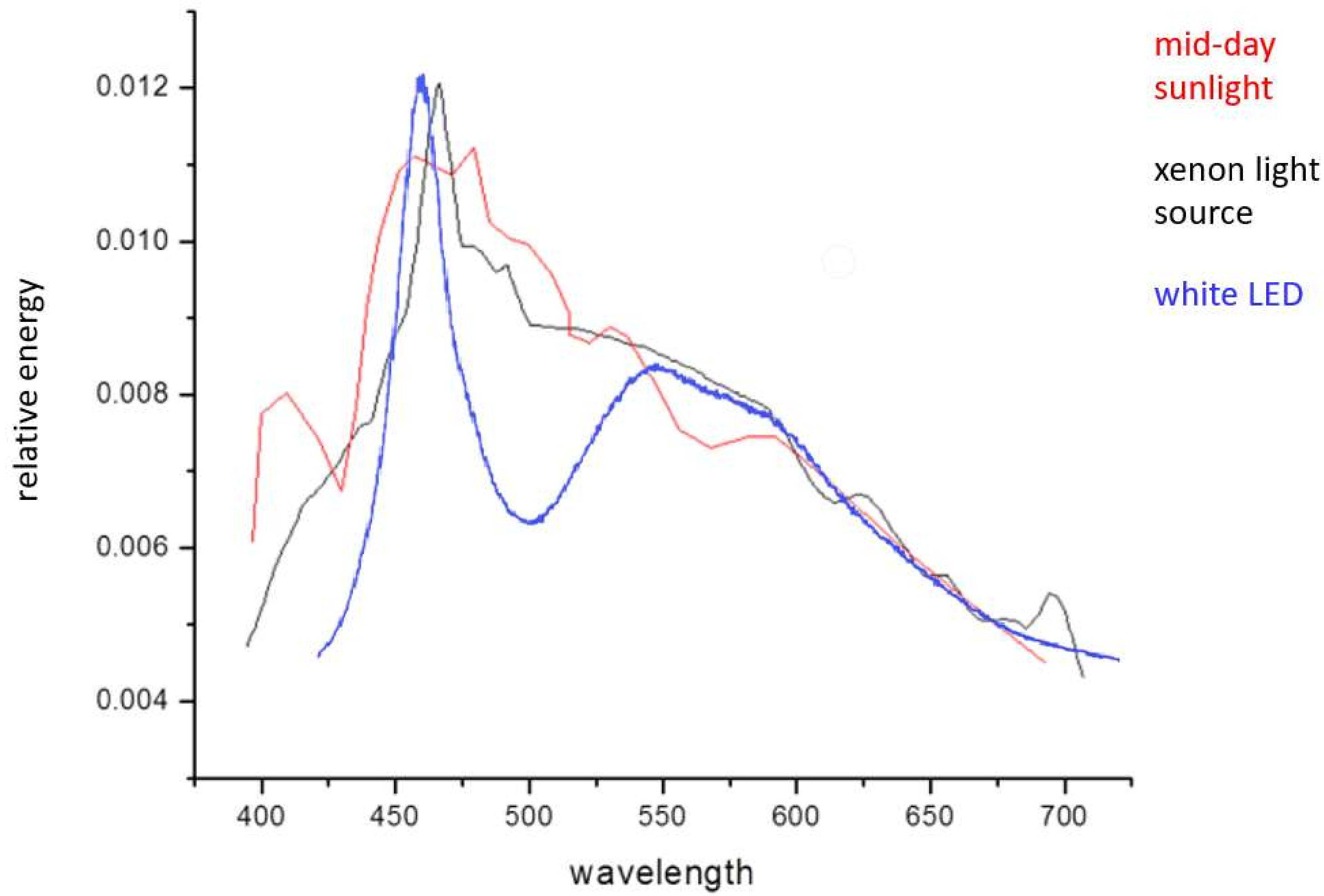
B

Figure 2



0.012
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0.008
0.006
0.004
relative energy
400
450
500
550
600
650
700
wavelength
mid-day sunlight
xenon light source
white LED

