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THE ACCURACY OF OBSERVERS' ESTIMATES OF THE EFFECT OF GLARE ON NIGHTTIME VISION: DO WE EXAGGERATE THE DISABLING EFFECTS OF GLARE?

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THE ACCURACY OF OBSERVERS' ESTIMATES OF THE EFFECT OF GLARE
ON NIGHTTIME VISION:
DO WE EXAGGERATE THE DISABLING EFFECTS OF GLARE?

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ABSTRACT

Designing headlights involves balancing two conflicting goals: maximizing visibility for the driver and minimizing the disabling effects of glare for other drivers. Complaints of headlight glare have increased recently. This project explored the relationship between subjective (discomfort and expected visual problems) and objective (actual visual problems) consequences of glare. Two experiments – a lab-based psychophysical study and a field study – quantified the accuracy of observers' estimates of the effects of glare on their acuity. In both experiments, participants over-estimated the extent to which glare degraded their ability to see a small high contrast target. Observers' estimates of the disabling effects of glare were more tightly linked with subjective reports of glare-induced visual discomfort than with objective measures of glare-induced visual problems.

TABLE OF CONTENTS

Table of Contents (Continued)

Table of Contents (Continued)

LIST OF TABLES

List of Tables (Continued)

List of Tables (Continued)

LIST OF FIGURES

List of Figures (Continued)

Figure   Page

List of Figures (Continued)

Figure   Page

List of Figures (Continued)

List of Figures (Continued)

Figure   Page

INTRODUCTION

In recent years – since the appearance of high intensity discharge (HID) headlighting – consumers have complained about glare from oncoming headlamps, and focus has been placed on reducing the effects of headlamp glare produced by vehicles at night. Because limiting the amount of light emitted by headlamps can limit drivers' ability to see objects ahead, it is important to achieve a satisfactory balance between the somewhat incompatible goals of maximizing roadway visibility and minimizing glare problems. Yet, little work has focused on the tradeoffs between roadway visibility and headlamp glare. This project will explore the estimated and actual effects of glare on visibility. It is hoped the project will provide useful knowledge that can be used to understand the objective and subjective responses to glare and to address the trade-off between headlamp glare and visibility.

There are a disproportionate number of nighttime roadway fatalities. Despite a reduction in nighttime traffic, 46% of all fatal crashes occur under nighttime conditions compared to 49% during daylight hours (NHTSA 2006). Furthermore, when accounting for the number of miles traveled, fatal crashes are 3 times more likely at night than during the day (National Safety Council, 2008). It is quite obvious that visual perceptual abilities are critical to driving and have long been identified as such (e.g., Brody, 1955). Poor visibility has been shown to be a key causal factor in nighttime crashes.

Owens and Sivak (1996) examined data from the Fatality Analysis Reporting System (FARS) over an 11 year period (1980-1990) and found that even when factors such as day of the week and alcohol were controlled, reduced visibility remained the greatest contributor to fatal nighttime crashes involving pedestrians and bicyclists. Nighttime crashes accounted for 65.3% of all fatal crashes, 12.1% greater than chance. Furthermore, when other conditions of poor visibility were included (e.g., fog, haze, etc.), the proportion of fatal crashes rose to 78.8%.

Further evidence of increased nighttime crashes due to poor visibility is provided by Sullivan and Flannagan (2002). Vehicle crash data from the FARS between 1987 and 1997 was investigated. Vehicle collision data from the weeks surrounding the time change associated with Daylight Savings Time (DST) were examined. (DST involves setting clocks one hour ahead in the spring and returning to standard time in the fall; effectively making sunrise and sunset 1 hour later. Daylight Savings Time is observed by the majority of the United States.) This scenario provides the ability to investigate crash data during similar periods of the day, when there would presumably be little change in vehicle or pedestrian traffic patterns. It was found that crash conditions involving especially challenging visual conditions (i.e. the detection of a pedestrian) were approximately 3-7x more likely in dark conditions than in light conditions. However, crash rates involving less visually challenging conditions (specifically single vehicle lane departure) remained virtually unchanged.

The discrepancy between crashes in light and dark conditions can be explained, in part, by the selective degradation hypothesis. Under low luminance conditions focal visual functions such as acuity, contrast sensitivity, and visual accommodation are degraded, and consequently the ability to recognize and identify objects is also reduced. In fact, (at moderate latitudes) the first 30 minutes after sunset and before sunrise contain the most drastic changes in our visual abilities (Owens, Francis, and Leibowitz, 1989). However, during similar low luminance conditions the ability to use vision to guide one's self through the world remains intact (*see* Schneider, 1967, 1969). It has been hypothesized that this selective degradation of the visual system is responsible for drivers' overconfidence in their abilities when driving at night (Leibowitz & Owens, 1977). That is, even when acuity is very low at night, drivers are surprisingly skilled at steering their vehicle to stay within their intended lane (Brooks, Tyrrell, & Frank, 2005; Owens & Tyrrell, 1999). And, in fact, drivers have even been shown to increase speed with more salient lane position information (e.g., Allen, O'Hanlon, & McRuer, 1977; Kallberg; 1993; Smiley, Bahar, & Persaud, 2004). As a result of the continual feedback in maintaining road lane position, the selective degradation hypothesis asserts that drivers are unable to appreciate the extent to which they are unable to detect and recognize obstacles (especially those of low contrast). Thus this pattern of selective visual functions being degraded while others are more robust can lead to a reduction in the ability to detect inconspicuous hazards (e.g., pedestrians, animals, or other objects in or along

the roadway) without a corresponding reduction in speed – a pattern commonly referred to as "overdriving one's headlights" (Leibowitz, Owens and Tyrrell, 1998).

There are different strategies to increase drivers' ability to detect objects of low contrast at night – presumably reducing the overall nighttime fatality rates. A viable option to increase the conspicuity of low contrast objects is the application of retroreflective material. For example, the use of retroreflective material in a biological motion (BioMotion) highlighting formation has been shown to dramatically enhance the conspicuity of pedestrians (e.g., Balk, Tyrrell, Brooks, Carpenter, 2008; Luoma, Schumann, & Traube, 1996; Owens, Antonoff & Francis, 1994; Wood, Tyrrell, and Carberry, 2005).

An emerging technological approach is the addition of an in-vehicle night vision enhancement system (NVES). While NVESs appear to be one promising solution, it is unclear whether these systems are able to aid drivers in the detection of low contrast objects (Mahlke, Rösler, Seifert, Krems, & Thüring, 2007). Further, many NVESs use infrared technology, thus relying on the heat emitted by objects to generate useful images. While this may aid in the detection of living beings (i.e. humans, animals), NVESs provide little advantage in the detection of inanimate objects (e.g., roadway debris, fallen trees).

Another way in which low nighttime visibility can be increased is by simply increasing ambient lighting. It has been shown that even small changes in ambient lighting effect crash rates. Sivak, Schoettle, and Tsimhoni (2007)

4

analyzed pedestrian fatality data from FARS from 1996 through 2005. Fatality rates on nights with a full moon were compared to those on nights with a new moon. Typical ambient illumination from the moon only varies from about 0.1 lx (full moon) to 0.001 lx (new moon). However, even with this relatively small difference in ambient luminance, pedestrian fatalities were 22 percent greater on nights with a new moon. This finding shows that even the increase in ambient lighting attributed to the moon is sufficient to provide increased nighttime (pedestrian) safety. Thus, it would be expected that the detection of other low contrast objects would increase with increased illumination. In turn, it appears that fatal nighttime crashes can be decreased via increasing visibility with illumination. This is especially relevant for crashes involving objects of low contrast. If overall light level is increased (thus increasing object contrast) obstacles in and along the roadway can be seen easily and thus responded to more quickly (Rea and Ouellette, 1988).

One way to increase ambient illumination is with increased street lighting (IESNA, 2000). This, however, contributes to light pollution, is expensive, and simply not feasible in many situations. A simple and quite effective alternative is to increase vehicle headlamp intensity (i.e., utilization of the high beam headlight setting). For example, in an on-road study, Wood, Tyrrell, and Carberry (2005) found that drivers were able to recognize pedestrians wearing dark clothing at a distance 3.5x greater when using high beams than when using low beams.

It has been shown, however, that drivers consistently underuse their high beam headlights. Hare and Hemion (1968) first examined the real world use of high beam headlights. The number of vehicles using high beam headlights was assessed on several roadways (17) across the United States. High beam vs. low beam usage data was collected from vehicles on dark rural roads where there was no opposing traffic, no lead vehicle (within 183 m; 600 ft), in clear weather (no fog or precipitation), and thus no reason not to use high beams. High beam use ranged from only 10% (Northwest) to 40% (Southeast), showing a gross underutilization of high beams. Furthermore, it has been shown that low beam headlights do not provide enough light at speeds greater than 32 km/h (20 MPH; Leibowitz, Owens, & Tyrrell, 1998; see also Perel, Olson, Sivak, & Medlin, 1983). This emphasizes the need and usefulness of increasing ambient nighttime lighting which can be accomplished with high beam headlamps.

Hare and Hemion (1968) used simple observer techniques to measure high beam vs. low beam usage. While it is unlikely that this methodology generated a great deal of error, recent studies have attempted similar measurements with improved technologies. Recent studies have also attempted to quantify high beam usage because it is reasonable to believe that high beam use rates may have changed since the late 1960s for two primary reasons. First, the number of vehicle miles travelled has been increasing over the past several decades (Bureau of Transportation Statistics; 2002). Yet, roadway infrastructure has remained steady, with little relative expansion. These factors combined lead

6

to more densely populated nighttime roads than those of the late 1960s. Thus, fewer appropriate opportunities (not following a lead vehicle, no oncoming traffic) to use high beam headlights exist. This idea is supported by Hare and Hemion's work, who found that high beam headlamp usages decreased as traffic density increased.

A second factor that may have modified high and low beam use is in-vehicle technologies. Most vehicles of the 1960s utilized a foot pedal to switch between high and low beam settings. Now, however, most headlamps are controlled using a switch, or stalk, where by the switch is pushed or pulled once to change the light setting (Federal Motor Vehicle Safety Standard No. 108). This methodology, which appears to be simpler, may have influenced driver headlight use behavior. Thus it was important to reexamine the real-world headlamp usage.

One such study was conducted by Sullivan, Adachi, Mefford, and Flannagan (2004). Two observers counted the number of unopposed vehicles using high beams along three dark, rural, straight roads. Light measurements were taken of vehicle lights traveling from one direction to provide an objective measurement of high vs. low beam use. In addition, both observers made judgments on all vehicles (reaching an agreement rate of 82.2%). Data combined from vehicles traveling both directions averaged about 50% high beam usage. While, this rate is greater than that of Hare and Hemion (1968) it remains clear that drivers regularly underuse high beam headlamps.

Similarly to Hare and Hemion (1968), Sullivan et al. (2004) found that drivers tend to decrease high beam usage as traffic density increases. While it seems plausible that drivers may just be reluctant to use high beams for reasons of convenience or effort, this cannot entirely explain the underuse. Here, high beam use *never* exceeded 70%, even at the lowest traffic densities.

As traffic cannot entirely explain the use/underuse of high beam headlights it is important to explore other feasible explanations. Another recent study investigated the effects of both driver gender and age on beam usage. In order to accomplish this Mefford, Flannagan, and Bogard (2006) asked young, middle aged, and older people to drive instrumented vehicles for an extended period of time (7-27 days). Approximately 21% of the miles traveled occurred at night. The results confirmed that drivers underused high beams. Even in ideal environments (dark rural roads, no opposing traffic, no lead vehicle), high beam use rate only rose to 25.4%. While there was no significant difference in high beam usage between genders, there was a significant effect of driver age. The older drivers (60-70 years of age), on average, used the high beam light setting 3x more often than the younger drivers (20-30 years of age).

Another recent study measured high beam headlamp usage using similar instrumented vehicles (Buonarosa, Sayer, & Flannagan, 2008). Participants drove the instrumented vehicles for an average of 26 days, with about 23% of the driving during nighttime hours. High beam headlights were used for approximately 9.8 minutes for each 100 km (62.14 miles) traveled. Whereas low

beam headlights were used for approximately 97.6 minutes per 100 km (62.14 miles) traveled. Yet again, it can be seen that high beam headlamps were greatly underused. While most types of lamp usage measured (e.g., turn signals) remained consistent across age and gender, high beam utilization varied for both. Interestingly, males drove 34% more nighttime driving hours than females, yet used their high beams only about half as frequently. Consistent with previous work (Mefford, Flannagan, and Bogard, 2006) it was found that older drivers use high beam headlights more frequently than younger drivers. In this study the older drivers (60-70 years) utilized their high beams 5x more often than the younger counterparts (20-30 years). This may indicate that older drivers understand their nighttime visual decrement to a greater extent than younger drivers and subsequently feel less confident in their ability to see during night driving.

Perhaps, then, drivers underuse their high beam headlamps because in general, they appreciate neither the need to improve visibility nor the benefits that high beams provide. As noted previously, the selective degradation hypothesis explains that even under low light levels, we are able to navigate our environment successfully, while failing to detect/recognize objects and obstacles (especially those of low contrast) in our path.

Drivers continually receive visual feedback about their ability to maintain lane position. Yet drivers very rarely receive feedback about the objects they fail to see. In other words, drivers are largely unaware of what they cannot see.

Thus, if drivers are constantly receiving information that they are driving well (successfully steering to maintain proper lane position), it seems reasonable to assume that drivers do not feel as though more light along the roadway is needed. This then would result in drivers not using high beam lighting. An additional possible reason that drivers regularly underuse high beam headlamps is a desire to minimize glare problems for oncoming drivers.

Oncoming headlights can produce glare. Luckiesh and Holladay (1925) first subcategorized glare. While many descriptions of glare were made two broad categories were outlined. The first type is physically disabling to vision ("disability glare") and the second causes a sensation of pain or discomfort ("discomfort glare"). This is not to say that these are the result of two different types of light, but rather they are simply two different ways to measure/classify glare from a single light source. The exact relationship between these two broad descriptions is yet to be clearly defined. As explained below, both discomfort and disability glare can be produced by the same light source. It is also possible that discomfort glare can be present in the absence of disability glare and vice versa. Very little is understood about these types of relationships. The current study explores the relationship between the feelings of discomfort that glare can trigger and the visual disabilities that can result from glare sources.

Glare described as being disabling (i.e., disability glare) inhibits our perceptual abilities to see. It is influenced by the object size and contrast as well as ambient light, eye health, light source orientation, et cetera. For example, the

contrast-reducing effects of veiling glare (optical light scattering) can make recognizing, or even detecting, low contrast objects nearly impossible. Glare can also decrease visibility distance. This combined with lowered contrast can increase reaction times and decrease the probability of detecting objects while driving (Miller and Benedek, 1973; Sivak & Olson, 1982; Frerebeau, 1988; NHTSA 2007). It is thought that disability glare can be estimated by approximating veiling luminance (light scattering that reduces contrast of the optical image; L_v; *see* Fry 1954). However, there are many ways in which disability can be measured dependent on the task at hand (e.g., object detection, lane maintenance, speed variability, etc.).

After exposure to an extraneous light source (glare) there can be a period of lingering visual disability. Rhodopsin is a pigment in the retina crucial to visual perception under low light levels. However, when the eye is exposed to a bright light (i.e. light shock) photobleaching occurs. That is, the rhodopsin is depleted and must be replenished prior to regaining full low light visual abilities. In visually healthy young adults, this process takes approximately 30 minutes. The most rapid recovery of the rhodopsin occurs in the first few minutes, yet the ability to detect objects (especially those of low contrast) can be inhibited throughout photopigment regeneration. In addition, if the light source is sufficiently intense, viewers can be subject to a mildly disabling negative after image.

Discomfort glare, on the other hand, describes the subjective feeling of pain, annoyance, or fatigue that results from exposure to an intense light source.

11

Feelings of discomfort are related to the size and the intensity of a light source, yet not to the energy emitted from the light source. That is, larger light sources of low intensity generally cause more intense feelings of discomfort than smaller light sources of greater intensity. When the size of the glare source remains constant, increased intensity leads to increased ratings of discomfort (e.g., Schwab & Hemion, 1972; Sivak, Flannagan, Traube, & Kojima, 1999). Duration of exposure to a light source also influences ratings of discomfort, but to a lesser extent than changes in intensity (Sivak, Flannagan, Traube, & Kojima, 1999).

Glare is rated as more bothersome in the upper portion of the field of view than in the lateral portion of the field of view (assuming consistent angular separation from the fovea; Miller and Benedek, 1973). Light source color has also been found to influence feelings of discomfort. Light sources in the red and blue spectrums have been shown to dramatically increase ratings of discomfort (e.g., Flannagan, Sivak, Ensing, & Simmons, 1989; Berman, Bullimore, Bailey, & Jacobs, 1996).

Discomfort glare is typically measured using a subjective rating scale of comfort. The most common scale ranges from 1 (unbearable) to 9 (just noticeable; deBoer, 1967). While the deBoer scale is quite simple, it has shown to be a consistent and reliable manner to measure feelings of discomfort resulting from glare. However, the deBoer scale tends to produce a great deal of between-subject variability. While this variability may be troublesome, it is likely a simple reflection of individual perceptual differences. There have been several

attempts to quantify discomfort glare utilizing objective measures. It is likely that individual differences in discomfort would be reflected in objective measures as well (e.g., Sturgis, Pulling, & Vaillancourt, 1981).

Objective measures of discomfort glare have been shown to be inaccurate and frequently inconsistent. For example, Berman, Bullimore, Jacobs, Bailey, and Gandhi (1994) made electromyographic (EMG) recordings around the eye of participants while presenting a variety of glare scenarios. Participants were also asked to give subjective ratings of discomfort. EMG recordings were used to generate an Objective Discomfort Ratio (ODR) to quantify the change in electrical activity around the eye. When the glare source luminance was increased to a value expected to increase EMG activity by 25%, ODR values moved in the expected direction in 79% of the participants. This is compared with 90% of the subjective measurements. Further, modifying the ambient room illumination produced the anticipated lower ODR values in 15 of 19 participants, and 20 out of 20 participants provided lower subjective ratings of discomfort. While this objective measure (EMG) follows the anticipated direction of activation, these recordings failed to reduce between-subject variability, a possibly undesirable characteristic of the subjective measurement. Furthermore, EMG recordings require expensive and obtrusive equipment. These factors combined give little to no advantage of this objective measure of discomfort glare over the simple paper-and-pencil subjective measure.

Other attempts at quantifying discomfort glare using objective measures of the pupil have been made. Hopkinson (1956) and Fry & King (1975) both found very small changes in pupillary oscillations in the presence of glare. However, these findings have not been found to be tightly correlated with participants' subjective feelings of discomfort. Furthermore, Howarth et al. (1993) found no difference in pupillary oscillations with changes in discomfort glare intensities, even when light levels neared the 'intolerable' level. Attempts at correlating electrical activity in the brain (EEG) and subjective feelings of discomfort have also failed (Emdad, Belkic, Theorell, Cizinsky, Savic, & Olsson, 1998). Mathematical computations (e.g., Hopkinson, 1960; Einhorn, 1961) have also found little success. Thus it seems that the relationship between subjective feelings of discomfort and physical responses is poorly understood as is the relationship between disability and discomfort glare (*see also*, Olson, Aoki, Battle, & Flannagan, 1990).

Oncoming headlight glare can result in both discomfort and disability glare and there are many factors that moderate its effects. One major factor is the condition of the observer's vehicle windshield. Over time dirt and grime accumulate on the windshield. This dirt causes light scattering and can further intensify the effects of glare. Specifically, the retinal contrast of objects in, or along, the roadway will be reduced (Rea, 2000). Scratches and cracks in windshields produce a similar effect. Much like filth and scratches on windshields, dirt and blemishes on headlamp casing causes light scattering.

14

Along similar lines, one study even reported that persons wearing visual correction also had a tendency (though non-significant) to report greater discomfort than those who did not (Sivak, Flannagan, Traube, & Kojima, 1999; see also Lauer & Kotvis, 1934).

Many other factors influence the discomfort and disability incurred from headlamps. One of these factors is head lamp type. High-intensity discharge (HID) lamps tend to emit a light of a bluish tint. This color tends to elicit higher ratings of discomfort than tungsten-halogen lights which are of a more yellow/white tint (e.g., Flannagan, Sivak, Ensing, & Simmons, 1989; Berman, Bullimore, Bailey, & Jacobs, 1996). Lamp mounting height also influences feelings of discomfort. Glare sources of greater eccentricity above the focal point tend to increase discomfort (Miller and Benedek, 1973; Akashi, Van Derlofske, Raghavan, & Bullough, 2008). Headlight alignment also plays an important role in discomfort ratings. Regulations for headlamp aim are specifically designed to maximize visibility distances while minimizing glare to oncoming drivers; poorly aimed headlamps can cause the opposite (U.S. Congress, 2001; Copenhaver & Jones, 1992).

Drivers often complain about glare from oncoming vehicle headlights. With the widespread use of HID headlamps, glare has become more salient to drivers. Such complaints have even made headlines in the popular press (e.g., Healey, 2001), and it appears that complaints about headlamps tend to increase as new technology is introduced (NHTSA, 2001). Each year the National Highway Traffic

15

Safety Administration (NHTSA) receives numerous complaints about vehicle headlamps. In fact, in 2001 NHTSA opened a public docket (NHTSA-01-8885) requesting public comments on glare and glare related issues. As of April 2008, 5800 comments had been received from members of the public (see also Docket Number: NHTSA-1998-4820). The comments received however, are often a biased sample, representing mostly complaints associated with headlights and their resulting glare. As a result, the NHTSA put forth an effort to further investigate nighttime headlight glare in a more objective manner.

In order to more clearly understand drivers' overall perceptions of glare, a formal survey was conducted by the NHTSA (Singh, & Perel 2003). The survey gathered opinions from drivers (18 years+) via random calling. A primary question asked of the drivers was "In the last 12 months, while driving at night, has the glare from the headlights of an oncoming vehicle been '*not noticeable*,' '*barely noticeable*,' '*noticeable but acceptable*,' '*disturbing*,' or did it cause a '*crash or near miss*'?" Only a small percentage of participants found oncoming headlight glare to be 'not noticeable' (6%) or 'barely noticeable' (5%). While fifty-seven percent of respondents reported that they perceived the glare to be 'noticeable but acceptable.' However, thirty-one percent of respondents perceived glare to be 'disturbing' and one percent reported a 'crash or near miss.' Thus nearly a third of survey respondents described an element of vehicles that is meant to be a safety device as having caused "disturbing" effects.

Older drivers generally report having more difficulty with nighttime glare as a result of age-related ocular changes (e.g., reduced ocular transmissivity, macular degeneration, detached retina, etc.). However, in this survey, older drivers' (65+; 11%) discomfort ratings were not significantly different from those of the younger drivers (18-24; 12%). Thus the high number of persons rating glare to be 'disturbing' cannot necessarily be associated with age differences.

Drivers finding glare to be disturbing may be a key component to understanding the underuse of high beam headlights at night. That is, drivers' may assume that because they feel discomfort when facing the high beams of other drivers, they must also be disabled. Subsequently, in an effort to minimize both disability and discomfort glare, drivers may abstain from using high beam headlights.

It is quite obvious that disability glare can negatively influence factors important to good driving – specifically, our nighttime visual abilities. As previously noted, decrements in visibility due to reduced illumination have been largely associated with crash rates (Owens & Sivak, 1996; Sullivan & Flannagan, 2002). In addition, persons who are especially sensitive to changes in nighttime illumination have higher crash rates than those who are visually healthy (Owsley, Stalvey, Wells, & Sloane, 1999; Owsley, Stalvey, Wells, Sloane, & McGwin, 2001). That is, persons with cataracts (clouding of the lens) are susceptible to major impairments in contrast sensitivity. Subsequently, people with severe contrast sensitivity decrements are almost 6 times more likely to be involved in a

recent crash (Owsley, et al., 2001). Yet, there has been difficultly directly associating crash rates with glare or a loss of visual abilities due to glare. A study conducted in the late 1960's found that no more that 1% of all fatal nighttime crashes could be associated with headlamp glare (Hemion, 1969). Further, a more recent study found that only about 0.3% of fatal nighttime crashes listed glare as a contributing factor (NHTSA, 2007). It is possible however, that these low rates are a result of poor reporting methods (e.g., not listed on incident report form, drivers involved do not/cannot report glare).

Much work has been focused on efforts to reduce/minimize nighttime headlight glare. This work has been, in part, motivated by the large number of complaints submitted to the NHTSA (e.g., Docket No. NHTSA-01-8885). The majority of these complaints were triggered by drivers experiencing discomfort and assuming that they were also experiencing disability glare. However, it is not clear that drivers are able to determine when they are visually disabled by glare and when they are not; to my knowledge this issue has never been addressed empirically. Thus complaints of excessive glare must not be taken as clear evidence that headlamp glare is a major problem. Indeed, one rarely hears about drivers complaining about their headlamps being too dim despite the fact that nighttime visibility problems are well documented. One of the goals of the present project is to explore and to explain the relationship between disability glare and discomfort glare and to quantify the accuracy with which drivers can estimate the magnitude of glare-induced reductions in their ability to see.

In response to these headlamp-glare related complaints the US Congress allocated $1,000,000 to NHTSA to investigate the effects and risks associated with oncoming headlight glare (U.S. Congress, 2005). Specifically, SAFETEA-LU states:

"(a) In General- Using funds made available to carry out section 403 of title 23, United States Code, for fiscal year 2005, the Secretary shall make $1,000,000 available to conduct a study on the risks associated with glare to oncoming drivers, including increased risks to drivers on 2-lane highways, increased risks to drivers over the age of 50, and the overall effects of glare on driver performance.

"(b) Report- Not later than 18 months after the date of enactment of this Act, the Secretary shall transmit to the Committee on Transportation and Infrastructure of the House of Representatives and the Committee on Commerce, Science, and Transportation of the Senate a report on the results of the study and any recommendations regarding measures to reduce the risks associated with glare to oncoming drivers."

The NHTSA has subsequently published many technical reports and summaries focused on headlamp glare (e.g., Akashi, Hu, Bulluough, 2008; Akashi, Van Derlofske, Raghavan, & Bullough 2008; Bullough, Skinner, Akashi, Van Delofske, 2008; Bullough, Skinner, Pysar, Radetsky, Smith, & Rea 2008; NHTSA, 2008a; & NHTSA, 2008b). The results of several of these studies

responding to the SAFETEA-LU (Safe, Accountable, Flexible, and Efficient Transportation Equity Act: A Legacy for Users) are discussed here.

Many aspects of headlamp glare were addressed in the series of studies conducted by the NHTSA. One of the major contributing factors to the perception of glare intensity is the angle of the glare source (Fry 1954; Miller and Benedek, 1973). As a result, a recent study examined the effects of headlamp mounting height (Akashi, Van Derlofske, Raghavan, & Bullough, 2008). Not surprisingly it was found that participants rated higher mounted headlamps to be more discomforting. Discomfort ratings, however, decreased as headlamp intensity decreased. Another way to reduce light intensity is through polarization. Polarization involves activating or placing a filter over headlamps as the driver approaches an oncoming vehicle. Schwab & Hemion (1972) showed that participants rated light from a polarized source as less discomforting than non-polarized light.

Another report examined both discomfort glare and visual abilities in varying amounts of illumination (Bullough, Skinner, Akashi, Van Delofske, 2008). Once again it was found that the discomfort ratings of glare increase as lamp mounting height increases as well as when lamp intensity increased. Unfortunately, no measures of disability were taken in the presence of oncoming glare. Visual abilities, however, were measured in varying amounts of fixed lighting (overhead pole-mounted lighting) with varying headlamp intensities. Participants were asked to sit in a stationary vehicle and indicate the presence of

an 18 cm x 18 cm (≈7 in x 7 in) board as it moved toward the vehicle from one of

five eccentricities (-15°, -5°, 0°, 5°, and 15°). As exp ected, the distance at which

the target board was detected was reduced as the roadway lighting decreased.

The targets most in the periphery (±15°) were also de tected at the closest

distances. Somewhat surprisingly, headlamp lighting only influenced (increasing

distance) the detection distance of one target board (+15°). That is, the ambient

illumination resulting from the roadway lights was sufficient enough to allow

participants to detect the target squares in the absence of headlight illumination.

The authors suggest that this provides evidence to support the idea of a lower

intensity 'city' headlamp setting (introduced by Schreuder, 1975). It is thought

that this setting would reduce the impact of oncoming headlamp glare.

This suggestion should, however, be taken with caution. First, in this

environment of fixed lighting, the headlamps did aid in object detection for the

15° target. Objects located just to the right of the vehicle (near 15°) are of great

importance to detect early. It is in this location that many pedestrians, animals,

etc. are located. These moving hazards are potentially able to move quickly into

the road with little to no warning. Further, as evidenced by high beam usage data

(Hare & Hemion, 1968; Sullivan, Adachi, Mefford, & Flannagan, 2004;

Buonarosa, Sayer, & Flannagan, 2008), drivers frequently use an inappropriate

headlight setting. If drivers were left to manually select a 'city' setting it is

possible that many people would inappropriately use the setting in non-fixed

lighting settings. This could further decrease nighttime visibility and subsequently

increase nighttime driving risk. In addition, headlamp glare may simply not be an issue in well-lit areas at night. Drivers generally report lower levels of discomfort glare in the presence of greater ambient illumination (e.g., Miller & Benedek, 1973; Flannagan, Sivak, & Gellatly, 1991). Furthermore, it is also not known if headlamp glare in these areas actually cause disability. This is especially relevant as visual acuity tends to improve as ambient illumination increases (Sturgis & Osgood, 1982).

Other non-government based groups have also focused on glare. For example, in 2001 the AAA Foundation for Traffic Safety published "Countermeasures for Reducing the Effects of Headlight Glare" (Mace, Garvey, Porter, Schwab, & Adrian). This document outlines numerous ways in which headlight glare can be minimized. These ways include beam pattern modification, annual headlamp beam re-aiming, adaptive headlighting, headlamp height requirement modifications. Other methods to reduce glare that do not involve vehicle headlamps are also mentioned, including the use of night driving glasses and glare screens (large physical barriers) between opposing lanes of traffic to reduce or eliminate glare produced by oncoming vehicle headlamps (Mace et al., 2001).

Despite the considerable literature on headlight glare and reducing headlight glare, little emphasis has been placed on the effects of glare on actual driving performance. To my knowledge, only two on-road studies and one simulator study have explored the actual effects of glare on driver performance.

22

Ranney, Simmons, & Masalonis (1999) asked twelve experienced commercial truck drivers to drive in a simulator for two eight-hour sessions. Throughout the drives participants were exposed to multiple periods of glare from a following vehicle. It was found that even with prolonged exposure to glare, participants' driving behavior was not negatively affected. A small decrement in pedestrian detection was found when drivers became sleepy, but was not attributed to glare. While the lack of a glare-related decrement in driving performance (e.g., pedestrian detection, vehicle in mirror detection, vehicle control, etc.) is encouraging, these findings may not generalize to many driving scenarios. First, the population tested was professional drivers. These drivers spend many more hours on the roadway than do other drivers. Secondly, this study focused on glare originating from following vehicles. This type of glare is quite different from glare from oncoming headlights. Finally, it is difficult to replicate nighttime driving conditions in a simulator. These factors may have had a significant effect on the findings of this study.

The first of the two on-road studies asked participants to drive instrumented vehicles along a straight roadway (Bullough, Skinner, Pysar, Radetsky, Smith, & Rea, 2008). The participant encountered two different vehicles with headlights of different intensities. While this study is limited in scope, it was found that with increased glare intensity there was a greater variability in throttle position (i.e. greater variability in speed). This finding is consistent with the second study.

The second of these two studies asked participants to drive an instrumented vehicle around a city course (Theeuwes, Alferdinck, & Perel, 2002). Along the course the participants were exposed to various intensities of glare (produced from a fixed source on the hood of the vehicle). The overall presence of glare affected driving speed. Participants drove, on average, 2 km/h (1.2 mph) slower with glare than without glare. However, there was not a significant difference in driving speeds between the different glare intensity levels. While driving speed variability is an indicator of higher task load (e.g., Törnros & Bolling, 2006), the slowing of the vehicle may not necessarily be an indicator of decreased driving performance. As previously mentioned, drivers often drive at speeds too fast for visibility conditions at night (e.g., Leibowitz, Owens and Tyrrell, 1998). While the issue has not been sufficiently researched, slowing the vehicle may actually be beneficial to nighttime road safety.

In the Theeuwes, et al. study, steering wheel reversals (a rapid change in steering wheel direction) were also measured throughout the participants' drive (Theeuwes, Alferdinck, & Perel, 2002). The presence of glare significantly increased steering wheel reversals in only one especially curvy portion of the road. Glare also affected object detection performance. During one portion of the drive participants were asked to identify low contrast boards made to represent pedestrians. In the low-intensity glare condition (350 cd), participants detected a similar number of boards as with no glare. The two strongest intensities (690 cd and 1380 cd), however, generated significantly shorter detection distances.

These two decrements to driving performance can be partially explained by the placement of the glare source lighting. In this study the glare source was mounted to the hood of the test vehicle. This placement prevents the possible lighting benefits gained from an oncoming vehicle. As a driver approaches an oncoming vehicle at night there is a brief period when there is greater total lighting along the roadway (i.e., the combination of oncoming headlighting and personal vehicle lighting provides more overall lighting on the road than personal vehicle lighting alone). This lighting may enable drivers to see a greater distance and subsequent portion of the road. This may then enable drivers to view the road ahead to better understand the curvature of the road as well as to identify objects (e.g., silhouetting) in or along the roadway. This possible lighting advantage was not present in this study. This view of oncoming headlight glare increasing visibility distances is supported by Flannagan, Sivak, Traube, & Kojima (2000).

Flannagan et al. (2000) measured seeing distance in a variety of lighting conditions. Participants sat in a stationary vehicle on a vacant, straight roadway and were exposed to low, medium, and high intensities of oncoming (stationary) glare headlights along with corresponding levels of their own ("seeing") headlights. It was found that as seeing headlamps and glare headlamps both increased proportionately (i.e., low vs. low, medium vs. medium, high vs. high), seeing distance also increased. In fact, seeing distance increased about 17% from the lowest intensity combination to the highest intensity combination. That

is, participants were able to recognize a pedestrian at a distance 17% greater in the high beam vs. high beam setting than the low beam vs. low beam setting. Despite this glare-induced increase in seeing distance, the greater the intensity of the glare source light, participants provided lower (i.e., more intense) deBoer scale ratings. That is, as glare intensity increased the observers experienced improved visual performance while also experiencing greater discomfort. It appears then that drivers' reports of discomfort are a poor predictor of nighttime visibility when encountering oncoming headlight glare.

Nighttime drivers commonly encounter oncoming vehicles using bright and often discomforting headlights. It is this discomfort that has led many drivers to complain about the intensity of headlights and the glare they cause. These complaints have led NHTSA to not only investigate glare, but also to generate ways in which glare can be reduced (e.g., Akashi, Hu, Bulluough, 2008; Akashi, Van Derlofske, Raghavan, & Bullough, 2008; Akashi, Van Derlofske, Watkinson, Fay, 2005; Bullough, Skinner, Akashi, Van Delofske, 2008; Bullough, Skinner, Pysar, Radetsky, Smith, & Rea, 2008; Bullough, Van Derlofske, Dee, Chen, & Akashi, 2003; Singh, and Perel, 2003; NHTSA, 2007; NHTSA, 2008a; & NHTSA, 2008b). It appears, however, that subjective feelings of discomfort are unable to accurately predict objectively measured decrements in visual performance. In addition, drivers, in general, can be poor judges of personal nighttime visual abilities in the presence of glare. Yet, it seems as if a great deal of research has been motivated at least in part by the assumption that subjective feelings of

discomfort are highly correlated with decrements in visual performance. It is possible that despite experiencing considerable discomfort drivers may not actually experience any disability (and vice versa). Despite drivers facing the glare of oncoming headlamps being acutely aware of their own discomfort, they may be quite unaware of their inability to see objects and hazards ahead. It may be the case that the light from oncoming headlights causes little or no decrement in visual ability even in drivers who feel "blinded" by the glare.

In order to clarify these issues (i.e. the relationship between feelings of discomfort and subsequent estimates of disability) observers' estimates of personal visual abilities must be quantified both with and without glare present. A recent methodological advance makes this possible. In order to determine whether drivers understand that visual acuity declines with luminance, Brooks and Tyrrell (2008) developed a technique to have participants estimate their own acuity under different luminances. In order to estimate acuity, participants were trained to use both a magnitude estimation technique (assigning a number to specify the size of the optotype that would be just recognizable) and a psychophysical matching technique (using calipers to estimate the height of the optotype) to different decimal acuity values (at 6 m; 20 ft). This methodology resulted in participants being able to accurately estimate known acuity values (represented by sized different squares) under daylight/room light conditions. (The verbal and manual estimates produced similar results and were further analyzed as a combined estimate score.) However, participants were

subsequently unable to estimate in acuity as accurately when illumination was lowered. Participants were able to successfully estimate that acuity worsens under low light levels. Yet, under low light levels, college-aged and middle-aged participants consistently underestimated their own acuity. Brooks and Tyrrell (2008) concluded that while participants generally understand the trend of their changing visual abilities under challenging conditions (non-daylight/room light), participants did not fully appreciate the extent to which their own acuity is affected by low luminance on acuity. That is, participants estimated that under low luminances their ability to distinguish fine detail was much worse than it really is. If people are not able to accurately assess their own visual abilities in differing light levels, it is feasible that people may dramatically overestimate the effects of headlight glare. More importantly for the present work, however, is the fact that the techniques developed by Brooks and Tyrrell (2008) provide a valuable means of assessing observer's estimates of their own visual abilities under changing visual conditions. This project will rely heavily on these techniques.

The primary goal of the current study is to determine how accurately drivers are able to estimate the extent to which glare sources affect their visual abilities. Experiment one utilized the laboratory-based psychophysical approach (developed by Brooks & Tyrrell, 2008) to explore participants' ability to estimate their own visual acuity in the face of differing intensities of glare. Participants estimated their own visual acuity in the presence of low, medium, and high glare intensities. Actual acuity was also measured at each of these intensities

Participants also provided subjective ratings of glare-induced discomfort using the deBoer scale

Experiment two utilized an outdoor in-vehicle method of assessing both the participants' ability to see in the face of an oncoming pair of headlights and their estimates of their ability to see in the same conditions. Participants estimated the distance at which they would be able to recognize the orientation of a retroreflective letter on the roadway ahead. This was done with seeing headlights (i.e., own vehicle) on both low and high beam settings and with glare lights (i.e., opposing vehicle) on both low and high beam settings. Participants again provided subjective ratings of glare source intensity using the deBoer scale.

In general, it was hoped that these two experiments will lead to a better understanding of how well drivers assess their personal visual abilities in the presence of glare. Specifically, these two experiments test the hypothesis that drivers overestimate the extent to which glare sources impair their ability to see objects. It is also hoped that a better understanding of the relationship between feelings of discomfort are related to actual visual abilities in the presence of glare.

EXPERIMENT 1

Method

<u>Participants:</u>

Twenty-four people participated (M = 19.3 years; 18 – 21 years) in exchange for credit in an undergraduate psychology course. Each achieved both a binocular and monocular visual acuity of at least 6/12 (20/40; the minimum requirement to attain a driver's license in South Carolina). No participants self-reported any visual pathologies (e.g. cataracts) other than corrected refractive errors. Those participants with refractive errors used contact lenses during the experiment – none wore glasses. All had a valid driver's license and had been driving for at least one year.

<u>Initial Visual Screening:</u>

After informed consent was obtained, both monocular and binocular visual acuity was measured using the Optec 2000 Vision Tester (Stereo Optical Company, Inc.). All participants achieved a visual acuity of at least 6/12 (20/40). Contrast sensitivity was also measured using the Pelli-Robson Contrast Sensitivity Test (M = 1.77, range = 1.65-1.95; Pelli, Robson & Wilkins, 1988). Participants were tested at 3 meters (9.8 ft) under normal room lighting. After assessing both acuity and contrast sensitivity measurements, participants were given a brief overview of the remainder of the experimental session.

Freiburg Visual Acuity and Contrast Test:

Participants were next sat at a table. The room lights were turned off and a small lamp was placed behind a temporary cloth wall to facilitate the use of the calipers (described later). Ambient illumination (measured at the viewer's eye) was approximately 0.18 lx for the remainder of the experimental session. While seated at the table, participants placed their chins in a rest which allowed the eyes to be aligned with the center of a computer screen placed 6 meters (20 ft) away from the viewer. While sitting at the table and using the chin rest, participants' acuity was measured using the Freiburg Visual Acuity and Contrast Test (version 3.3; FrACT3.3). The FrACT3.3 requires the viewer to determine the orientation of a size-varying Landolt C (presented at orientations of 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°) using a numeric key   pad (*see* Figures 1 and 2). A 70% contrast setting was used. This however, actually generated a contrast of about 78%, the Landolt C characters had a mean luminance of 11.06 cd/m^2 (R = 89, G = 89, B = 89) and the background had an mean luminance of 92.16 cd/m^2 (R = 233, G = 233, B = 233). Participants were required to attain a minimum monocular (right eye) acuity of 0.0 logMAR (20/20) in order to continue to acuity estimation training.
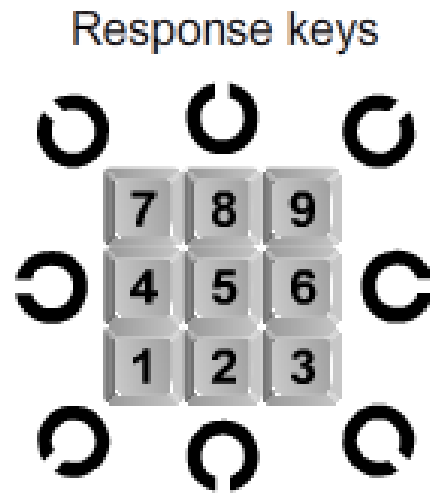
Figure 1. Representation of numeric keypad response based on Landolt C
orientation.

Figure 2. Response keypad with (hook and loop closure) tactile cues.

<u>Glare Source:</u>

A "glare box" (323 mm high, 325 mm wide, and 42 mm deep) was placed between the participant and the computer screen, ≈ 44 cm from the viewer's eye (*see* Figure 3). Participants looked through a hole (72 mm in diameter) in the center of the box (*see* Figure 4). The hole was aligned with the center of the computer screen. Around the hole is an illuminated white annulus (or "glare ring"), 11 mm in width. Light is reflected through this ring toward the viewer. This light is generated by six, 100-watt, tungsten halogen bulbs. Light intensity was controlled by using a variac to vary the voltage supplied to the bulbs. The variac was used to create 3 different light intensities by attenuating the voltage supplied to the bulbs (37%, 77%, and 98% of maximum). Luminance measurements were taken at various points around the glare ring to determine the luminance of each glare level (4 measurements at each of the cardinal directions). The low intensity averaged 120.72 cd/m^2, the medium intensity averaged 3116.13 cd/m^2, and the high value averaged intensity 7098.06 cd/m^2 (*see* Table 1 for mean values at each of the measurement regions). The illumination, measured at the participant eye was 0.18 lx at no light, 5.87 lx at the low light level, 119.25 lx at the medium light level, and 257 lx at the high light level. The entire box is painted with heat resistant matte paint, the light ring is white in color and the remainder of the exposed area is black.

Distance from the computer screen to participants' eyes is 6 m (20 ft).

Distance from glare box to participants' eyes is 44 cm.

Laptop computer used to present stimuli
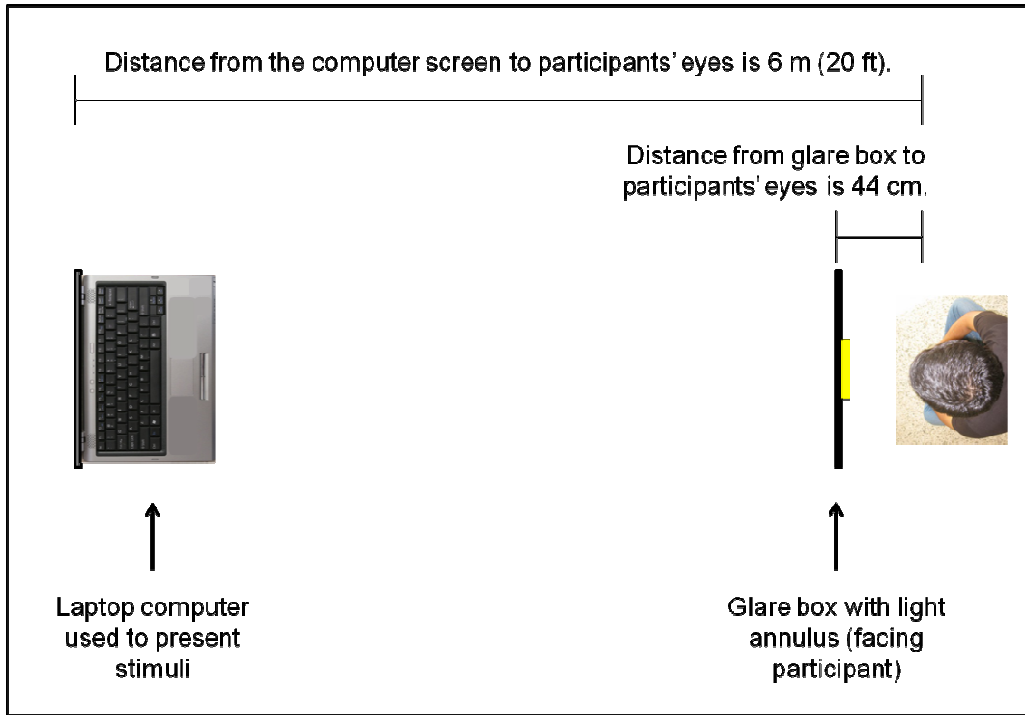
Glare box with light annulus (facing participant)

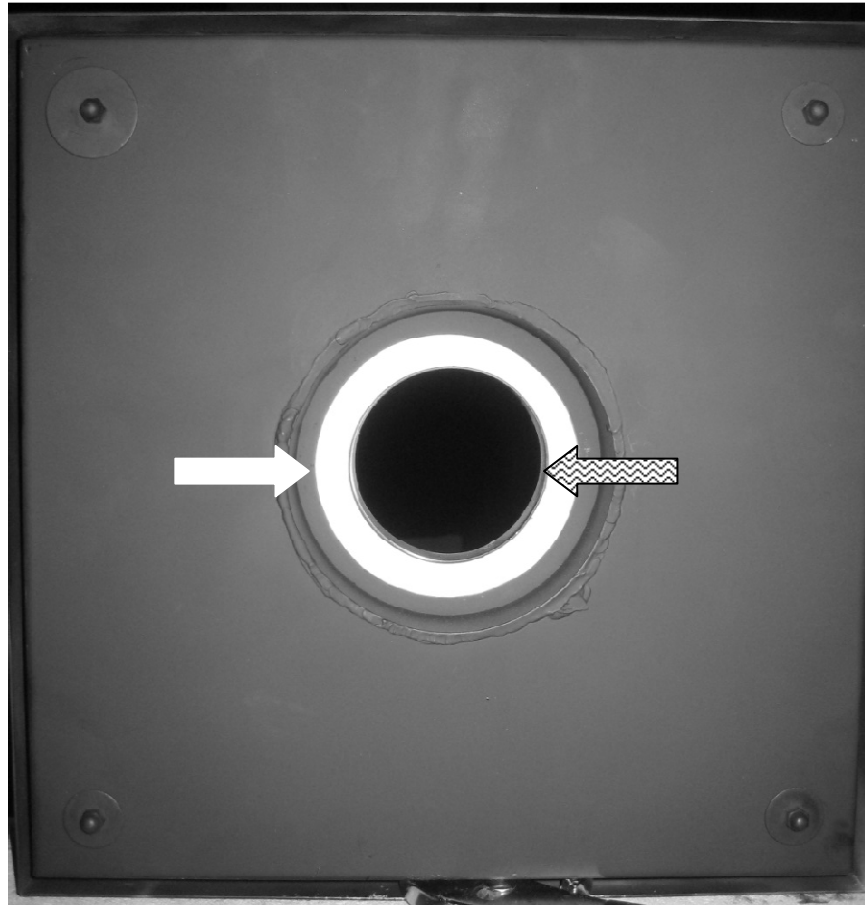Figure 3. Aerial view of experimental setup.

Figure 4. Glare source. The leftmost white arrow is pointing to the outer edge of the white "glare ring." The rightmost shaded arrow is pointing to the right edge of the "viewing aperture."

Due to the distance between the glare box and the computer screen, the left eye was occluded in order to prevent problems associated with retinal disparity. Each participant's left eye was covered with an eye patch (a piece of felt was placed between the eye and the eye patch for comfort) after binocular acuity was measured during the initial vision screening. Monocular vision was

used for the remainder of the experimental session. Participants looked through

the hole in the glare source box throughout the experimental session, even when

it was not in use.

Table 1. Mean luminance values by variac percentage of maximum voltage

supplied to the glare source. The variac set to the 37% voltage generated the low

glare intensity, 77% generated the medium glare intensity, and 98% generated

the high glare intensity.

Region of light annulus	Luminance mean values (cd/m^2)		
	Variac 37% maximum voltage	Variac 77% maximum voltage	Variac 98% maximum voltage
Top	57.81	1458.8	5859.0
Left	139.45	3693.5	7682.8
Bottom	152.2	3993.0	7784.0
Right	133.48	3319.3	7066.5
Overall Mean Values	**120.7**	**3116.1**	**7098.1**

Acuity Estimation Training:

Next, the experimenter explained to the participant that he/she would be

making two different types of acuity estimates, verbal and manual. It was

emphasized that participants could have as much training as necessary until they

felt comfortable making size estimates. Participants were shown a square on the

computer screen the same height as the height of a logMAR 0.0 letter (Snellen

equivalent 6/6 or 20/20; 8.7 mm x 8.7 mm). Participants were also provided with

a small metal square of the same dimensions (8.7 mm x 8.7 mm). This was to be

used as a reference for a "size 1" and all size estimates were based on this size

(*see* Figure 5). For example, something 2x taller would be called a "size 2".

Participants were allowed to hold and/or feel the metal square at any time, but

were not allowed to look at it either during the acuity estimation phase or the
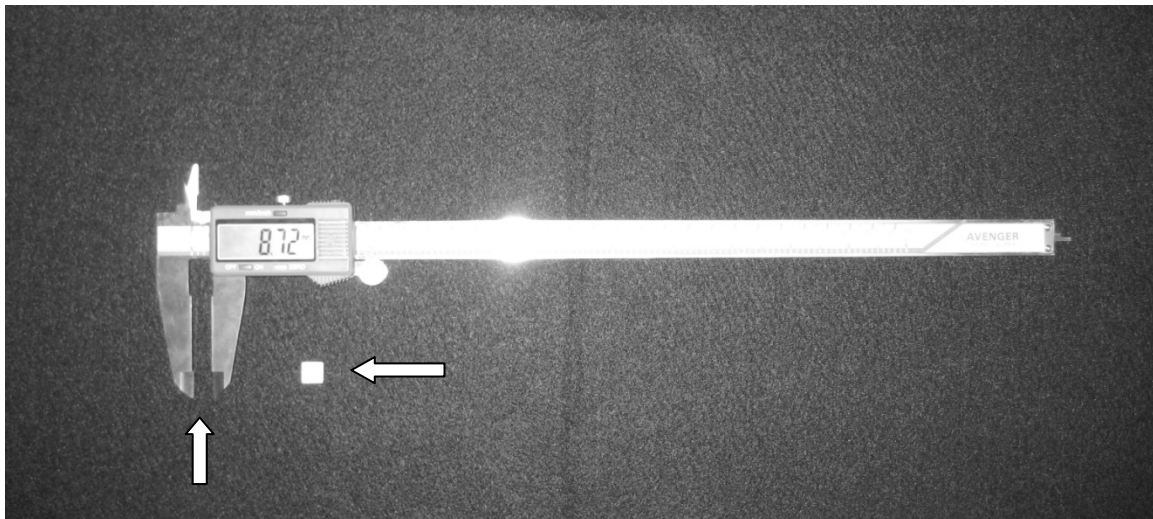
testing size estimation ability phase.

Figure 5. Training square and calipers. The leftmost arrow points to the gap in

the calipers, which the same size as the metal size one square. The rightmost

arrow points to the metal square.

The experimenter then showed the participant the square on the computer

screen again. The digital squares matched the contrast of the Landolt C (78%),

the squares had a mean luminance of 11.46 cd/m^2 (R = 89, G = 89, B = 89) and

the background had a mean luminance of 92.16 cd/m^2 (R = 233, G = 233, B =

233).   The relationship between the height of the different sized squares on the

screen and the metal square was emphasized. For example, two size one

squares were held up to the computer screen and the participants were told: "this square is a size two and it is exactly two size 1 squares tall." Squares that were 1.3, 1.6, 2, 2.5, 3.2, 4, and 5 times taller than the size 1 square were shown to the participants (*see* Table 2). Additionally, if a participant's acuity exceeded 6/6 (20/20) then square sizes smaller than 1 were also shown (i.e., .8, .6, .5, .4, and .3) as necessary. Square sizes were presented in two blocks (1-2 and 2.5-5). After participants reported being comfortable producing verbal estimates for each block of square sizes, the entire set was practiced. Feedback was provided as necessary (e.g., "good job," "only off by one size, this is actually a size…," etc.). When participants felt comfortable giving verbal size estimates for each of the computer square sizes, they were shown how to make manual magnitude estimates using calipers. Participants were instructed to hold the calipers in a vertical fashion (numbers facing the experimenter) and to generate the height of each of practice square sizes. This was done starting with the calipers in both the closed and open positions. Participants practiced making manual estimates with the calipers until they were both proficient and comfortable with the task. If the participant attained acuity better than 6/6 (20/20), an opportunity to practice making manual caliper estimates for square sizes smaller than 1 was provided. The entire training processes lasted between 20-40 minutes to complete, depending on how quickly participants were able to grasp the task.

Table 2. Square sizes with equivalent acuity and letter height.

Square size	Caliper size (mm)	LogMAR Acuity	Snellen Acuity (m)	Snellen Acuity (ft)
0.3	2.8	-0.5	6/1.9	20/6.3
0.4	3.5	-0.4	6/2.4	20/8
0.5	4.4	-0.3	6/3	20/10
0.6	5.5	-0.2	6/3.8	20/12.5
0.8	6.9	-0.1	6/4.8	20/16
1.0	**8.7**	**0**	**6/6**	**20/20**
1.3	11	0.1	6/7.5	20/25
1.6	14	0.2	6/9.6	20/32
2.0	17	0.3	6/12	20/40
2.5	22	0.4	6/15	20/50
3.2	28	0.5	6/189	20/63
4.0	35	0.6	6/24	20/80
5.0	44	0.7	6/30	20/100

Testing Size Estimation Ability:

To ensure that participants were able to estimate letter size accurately, their abilities were tested. Participants were presented with the 8 different square sizes in a random order (ranging from size 1 to size 5). Participants were asked to give 2 verbal estimates and 2 manual caliper estimates for each square size. No feedback was provided to the participants. Participants were informed that they were able to change their verbal size estimate from the first to second response. Participants either first responded with verbal response followed by a manual caliper response (and repeated) or first responded with a manual caliper response followed a verbal response (and repeated). Whether participants

responded with the verbal or manual response first was randomized between

participants. To reduce the possible effects of magnitude under or overestimation

bias while using the calipers, participants estimated size once starting with the

calipers closed and once starting with the calipers open. This order was

randomized across participants and the two manual responses were averaged.

The two verbal responses were also averaged.

<u>Acuity Estimation:</u>

Once the participants both felt comfortable and were able to accurately

estimate square sizes (each square verbal estimate correct a minimum of four

times and each manual estimate correct two times) in estimating sizes, they were

then deemed able to use verbal and manual techniques to estimate their own

visual acuity. During the acuity estimation portion of the experiment the

participants' task was to "estimate the size of the C whose orientation you would

just barely be able to determine." The computer screen remained blank (solid

grey, matching the background color of the acuity test and square training

screens) during this time. Participants were reminded that they could estimate

any size that they desired and were not constrained to using the previous square

sizes they had practiced. Before giving any acuity estimates, participants were

verbally reminded of the smallest size Landolt C whose orientation they

determined earlier (based on logMAR acuity; *see* Table 2). Participants gave 2

verbal and 2 caliper estimates (in the same order as during the test at the end of

size estimate training) at four different light/glare intensities (low, medium, high, and no light source; see Figure 6). Acuity estimates were always made in either ascending or descending glare order. Half of the participants made estimates beginning with no light (and progressed to the high glare level) and half began with the high glare (and progressed to no light). After the acuity estimation at each glare intensity level participants waited 1-5 minutes for the afterimage of the glare source to dissipate.

Figure 6. Participant estimating acuity using calipers.

<u>Actual Acuity Measurements:</u>

After participants estimated their acuity at each of the 4 luminance levels, actual acuity was measured using the Freiburg Visual Acuity and Contrast Test (FrACT version 3.3; eight possible Landolt C orientations, 50 trials each). This was done twice at each of the 4 luminance levels in the same order in which acuity estimates were made. The two acuity measurements were later averaged. Again, participants waited 1-5 minutes for the afterimage of the light source to dissipate between each acuity measurement.

<u>Subjective Ratings of Light Source Discomfort:</u>

Participants were asked to provide a subjective measure of the intensity of the glare at each light level (after the first acuity measurement at each light level). This was assessed using the deBoer measurement scale. This scale ranges from 9 (unnoticeable) to 1 (unbearable; *see* Table 3).

Table 3. deBoer scale used to subjectively rate light intensity.

Unnoticeable	9
	8
Satisfactory	7
	6
Just admissible	5
	4
Disturbing	3
	2
Unbearable	1

Questionnaire:

      After all acuity measurements were taken, participants were asked to answer several short questions about their nighttime driving attitudes and behaviors (see Appendix A). Upon completing this questionnaire, participants were given an opportunity to ask any questions, and thanked for their time.

Results Experiment 1

It should be noted that all analyses on actual and estimated acuity values were conducted after the data had first been transformed into log(MAR) units. Caliper estimates were made in letter height (mm) and were converted to log(MAR) units directly. Verbal estimates required an extra conversion. The verbal estimates were multiplied by 8.727 (the mm height of a size 1) – creating a letter height (in mm) from which the log(MAR) conversion was made.

Training:

As described earlier, after the conclusion of the acuity estimation training, participants estimated the sizes of all eight training square sizes in a random order. For each square size, participants provided 1 manual estimate starting with the calipers closed, 1 manual estimate starting with the calipers open, and 2 verbal estimates. The two caliper estimates were averaged to create a single manual score and the two verbal estimates were averaged to create a single verbal score. The training test was completed without feedback from the experimenter (i.e., participants were not told if responses were accurate). The squares were presented in the same order for all participants during the training test. All participants passed the training testing with a minimum correlation between the estimated square size and the actual square size of $r = .90$ (in both the verbal and manual techniques).

Verbal technique. Participants appreciated the differences in physical

square sizes using the verbal technique, $F(7, 161) = 388.96$, $p < .001$. Linear

regression models were calculated for each participant to describe accuracy with

which the participants estimated the square sizes (see Appendix B). The R^2

values were then averaged across all participants, resulting in a mean R^2 value

of .95. This indicates that participants were able to accurately estimate square

size using the verbal technique. Figure 7 presents the verbal, manual, and

combined verbal + manual square size estimates averaged across all
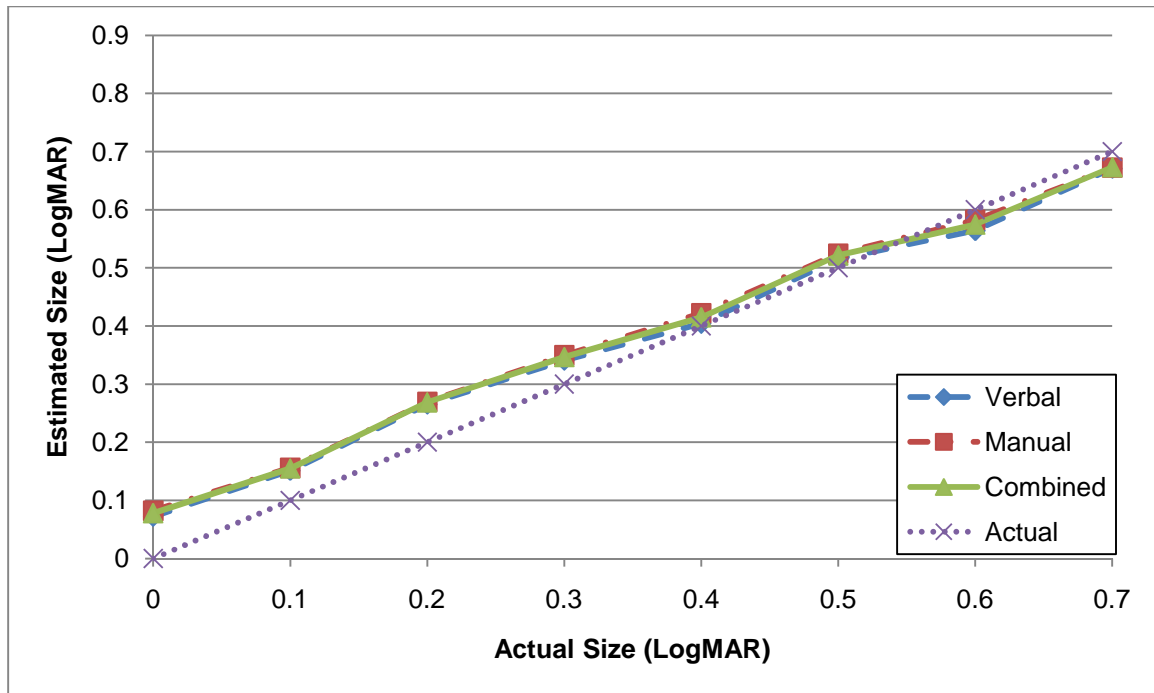
participants.

Figure 7. The mean participant estimated square size during training test using the verbal technique, manual technique, and the combined verbal + manual score.

Manual technique. Participants appreciated the differences in square sizes using the manual technique, $F(7, 161) = 312.94$, $p < .001$. Linear regression models were calculated for each participant to describe how accurately the participants estimated the square sizes (see Appendix B). The R^2 values were then averaged across all participants, resulting in a mean R^2 value of .94. This indicates that participants were able to accurately estimate square size using the manual technique.

Verbal and Manual Techniques. A repeated measures ANOVA compared

the verbal and manual techniques. No significant difference between the two

estimation techniques was found, $F(1, 23) = .62$, $p > .05$. Subsequently, a

averaged (verbal + manual) estimate was created for each participant. Using this

score linear regression models were calculated for each participant to describe

how accurately the participants estimated square sizes (see Appendix B). The

R^2 values were then averaged across all participants, resulting in a mean R^2

value of .95. Table 4 presents the mean R^2 and standard deviation for the verbal,

manual, and combined estimate scores. For the remainder of the analyses the

averaged estimate was used as the measure of estimated acuity.

Table 4. Mean R^2 and standard deviation values. Each participant's correlation

between judged and actual square size during training test. All participant values

were then averaged.