Figure 3


Spokes
Halos
Spokes and Halos (Starbursts)
2-Point Light Scatter

Figure 4

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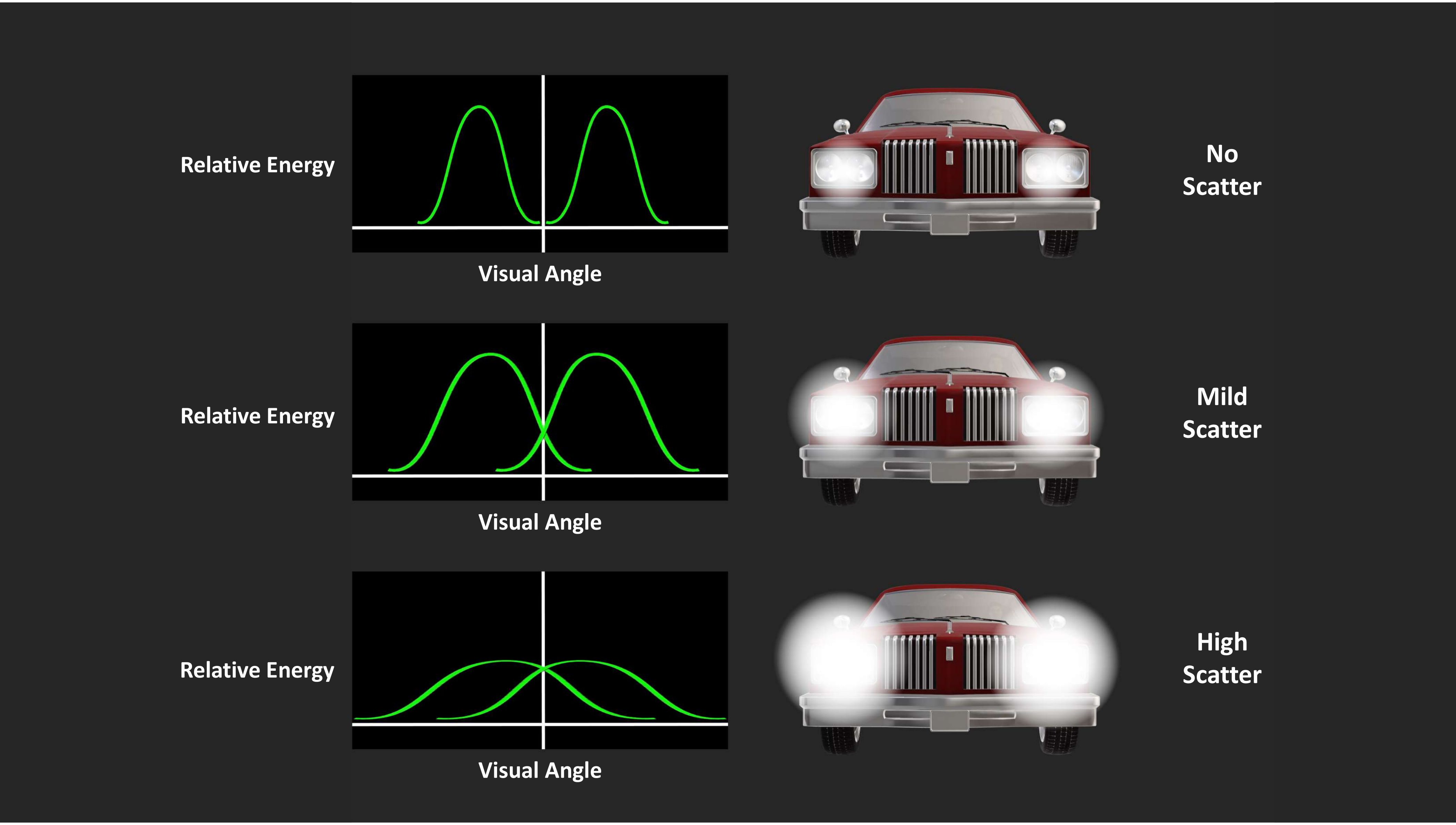