	Verbal Technique	Manual Technique	Combined
Mean R^2 value	.95	.94	.95
Standard Deviation	.04	.05	.04

Actual Acuity:

Table 5 presents the mean acuity and standard deviation (including all 24

participants) at each of the four glare intensity levels (none, low, medium, and

high; see also Figure 7). Interestingly, glare level did not significantly affect

measured acuity, $F(3, 69) = 1.309$, $p > .05$, $\eta_p^2 = .05$.

Table 5. The mean measured acuity (logMAR) and standard deviation at each of

the glare light levels.

	No Glare	Low Glare	Medium Glare	High Glare
Mean Measured Acuity (Snellen Denominator, ft)	-.075 (16.8)	-.075 (16.8)	.-085 (16.4)	-.060 (17.4)
Standard Deviation	.087	.103	.091	.104

Estimated Acuity:

Table 6 presents the mean estimated acuity and standard deviation

(including all 24 participants) at each of the four glare intensity levels (none, low,

medium, and high). Participants believed that glare level would significantly

affect acuity, $F(3, 69) = 21.78$, $p < .001$, $\eta_p^2 = .49$. Pairwise comparisons (LSD)

revealed that acuity was estimated to decline significantly with each increase in

intensity of the glare source light. That is, participants estimated acuity to be

maximal with no glare light, and the acuity estimates were progressively and

significantly worse with the low, medium, and high glare levels. Participants

estimated acuity at the medium and high glare levels to be worse than the low

glare. Finally, participants estimated acuity to be worse at the high glare level

than the medium glare level (*see* Figure 8).

Table 6. The mean estimated acuity (logMAR) and standard deviation at each of the glare light levels.

	No Glare	Low Glare	Medium Glare	High Glare
Mean Estimated Acuity (Snellen Denominator, ft)	-.018 (19.2)	.048 (22.3)	.108 (25.6)	.161 (29.0)
Standard Deviation	.090	.147	.181	.207

Actual vs. Estimated Acuity:

The estimations and measurements at the no light level have been excluded from comparisons between estimated and actual acuity. This was done because participants were told their 'correct' answer (the baseline acuity originally measured using FrACT) when estimating acuity under the no light condition. This was done so that participants were provided with an anchor from which other estimates could be based.

A 4 (glare level) x 2 (actual v. estimated) repeated measures ANOVA revealed a significant difference between estimated and actual acuity, $F(1, 23) = 40.86$, $p < .001$, $\eta_p^2 = .64$. Overall, participants estimated acuity (M = .11 logMAR; 20/25.8) to be significantly worse than the mean of the actual measures of acuity (M = -.07 logMAR; 20/17). Further, a significant interaction between glare level and acuity (estimated vs. actual) existed, $F(2, 46) = 7.04$, $p = .002$, $\eta_p^2 = .23$. This interaction confirms that the discrepancy between estimated and actual acuity increases with increases in glare level. Still, participants estimated their acuity to be significantly worse than their actual acuity at the low ($F(1, 23) =$

24.75, $p < .001$, $\eta_p^2 = .52$), medium, ($F(1, 23) = 36.56$, $p < .001$, $\eta_p^2 = .61$), and

high ($F(1, 23) = 33.88$, $p < .001$, $\eta_p^2 = .60$), glare levels. Figures 8 and 9 depict

the relationship between measured and estimated acuities averaged across

participants (individual participant data can be seen in Appendix C).
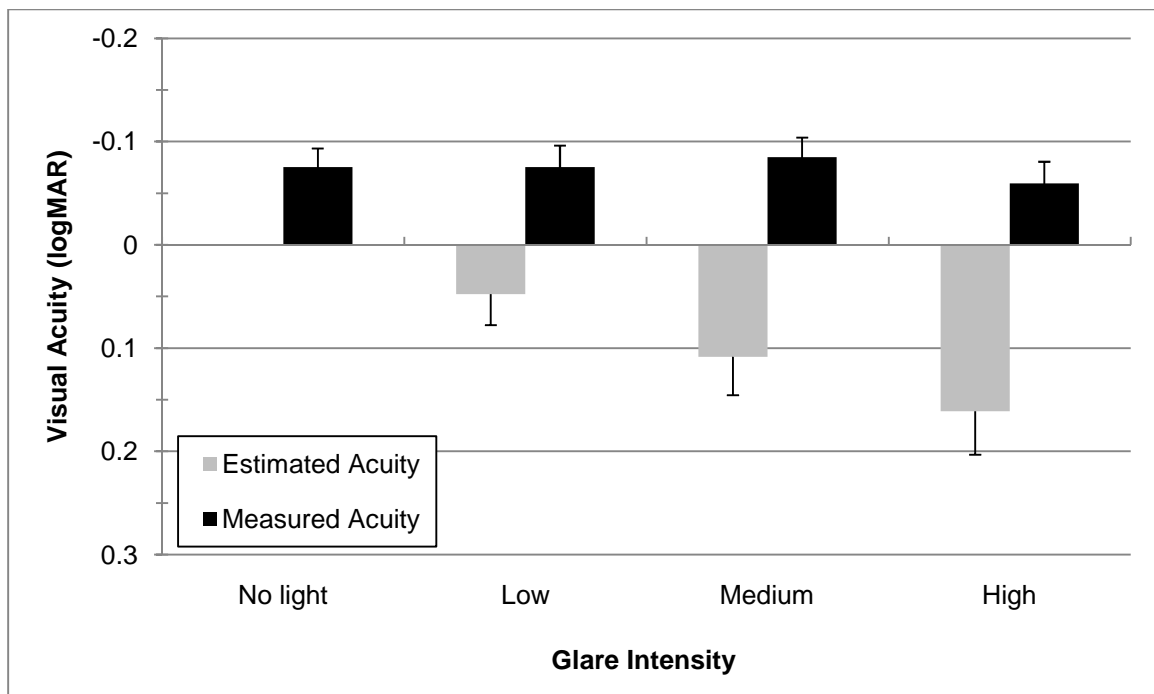
Figure 8. Mean (+ or – 1 standard error of the mean) estimated and actual
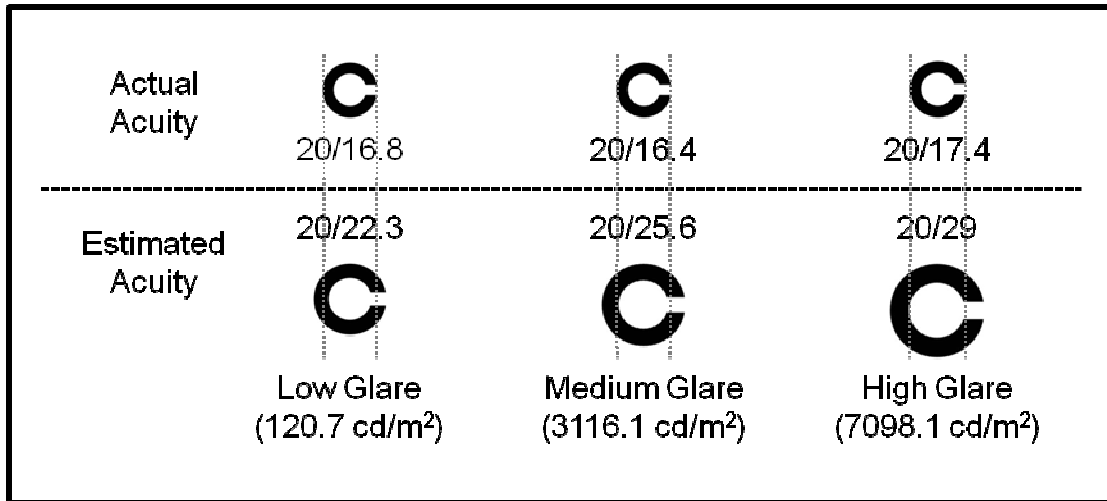
acuity.

Figure 9. Comparisons of estimated acuity and actual acuity.

Acuity Estimate Accuracy & Glare:

In order to better understand participants' ability to correctly estimate their acuity under different levels of glare a difference (error) score was created. For each level of glare (Low, Medium, and High) each participant's estimated acuity was subtracted from their actual acuity measurement. Thus, a positive error score represents an overestimation of acuity and a negative error score represents an underestimation of acuity (recall that smaller logMAR values indicate better acuity).

Table 7. Difference scores (logMAR) and standard deviation for each of the glare levels. Negative values indicate acuity underestimation.

	Low Glare	Medium Glare	High Glare
Mean difference	-.123	-.193	-.221
Standard Deviation	.121	.157	.186

A repeated measures ANOVA revealed a significant effect of glare level, $F(2, 46) = 7.04$, $p = .002$, $\eta_p^2 = .23$ confirming that the magnitude at which participants underestimated their acuity significantly increases as glare level increases (see Figure 10). Acuity estimates showed the least error in the low glare light condition. The medium and high glare levels generated significantly greater overestimates than the low glare levels, but were not significantly greater than each other. Table 7 presents the mean acuity underestimation and standard deviation for each of the glare levels (low, medium, and high).
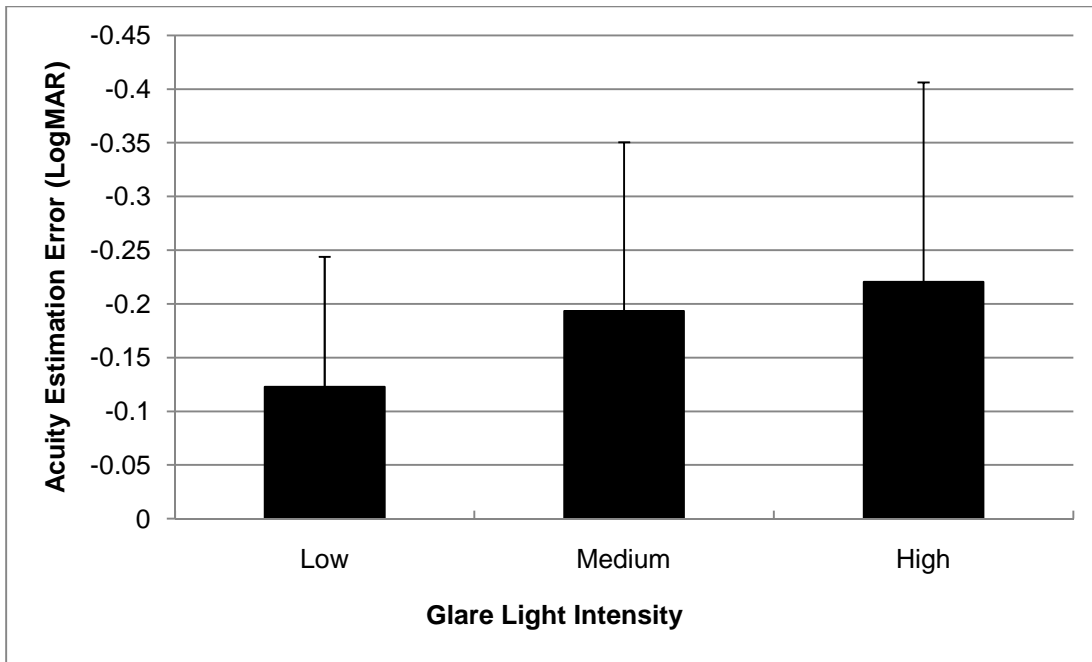
Figure 10. Mean estimation error (minus 1 standard error of the mean) as a

function of glare intensity. Negative values indicate an underestimation of acuity.

deBoer Ratings:

A repeated measures ANOVA revealed a significant effect of glare

intensity on deBoer ratings, $F(2, 46) = 87.71$, $p < .001$, $\eta_p^2 = .79$ (see Figure 11).

Participants rated each of the light levels significantly different from one another.

The mean deBoer ratings were: low glare = 6.1 (between "*Satisfactory*" and "*Just*

Admissible"), medium glare = 4.5 (slightly more discomforting than "*Just*

Admissible"), and high glare = 3.4 (slightly less discomforting than "*Disturbing*";

recall that a lower rating indicates a higher level of discomfort).
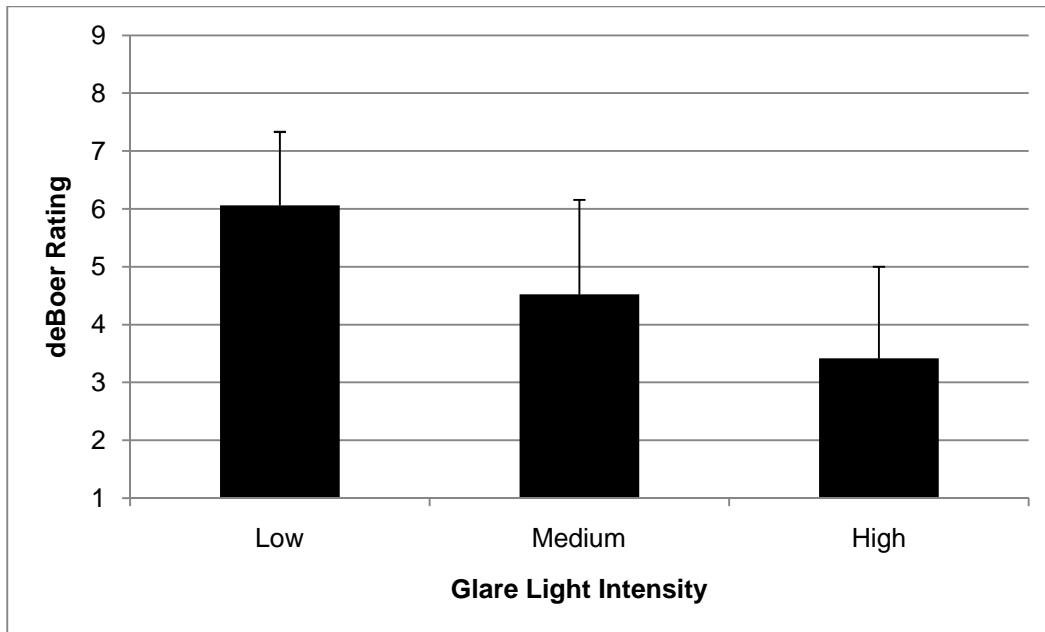
Figure 11. Mean deBoer ratings (plus 1 SEM) of discomfort at each glare

intensities. Lower deBoer values indicate a higher level of discomfort.

deBoer scale and estimated acuity. In order to better understand the

relationship between estimated acuity and deBoer ratings, correlations were

calculated for each participant (a table of individual R^2 values can be found in

Appendix D). The mean individual R^2 between deBoer ratings and estimated

acuity is .76 (range = .07 to .99). The mean r = -.44 (range -.99 to .96). That is,

as ratings of discomfort increased (lower deBoer numerical rating) acuity

estimates also tended to increase (i.e. poorer acuity).

Because there was considerable variability between individual participant

R^2 values, a second approach to this relationship was taken. The R^2 for the

average estimated acuity and the average deBoer ratings at each of the glare

54

levels was calculated. The average estimated acuity at each of the light levels
was strongly correlated with the average deBoer rating at each of the glare
levels, $R^2 = .99$, $p < .05$ (y = -0.0427x + 0.3048; *see* Figure 12). That is, as
participants' feelings of discomfort worsened, it was estimated that acuity also
worsened.
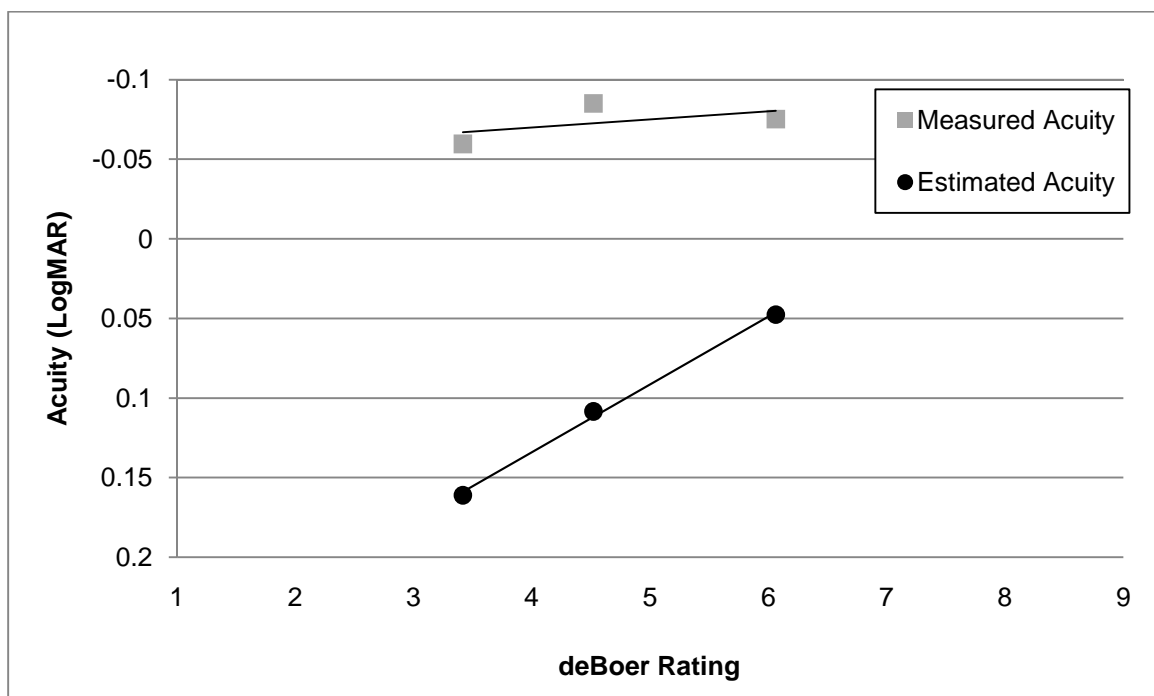
Figure 12. Mean deBoer ratings by average estimated and actual acuity.

deBoer scale and measured acuity. In order to better understand the
relationship between actual acuity and deBoer ratings, correlations for each
participant were calculated (a table of individual R^2 values can be found in
Appendix D, graphical representations of each participant can be seen in

Appendix E). The average individual R^2 between deBoer ratings and actual

acuity is .44 (range = .00 to .99). The mean r = -.29 (range -.99 to .97). The

mean measured actual acuity at each of the light levels was correlated with the

average deBoer rating at each of the glare levels, R^2 = .28, p > .05 (y = -0.0051x

- 0.0493; see Figure 12).

deBoer ratings and actual/estimated acuity. In order to further investigate

the relationship between deBoer ratings and estimated vs. actual acuity, R^2

values were compared. An r to t transformation was conducted to determine if

these two correlations are significantly different from one another (Cohen &

Cohen, 1983; Applied Multiple Regression/Correlation Analysis for the Behavioral

Sciences). This analysis revealed a significant difference in the relationships,

further emphasizing the strong relationship between feelings of discomfort and

estimated acuity, $t(21)$ = -13.56, p < .001.

deBoer ratings and acuity estimation accuracy. Yet another way to

examine the relationship between deBoer ratings and acuity estimates is to

utilize acuity estimation error. The relationship between the mean acuity

estimation error and the mean deBoer rating yielded R^2 = .98 (y = .038x - .35;

see Figure 13). This illustrates that as participant underestimation of acuity

increases, subjective feelings of discomfort also increase.
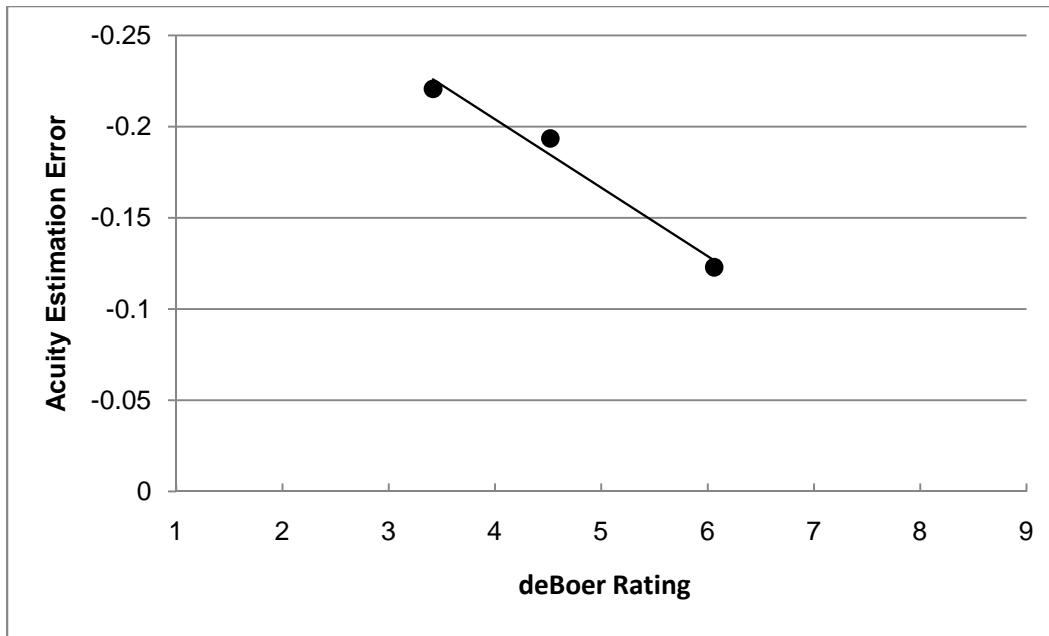
Figure 13. deBoer ratings of discomfort by acuity estimate error. Recall that lower values on the deBoer scale indicate greater ratings of discomfort.

deBoer ratings and eye color. It has previously been reported that people with light colored irises report greater glare sensitivity than those with darker irises (e.g., Desilva & Robinson, 1938). In order to determine whether eye color was related to the participants' subjective feelings of discomfort from the glare source, a chi-square was performed at each of the light levels. No significant differences in feelings of discomfort between light and dark eyes was found in the low ($\chi^2(8) = 3.73$, $p > .05$), medium ($\chi^2(8) = 8.56$, $p > .05$), or high ($\chi^2(8) = 2.9$, $p > .05$) glare levels.

Discussion

Experiment 1 sought to determine the relationship between estimates of acuity and actual acuity in the presence of glare. Participants were successfully able to learn how to estimate acuity using both a verbal and manual technique. Because there was no significant difference between the verbal and manual techniques, the estimates were averaged together. Ratings of discomfort were assessed and participants' actual acuity was measured and compared to estimated acuity in the presence of three different glare intensities. As hypothesized, as ratings of glare resulting discomfort increased, participants estimated that acuity worsened.

Actual measures of visual acuity, however, were unaffected by the intensity of the glare source. This is presumed to be a consequence of several factors. First, independent of the intensity of the glare source, the luminance of the stimulus (i.e. the laptop screen presenting the Landolt C) was constant across conditions. Thus neither the luminance nor the contrast of the distal stimulus changed across conditions.

Second, because the stimulus was positioned in the center of the glare annulus, there was a distance of ≈4.65° between the stimulus and the glare light. As a glare source moves closer to the line of vision, the negative (retinal-contrast reducing) effects of that glare source increase (Cobb & Moss, 1928; Luckiesh, 1944). However, if a stimulus is of sufficient contrast and brightness, glare does

not *significantly* affect discrimination abilities (Cobb & Moss, 1928; Luckiesh, 1944).

Luckiesh (1944) determined the minimum threshold size to determine the presence of two equally sized bars with a gap of the same size. The bars were presented in four contrasts (2%, 5%, 20%, 100%) at three different brightness levels (3.4 cd/m^2, 34.3 cd/m^2, and 342.6 cd/m^2). At the greatest luminance, the effect of glare almost entirely disappears, regardless of contrast. At 34.3 cd/m^2 luminance and 20% contrast, glare only reduced threshold by 0.19 (arcmin) and by only 0.03 (arcmin) at 100% contrast. At maximum luminance (342.6 cd/m^2) and 20% contrast, glare only reduced threshold by 0.03 (arcmin) and by 0.01 (arcmin) at 100% contrast. The stimulus in the present experiment had a luminance of 92.16 cd/m^2 and contrast of 78%. While these conditions are do not fit perfectly to those of Luckiesh, the Luckiesh data suggest that glare would have a minimal (if any) effect on acuity.

The findings of Luckiesh (1944) complement those of Cobb and Moss (1928). Cobb and Moss determined the minimum size/visual angle required to determine the presence of test rectangles of different contrasts (the same type as those used by Luckiesh, 1944) with three different luminance levels (3.4 cd/m^2, 34.3 cd/m^2, and 342.6 cd/m^2). A glare source was placed at 5°, 10°, 20°, and 40° above the test object. Overall, as the glare source was positioned closer to the line of sight, the visual angle required to determine the presence of the rectangular bars increased (i.e. the bars and the space between increased).

However, as the luminance and the contrast of the test object increased, the effects of glare were muted. These data show that with sufficient stimulus luminance and contrast, the acuity reducing effects of glare are negligible. These data are consistent with the finding in the present study that glare did not affect the participants' acuity to the stimulus with 78% contrast.

Third, pupil size varied across conditions. Pupil size is a complex and important component of visual acuity. A large pupil size allows for more light to enter the eye (to stimulate the retina). On the other hand, a smaller pupil size reduces optical aberrations. As the intensity of the glare source increased in Experiment 1, the size of the pupil decreased (see Figure 14), thus reducing retinal illuminance. Retinal illuminance is measured in trolands, the log-product of the distal stimulus luminance (cd/m^2) and pupil area (mm^2). This calculation, however, does not take into account other factors which influence retinal illuminance (e.g., clouding of the lens, non-stimulus related light). Further, while the luminance of the far stimulus (the computer screen) remains constant across conditions, the luminance of the glare source changes (and subsequently retinal illuminance changes). In order to approximate retinal illumination trolands were calculated using the luminance of the near stimulus (glare annulus) rather than the far stimulus (computer screen). The mean approximate retinal illuminance values in Experiment 1 are: low glare, 3.24 trolands, medium glare, 4.36 trolands, high glare, 4.58 trolands. It has been shown that as retinal illuminance increases, visual acuity improves. However, this is a non-linear function. In the region of the

steepest slope, an increase in intensity of 0.8 log-trolands improves acuity about 0.2 (log) (Graham et al., 1965). However, the retinal illuminance values of Experiment 1 lie in a horizontal asymptote. That is, based on retinal illuminance alone, one would not necessarily expect acuity to vary significantly in the present experiment.

Pupil size also affects depth of field. In general, as pupil size decreases resolving power (and acuity) increases (e.g., Ogle & Schwatz, 1959; Graham et al., 1965). This however, is only true to a certain extent. Acuity steadily increases as the diameter of the pupil approaches 2.0 mm, after which acuity stabilizes (see Graham et al., 1965, p.333 for summary of data). Mean pupil diameter in the present study ranged from 2.6 mm (high glare) to 4.2 mm (low glare; see Figure 14) – values within the range of maximal stable acuity. Based on pupil size alone, one would not expect acuity to vary significantly between glare conditions. It appears then that the decrease in pupil size reduced the amount of glare source light entering the eye and effectively muted the negative effects (intraocular light scattering, resulting in a reduction of stimulus contrast) of the glare source on acuity. As a result of these factors (constant luminance and contrast of the distal stimulus, and pupil size) it is not surprising that participant acuity did not change across glare conditions. It is certainly possible, of course, that if the acuity stimulus had a lower contrast that acuity values would be reduced as the intensity of the glare source increased.
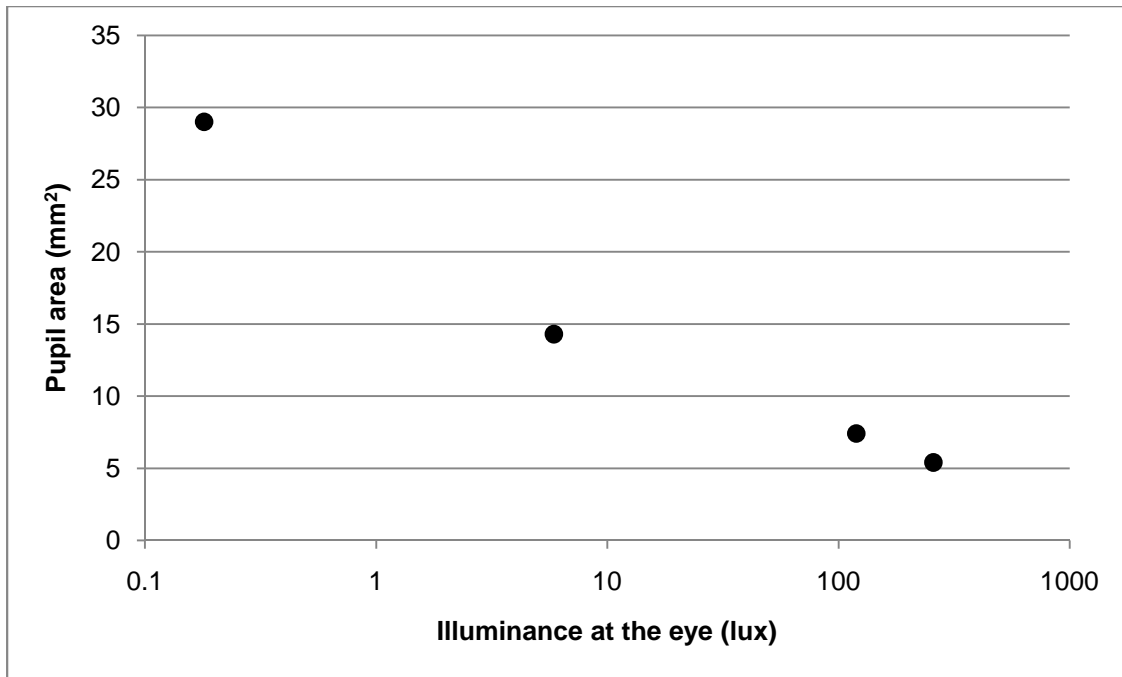
Figure 14. Mean pupil area (mm^2) as a function of the illumination at the eye in each of the four glare conditions. Measurements are from five non-participants of similar age as the participants in Experiment 1 and in the same apparatus (see Appendix F for individual plots).

While changes in glare source intensity did not affect participants' measured acuity, the changes did affect the participants' estimates of their own acuity. Overall, participants estimated that acuity would decline significantly with each increase in glare source intensity.

This finding indicates that, in general, estimates of acuity in the presence of a glare source can be dissociated from measures of actual visual acuity. That is, observers exaggerate the effects of glare on visual acuity. If estimates of acuity are not necessarily related to actual acuity, then it is important to

investigate other factors that may influence estimates of acuity; which, in this case are glare-induced feelings of discomfort.

Each of the three glare light intensities was rated as resulting in a significantly different level of visual discomfort. The low glare level obtained a mean deBoer rating of 6.1 – between "*Satisfactory*" and "*Just Admissible.*" The medium glare level obtained a mean score of 4.5 – slightly more discomforting than "*Just Admissible.*" The high glare level obtained a mean score of 3.4 – slightly less discomforting than "*Disturbing.*"

The mean deBoer ratings were not good predictors of mean measured acuity. However, mean deBoer ratings were strongly correlated with mean acuity estimates. This finding supports that hypothesis that discomfort, rather than actual abilities, guide observers' estimates of their own acuity in the presence of a glare source. This finding makes sense at an intuitive level. In order to estimate our abilities we rely on readily available and salient information. In Experiment 1, the feelings of discomfort resulting from the glare source were both available and salient and were subsequently tightly linked to acuity estimates. Further feelings of physical discomfort are often linked with performance decrements (e.g., a hiker can experience muscular fatigue and feel the need to slow down).

Experiment 1 has provided valuable insight related to the accuracy with which we judge the effects of glare on vision. It is expected that the effects measured in the laboratory are generalizable to other environments, especially those involving acuity-based tasks. Because of the relevance of this work to the

63

on-road setting in which the headlights of opposing vehicles can induce feelings of discomfort glare, it is important to determine whether these findings generalize to the context of night driving.

A field test of the effects measured here is needed. It is possible that there is something about the night driving context that triggers driving-specific subjective responses to glare that were not triggered in the laboratory setting. Understanding these subjective responses and their relationship to glare-induced visual decrements is important for several reasons. First, a better understanding of how people estimate vision is affected by glare in nighttime driving environments will be gained. Secondly, participants' estimates of how glare affects their vision in an indoor (laboratory) environment can be compared to an outdoor driving environment. That is, if both the indoor and outdoor studies (which employ very different methodologies) produce similar patterns of results, a higher degree of convergent validity will support the argument that the effects are fundamental and not limited to one particular experimental context.

To extend the findings from Experiment 1 to a setting that is closer to the night driving situation, participants sat in a test vehicle that faced another stationary vehicle under four different headlamp conditions (using combinations of high and low beams) and were asked to estimate the distance at which they could determine the orientation of a Landolt C that was positioned next to a vehicle. The distance at which the orientation could actually be determined was also measured. This provides the opportunity to measure the accuracy of

participants' judgments of their glare-induce visual decrements, and subjective

feelings of discomfort in a context that more closely resembles nighttime driving.

EXPERIMENT 2

Method

Participants:

Sixteen people participated (M = 20 years; 18 – 33 years). Each achieved

a visual acuity of at least 6/12 (20/40; the minimum requirement to attain a

driver's license in South Carolina). None reported visual pathologies (e.g.

cataracts) other than corrected refractive errors. Participants wearing glasses

were provided an opportunity to clean their lenses prior to the beginning of the

experiment. All had a valid driver's license. Each experimental session took place

at least 1 hour after sunset on nights free of precipitation and fog.

Visual Screening:

After informed consent was obtained, visual acuity was measured using

the Optec 2000 Vision Tester (Stereo Optical Company, Inc.). Contrast

sensitivity was also measured using the Pelli-Robson Contrast Sensitivity Test

(Pelli, Robson & Wilkins, 1988). Participants were tested at 3 meters (9.8 ft)

under normal room lighting (M = 1.72; range 1.5-1.95). After assessing both

acuity and contrast sensitivity measurements, participants were given a brief

overview of the remainder of the experimental session. Participants were then

driven to the test site.

<u>Test Site:</u>

The testing site was an unilluminated (<0.01 lx), semi-rural utility road adjacent to a campus golf course. The 3.05 m-wide road includes a 230 m (≈755 ft) section of straight and level unobstructed non-delineated roadway. The road is free of pavement/street markings and streetlights (see Figure 15).

Figure 15. Daytime view of test site.

A vehicle (2008 Infiniti EX35) was parked near the end of the straight portion of the test site roadway. The high intensity discharge (low beams are xenon; high beams are low beam xenon + halogen) headlamps were self-aligning and were cleaned each night prior to data collection. Neither additional lighting nor filters were used to modify the glare source. Figure 16 presents illumination at the participant eye measured at distances ranging from 25 feet to 700 feet for both high and low beam settings.
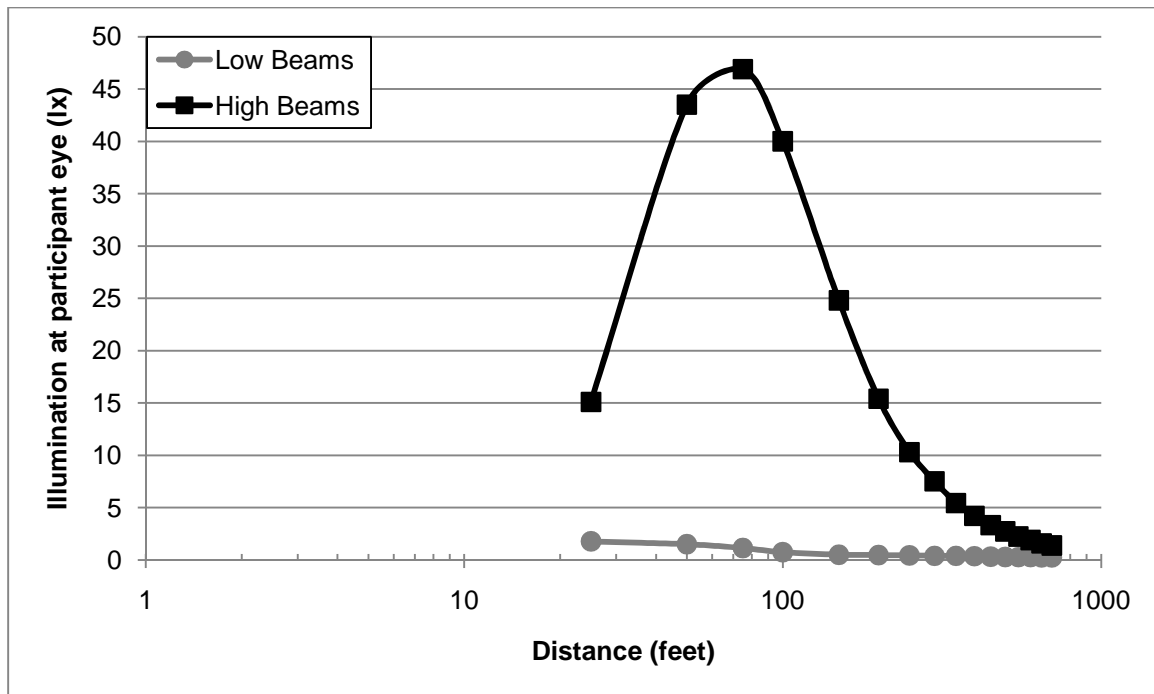
Figure 16. Illumination from glare source vehicle (as measured from the passenger seat of the test vehicle) for both high and low beam headlamps.

<u>Participant Vehicle:</u>

Only one participant was tested at a time. The participant sat in the front passenger seat of the test vehicle (2005 Scion Xb) while an experimenter drove. The vehicle's headlamps were adjusted to manufacturer specification. Both the vehicle headlamps and windshield were cleaned each night prior to data collection. Neither additional lighting nor filters were used to modify the headlights.

<u>Measuring Participants' Estimates of Recognition Distance:</u>

Participants were asked to estimate the maximum distance at which they would just be able to determine the orientation of a retroreflective Landolt C (*see* Figure 17) that was positioned directly in front of their vehicle. The Landolt C was 8 cm in diameter (16 mm stroke width and gap) and made from 3M Scotchlite 8906 silver retroreflective fabric. The letter was placed on a dark circular mounting board. The mounting board was placed on a tripod to the right of the test vehicle (as seen from the participant's position) and at the same distance from the test vehicle as the glare vehicle. The center of the Landolt C was approximately 80.5 cm above the ground. From the participant's perspective, the Landolt C was located 1.52 m (5 ft) to the right of the glare vehicle's front tire and 1.17 m (3.83 ft) to the left of the right edge of the roadway (see Figure 18 and Figure 19).
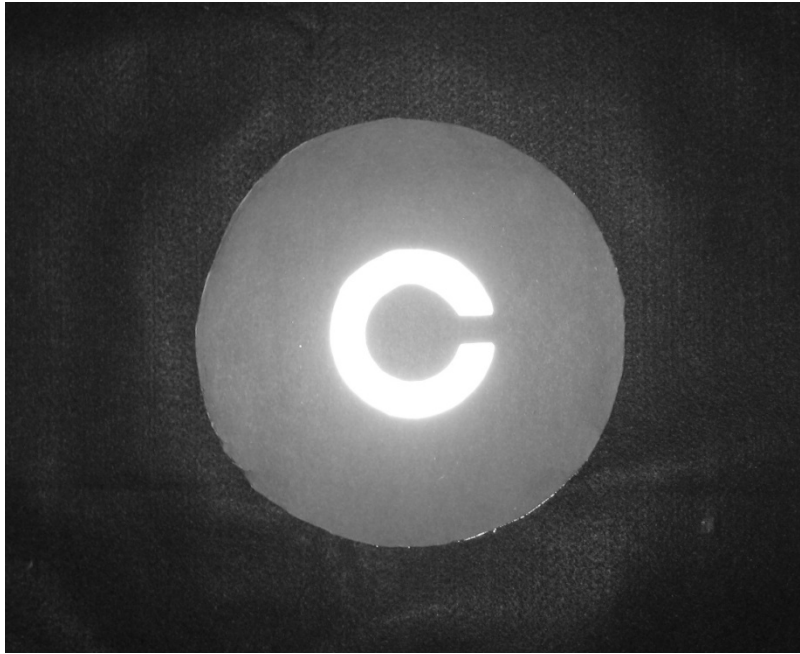
Figure 17. Outdoor Landolt C stimulus.
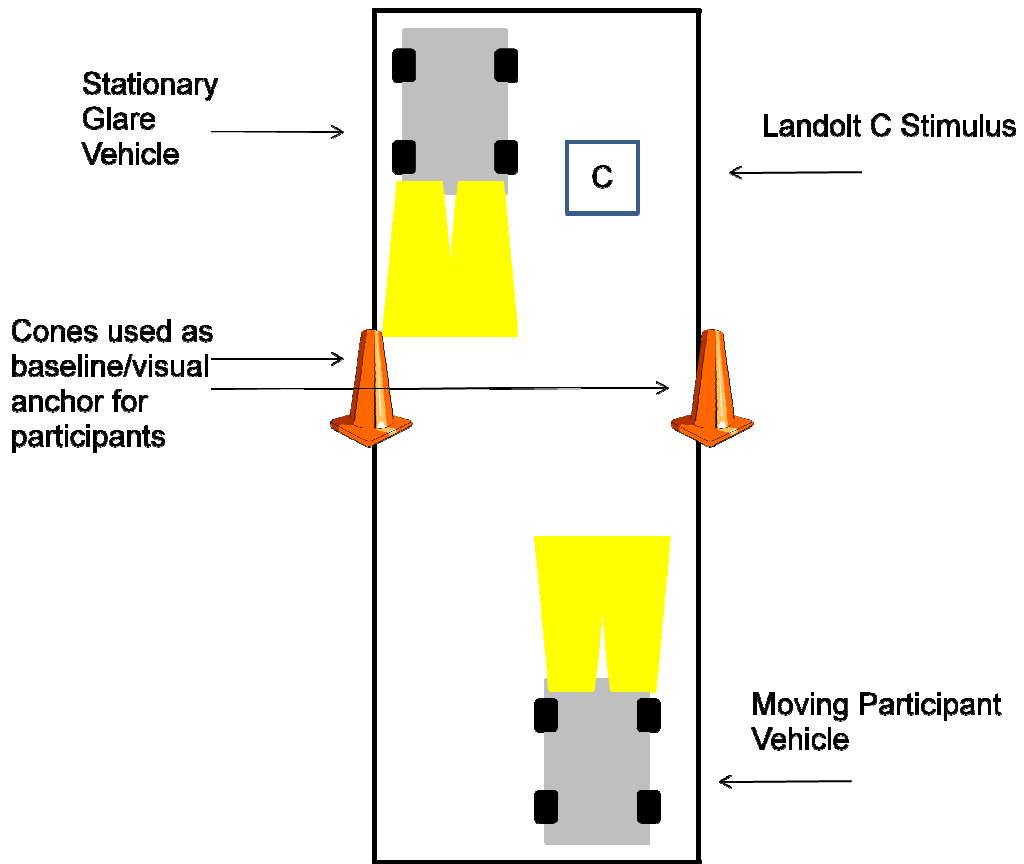
Figure 18. Diagram of Experiment 2 setup; aerial perspective. The road contains

no lane delineation markers, other major signs, or road markers.

Figure 19. Position of the Landolt C stimulus in relation to the glare source vehicle. Both the glare source vehicle and the participant vehicle have high beam headlights turned on. The camera flash was not used.

Just as in Experiment 1, each participant was provided a baseline from which future estimates could be made. In the previous experiment, each participant was periodically reminded of the square size that was equivalent to their acuity and could then rely on this knowledge while making acuity estimates. In order to create the baseline marker in this experiment, participants were slowly (i.e., at approximately 3.2- 8.0 kph; 2-5 mph) driven toward the Landolt C stimulus. The low beam headlights on the participant vehicle were turned on, but the glare vehicle's lamps remained off. The point at which participants indicated they could just barely determine the orientation of the Landolt C was marked on

both the right and left shoulders of the roadway with 28" tall orange traffic cones (without retroreflective markings). Participants were allowed to use these cones as a reference during the distance estimations that followed. The reflective portion of the Landolt C was then covered and the test vehicle returned to the beginning of the test road (which was 213.4 m from the glare vehicle).

To estimate recognition distance, participants were slowly driven toward and away from the glare source vehicle while the headlamps of the test vehicle remained pointed toward the stimulus. Participants were asked to look toward the stimulus (the stand holding the Landolt C stimulus remained in position, while the retroreflective portion was covered with a black cloth). When driving toward the glare source vehicle, participants were asked to indicate when they reached the point at which they would just barely be able to determine the orientation of the Landolt C had it been present. When driving away from the Landolt C, participants were asked to indicate when they reached the point at which they would just barely lose the ability to determine the orientation of the Landolt C. Participants used their right hand to drop weighted bags out of the open right window to mark these points (described in more detail later).

Participants were shown combinations of headlamps on low and high beam settings of the two vehicles (Low vs. Low; Low vs. High; High vs. Low; and High vs. High). After participants were shown a single lighting combination, they were asked to make distance estimates. This was done starting in 2 different positions for each lighting combination; once when the vehicles started 7.62 m

(25 ft) apart (a reverse moving trial) and once when the vehicles started 213.36

m (700 ft) apart (forward moving trial). For trials that started at the greater

starting distance, the participants were told "As we move forward, imagine that

the C was present in the same place you saw it before. At the moment you think

that you would just barely be able to determine the orientation of the C, drop this

bag out of your window." For trials that started at the shorter distance, the

participants were told "As we move backward, imagine that the C was present in

the same place that you saw it before. At the moment you think that you would

just barely be *un*able to determine the orientation of the C, drop this bag out of

the window."

The bags [17 cm x 11cm plastic bags filled with ≈ 118 cm^3 (.5 cup) of rice]

that participants dropped out of the window were coded to mark trial numbers

(see Figure 20). The distances of each bag dropped by the participant (from the

Landolt C stimulus) were later measured by an experimenter using a measuring

wheel.

Figure 20. An example of bags used by participants to mark response distances.

Participants made a total of 8 distance estimations. The participants made one estimate moving toward and one estimate moving away from the Landolt C stimulus location for each of the 4 headlight combinations (Low vs. Low; Low vs. High; High vs. Low; and High vs. High). The approaching distance and the reversing distance were later averaged to comprise a single estimated recognition distance for each of the four headlighting combinations. See Table 8 for a complete listing of trial combinations; the 8 combinations were presented in a new quasi-random order for each participant.

Table 8. Lighting and vehicle movement combinations in which participants estimated recognition distances.

Combination #	Participant vehicle movement	Participant vehicle lights	Glare source vehicle lights
1	Forward	Low Beams	Low Beams
2	Forward	Low Beams	High Beams
3	Forward	High Beams	Low Beams
4	Forward	High Beams	High Beams
5	Reverse	Low Beams	Low Beams
6	Reverse	Low Beams	High Beams
7	Reverse	High Beams	Low Beams
8	Reverse	High Beams	High Beams

Measuring Actual Recognition Distances:

After participants completed the 8 recognition distance estimates, measures of actual recognition distances were made. In each condition, the actual recognition distances were defined as the distance at which the participant could just recognize the orientation of the Landolt C stimulus (using the method of limits). Actual recognition distances were measured for each of the four headlight combinations (Low vs. Low; Low vs. High; High vs. Low; and High vs. High); once when moving toward the Landolt C stimulus and once when moving away from the stimulus. When moving toward the Landolt C, participants first dropped a bag. The experimenter driver then stopped the vehicle. The participant then announced the orientation of the Landolt C by indicating the direction of the gap. This was done by pointing to a C on a sheet of paper (*see* Figure 21) that

matched the orientation of the reflective C stimulus (i.e., orientations of 0°, 45°,

90°, 1 35°, 180°, 225°, 270°, and 315°   ). Participants always correctly identified

the orientation of the Landolt C.

Top

Bottom
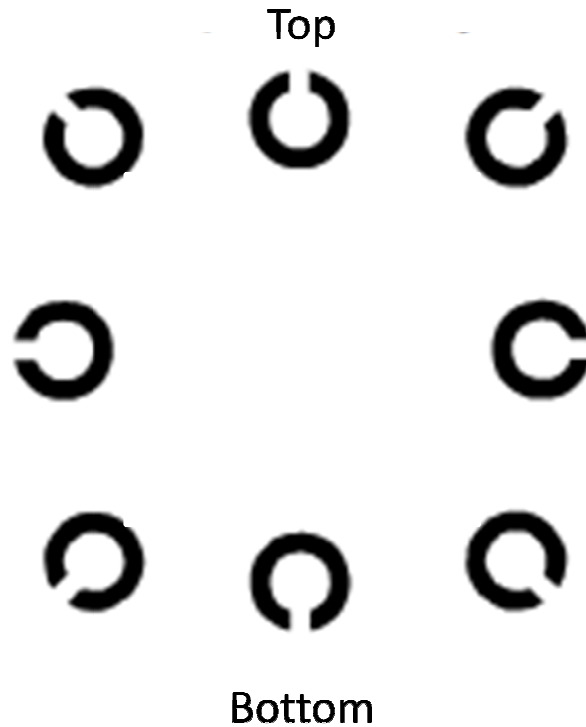
Figure 21. Image on a piece of paper that participants used to indicate the

orientation of the reflective C stimulus.

Actual recognition distances were also measured when the vehicle moved

away from the stimulus. When the vehicle slowly reversed away from the Landolt

C stimulus, the participant dropped a bag to indicate when they could no longer

indentify the orientation of the C. The order in which the 8 trials were completed

matched the order in which the estimates were measured. The orientation of the stimulus was changed between trials; the stimulus was at one of 8 possible orientations, selected at random for each trial. The approaching distance and the reversing distance were later averaged to comprise a single actual recognition distance for each of the four headlight combinations.

<u>Subjective Ratings of Discomfort Glare:</u>

After each estimated and actual recognition distance was measured, participants were asked to use the deBoer scale (*see* Table 3) to provide a subjective description of the intensity of the opposing vehicle's headlamps. While formulating their rating participants were asked to look down the roadway as if they were driving. Subjective ratings were recorded with the participant positioned in the test vehicle with the vehicle parked. Subjective ratings were made for each of the four headlighting combinations at several locations. After each estimated and actual recognition distance, participants provided a subjective judgment of discomfort. In addition, subjective deBoer ratings (for all four headlight combinations) were made at 23.0 m (75 ft), 61.0 m (200 ft), 213.4 m (700 ft), and at each participant's respective baseline marker. The 23.0 m distance was chosen because it is the distance at which the illumination (at the viewers' eye) is maximal from the glare source vehicle's high beam setting. In total participants made 24 ratings of discomfort.

The (23.0 m, 61.0 m, and 213.4 m) distances provided three consistent locations for subjective judgments of discomfort across participants. Because the illumination from the glare vehicle's headlamps depends on the distance from it, this allowed there to be ratings of discomfort with consistent lighting across participants. At these three distances, participants made four subjective ratings of discomfort (one for each of the headlighting combinations: Low vs. Low; Low vs. High; High vs. Low; and High vs. High). The four ratings were measured in the same order in which estimates of recognition were made.

After completing the subjective ratings, the participants completed a short questionnaire about nighttime driving attitudes and behaviors (see Appendix A). While participants completed the questionnaire, the experimenter measured and recorded the distance of each bag from the Landolt C. The participants were given time to ask any questions, thanked for their time, and driven back to Brackett Hall.

Results Experiment 2

Baseline Recognition Distance:

Participants were initially slowly driven toward the Landolt C stimulus while the participant vehicle used low beams and the glare source vehicle did not have any lights turned on. This method was used to create a baseline from which estimates of Landolt C recognition distance could be based. The mean baseline Landolt C recognition distance was 35.25 m (105.82 ft; range 16.0 – 48.4 m)

Estimated Recognition Distances:

Estimated measures of recognition distance are operationally defined as the mean of the appropriate forward-moving and backward-moving trials. A 2 x 2 repeated-measures ANOVA revealed that estimates of recognition distance were significantly different based on glare vehicle headlights, $F(1, 15) = 47.91$, $p < .001$, $\eta_p^2 = .76$ (see gray bars in Figure 22 and top row of Table 9). Participants estimated significantly shorter Landolt C recognition distances when the glare source vehicle used high beams (25.13 m; 82.46 ft) than when it used low beams (37.08 m; 121.65 ft). That is, participants believed that the glare vehicle's beam setting would affect recognition distances. In addition, 95% confidence intervals were calculated: Glare vehicle: low, Participant Vehicle: low 29.56 – 40.64 m (96.98 – 133.32 ft); Glare vehicle: low, Participant Vehicle: high 33.71 – 44.41 m (110.61 – 145.70 ft); Glare vehicle: high, Participant Vehicle: low 21.02 – 28.48 m

(68.97 – 93.43 ft); Glare vehicle: low, Participant Vehicle: high 21.35 – 29.69 m

(70.04 – 97.42 ft).

Estimates of Landolt C recognition distance were also influenced by

participant vehicle headlights, $F(1, 15) = 13.42$, $p = .002$, $\eta_p^2 = .47$. Participants

estimated significantly greater recognition distances when the participant vehicle

was using high beams (32.29 m; 105.94 ft) than when using low beams (29.93

m; 98.18 ft). That is, participants believed that *seeing* high beams would increase

the distance at which the Landolt C could be recognized. No significant

interaction between glare vehicle headlights and participant vehicle headlights

was found, $F(1, 15) = 2.66$, $p > .05$ (*see* Appendix G for individual participant

plots).
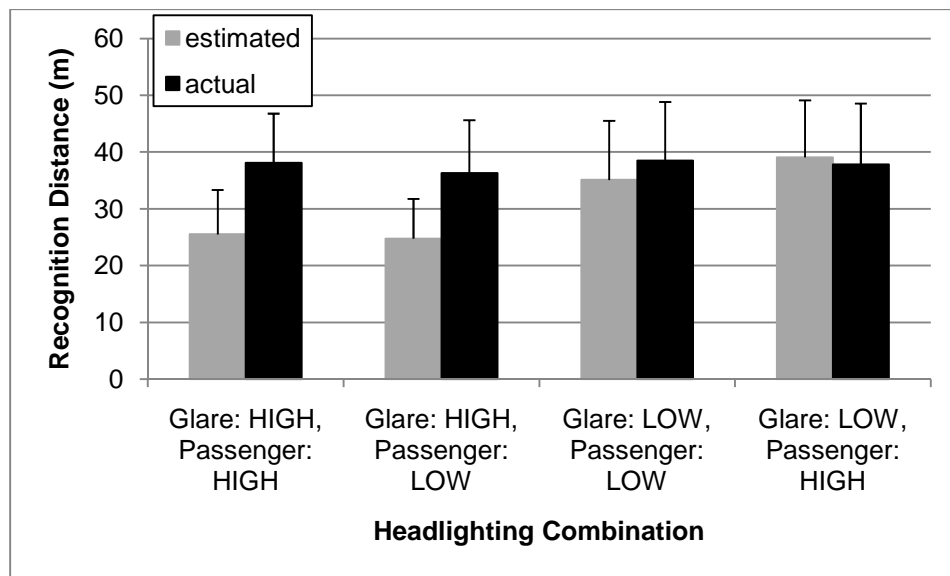
Figure 22. Estimated and actual Landolt C recognition distances (plus 1 standard

error of the mean) at each of the four headlight combinations.

Actual Recognition Distances:

Actual measures of recognition distance are operationally defined as the mean of the appropriate forward-moving and backward-moving trials. A 2 x 2 repeated measures ANOVA revealed no significant effects of glare vehicle headlights on actual Landolt C orientation recognition distances, $F(1, 15) = .35$, $p > .05$, $\eta_p^2 = .02$ (see black bars in Figure 22 and bottom row of Table 9). Further, participant vehicle headlights did not affect actual recognition distances, $F(1, 15) = .42$, $p > .05$. No significant interaction was found, $F(1, 15) = 1.27$, $p > .05$. In other words, headlight combination did not affect the actual recognition Landolt C recognition distances. In addition, 95% confidence intervals were calculated: Glare vehicle: low, Participant Vehicle: low 32.99 – 43.99 m (108.23 – 144.34 ft); Glare vehicle: low, Participant Vehicle: high 32.10 – 43.53 m (105.30 – 142.83 ft); Glare vehicle: high, Participant Vehicle: low 31.35 – 41.26 m (102.84 – 135.37 ft); Glare vehicle: low, Participant Vehicle: high 33.51 – 42.74 m (109.95 – 140.22 ft).

Table 9. Mean estimated and actual recognition distances for each of the four headlight combinations. Standard deviation values are presented in parentheses.

	Glare: HIGH, Passenger: HIGH	Glare: HIGH, Passenger: LOW	Glare: LOW, Passenger: HIGH	Glare: LOW, Passenger: LOW
Estimated Distance	25.52 m (7.8)	24.75 m (7.0)	39.06 m (10.0)	35.10 m (10.4)
Actual Distance	38.12 m (8.7)	36.30 m (9.3)	37.82 m (10.7)	38.49 m (10.3)

Actual vs. Estimated Recognition Distances:

A 2 x 2 x 2 repeated measures ANOVA was used to examine the relationship between estimated and actual recognition distances and headlighting combination. A significant difference between estimated and actual Landolt C recognition distances, $F(1, 15) = 8.63$, $p =.01$, $\eta_p^2 = .37$ was found. Actual recognition distances (37.69 m; 123.64 ft) were significantly longer than estimated recognition distances (31.12 m; 102.06 ft). That is actual recognition distances were 17% longer than participants estimated.

The repeated measures ANOVA also revealed a significant interaction between estimated/actual Landolt C recognition distances and glare vehicle headlights, $F(1,15) = 61.47$, $p < .001$, $\eta_p^2 = .80$. An interaction between estimated/actual Landolt C recognition distances and participant vehicle headlights was also found, $F(1,15) = 9.04$, $p = .009$, $\eta_p^2 = .38$. As previously noted when examining actual recognition distances alone, headlighting did not affect recognition distance. However, headlight combination did affect estimated recognition distances; such that high beam headlight glare significantly reduced estimate distances.

Accuracy of Estimated Recognition Distances:

In order to better understand participants' ability to estimate accurately the distance at which the orientation of the Landolt C stimulus can be determined under different headlighting conditions, a difference (error) score was created.

For each level of headlight glare (Low vs. Low; Low vs. High; High vs. Low; and High vs. High) each participant's estimated recognition distance was subtracted from the actual recognition measurement. Thus, a positive error score represents an overestimation and a negative error score represents an underestimation.

Using this error score, a 2 x 2 repeated measures ANOVA revealed that glare vehicle headlights significantly affected the accuracy of participants' estimated Landolt C orientation recognition distances, $F(1, 15) = 61.47$, $p < .001$, $\eta_p^2 = .80$. Participants' errors in recognition estimates were significantly greater when the glare vehicle used high beams than when it used low beams. Participants underestimated Landolt C recognition distances by -12.08 m (-39.63 ft) when the glare vehicle used high beams and by -1.08 m (-3.53 ft) when it used low beams.

However, participant vehicle headlights significantly affected the accuracy of participants' estimated Landolt C orientation recognition distances, $F(1, 15) = 3.22$, $p > .05$. There was also no significant interaction between glare vehicle and participant vehicle headlights, $F(1, 15) = 3.23$, $p > .05$.

deBoer Ratings:

Participants were asked to provide subjective judgments of discomfort. This was done after each estimated and actual Landolt C recognition distance. A repeated measures 2 x 2 x 2 ANOVA revealed that deBoer ratings of discomfort

did not differ based whether participants were estimating recognition distance or providing actual recognition distances, $F(1, 15) = .55$, $p > .05$ (see Table 10).

Participants deBoer ratings of discomfort were influenced by whether the glare vehicle used high or low beams, $F(1, 15) = 95.73$, $p < .001$, $\eta_p^2 = .87$. Participants rated high beam headlight glare (3.78, slightly less discomforting than "*Disturbing*") as significantly more discomforting than low beam headlight glare (7.39, slightly less discomforting than "*Satisfactory*").

Ratings of discomfort were not influenced by participant vehicle headlights, $F(1, 15) = 1.38$, $p > .05$. Further there was not a significant interaction between glare vehicle headlights and participant vehicle headlights, $F(1, 15) = .006$, $p > .05$. That is, participant ratings of discomfort were based solely on the glare vehicle's headlights and were not influenced by the participant vehicle headlights.

Table 10. Mean deBoer ratings of discomfort given at estimated and actual recognition distances (numerical and verbal equivalent) based on headlighting combination.

	Glare: HIGH, Passenger: HIGH	Glare: HIGH, Passenger: LOW	Glare: LOW, Passenger: HIGH	Glare: LOW, Passenger: LOW
Numerical rating	3.72	3.83	7.34	7.44
Verbal rating	Slightly less discomforting than "*Disturbing*"	Slightly less discomforting than "*Disturbing*"	Slightly less discomforting than "*Satisfactory*"	Slightly less discomforting than "*Satisfactory*"

deBoer scale and estimated recognition distances. In order to investigate the relationship between ratings of discomfort and recognition distances, individual correlations were calculated for each participant; one for the correlation between his or her estimated recognition distances and the corresponding deBoer ratings and a second between his or her actual recognition distances and the corresponding deBoer ratings. The mean R^2 between estimated recognition distance of the Landolt C and deBoer ratings is .70 (range = .00 to .99; individual R^2 values can be found in Appendix H). The mean r is .84 (range = -.05 to .99). That is, as ratings of discomfort increased, estimates of Landolt C recognition distance also tended to decrease.

Because there was considerable variability between individual participant R^2 values, a second approach to this relationship was taken. The R^2 for the mean estimated recognition distances and the mean deBoer ratings at each of the four headlighting combinations was calculated. Using this methodology, the $R^2 = .94$, $p < .05$ (y = 2.93x + 15.13; see Figure 23). That is, as participants' feelings of discomfort worsened, it was estimated that acuity also worsened.
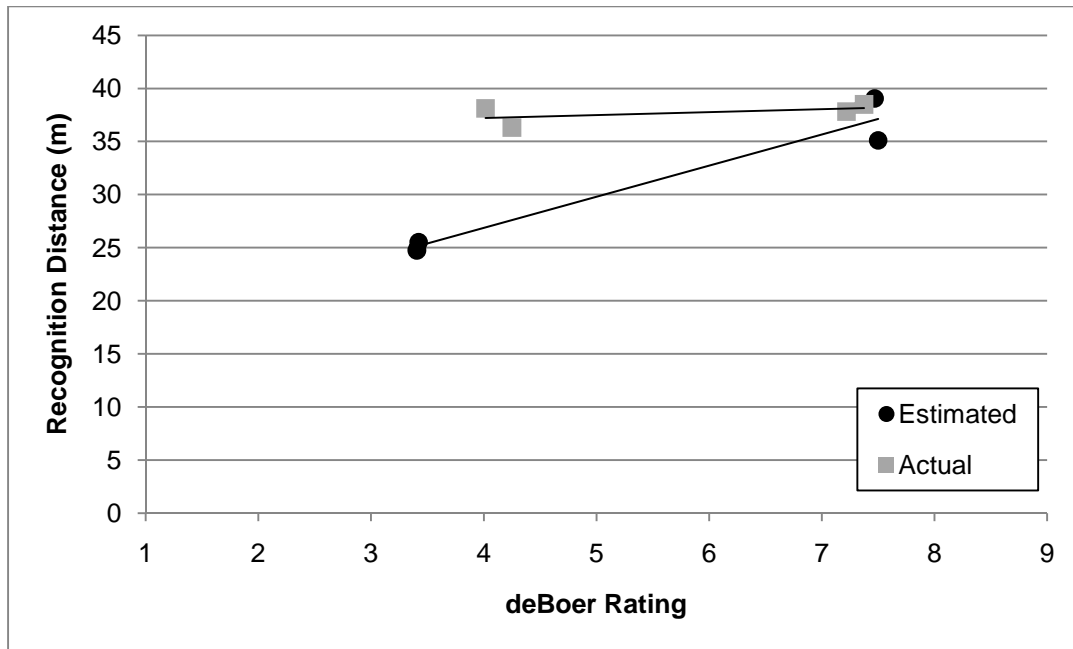
Figure 23. Mean deBoer ratings by estimated and actual Landolt C recognition

distances.

      deBoer scale and actual recognition distance._ The mean R^2 between

actual recognition distance of the Landolt C and their corresponding deBoer

ratings is R^2 = .00 (range = .00 to .94). The mean *r* is .00 (range = -.88 to .97).