Figure 5

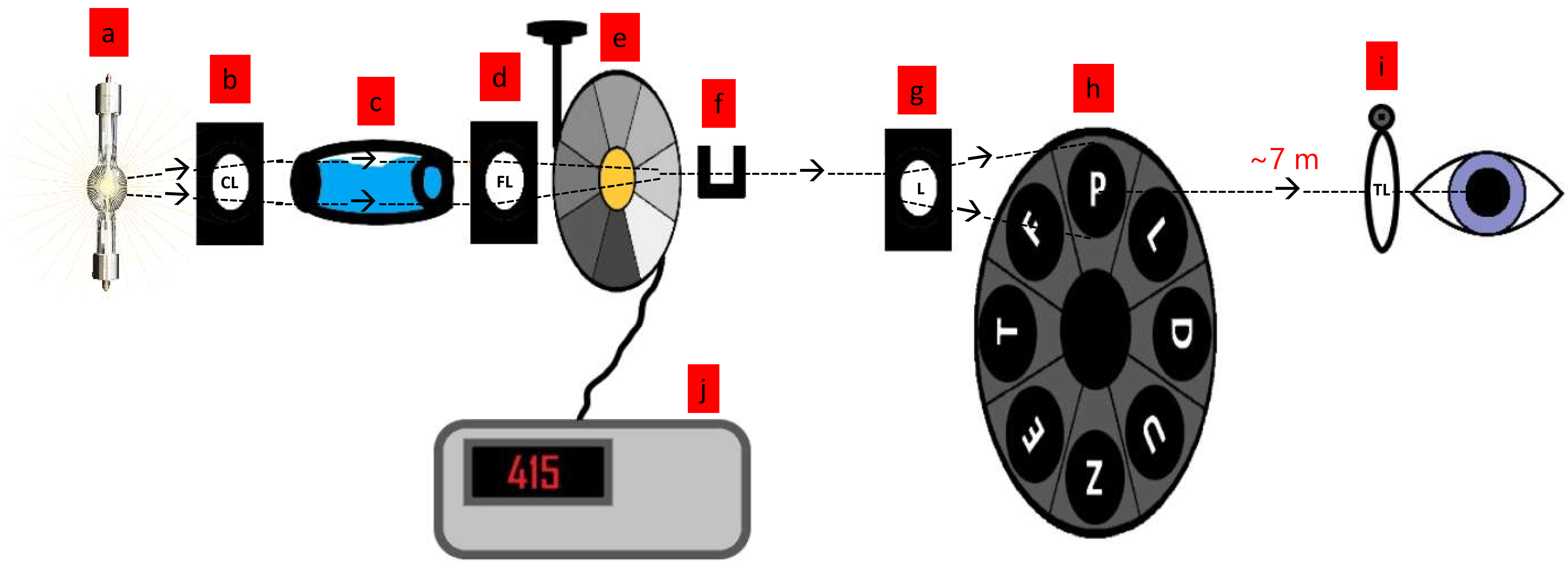


Figure 6


Variation in Letter Recognition at a Fixed Bright Intensity Level
Number of Subjects
0
1
2
3
4
1
2
3
4
5
6
7
8
Number of Letters Correctly Identified