Once again, a second approach was used to examine the relationship between

deBoer ratings of discomfort and actual recognition distances. The R^2 for the

mean actual recognition distances and the mean deBoer ratings at each of the

four headlighting combinations was .28, *p* > .05 (y = .28x + 36.09; see Figure 23).

      deBoer ratings and actual/estimated recognition distance._ In order to

further investigate the relationship between estimated vs. actual Landolt C

recognition distances and their corresponding deBoer ratings, R^2 values were

compared. An *r* to *t* transformation was conducted to determine if these two

correlations are significantly different from one another (Cohen & Cohen, 1983;

Applied Multiple Regression/Correlation Analysis for the Behavioral Sciences).

This analysis revealed a significant difference in the relationships, further

emphasizing the strong relationship between feelings of discomfort and

estimated visual abilities, $t(13) = -3.70$, $p < .001$. In other words, the relationship

between estimated recognition distances and their respective deBoer ratings of

discomfort was stronger than the relationship between actual recognition

distances and their respective deBoer ratings of discomfort.

deBoer ratings and recognition estimation accuracy. Yet another way to

examine the relationship between deBoer ratings and acuity estimates is to

utilize estimation error. The relationship between the mean acuity estimation

error and the mean deBoer rating (measured at the estimation distance) yielded

$R^2 = .96$, $p < .05$ (y = 2.70.x – 21.28; see Figure 24). This illustrates that as

participant underestimations of recognition distance increases, subjective

feelings of discomfort also increase.
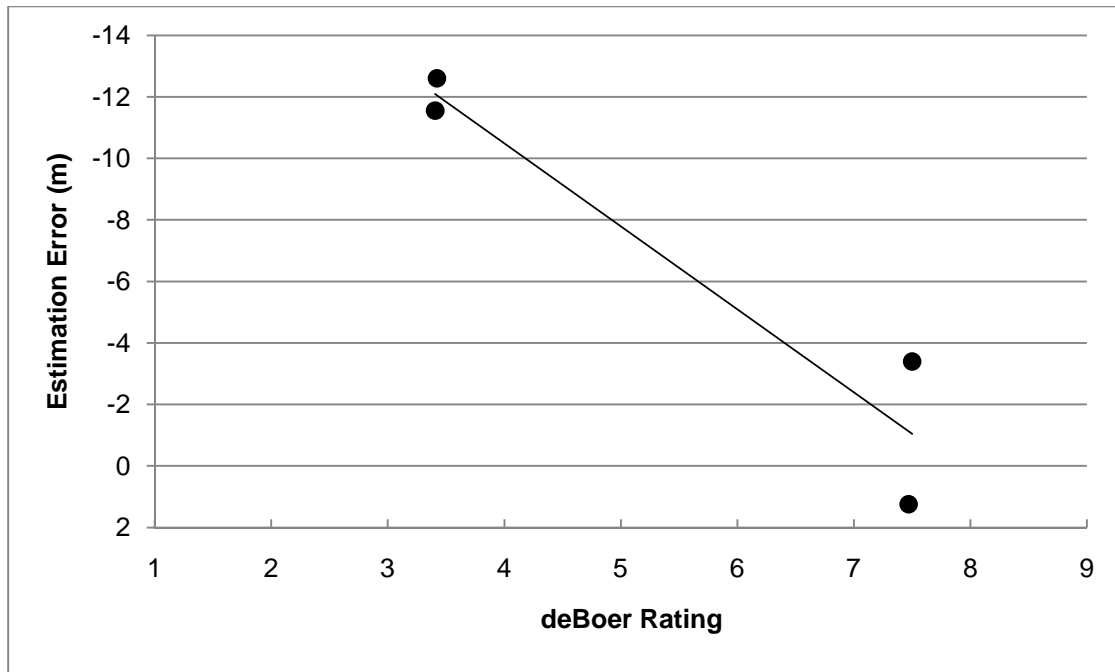
Figure 24. deBoer subjective ratings of discomfort (given at the estimated Landolt C recognition distance) by recognition estimation error. Recall that lower values on the deBoer scale indicate greater ratings of discomfort.

deBoer ratings at fixed distances: Participants also provided deBoer ratings at three fixed distances (75 ft, 200 ft, and 700 ft) for each of the four headlight combinations. Overall, 2 x 2 x 3 ANOVA revealed no significant difference in deBoer scale ratings was found based on distance alone, $F(2, 30) = 2.23$, $p > .05$, $\eta_p^2 = .13$. Participant vehicle headlights did not influence deBoer ratings, $F(1, 15) = 1.22$, $p > .05$, $\eta_p^2 = .08$.

The glare vehicle headlights, however, did influence deBoer ratings of discomfort, $F(1, 15) = 111.58$, $p < .001$, $\eta_p^2 = .88$. Ratings of discomfort were significantly greater when the glare vehicle used high beams (3.16, "*Disturbing*")

than when it used low beams (7.65, slightly less discomforting than

"*Satisfactory*"). Table 11 presents mean ratings for each of the fixed distance

measurements at each of the four headlighting combinations.

Table 11. Mean deBoer ratings of discomfort glare (numerical and verbal equivalent) based on headlighting combination and distance.

	Glare: HIGH, Passenger: HIGH	Glare: HIGH, Passenger: LOW	Glare: LOW, Passenger: HIGH	Glare: LOW, Passenger: LOW
Numerical rating (75 ft)	2.81	2.44	7.63	7.75
Verbal rating (75 ft)	Slightly more discomforting than "*Disturbing*"	Slightly more discomforting than "*Disturbing*"	Slightly less discomforting than "*Satisfactory*"	Slightly less discomforting than "*Satisfactory*"
Numerical rating (200 ft)	2.97	2.56	7.69	7.81
Verbal rating (200 ft)	Slightly more discomforting than "*Disturbing*"	Slightly more discomforting than "*Disturbing*"	Slightly less discomforting than "*Satisfactory*"	Slightly less discomforting than "*Satisfactory*"
Numerical rating (700 ft)	4.19	4.00	7.63	7.38
Verbal rating (700 ft)	Between "*Just Admissible*" and "*Disturbing*"	Between "*Just Admissible*" and "*Disturbing*"	Slightly less discomforting than "*Satisfactory*"	Slightly less discomforting than "*Satisfactory*"

A significant interaction between glare vehicle headlights and the distance of the deBoer rating was found, $F(2, 30) = 9.67$, $p = .001$, $\eta_p^2 = .39$. At each of the fixed distances, 2 x 2 ANOVAs revealed a significant effect of glare vehicle headlights on deBoer ratings of discomfort (75 ft, $F(1, 15) = 120.76$, $p < .001$, $\eta_p^2 = .89$; 200 ft, $F(1, 15) = 111.33$, $p < .001$, $\eta_p^2 = .88$; 700 ft, $F(1, 15) = 40.59$, $p < .001$, $\eta_p^2 = .73$). At each distance, deBoer ratings were significantly more discomforting worse when the glare vehicle used high beams then when the glare vehicle used low beams. However, at the distance of 700 feet, when the

glare vehicle used high beams, ratings of discomfort dropped to a mean rating of 4.10 as compared to 2.77 at 200 feet and 2.63 at 75 feet. Ratings when the glare vehicle used low beams did not significantly vary across distances.

deBoer ratings and eye color. In order to determine whether eye color influenced subjective feelings of discomfort from the glare source, a chi-square was performed for each of the headlight combinations at the 75 feet distance (maximal illumination measured at the participant eye). No significant differences in feelings of discomfort between light and dark eyes was found in the glare vehicle: low beams, participant vehicle: low beams, ($\chi^2(8) = 4.36$, $p > .05$), glare vehicle: low beams, participant vehicle: high beams, ($\chi^2(8) = 3.2$, $p > .05$), glare vehicle: high beams, participant vehicle: low beams, ($\chi^2(8) = 8.63$, $p > .05$), or glare vehicle: high beams, participant vehicle: high beams, ($\chi^2(8) = 4.36$, $p > .05$) headlight combinations.

Discussion

Experiment 2 sought to determine the relationship between estimates of Landolt C orientation recognition distances and the actual distance at which the orientation can be determined in the presence of glare. It was hypothesized that participants would exaggerate the disabling effects of high-beam headlight glare.

Participants estimated the distance at which the orientation of a Landolt C could be recognized in each of four combinations of headlights (Low vs. Low; Low vs. High; High vs. Low; and High vs. High). The actual distance at which participants recognized the orientation of the Landolt C with each of the headlighting combinations was also recorded.

Overall the actual distances at which participants were able to determine the orientation of the Landolt C were neither dependent on glare vehicle headlights nor participant vehicle headlights. This is not surprising considering that (similarly to Experiment 1) the stimulus was of high contrast. As previously noted, the ability to discriminate stimuli of sufficient contrast is minimally affected by the presence of glare. This finding is supported by Wood et al. (2005), whose participants were asked to respond when confident that a pedestrian was present while driving through a closed-road track at night. In the presence of glare, participants had more difficultly identifying low contrast pedestrians than high contrast pedestrians. When the participant vehicle used low beam headlights, a pedestrian wearing all black (low contrast) was only detected by 5% of the drivers, whereas a pedestrian wearing retroreflective material in a biological

motion configuration (high contrast) was detected by 85% of the drivers. Overall, pedestrians were identified more frequently when the driver used high beams than when low beams were used. However, low contrast pedestrian (wearing all black) detection increased by 30% when switching to high beams and high contrast pedestrian (wearing retroreflective material in a biological motion configuration) detection only increased by 5%. This suggests that retroreflective material may provide be sufficient contrast for recognition, even when using low beams.

However, the fact that recognition distances did not increase when the test vehicle used high beam headlights is not consistent with the findings of Flannagan et al. (2000) who found that participants were able to recognize a pedestrian at a distance 17% greater when experiencing high vs. high beams over low vs. low beams. This discrepancy, however, can be easily explained. The stimulus (i.e. pedestrian) in Flannagan et al. moved between the glare vehicle and the stationary vehicle. This methodology allowed the participant to gain visual benefits of stimulus backlighting/shadowing. In the present study, the Landolt C stimulus was placed in a position (adjacent to the glare source vehicle) that did not allow for backlighting/shadowing from the glare source vehicle.

While actual recognition distances of the Landolt C did not vary across headlight combinations, participants estimated that the recognition distances would change. Overall, participants believed that when the glare source vehicle

94

used high beam headlights recognition distances would be significantly (32%) shorter than when low beam glare lights were used.

Further, these estimates were not representative of actual recognition distances. That is, participants were not accurate in estimating the distance at which the orientation of the Landolt C could be determined. Overall, participants had a tendency to underestimate visual abilities by 18%. Specifically error in distance estimation increased (i.e., underestimates grew) when glare headlights were switched to high beams. Accuracy varied with headlight condition such that underestimates were as follows: glare vehicle: high beams, participant vehicle: low beams, 32%; and glare vehicle: high beams, participant vehicle: high beams, 33%; glare vehicle: low beams, participant vehicle: low beams, 9%. When the glare vehicle used low beams and the participant vehicle used high beams, participants slightly overestimated recognition distances by 3%, thus when the glare vehicle used low beams, participants more accurately appreciated the benefits of using high beam over low beams 'seeing' lights

Similar to Experiment 1, observers overestimated the extent to which a glare source would degrade their ability to see a small high contrast target. Correlational analyses suggested that observers' estimates are tightly linked to the visual discomfort that they experience while exposed to the glare source. Participant estimates of recognition distance are strongly correlated with deBoer ratings of discomfort. Yet there is not a significant relationship between actual recognition distances and subjective feelings of discomfort. As a result, it

95

appears that feelings of discomfort produced by the glare source informed the

observers' recognition estimates.

GENERAL DISCUSSION

Two experiments used two very different methodologies to explore people's abilities to accurately estimate visual abilities in the presence of a glare source. Experiment 1 asked participants to estimate their visual acuity in the presence of three different glare intensities. Experiment 2 asked participants to estimate the distance at which the orientation of a reflective Landolt C could be determined while in the presence of four different headlighting combinations (Low vs. Low; Low vs. High; High vs. Low; and High vs. High).

In both experiments it was hypothesized that, despite widely discrepant methodologies, observers would overestimate the disabling effects of glare. This pattern was found in both experiments. Whether in the presence of a table-top glare source (Experiment 1) or a pair of opposing high beam headlamps (Experiment 2), observers underestimated their ability to see small high contrast targets when a glare source was present. Furthermore, rather than actual visual abilities, subjective feelings of discomfort appear to have informed the observers' estimates of their ability to see when glare was present.

These findings have several important implications. If a driver believes that his or her vision is impaired when encountering a vehicle using high beam headlights, he or she may take cautionary measures. For example, drivers may reduce speed, which may increase driving safety. As previously noted, people often "overdrive" their headlights (Leibowitz, et al. 1998). A reduction in speed allows drivers more time to see and recognize objects along the roadway.

Drivers who are annoyed by headlight glare may also be tempted to look away from the glare source to reduce the discomforting effects of glare. If drivers look away from the roadway when averting their eyes, it is possible to fail to detect relevant objects in or along the roadway or even to drift outside of one's lane. This could result in especially dangerous situations where pedestrians are present.

Additionally, if drivers are unable to distinguish between the effects of disability glare from the effects of discomfort glare, they may be less likely to use their own high beam headlights. High beam headlights place light in a broader area in and along the road which may help drivers to see and recognize objects of importance (especially those of low contrast; e.g., pedestrians). The use of high beam headlights is a simple and effective way to increase nighttime visual abilities (e.g., Leibowitz, et al., 1998; Wood, et al., 2005). A driver who is reluctant to use his or her high beams due to a desire to avoid "blinding" approaching drivers may unwittingly assume a greater risk of a collision with objects on the roadway at night.

It appears as though these feelings of discomfort do indeed prevent (young) drivers from using high beam headlights. Survey data revealed that participants only reported using high beam headlights during nighttime driving about 26% of the time. Participants also provided comments such as "I usually use low beams all the time," "normally don't think about it (using high beams)," and "(I consider) the vision of other drivers." These comments suggest that

participants are reluctant to use high beam headlights in a variety of situations.

This implies drivers do not fully appreciate the benefits of high beam headlights.

The comments also suggest that young drivers believe that high beam headlights

are harmful to the vision of oncoming drivers, when in fact high beams are likely

not as disabling as is thought most drivers. Drivers who believe (1) that glare

from high beams can severely disrupt other drivers' ability to see, and (2) that

they can see well enough with low beams (e.g., Tyrrell, et al., 2004) are likely to

be particularly reluctant to use their high beams. This pattern of beliefs can result

in a dangerous over-reliance on low beams that might go unnoticed until an

unexpected object or pedestrian is encountered on a roadway at night.

As noted previously, drivers often complain about discomfort from

headlight glare. It has been largely due to these complaints that a great deal of

research and monetary effort has been placed on reducing headlight glare.

However, if typical drivers are unable to distinguish between the effects of

discomfort glare and disability glare (i.e., exaggerate the effects of glare),

perhaps the magnitude of the glare problem as it affects driving performance is

smaller than many might have thought. That is, drivers are not *blinded* by glare

(as drivers often complain) and it may not actually be as large of a problem as

some believe. In the context of the present work, acuity (using high contrast

stimuli) was not negatively affected by glare. This is not to say that glare does not

negatively affect other visually based driving tasks (e.g. simple detection tasks)

or driving performance. Perhaps then, more research focus should be placed on

the possibly negative effects of glare on driving performance. In other words, does glare actually effect driving performance, or does it simply cause driver annoyance? (This, of course, is not to say that simple annoyances do not affect driving performance.) To untangle the subjective and objective consequences of headlight glare a systematic program of research on the effects of headlight glare is needed.

While people often complain about the "blinding" effects of glare, it is difficult to find a complaint about low light levels on the roadway at night (NHTSA, 2001). Perhaps unfortunately, these complaints have driven research focusing on reducing glare. Yet, this preliminary research has revealed that drivers can overestimate the extent to which glare reduces their ability to see; it seems possible that relying on citizens' complaints about headlight glare to determine research priorities can be problematic. Subjective measures of discomfort glare should not be used as a substitute for objective measures of disability glare, regardless of the relative ease with which discomfort glare can be measured and the frequency of complaints from citizens. Indeed, reducing glare by reducing forward headlighting could actually decrease nighttime safety by reducing the total amount of light in and around the roadway.

The present data have revealed that the average young driver does not fully understand how vision is affected by glare. This misunderstanding often leads to complaints about glare with little understanding of its objective effects. It is clear that more work is necessary to fully understand how vision and driving

performance are affected by nighttime headlight glare as well as drivers' perceptions of these effects.

The present study has many limitations. Only young, visual healthy adults participated. Also, the experiments presented relatively simple and non-challenging tasks. Real world nighttime driving involves many more factors than were present in the current work (e.g., maneuvering the vehicle). Because of these (and other limitations), further research is needed to accurately understand how glare affects real-world nighttime driving and drivers beliefs about these effects.

Another limitation of the present experiments is that both relied on very high contrast, acuity-based stimuli. While this is a good first step, drivers often need the visual capacity to detect lower contrast objects with lower spatial frequencies and greater angular extents (e.g., typical pedestrians). As previous research has shown (Cobb & Moss, 1928; Luckiesh, 1944), high contrast acuity-based stimuli are relatively robust to the effects of glare. Even though it is important to be able to recognize and read roadway signs at night, the failure to accurately read these signs may generally be of less consequence than failing to respond to the presence of an object or person in the roadway (who are especially at risk in areas where one would not expect to encounter a pedestrian). As such, it is important to gain a better understand of how glare affects low contrast stimuli as well as how drivers believe their vision is affected in such scenarios. A key issue here is likely to be the extent to which typical

drivers understand the concept of contrast and its relevance to the driving task. That is, do drivers understand the importance of detecting low contrast and less salient objects in the nighttime driving environment.

Future research should be conducted to determine the effects of headlight glare on real world driving tasks. For example, does high beam headlight glare help or hinder the detection of low contrast *and* how drivers think their visual abilities are affected. As a result of the severe consequences, special attention should be given to scenarios involving pedestrians. As noted previously, headlight glare may cause drivers to modify driving behavior. It is important to understand how people react behaviorally to glare. That is, do drivers look away from the road (to minimize the presumed glare effects), look towards the glare source (due to novelty or interest), reduce speed, deviate from their lane, et cetera. Such data will better inform policy and engineering decisions regarding the design of headlighting systems.

In both of the present experiments glare did not affect observers' ability to see an object ahead of them. However, both studies relied on visually healthy young observers and different patterns may emerge from older drivers due to age-related visual changes. As we age, we experience a variety of different changes which affect the way we see (e.g., Shieber & Shinar, 1991). Older adults are more prone to developing visual pathologies including cataracts and glaucoma and adapt to the dark more slowly. To my knowledge no research has explored the extent to which either normal age-related visual changes or visual

pathologies affect the accuracy with which drivers understand their own visual limitations.

Further, as we age, the muscles of the iris weaken. That is, the pupil does not decrease to sizes that it was once able to produce. The inability to fully contract the iris can mean that the eye experiences a loss in resolving power. In other words, the depth of field is reduced and we are less able to clearly focus (especially on stimuli at closer distances). And a reduction in the ability to reduce pupil size in response to glare can reduce the eye's ability to moderate the effects of glare by changing pupil size. The combination of larger pupil sizes and cataracts means that many older drivers are experiencing more intraocular light scattering and a reduction of retinal contrast. This reduction of contrast makes objects (especially those of low contrast) more difficult of see and recognize. Because of the effects of aging on the eye, it is likely that glare effects older drivers (especially those with cataracts) in a different and more disabling way than younger adults. It is also likely that because these visual impairments are magnified in nighttime driving, older drivers are more vocal about headlight glare and tend to drive less at night than younger drivers.

Because visual abilities of older adults are different than those of younger drivers it is important to further investigate this population of drivers. It is important to investigate both the actual effects of nighttime headlight glare and how drivers believe vision is affected in this special population of drivers. It is expected that older drivers' vision is negatively affected by glare. It is also

expected that older drivers will follow similar patterns of exaggerating the disabling effects of glare.

Beyond the current findings, it is important that drivers are informed of the benefit of high beam headlights in seeing and recognizing important objects in and around the roadway (e.g. Wood et al., 2005). High beam headlights spread more light in and around the roadway. This light increases drivers' abilities to see and recognize objects. This increase in visual detection abilities affords drivers more time to see and respond to objects/pedestrians. One can assume then, that an increase in high beam headlight use would result in a decrease of nighttime crashes into objects and pedestrians (i.e., an increase in nighttime driving safety). The tendency measured in the present experiments to exaggerate the visually disabling effects of glare may be counter-productive by limiting drivers' use of their own high beams.

However, if drivers are unaware of the benefits of using high beam headlights, it seems unlikely that usage will increase. This is especially true if estimates of our nighttime visual abilities rely on exaggerations of the disabling effects of glare. However, simple educational procedures might be useful in informing drivers of the benefits of high beam headlights over low beam headlights. Tyrrell, Patton, and Brooks (2004) found that two months after hearing a lecture on visual issues relevant to night driving, pedestrians better estimated their visibility to drivers at night. Participants were asked to estimate the distance at which they believed a driver would be able to recognize them as a

pedestrian. Participants who heard a relevant, graphic-intensive lecture provided conspicuity estimates that were 56% shorter than a control group who had not heard the lecture. This shows that education methods may be a viable and productive way to inform road users about nighttime driving issues such as the limitations of low beam headlights.

The present studies used two widely different methodologies to assess how people believe their visual abilities are affected by glare. As hypothesized, estimates appear to have been guided by subjective feelings of discomfort, despite the lack of relationship between subjective discomfort and objective measures of actual visual abilities. It is hoped that the current work represents a starting point to a new area of research on night driving that will ultimately increase our knowledge of the relationship between how drivers believe their vision is affected by frequently encountered visual challenges as well as the actual effects of the same visual challenges. It is hoped that such an understanding can be leveraged into a measurable increase in roadway safety.

APPENDICES

Appendix A

Participant Questionnaire

Part I. General questions. Please remember that all answers will be kept confidential, so please answer as candidly as possible.

1. How many years of driving experience do you have? _____

2. Of the total time you spent driving in the last 12 months, approximately what percentage of the time did you spend driving on each of the following types of roads?

   a. in town/city? _____
   b. in suburbs or country? _____
   c. on highways? _____

3. Of the total time you spent driving in the last 12 months, approximately what percentage was done during the nighttime (after sunset and before sunrise)? _____

4. How comfortable do you feel driving *at night in good weather*? (circle one)

   a. Very Comfortable
   b. Comfortable
   c. Neutral
   d. Uncomfortable
   e. Very Uncomfortable

5. How comfortable do you feel driving *at night in bad/stormy weather*? (circle one)
   a. Very Comfortable
   b. Comfortable
   c. Neutral
   d. Uncomfortable
   e. Very Uncomfortable

6. Which of the following driving situations do you generally try to avoid?

(Insert one of the letters listed below to indicate how strongly you avoid each situation.)

N   Never avoid

P   Prefer to avoid

A   Always avoid (except emergencies)

heavy traffic, daylight _____   heavy traffic, night   _____

rain, daylight   _____   rain, night   _____

fog, daylight   _____   fog, night   _____

Part II. Ease of Driving in Different Conditions

How easy do you feel it is to drive under each of the following conditions?

(Assume good weather and daytime conditions unless otherwise specified.)

Assign a number from 1 to 7 to each item using the following scale as a guide:

	1	2	3	4	5	6	7	

Not at all
Easy

Very
Easy

---

7.   through a quiet residential neighborhood _____

8.   through a busy shopping mall, parking lot _____

9. in city traffic _____

10. making a right turn in city traffic _____

11. changing lanes on a divided highway/interstate _____

12. entering a divided highway/interstate _____

13. exiting a divided highway/interstate _____

14. making a U-turn on a wide city street _____

15. parallel parking along the curb of a busy street _____

16. pulling into a parking space at the supermarket _____

17. reversing out of a parking space at a supermarket _____

18. on a divided highway/interstate in clear weather, daylight _____

19. on a divided highway/interstate in clear weather, nighttime _____

20. on a divided highway/interstate in rainy weather, daylight _____

21. on a divided highway/interstate in rainy weather, nighttime _____

22. What percentage of the time do you use <u>high beam</u> headlights when driving at night in the following situations?

    a. on city streets   _____

    b. on highways/interstates   _____

    c. on country roads   _____

    d. on suburban roads   _____

23. When you are driving on divided highways/interstates at night, how frequently do the headlights of oncoming traffic seem troublesome?

    a. Rarely   _____

    b. Occasionally   _____

    c. Often   _____

    d. At every encounter   _____

24. Estimate the distance at which you can see the following objects when driving at night: (in meters or feet)

    a. Other vehicles: _____

    b. Cyclists: _____

    c. Pedestrians wearing white: _____

    d. Pedestrians wearing black: _____

    e. Traffic signs: _____

25. Are there any precautions you take when driving at night?

26. What influences your nighttime low-beam headlight usage over high beam headlight usage (or vice versa)?

27. What type of vehicle do you drive most of the time (e.g., sedan, hatchback, station wagon, sports car, van, truck). If you frequently drive more than one vehicle, please indicate what type of vehicle you assumed in the preceding questions.