Figure 7A

Click here to access/download;Figure;JoVE_Figure 7a.pdf

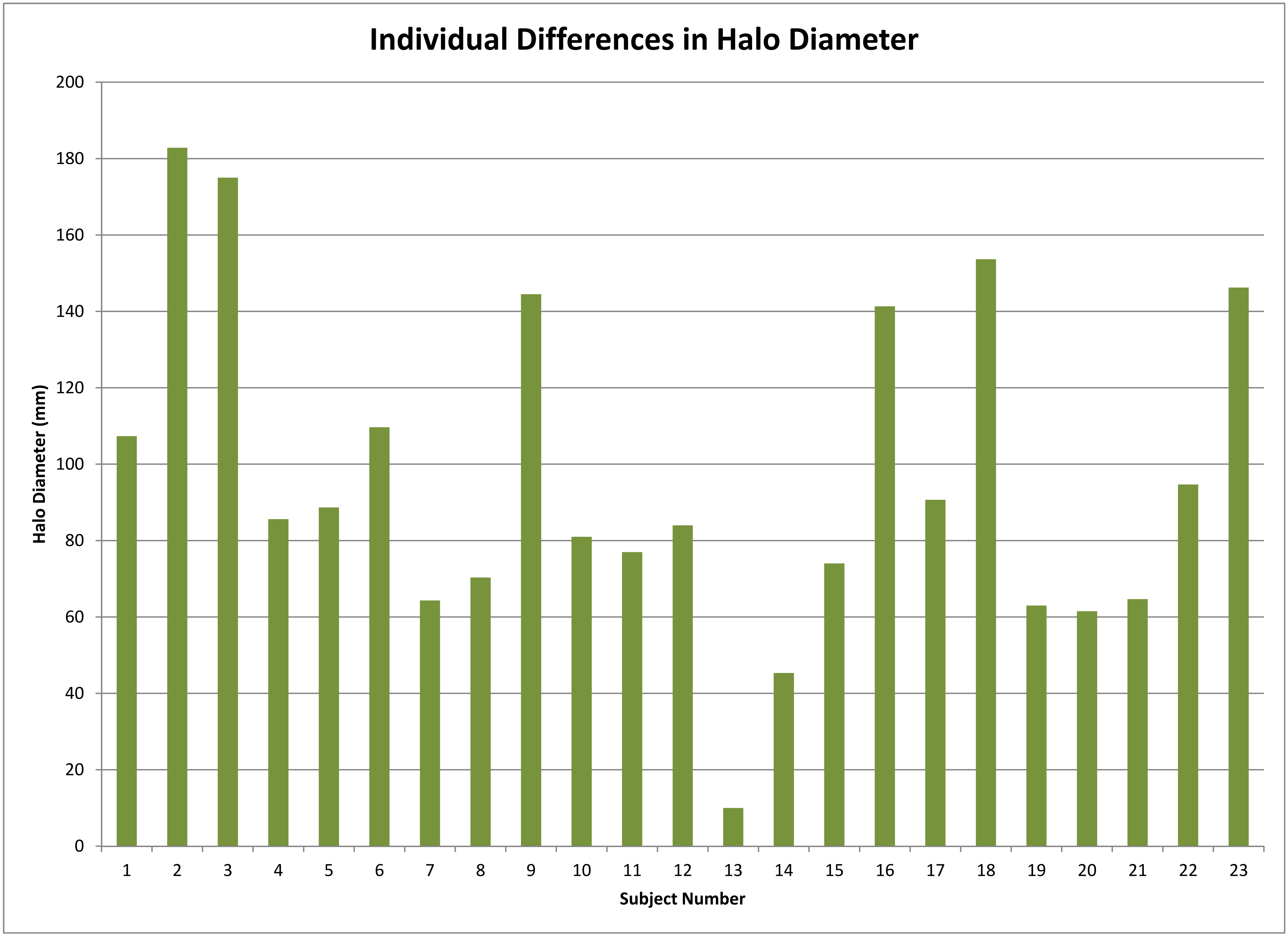
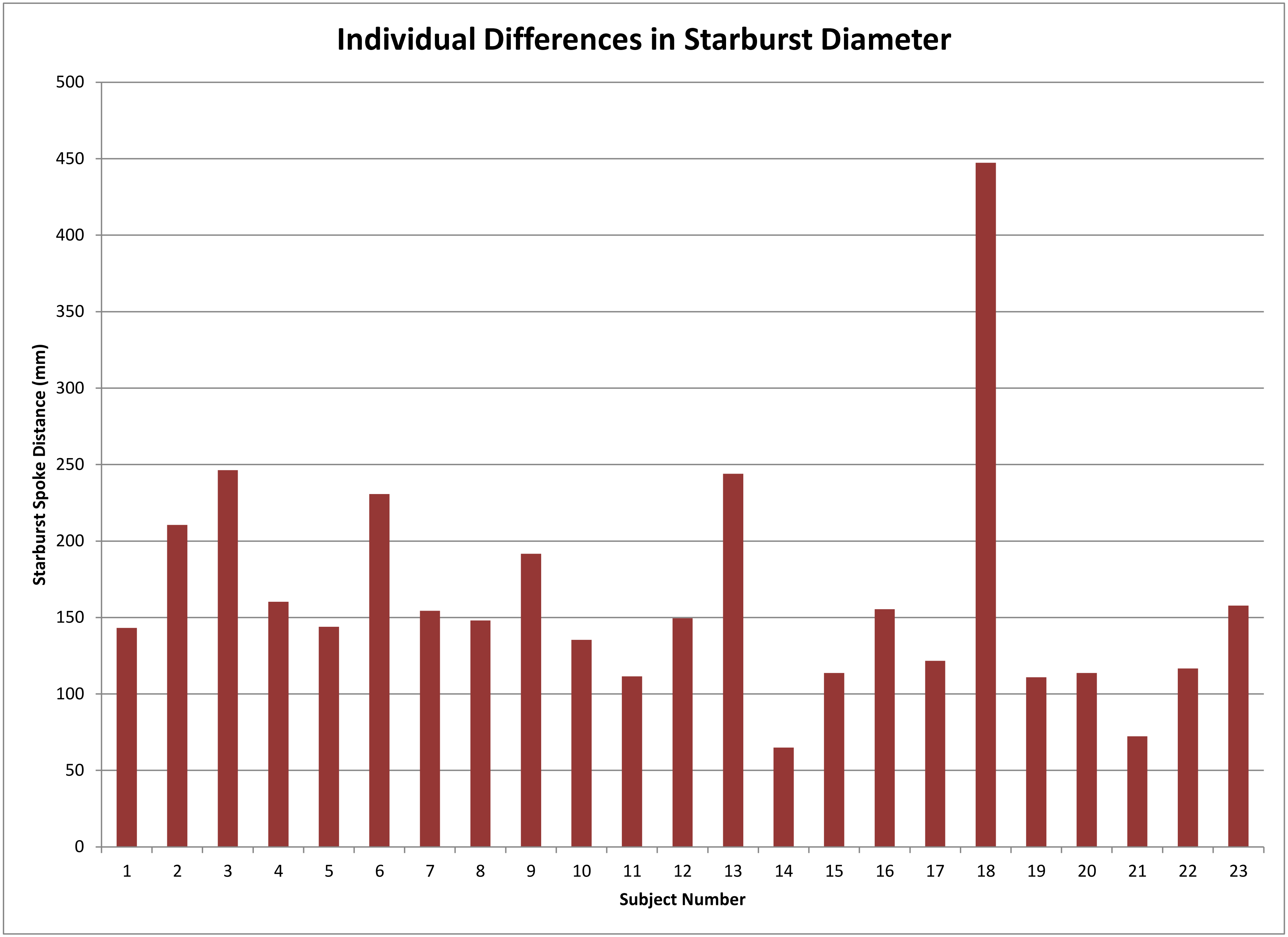
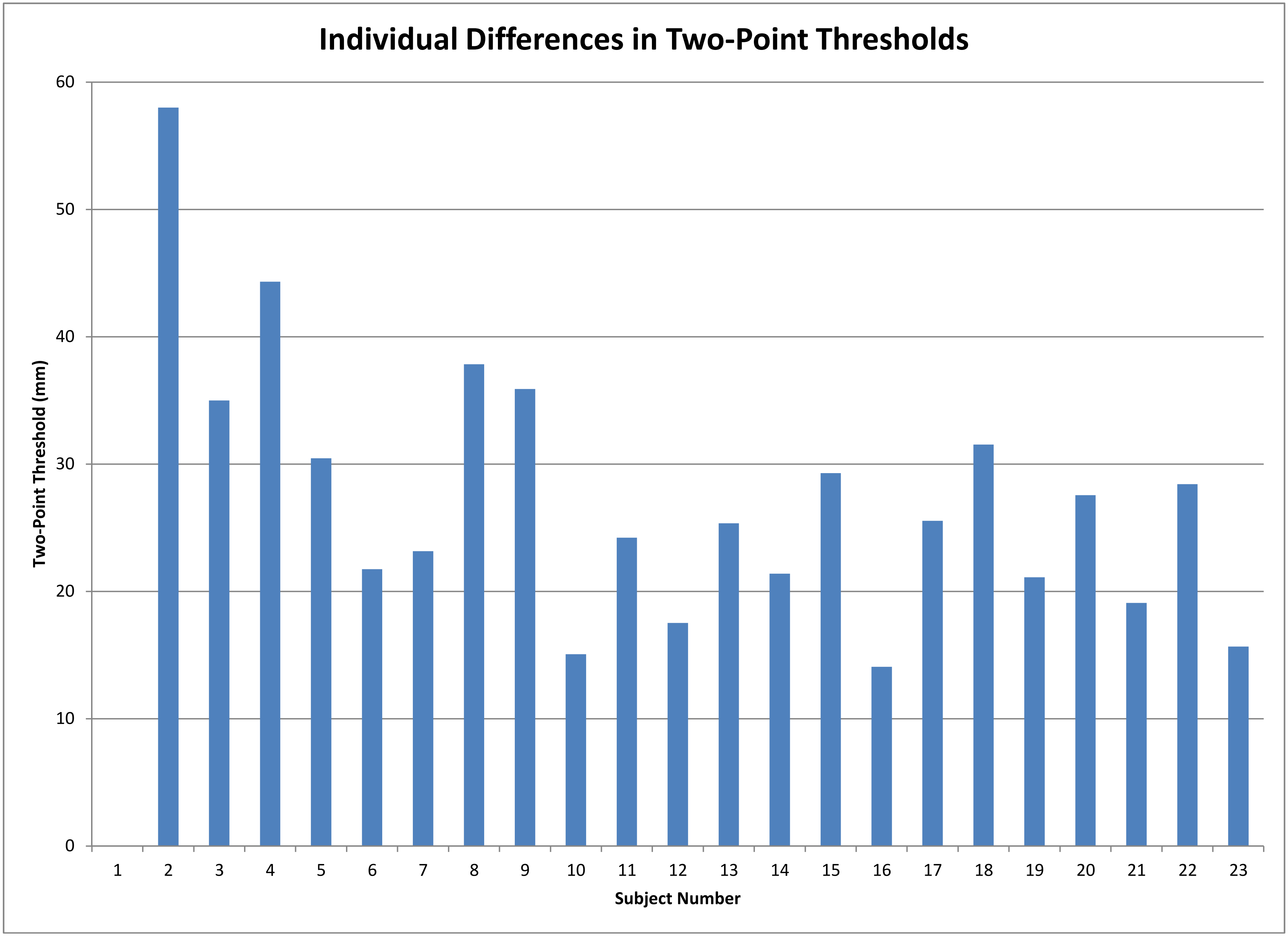


Figure 7B


Individual Differences in Starburst Diameter
Starburst Spoke Distance (mm)
500
450
400
350
300
250
200
150
100
50
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
Subject Number


Individual Differences in Two-Point Thresholds
Two-Point Threshold (mm)
0
10
20
30
40
50
60
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
Subject Number

Name of Material/ Equipment	Company	Catalog Number
Glare Recognition Acuity: *Indicates handmade equipment		
100 mm Circular Neutral Density Filter	Edmund's Optical	Stock #54-082
1000W xenon arc lamp Bulb)	Newport	Model 6271
Breadboard optics table	Newport	Model IG-36-2
*Chin rest assembly		
*Circular rotator and letter apertures		
*Digital potentiometer and readout		
Plano-convex achromatic lenses	Edmund's Optical	Model KPX187-C
Radiometer	Graseby Optronics United Detection Technology (UDT)	Model S370
Research arc lamp housing and power supply	Newport	Model 66926
Spectral radiometer	PhotoResearch Inc	PR650
Trial lenses	Premier Ophthalmic Services	SKU: RE-15015
*Water bath		
Halometer: *Indicates handmade equipment		
1000 W xenon arc lamp	Same as above	
Arc lamp power supply	Same as above	
Breadboard optics table	Same as above	
*Calipers		
*Chin and forehead rest		
Digital micrometer	Widely available	