28. Do you have any other comments about your experiences driving at night?

Graphs depicting individual participant data resulting from the training test in Experiment 1
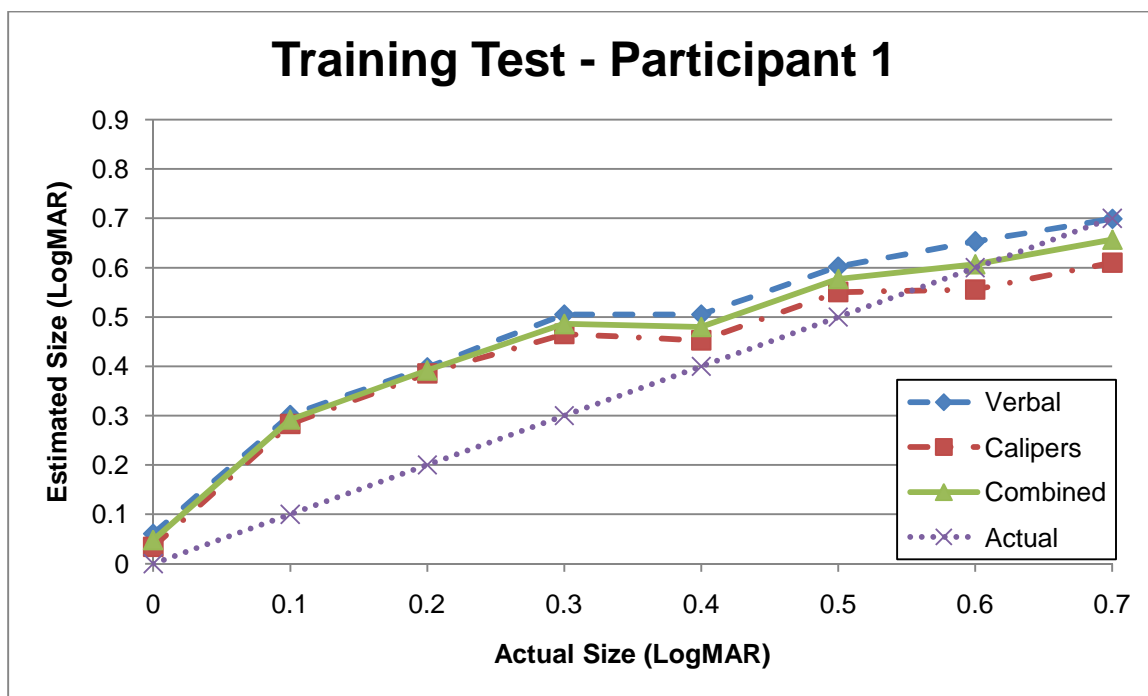
Appendix B; Figure 1. Participant 1 training test data; verbal R^2= .92, manual R^2=.85, and combined verbal + manual R^2=.89.
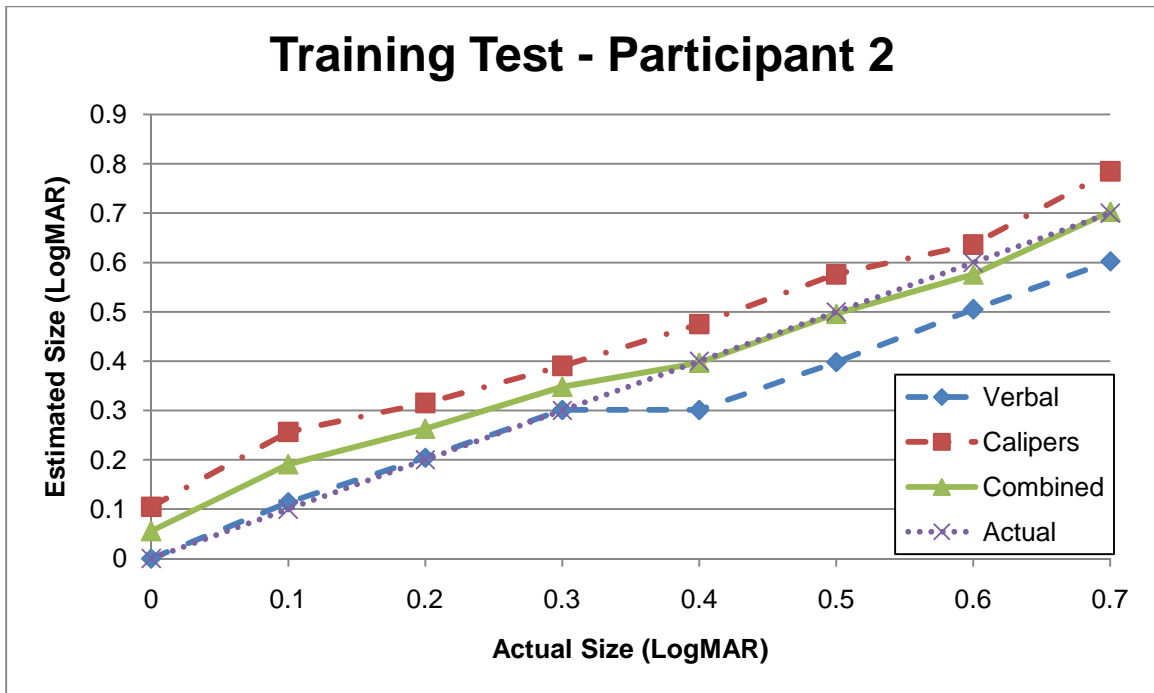
Appendix B; Figure 2. Participant 2 training test data; verbal R^2 = .98, manual R^2 =.99, and combined verbal + manual R^2 =.99.
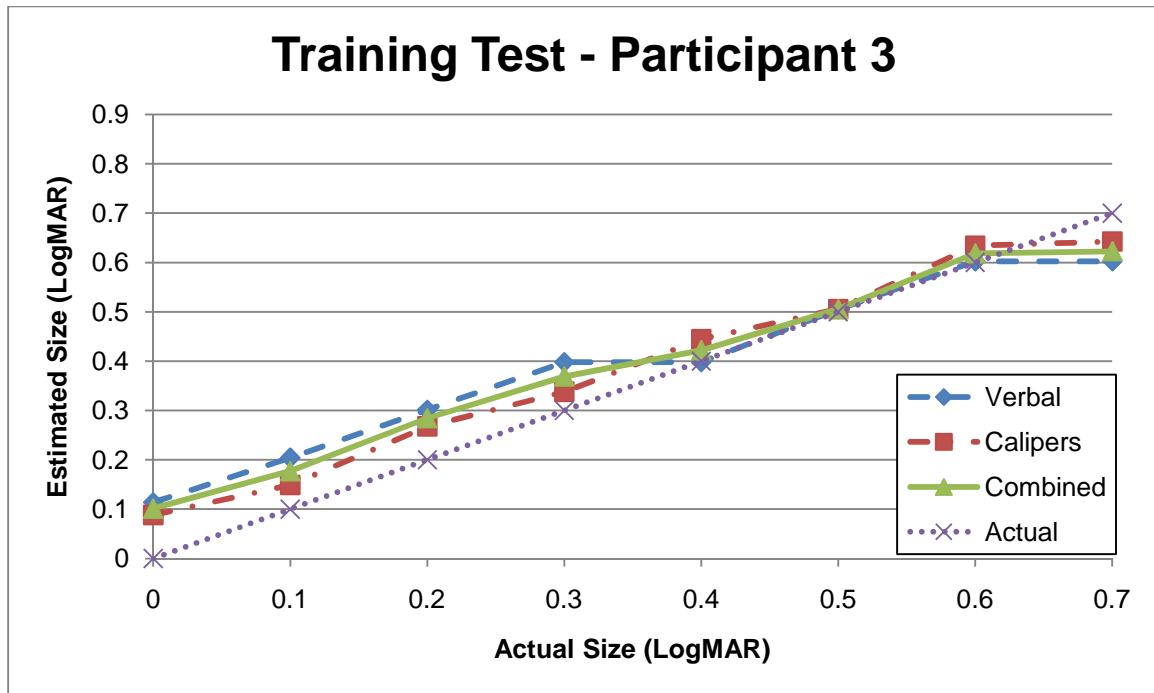
Appendix B; Figure 3. Participant 3 training test data; verbal R^2= .94, manual R^2=.96, and combined verbal + manual R^2=.96.
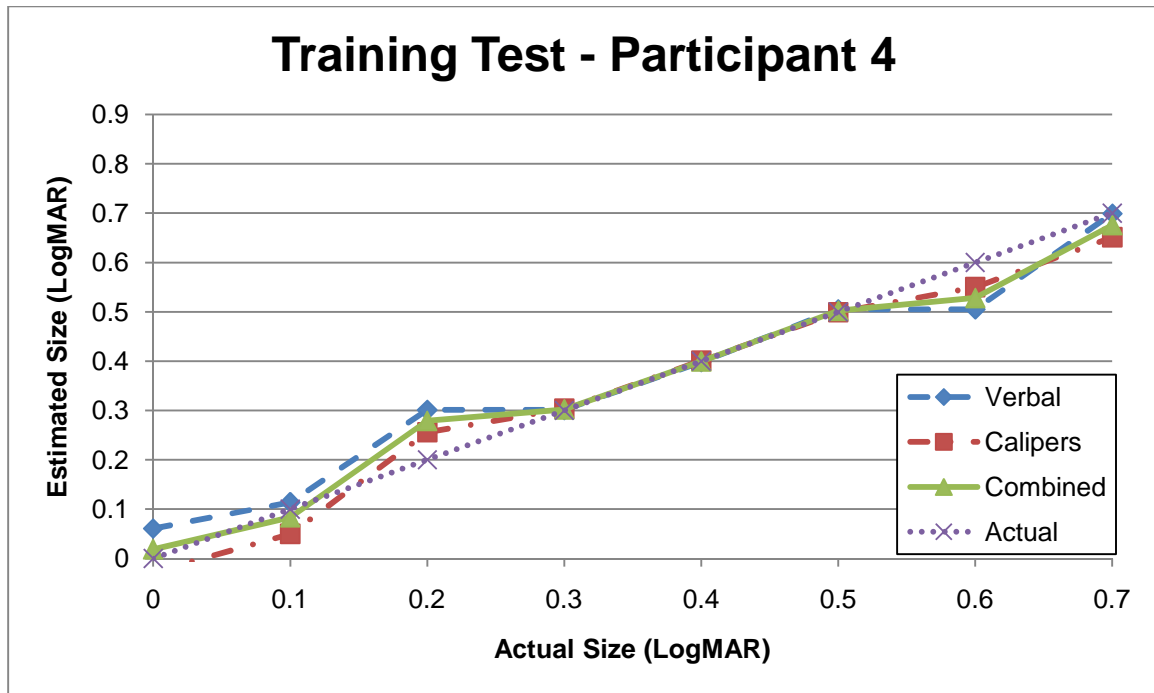
Appendix B; Figure 4. Participant 4 training test data; verbal R^2= .95, manual R^2=.98, and combined verbal + manual R^2=.97.
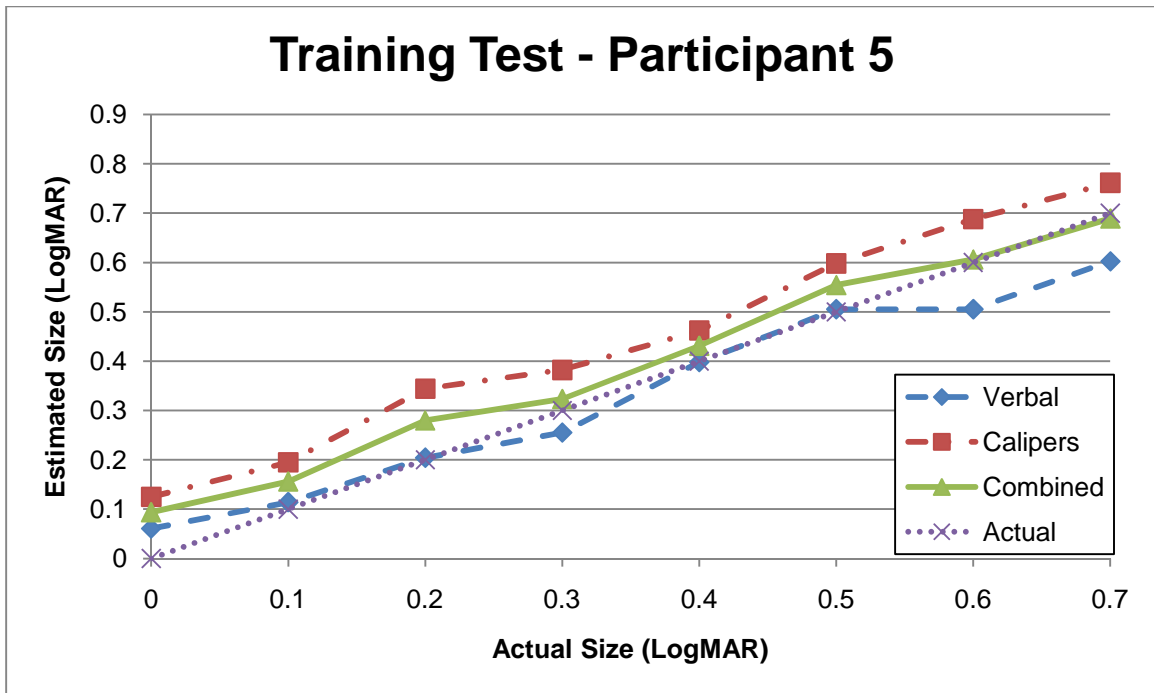
Appendix B; Figure 5. Participant 5 training test data; verbal R^2= .96, manual R^2=.99, and combined verbal + manual R^2=.99.
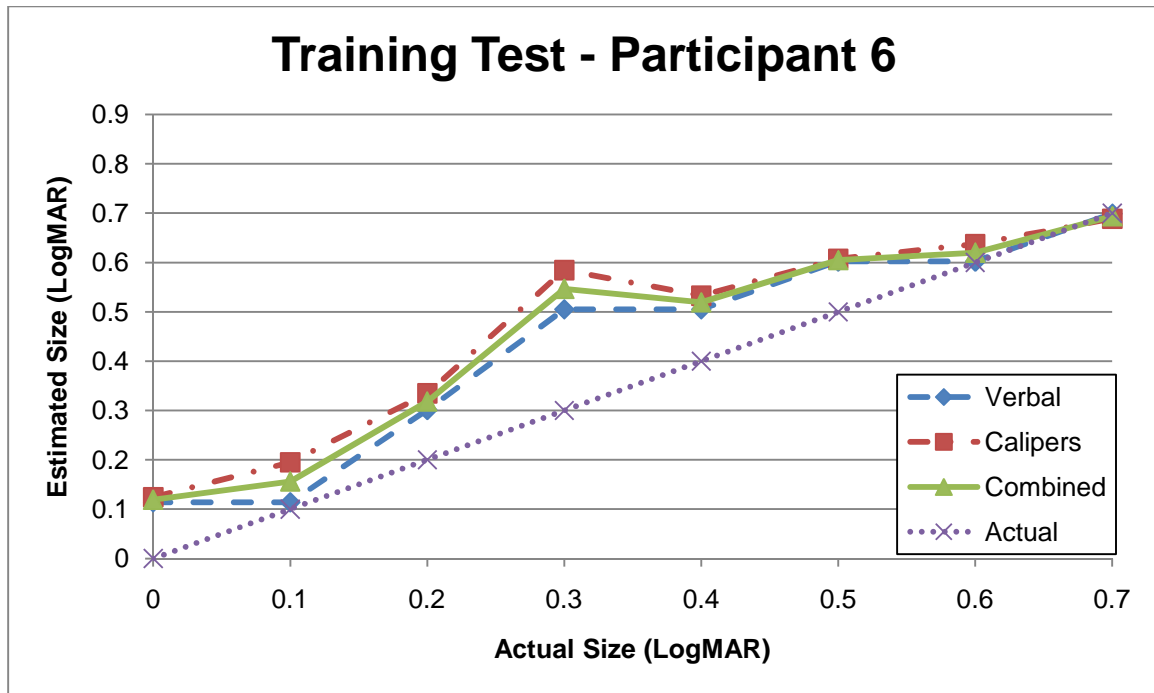
Appendix B; Figure 6. Participant 6 training test data; verbal R^2= .90, manual R^2=.82, and combined verbal + manual R^2=.87.
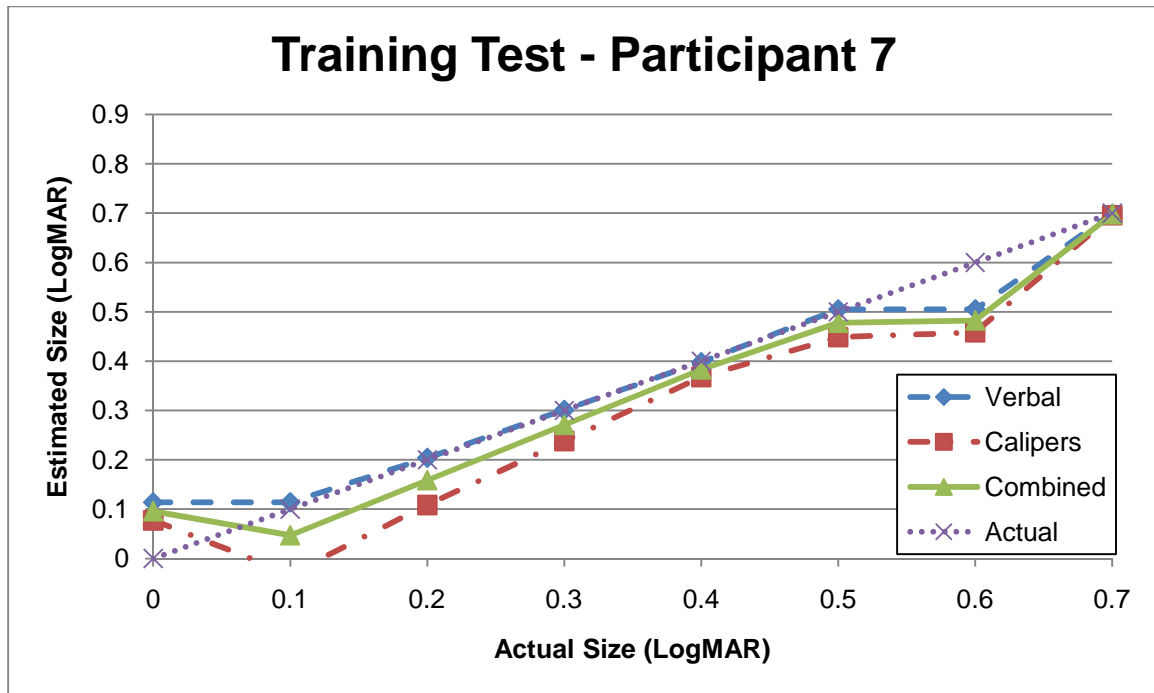
Appendix B; Figure 7. Participant 7 training test data; verbal R^2= .95, manual R^2=.93, and combined verbal + manual R^2=.94.
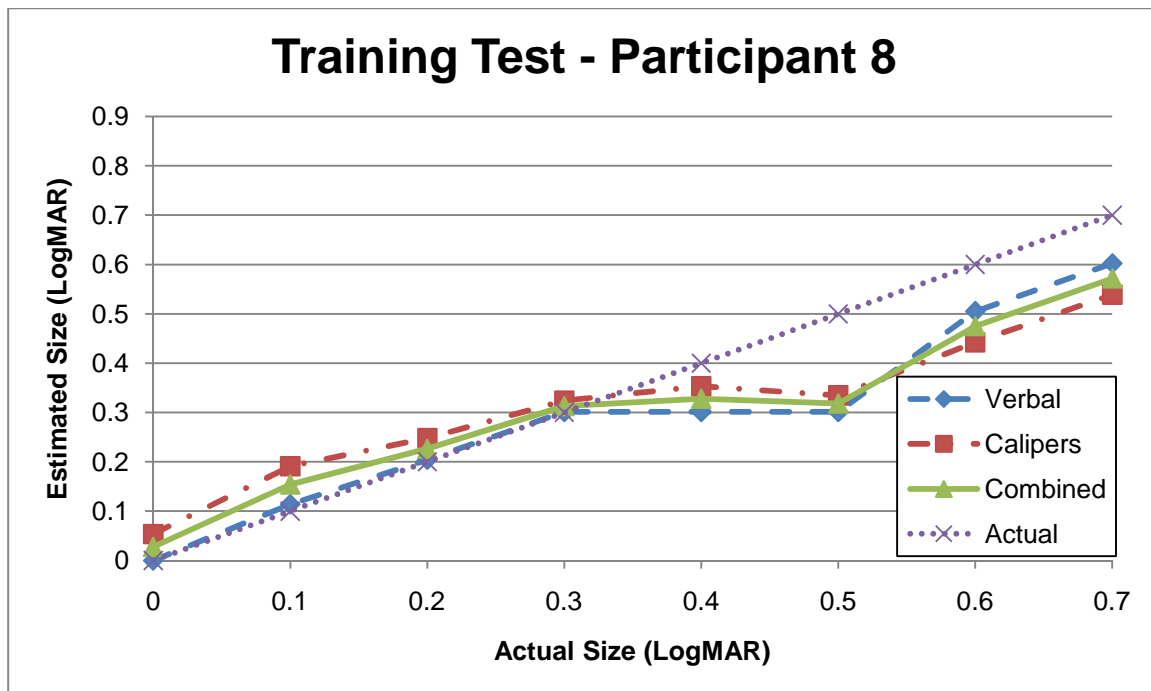
Appendix B; Figure 8. Participant 8 training test data; verbal R^2= .93, manual R^2=.93, and combined verbal + manual R^2=.94.