*Light shield	
Plano-convex achromatic lens	Edmund's Optical

Comments/Description

Letter apertures can be constructed or purchased as metal stencils

This simply supplies a nominal readout for the position of the circular wedge (essentially a voltmeter connected to a potentiometer)

100 mm EFL, anti-reflective coating in the visible, 50.8 mm diameter (mounting is also available from this supplier)

Two optical flats enclosing a cylindrical tube filled with water containing a small amount of formalin

Must be able to serve as a baffle, equipped with a collapsible baffle,
equipped with two movable apertures (2 mm each)

200 mm Effective Focal Length

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Department of Psychology
Vision Science Laboratory

1/13/2021

Manuscript Number: JoVE62290

Thank you for your consideration of our work. What follows is our response to the editorial comments and comments of the reviewers (indicated with blue colored font).

Editorial Comments:

1: Please take this opportunity to thoroughly proofread the manuscript to ensure that there are no spelling or grammar issues.
The manuscript has been thoroughly proofed.

2: Please revise the following lines to avoid previously published work: 240-242, 247-253, 261-263, 331-367, 338-343.
These sections have been reworded.

3: Please provide the complete address of the affiliations.
[added]

4: Please revise the text to avoid the use of any personal pronouns (e.g., "we", "you", "our" etc.).
[updated]

5: Please define all abbreviations before use (IOL).
[updated]

6: Please adjust the numbering of the Protocol to follow the JoVE Instructions for Authors. For example, 1 should be followed by 1.1 and then 1.1.1 and 1.1.2 if necessary. Please refrain from using bullets or dashes.
[updated]

7: Please ensure that all text in the protocol section is written in the imperative tense as if telling someone how to do the technique (e.g., “Do this,” “Ensure that,” etc.). The actions should be described in the imperative tense in complete sentences wherever possible. Avoid usage of phrases such as “could be,” “should be,” and “would be” throughout the Protocol. Any text that cannot be written in the imperative tense may be added as a “Note.” However, notes should be concise and used sparingly.
[updated]

8: Please add more details to your protocol steps. Please ensure you answer the “how” question, i.e., how is the step performed? Alternatively, add references to published material specifying how to perform the protocol action.
We have added additional procedural detail and references.

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9: Please include a one line space between each protocol step and highlight up to 3 pages of protocol text for inclusion in the protocol section of the video. This will clarify what needs to be filmed.
[updated]

10: Line 318-319: Please ensure that the Figure Legend includes a title and a short description of the data presented in the Figure and relevant symbols. The Discussion of the Figures should be placed in the Representative Results. Details of the methodology should not be in the Figure Legends, but rather the Protocol.
[updated]

11: Please try to include any limitations of the protocol described.
We have added possible protocol limitations.

12: Figure 3: Please define the units of the X and Y- axis.
Figure 3 is simply an illustration of the symptoms of positive dysphotopsia (PDP). Only images are shown, there are no axes nor units to define.

13: Figure 4: Please provide more details to the graphical representation on the left panel. Please try to include X and Y-axis and provide the details in the Figure Legends.
Figure 4 is also semantic and is simply an illustration of how the point spread function (a common conception in optics) relates to the real-world experience of seeing headlights. We have added some more clarification to the figure to make this more obvious.

14: Figure 5: Please specify the direction of flow. Please ensure that the contents in the figure and the figure labels do not contain the same alphabets. This may be misleading.
[updated]

15: Figure 6/7/8: Please include the details of the statistics in the Figure Legends.
These figures show column charts (a sampling of the type of data each method yields). These column charts are descriptive statistics and no other statistics were used.

16: Please sort the Table of Materials in alphabetical order.
[updated]

Reviewer 1:

Please do not use inches, feet, etc. Use metric only.
[updated]

fig 2 is not referenced in the text. Please do.
Figure 2 is referenced on line 68

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line 162 please give letter optotypes and sizes. Please discuss the choice of optotype. Hopefully optotype complies with standard (Sloan). If not, please give justification. Please give sizes in mm, but more importantly, also in degrees or arcminutes.
Optotypes used in this procedure are listed on line 197 and the size of the letter aperture (in mms and degrees) is now described in section 1.7 (as well as the justification for their use).

line 231 this is not shown in the schematic. Please correct.
The schematic being referenced does show centering calipers positioned between the light shield and subject's head position, further clarification regarding the schematic has been provided in step 3.4.

line 239 why is this useful? Please explain. This lens has a magnification effect. Please specify how much precisely.
This is now explained in section 3.6. The basic idea is that it simply magnifies the distance necessary for subjects to discern two light points (reduces the restriction in range).

For the present study, one would expect clear definitions of the photometric values. This however is not the case. The photometric values are not specified in an acceptable way. They are incomplete or vague. At Line 137 "constant light output" is claimed. But at Line 230 it says "about 10-20 cd/msq" (double vagueness), and "not overly intense". Nowhere the other tests are specified with their luminances. Only in the discussion at line 332 "10 cd/m2 in our setup" is specified. Since the other tests are defined differently in the set-up this seems unlikely. Well, anyhow, it is vagueness all over. Please be scientific in the definitions of luminances. And please let us know how luminances were assessed.
Often, in scientific reports, one describes methods/procedures that are very exacting because the goal is to provide enough detail in order to exactly replicate results that are relevant to some tested hypothesis. JOVE, however, (based on the instructions) has a teaching component (so the concepts behind the measures are discussed). We have added more photometric details while still attempting to stay consistent with the goals outlined by JOVE. See section 3.7, for instance.

Also, please note that, just because we indicate that it is possible to use a range of luminances for a given measure (different people need different intensities based on their goals), this does not mean that one would want the source illumination to vary (not just a "claim," obviously, we noted that the system has optical feedback sensors).

Line 266 "remarkably consistent … several trials are useful…" vagueness. Moreover the claim of consistency is not substantiated. Please remove that claim. How many trials precisely were used for all the tests? Please specify.
[updated]

As the authors observe themselves, it is remarkable that the very homogeneous subject groups show rather variable results. It is unclear for this reviewer whether this may be due to the vagueness of definitions used by the authors. Anyhow, scientific reviews on straylight variation have shown a rather clear picture. The present variation seems to be very different. The authors should discuss this difference in variation. Also, the authors should compare their results to the individual straylight values

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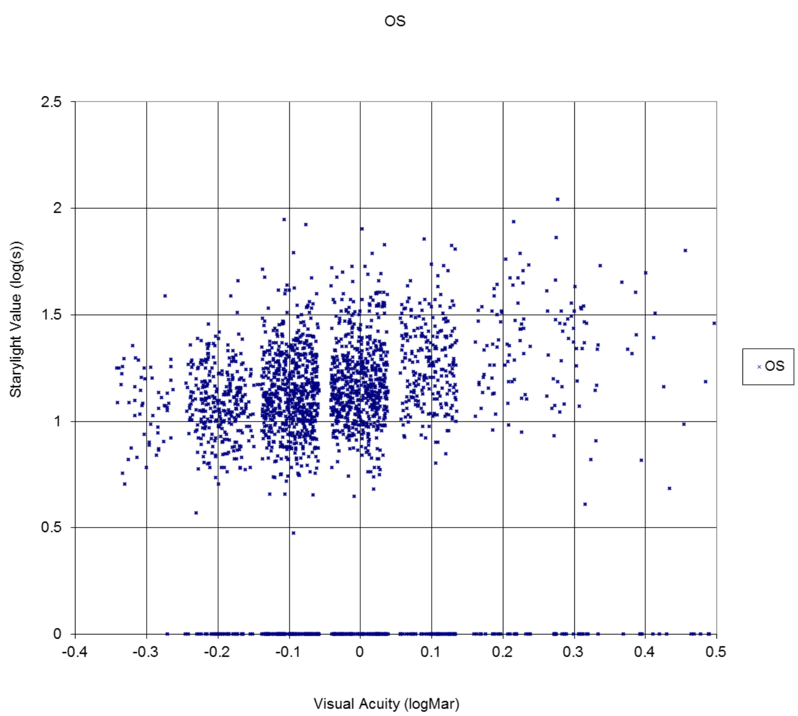
of their subjects. Otherwise we are at a loss what to think of the variation shown in the present paper. It is unscientific to compare one's results to nothing.

As we pointed out in our original submission, our behavioral results are quite consistent with the published data obtained using direct objective methods. For example, in the second paragraph we discuss the results by van den Berg et al. (2007). For your ease of reference, here is a graph from that study:



This graph shows fairly dramatic variation in intraocular scatter with little or no relation to acuity (hence, a motivation for our study combining acuity directly with scatter). Our results compare well with the existing literature. It should also be noted that it is not "unscientific to compare one's results to nothing." We did not compare our results to "nothing," but our method is relatively novel.

Line 312 "J" misses. Please correct.
[updated]

Line 316 please give cd/msq.
[updated]

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Line 343 "2" ? please correct.
[updated]

In general, please use units of scientific nature applicable. In particular, please give angular values where mm values are given for observation sizes. The authors use several distances such as 32 feet (please do use metric only), 100 cm, and 60 cm. please be more clear, and give results in the figures in angular measures (degrees or arcminutes) only.
[updated]

Line 288 "are failing" this is very presumptive in view of the shaky nature of the presented evidence. Please remove this sentence, and please be more modest all over about your own work.
[updated]

Lines 314, 318, 321 these are not "frequency histograms" please correct
[updated]

Figure 4 The schematics to the left are not suitable. Please remove. They send an erroneous message, and will confuse the readers.
We have revised this figure to improve clarity.