Training Test - Participant 9
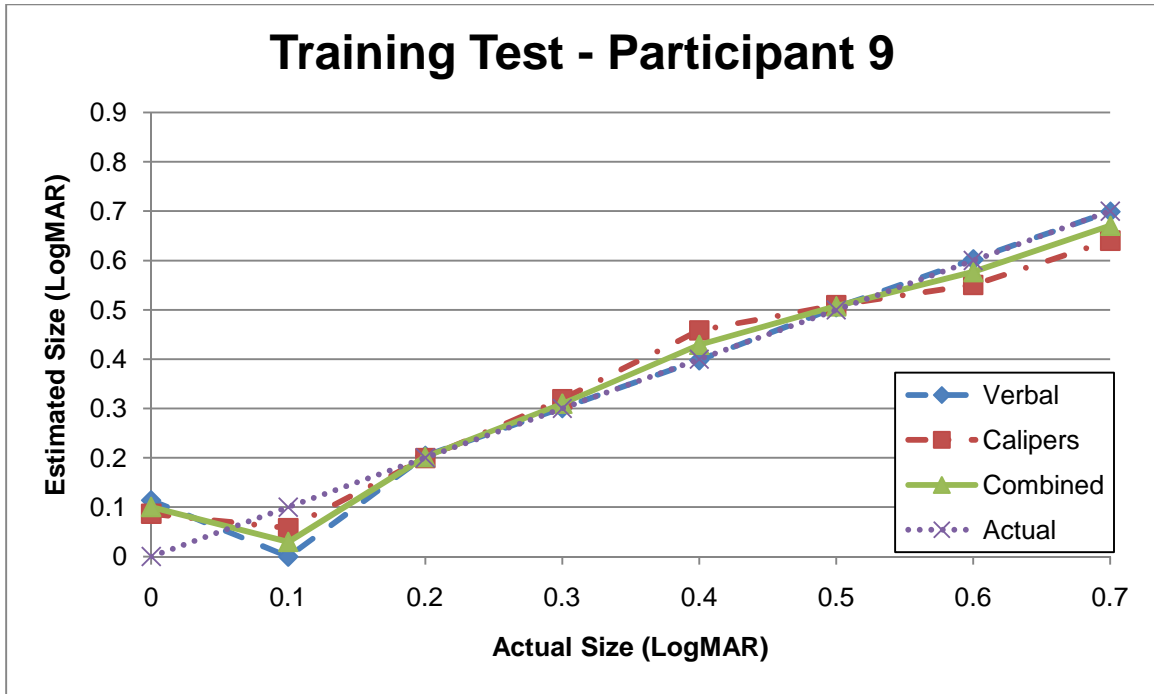
Appendix B; Figure 9. Participant 9 training test data; verbal R^2= .99, manual R^2=.96, and combined verbal + manual R^2=.98.
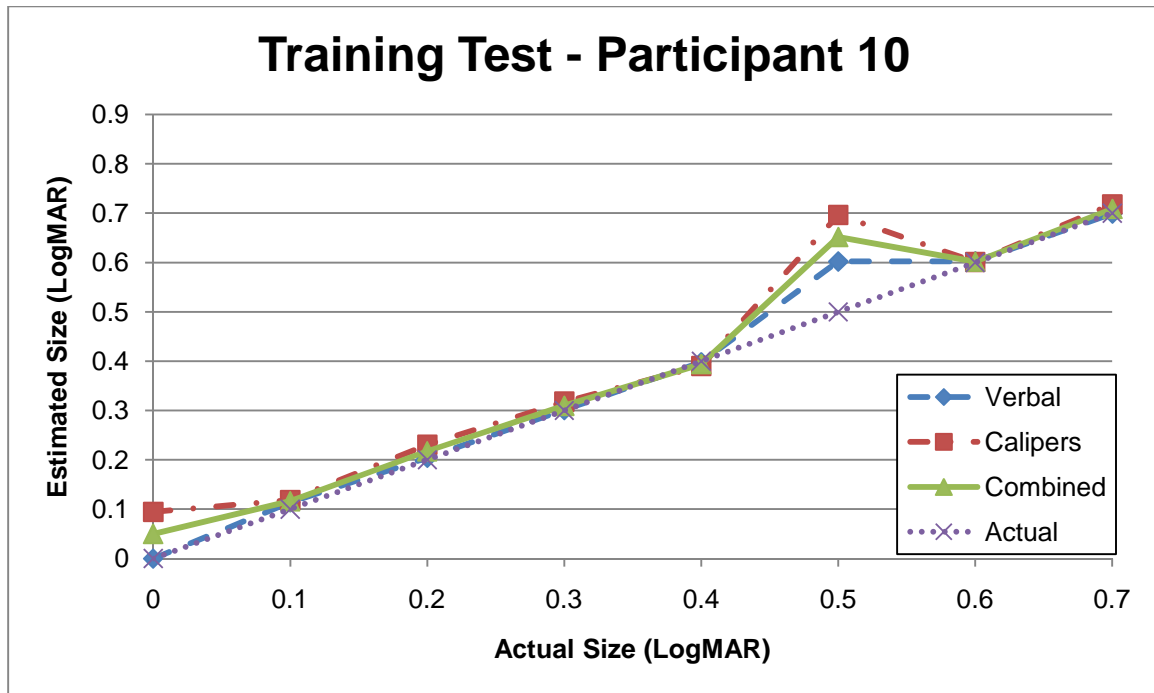
Appendix B; Figure 10. Participant 10 training test data; verbal R^2= .96, manual R^2=.87, and combined verbal + manual R^2=.92.
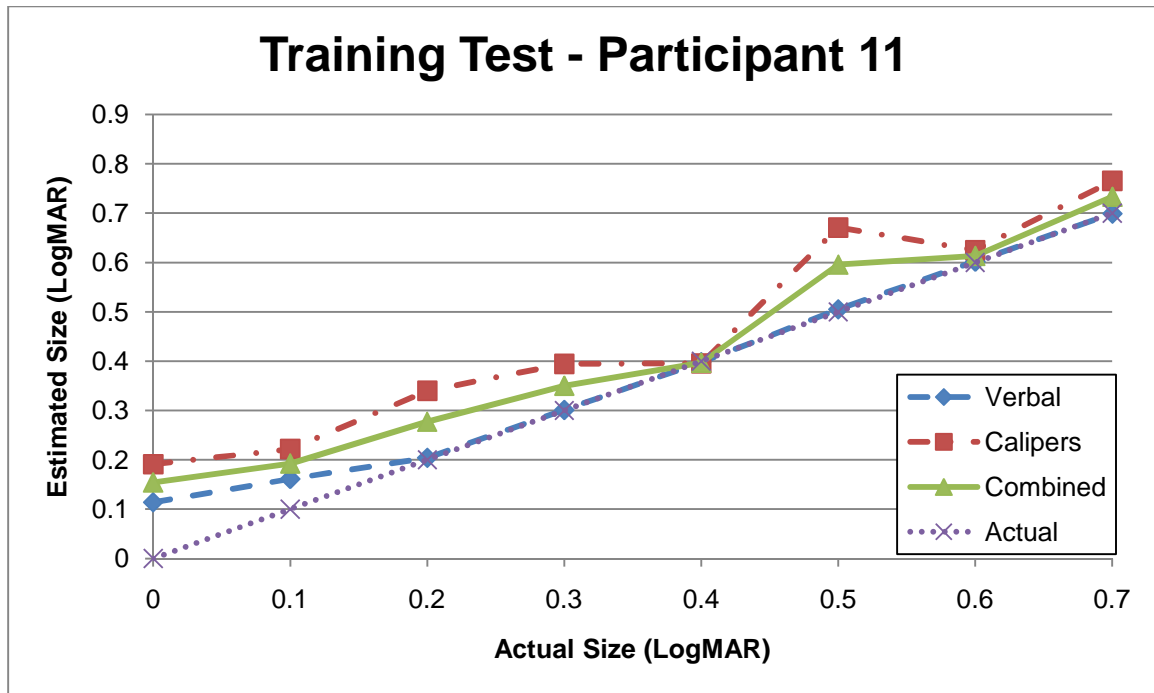
Appendix B; Figure 11. Participant 11 training test data; verbal R^2= .99, manual R^2=.92, and combined verbal + manual R^2=.98.
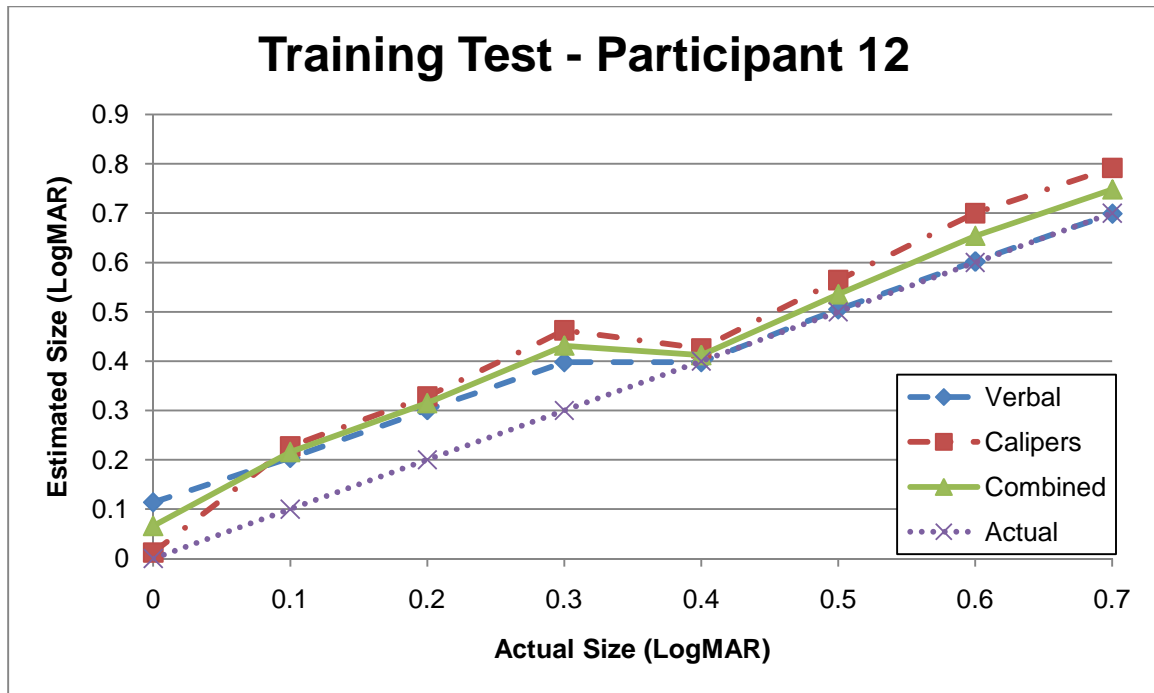
Appendix B; Figure 12. Participant 12 training test data; verbal R^2= .99, manual R^2=.98, and combined verbal + manual R^2=.98.
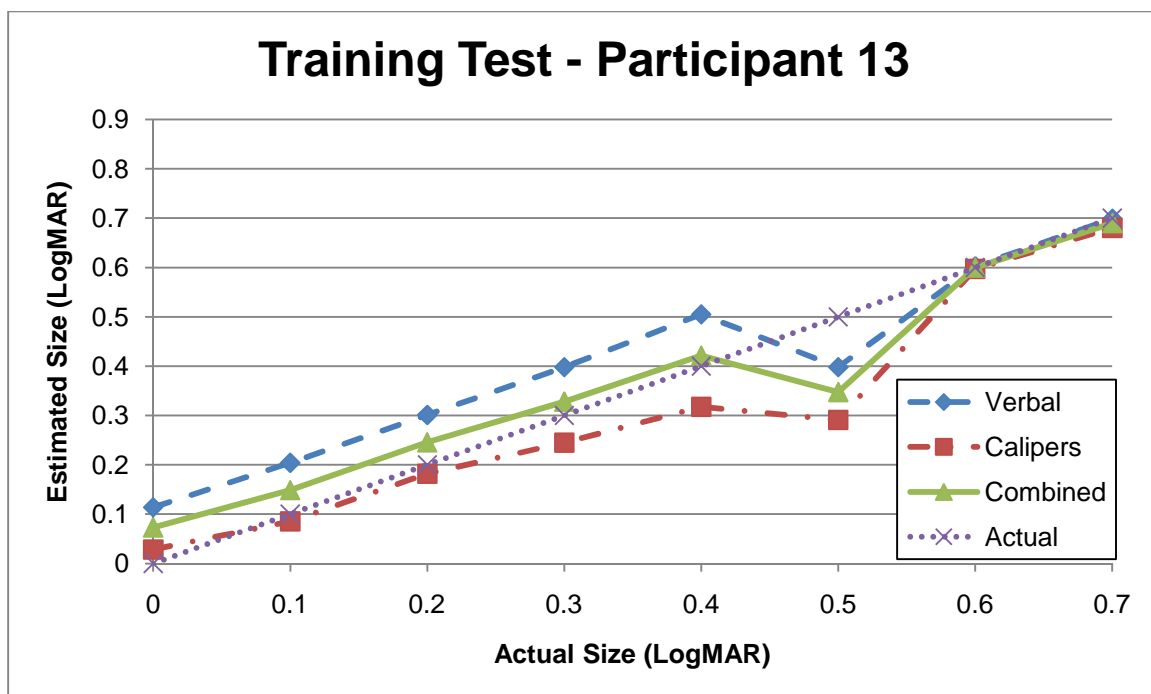
Appendix B; Figure 13. Participant 13 training test data; verbal R^2= .91, manual R^2=.91, and combined verbal + manual R^2=.93.
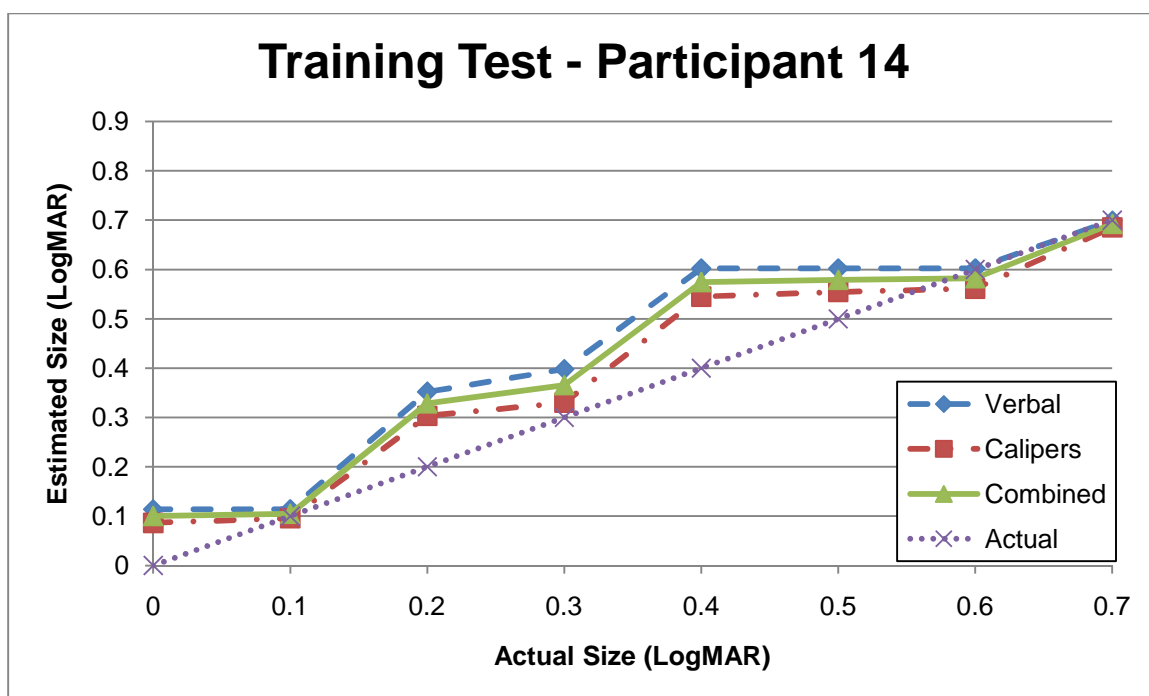
Appendix B; Figure 14. Participant 14 training test data; verbal R^2= .87, manual R^2=.91, and combined verbal + manual R^2=.89.
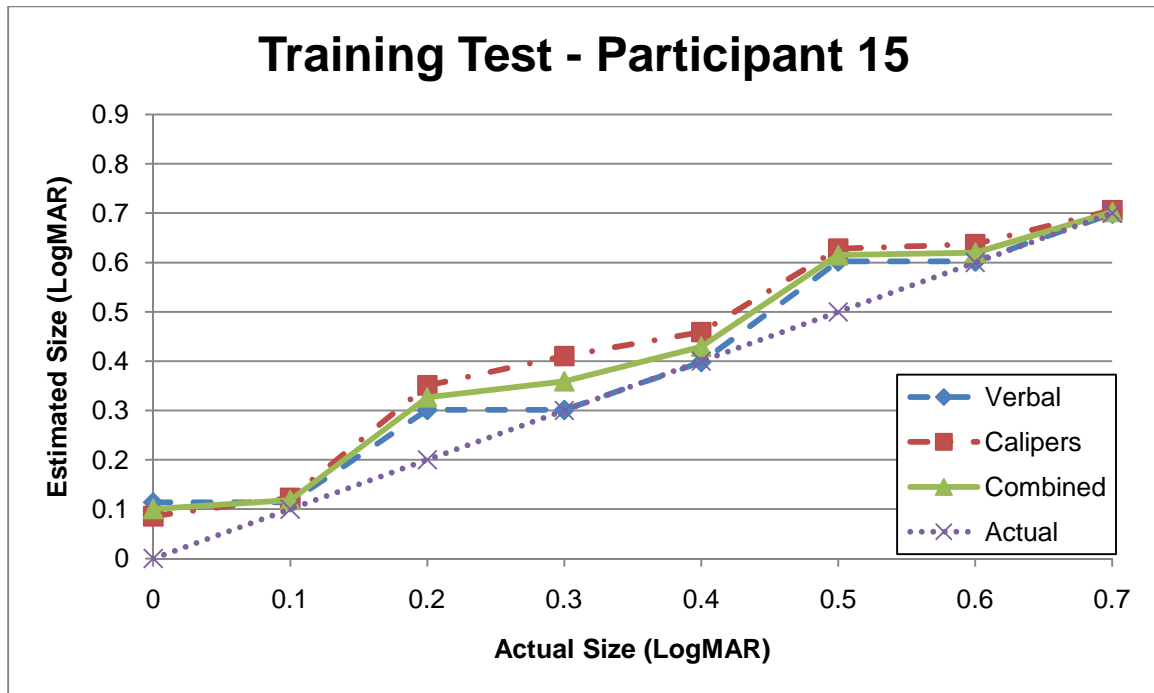
Appendix B; Figure 15. Participant 15 training test data; verbal R^2= .96, manual R^2=.95, and combined verbal + manual R^2=.96.
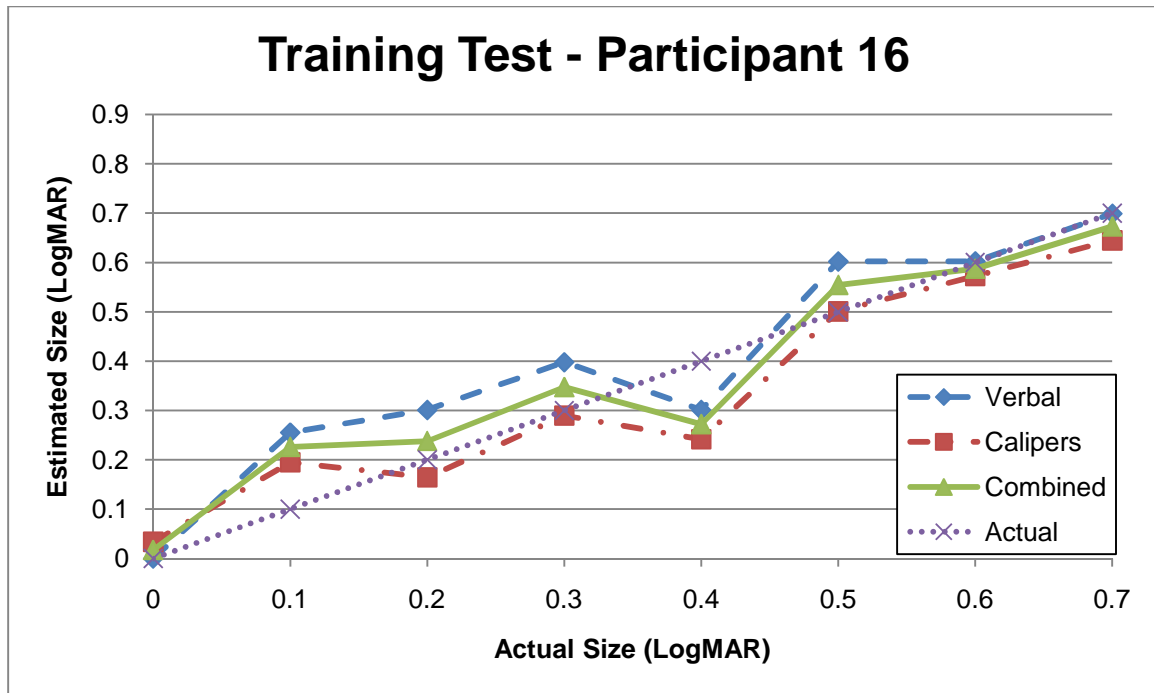
Appendix B; Figure 16. Participant 16 training test data; verbal R^2= .91, manual R^2=.95, and combined verbal + manual R^2=.94.
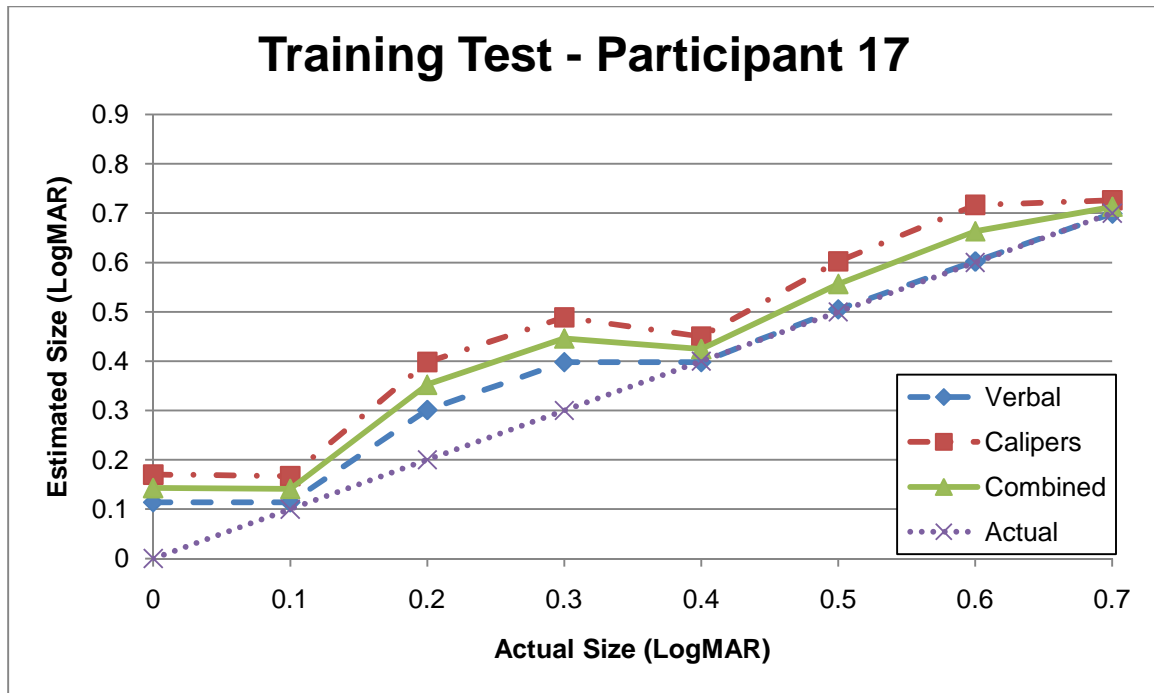
Appendix B; Figure 17. Participant 17 training test data; verbal R^2= .98, manual R^2=.93, and combined verbal + manual R^2=.97.
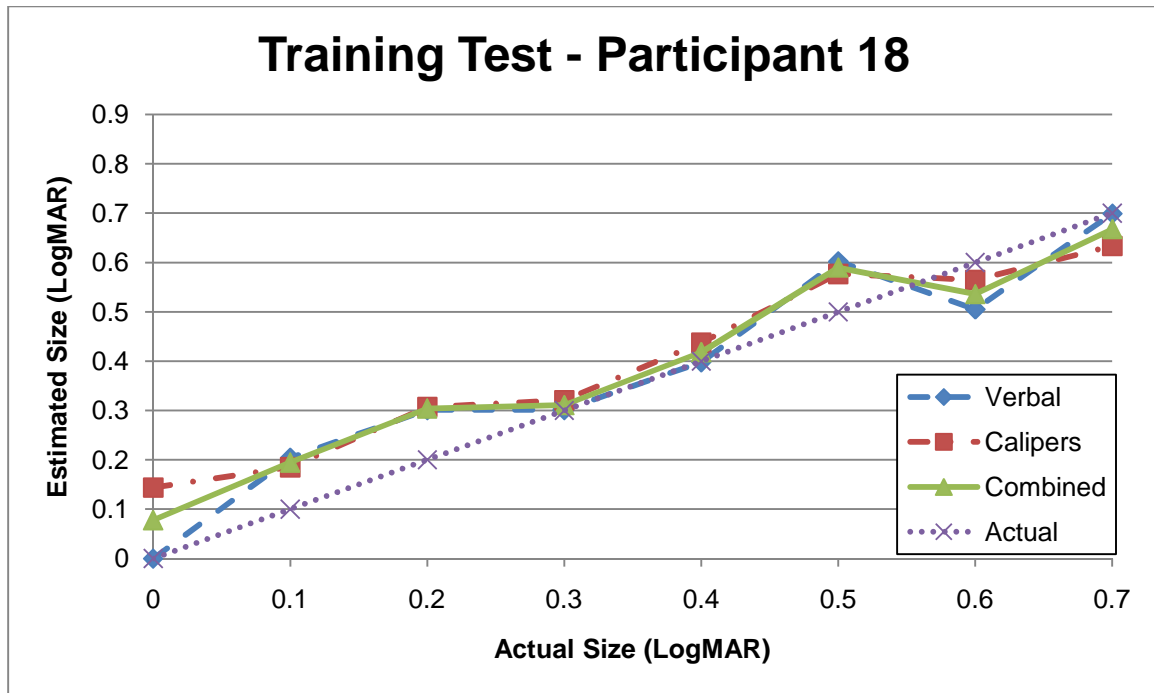
Appendix B; Figure 18. Participant 18 training test data; verbal R^2= .89, manual R^2=.94, and combined verbal + manual R^2=.93.
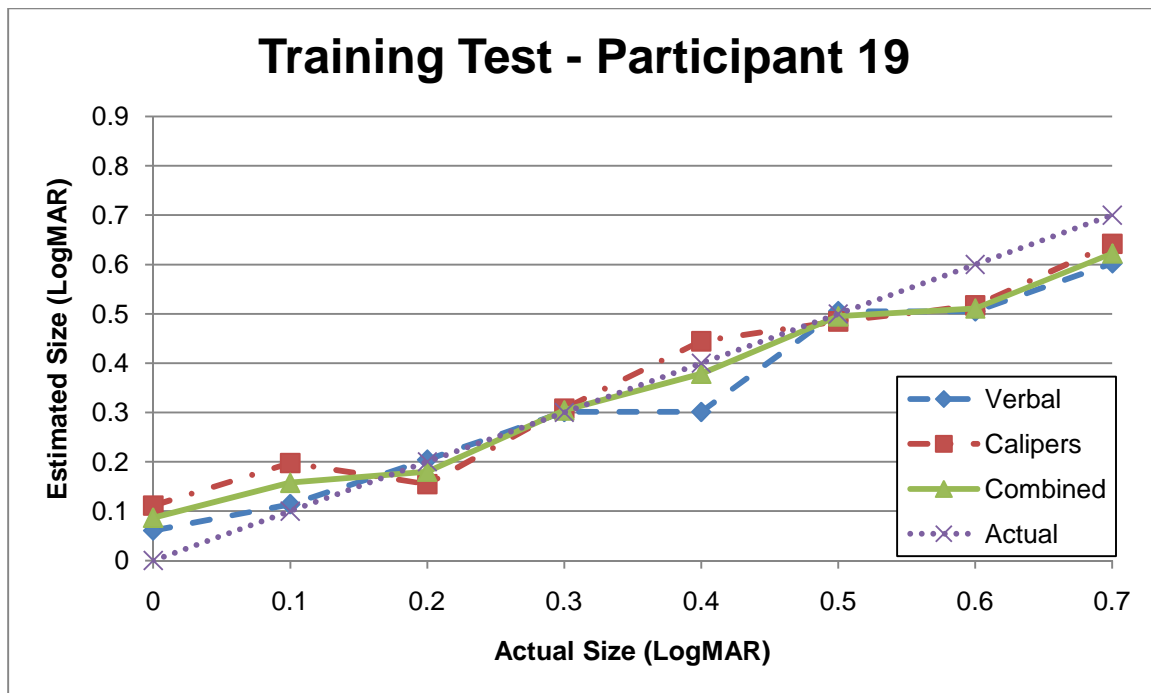
Appendix B; Figure 19. Participant 19 training test data; verbal R^2= .96, manual R^2=.96, and combined verbal + manual R^2=.98.
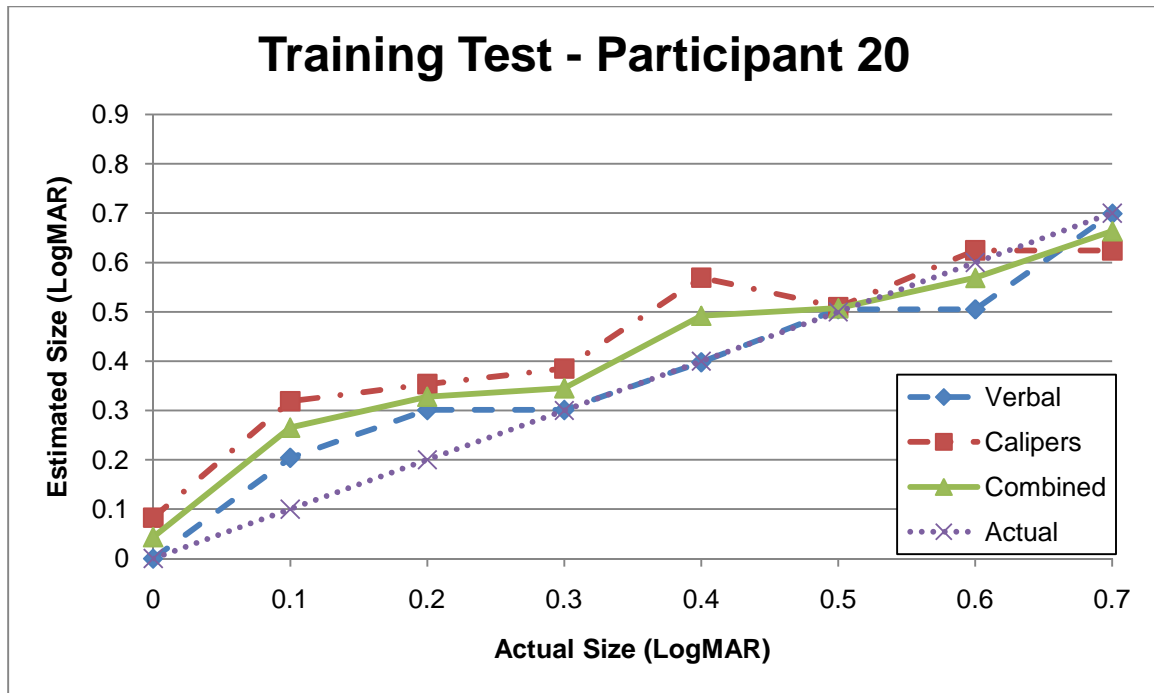
Appendix B; Figure 20. Participant 20 training test data; verbal R^2= .94, manual R^2=.84, and combined verbal + manual R^2=.95.
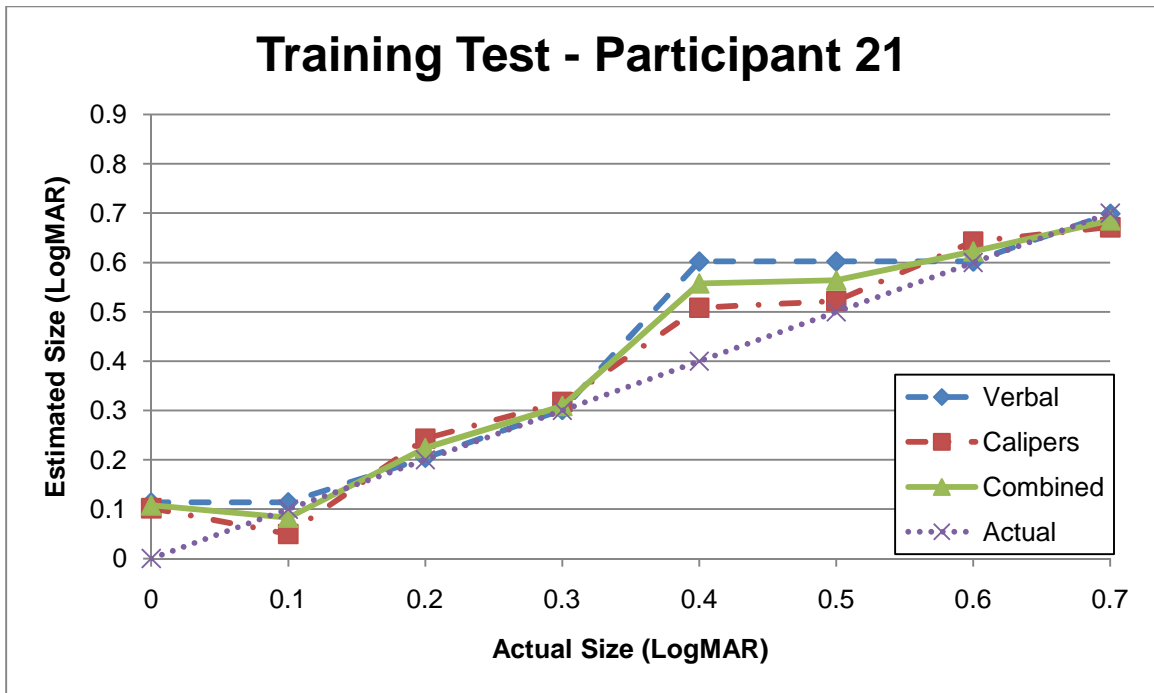
Appendix B; Figure 21. Participant 21 training test data; verbal R^2= .86, manual R^2=.95, and combined verbal + manual R^2=.92.
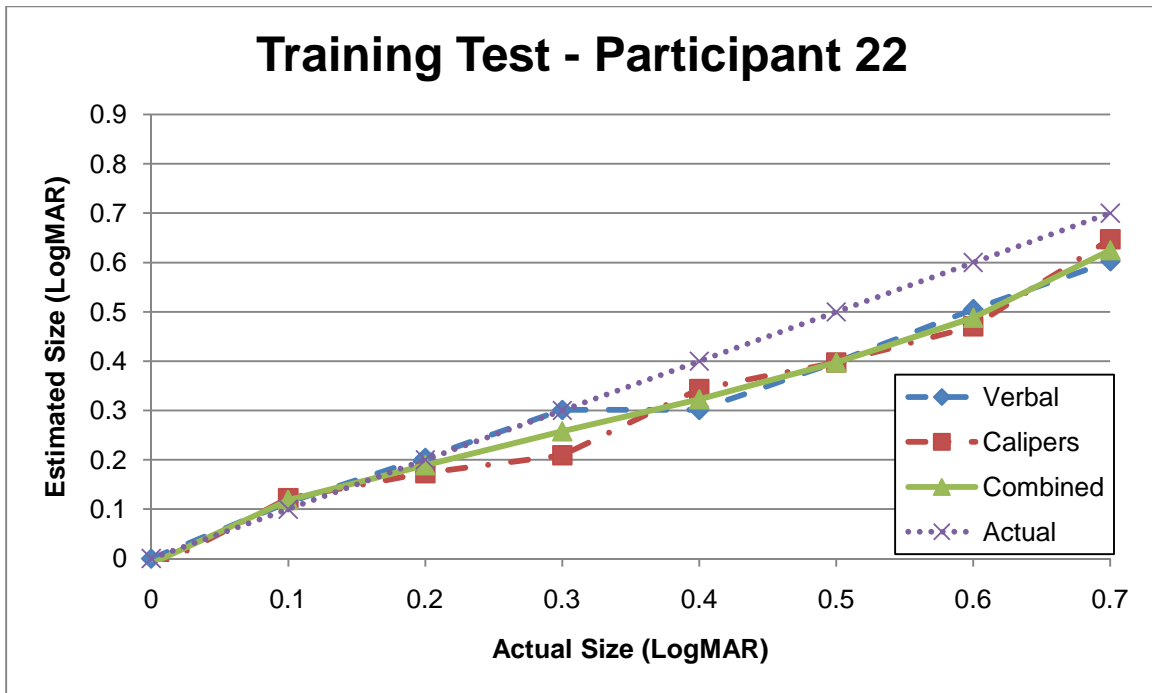
Appendix B; Figure 22. Participant 22 training test data; verbal R^2 = .98, manual R^2 =.96, and combined verbal + manual R^2 =.98.
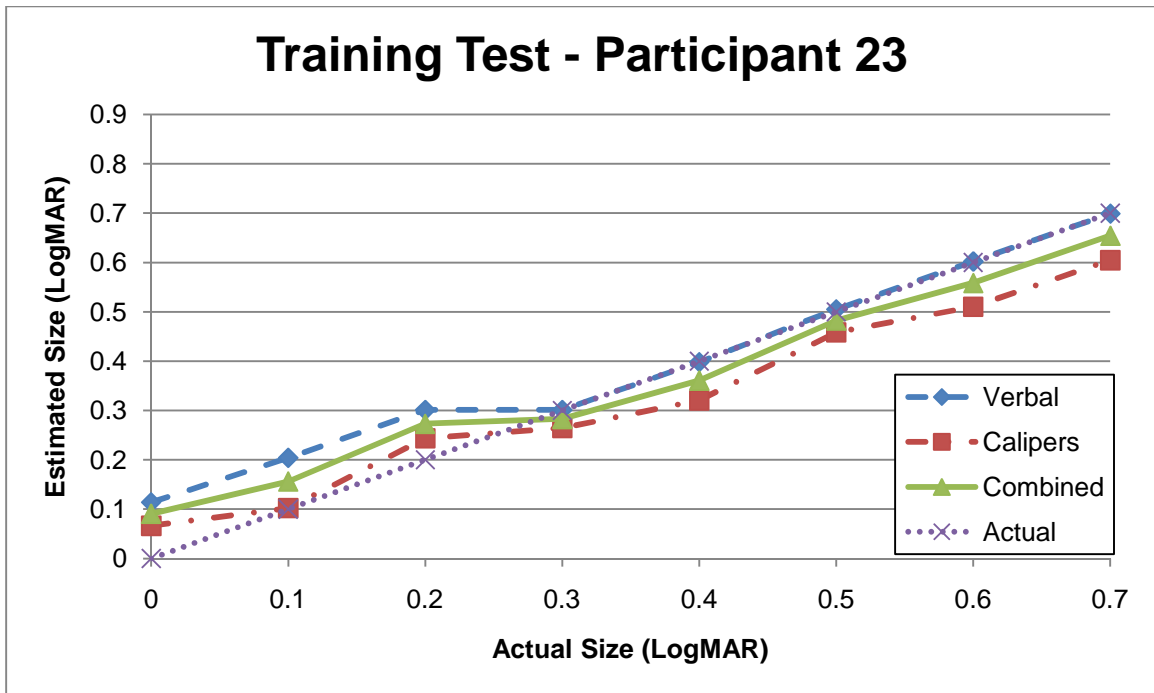
Appendix B; Figure 23. Participant 23 training test data; verbal R^2= .99, manual R^2=.99, and combined verbal + manual R^2=.99.
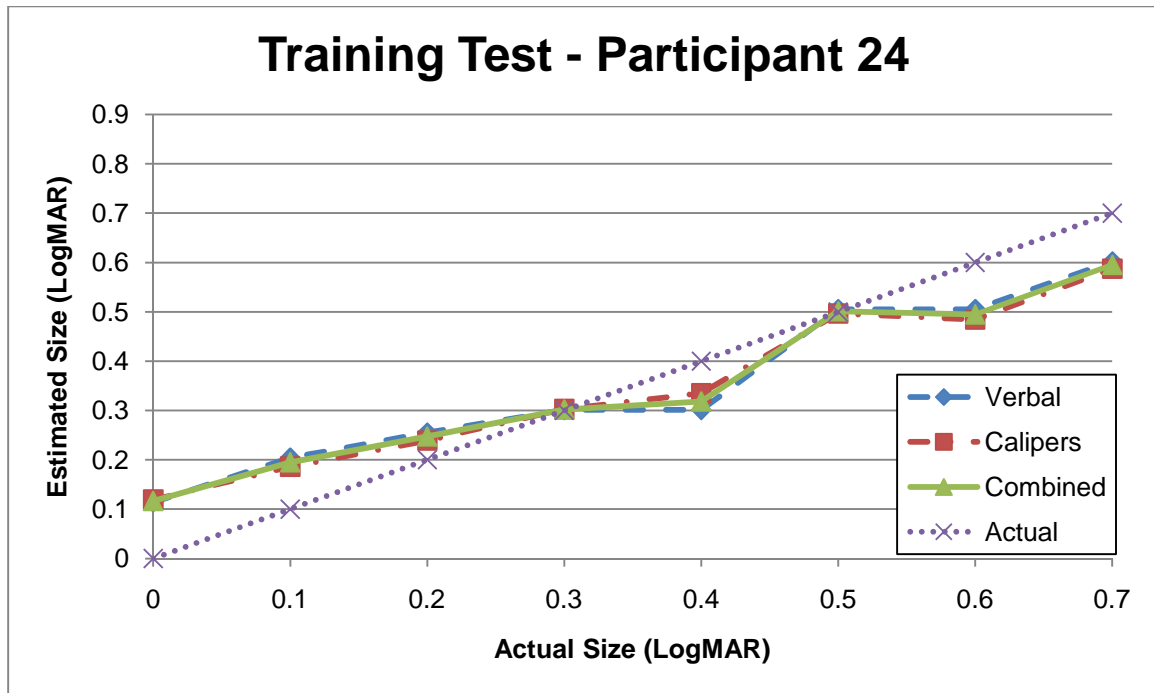
Appendix B; Figure 24. Participant 24 training test data; verbal R^2= .95, manual R^2=.96, and combined verbal + manual R^2=.96.