Reviewer 2:

Major Concerns:
(a) In my opinion, the words "ecological" and "ecologically" used in this manuscript are not appropriate. Why ecological? Do authors want to mean "simulating real-life conditions? Please, used more accurate terms.
Ecological validity is a term used in the behavioral sciences to describe whether the study findings can be generalized to real-life settings. It is a subtype of external validity and the term was used in this manuscript not to simply indicate that the protocol was simulating real-life conditions, but that the measurements and materials used can translate to real-life settings, improving upon past studies that have not taken this type of validity into account when developing their methodology. For more information see:

Schmuckler, M. A. (2001). What is ecological validity? A dimensional analysis. *Infancy*, *2*(4), 419-436.

(b) The authors highlight the importance of measuring glare and positive dysphotopsias such as as halos and spokes. They perform visual recognition tasks instead of detection tasks to characterize glare and detection tasks for halos and spokes. The authors should cite previous works which have used different halometers (using detection tasks but also recognition tasks). In addition, some (short) discussion would be addressed about these previous halometers to measure halos and starbursts. Two examples of two different halometers and very used are bellow (the first reference using recognition tasks and the second one with detection tasks):

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- Puell MC, Pérez-Carrasco MJ, Palomo-Alvarez C, Antona B, Barrio A. Relationship between halo size and forward light scatter. Br J Ophthalmol. 2014 Oct;98(10):1389—
- Castro JJ, Ortiz C, Pozo AM, Anera RG, Soler M. A visual test based on a freeware software for quantifying and displaying night-vision disturbances: study in subjects after alcohol consumption. Theor Biol Med Model. 2014;11 Suppl 1(Suppl 1):S1. doi:10.1186/1742-4682-11-S1-S1.

In our original submission, we included an entire section that discussed different halometers and even some of the history. Here is that section for ease of reference.

"The first halometer designed to precisely measure visual halos/spokes was described in 1924 by Robert Elliot. The device was essentially a lamp in a box with a small aperture and a slide rule (even earlier versions used drawings of the visual effects from candles). Several variations of that theme followed[9] until a device finally reached market called the Aston Halometer. This device[10,11] is based on a bright white LED in the center of an iPad (subjects identify letters surrounding the iPad as they move centrifugally in 0.5 degree steps). One challenge with this design is, as noted earlier, white LEDs are not a great match for the sun. Another is simply that the source (a single LED) is not sufficiently bright to induce significant halos and glare spokes. The researchers imposed Bangeter occlusion foils (essentially a diffuser) to increase light scattering (and decrease specular reflections from the surface of the iPad) but this risks confounding the source (meaning, much of the scatter then comes from the diffuser and not the inhomogeneities within the eye itself – the very variable that needs to be quantified)."

(c) Figure 5 must be improved. Letters inside a red squared should be related with the text and description of the device. It is advisable an identification of each element in the schemme. In addition, a more clear ray tracing should be made in the scheme in order to show the optical path (at least, two rays to show collimated rays, rays focusing in a point…).

Each component of the step 5 Figure, indicated by a letter (a-j), has now been referenced in the manuscript in step 1 – Constructing the Glare Acuity Apparatus – of the Protocol. Arrows have been added to the scheme in order to indicate the direction of flow through the system. Additionally, and as implemented in the original scheme, collimated rays are indicated by 2 distinct light paths and rays focused to a point are shown between **e** and **f** at which point they converge back into one light path. At **g** the light is once again collimated, and in **h,** light travels in a singular path through the letter aperture into the eye.

Minor Concerns:

(a) Figure 5 20 ft, line 129, 23 feet. Please review if it is the same distance in both cases.

Figure 5 has been revised to be consistent with the text in the manuscript. Additionally, the distance has been converted to meters.

(b) Authors use inches, feets, cm and mm. Authors should unify criteria. As the authors use milimeters for describing the apertures of the device, an option would be use metrics system (meters and, when neccessary for apertures, millimeters). Furthermore, in line 151-152 the authors indicates a small area and, however, they give lengh units. Please, review it.

Manuscript has been updated converting all units to metric. Lines 151-152 have been updated giving proper units for area.

(c) Lines 149-150. These lines are not clear: light is focused on a circular filter. Why the authors use the term "optical wedge"? Is not a prism/optical wedge, is it? Following the stock number in the Table of Materials, it would be an adjustable ND filter. Please it.
[updated]

(d) Line 328: Effect or Affect? Please, review it.
[updated]

Please let us know if you have any further questions and thank you again for your consideration of this work.

Sincerely,

Jeffrey Nightingale, Graduate Research Assistant
University of Georgia, Vision Sciences Laboratory

Billy Hammond, Professor
University of Georgia, Vision Sciences Laboratory