Appendix C

Graphs depicting individual participant estimated and actual acuity data in
Experiment 1
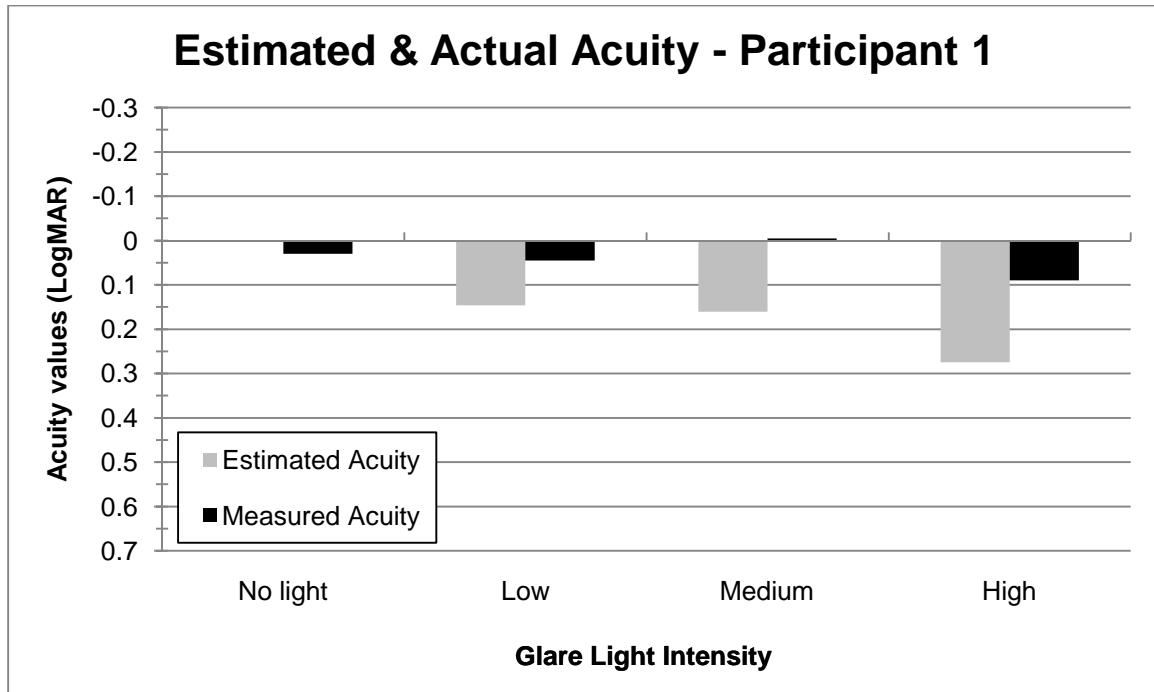
Appendix C; Figure 1. Participant 1 estimated and actual acuities.
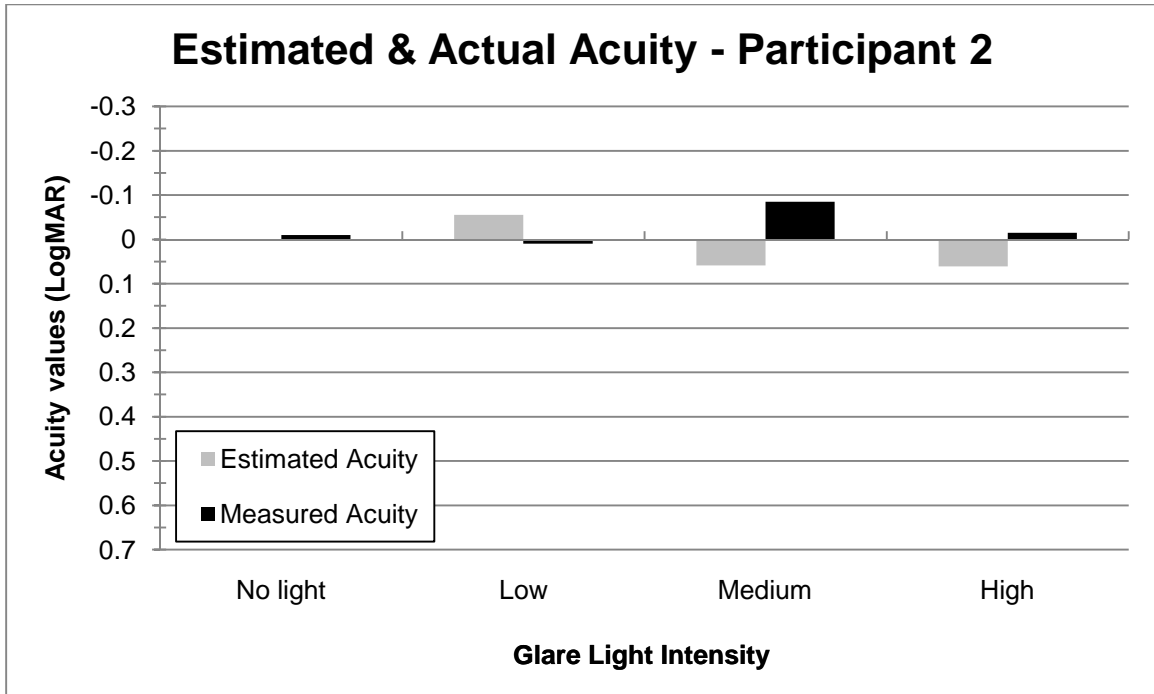
Appendix C; Figure 2. Participant 2 estimated and actual acuities.
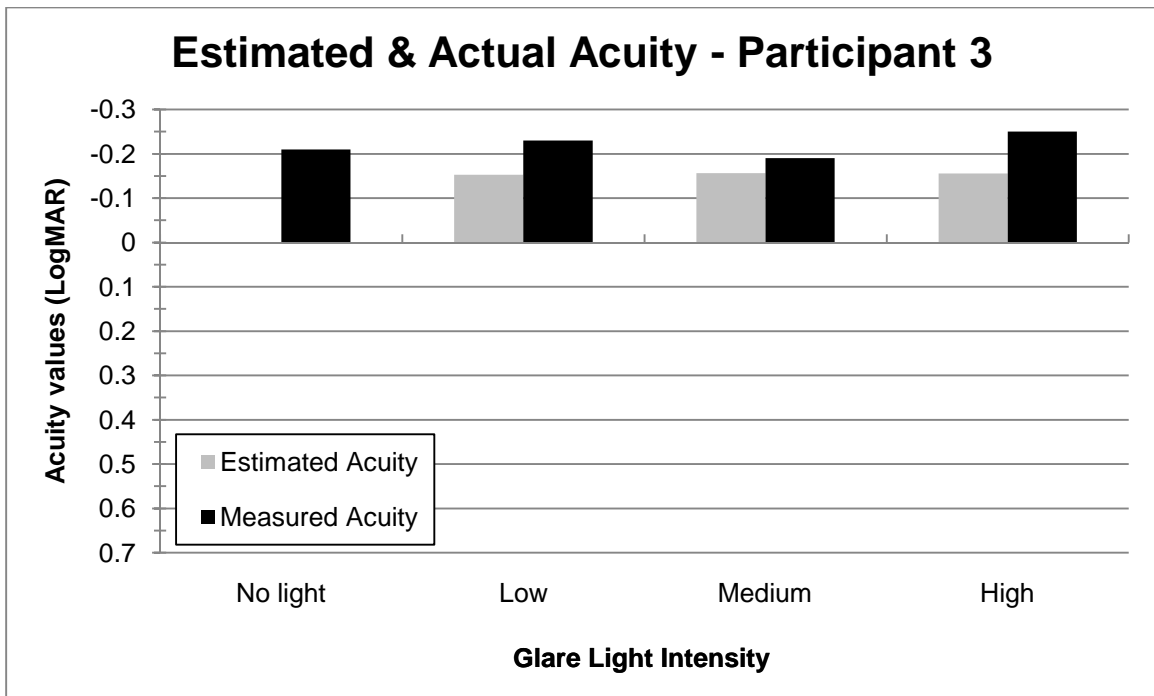
Appendix C; Figure 3. Participant 3 estimated and actual acuities.
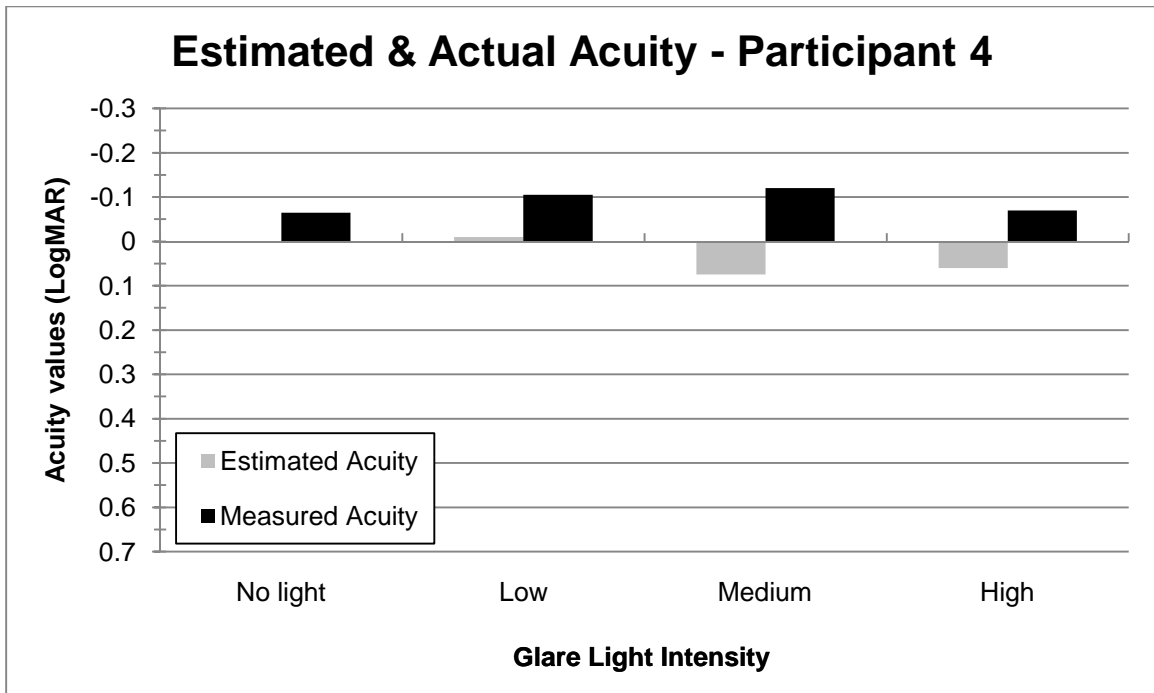
Appendix C; Figure 4. Participant 4 estimated and actual acuities.
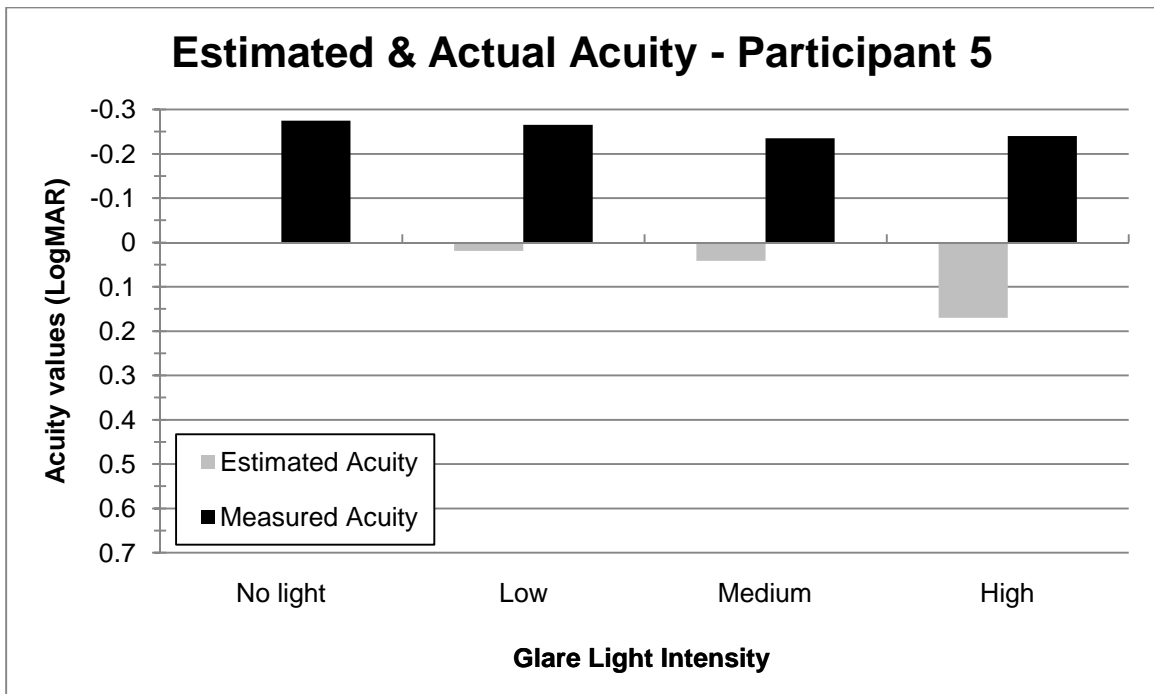
Appendix C; Figure 5. Participant 5 estimated and actual acuities.
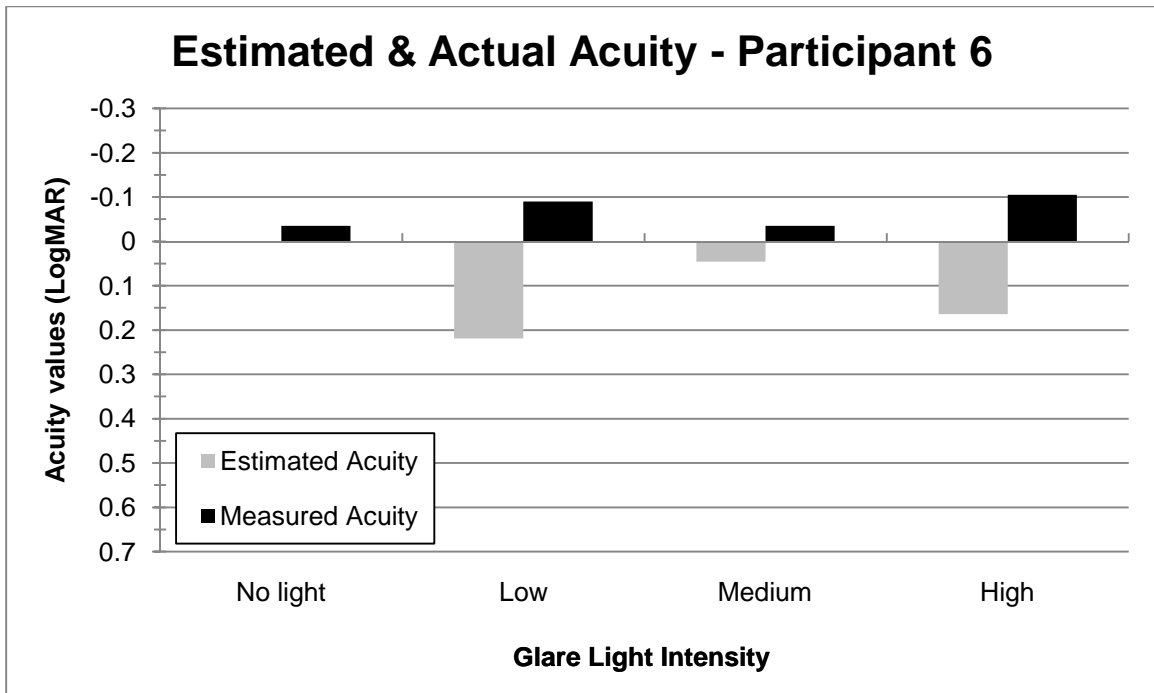
Appendix C; Figure 6. Participant 6 estimated and actual acuities.
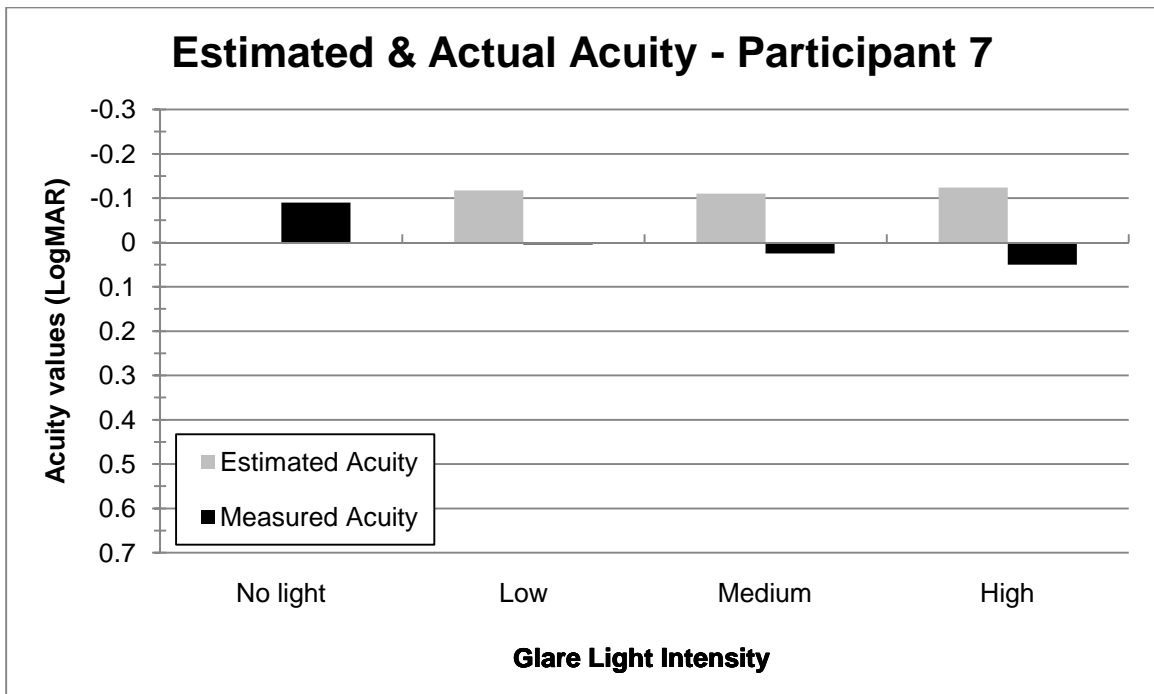
Appendix C; Figure 7. Participant 7 estimated and actual acuities.
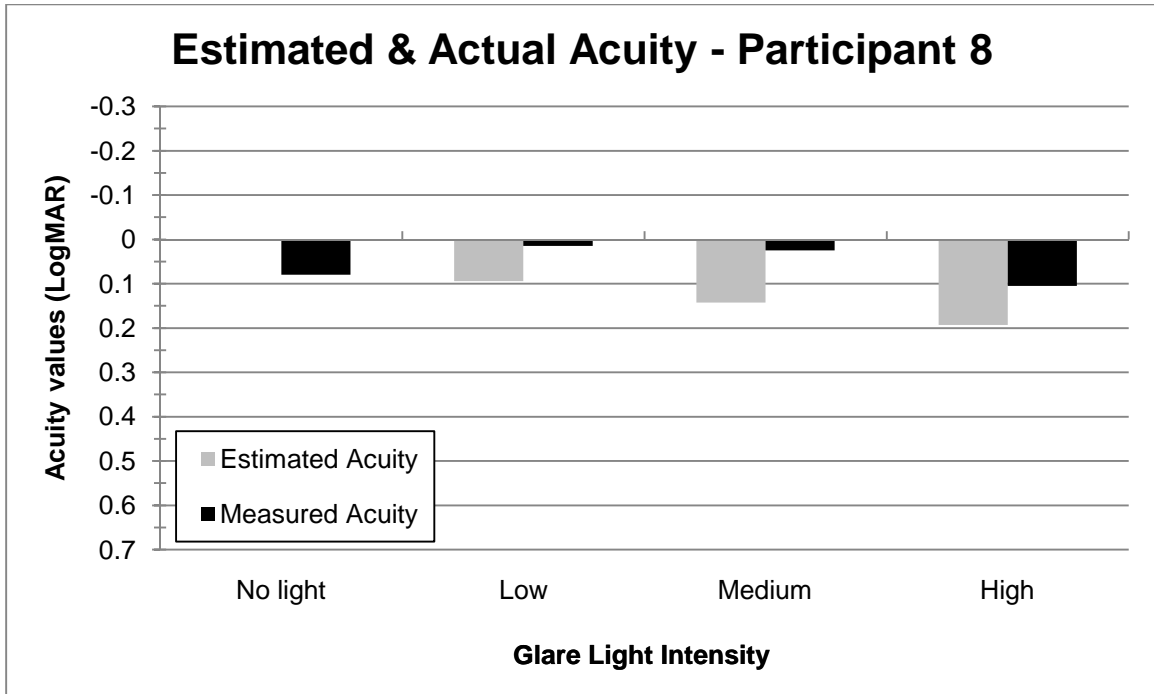
Appendix C; Figure 8. Participant 8 estimated and actual acuities.
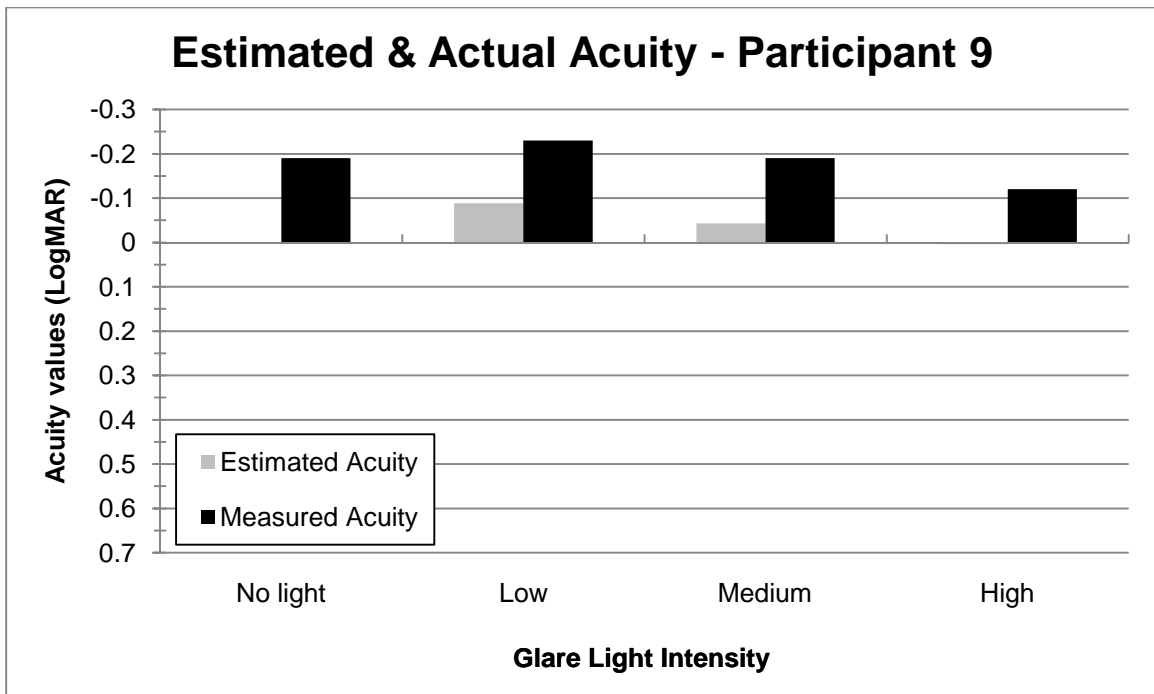
Appendix C; Figure 9. Participant 9 estimated and actual acuities.
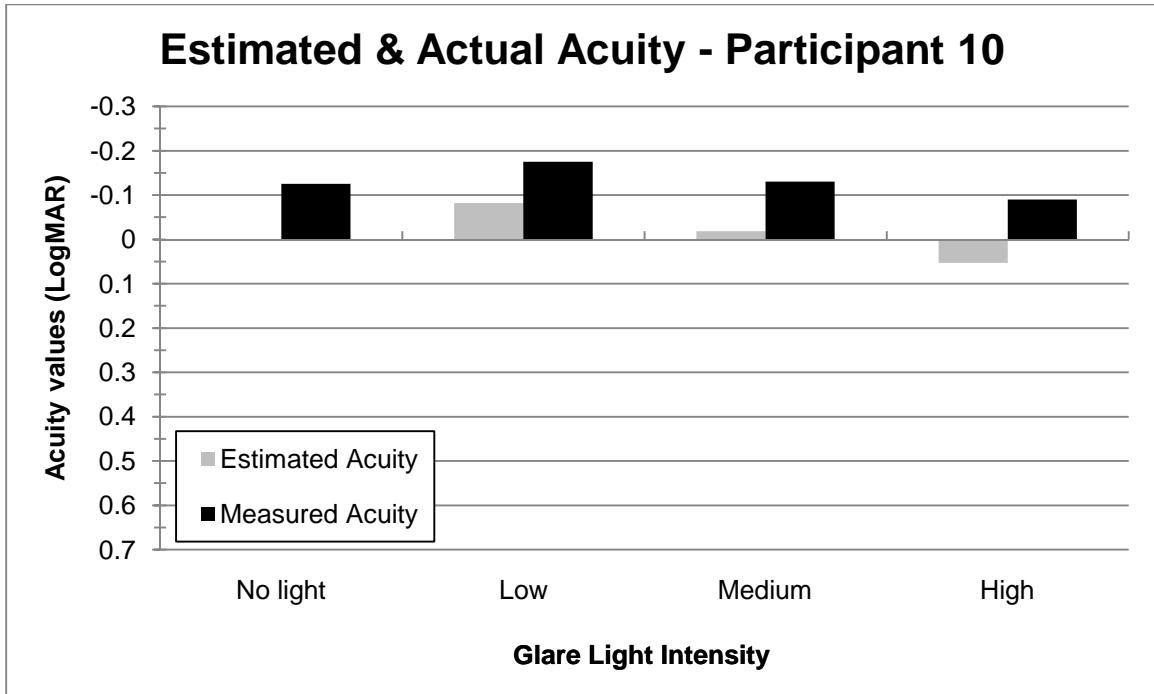
Appendix C; Figure 10. Participant 10 estimated and actual acuities.
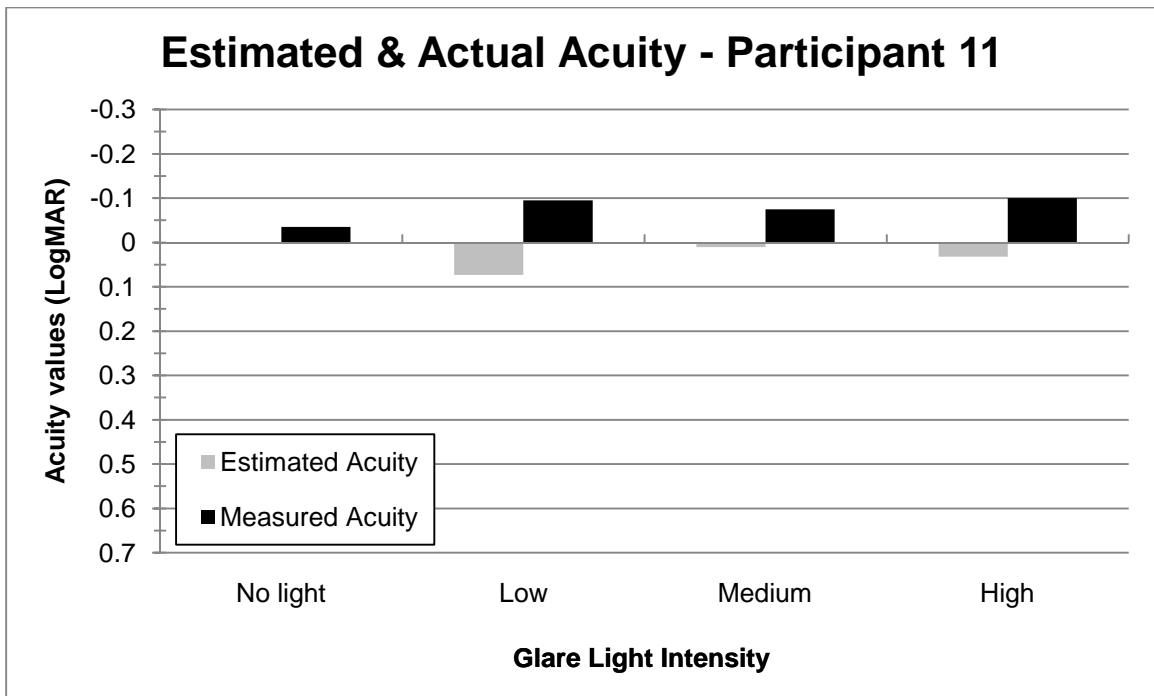
Appendix C; Figure 11. Participant 11 estimated and actual acuities.
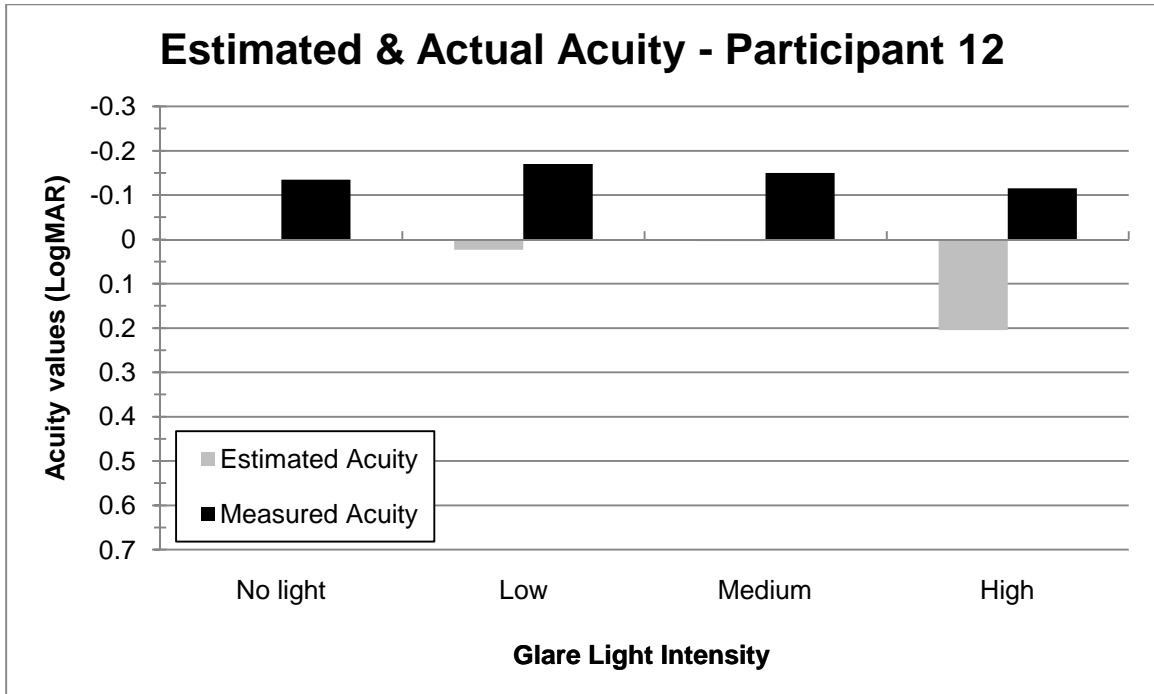
Appendix C; Figure 12. Participant 12 estimated and actual acuities.
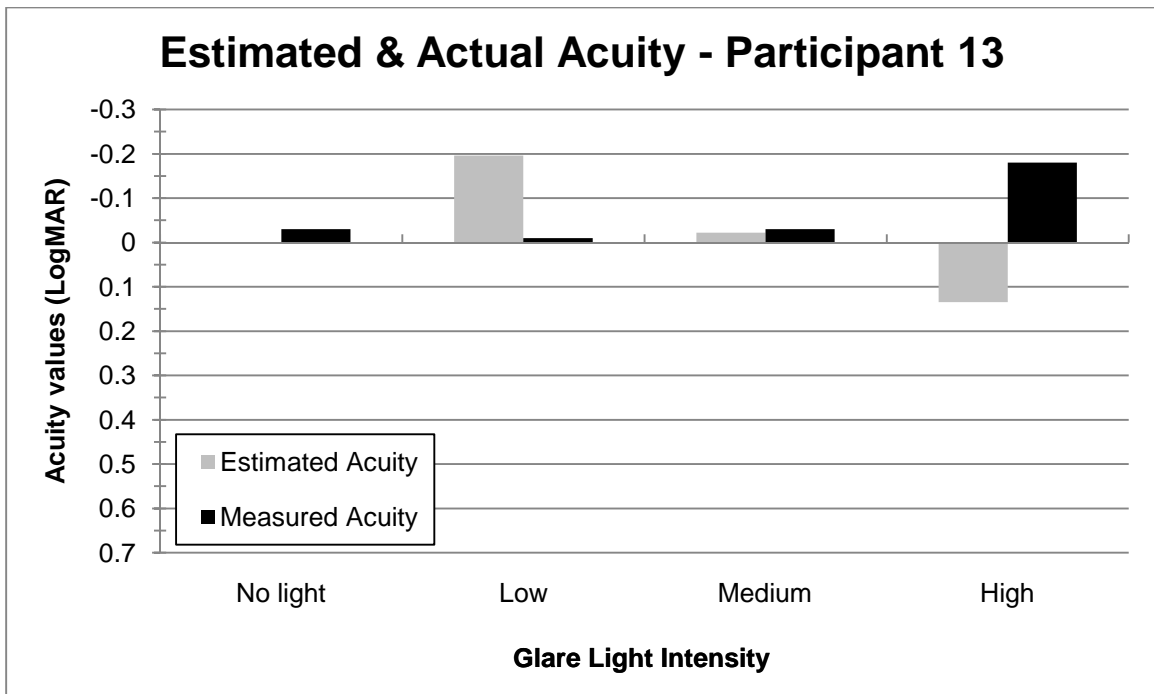
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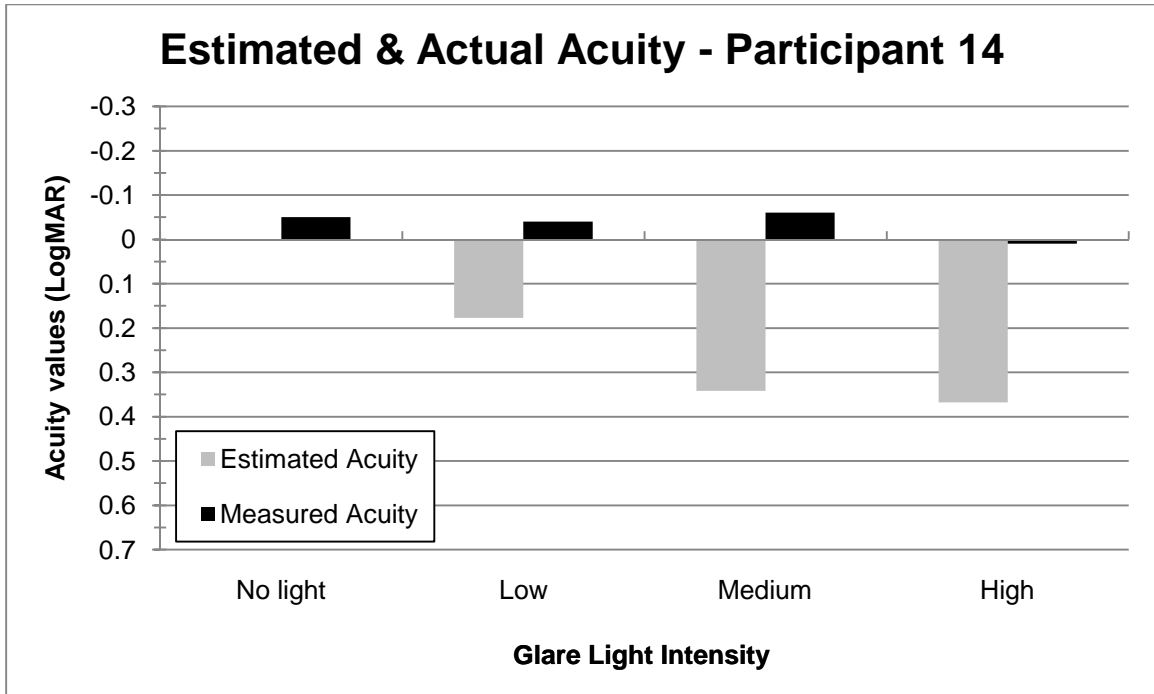
Appendix C; Figure 14. Participant 14 estimated and actual acuities.
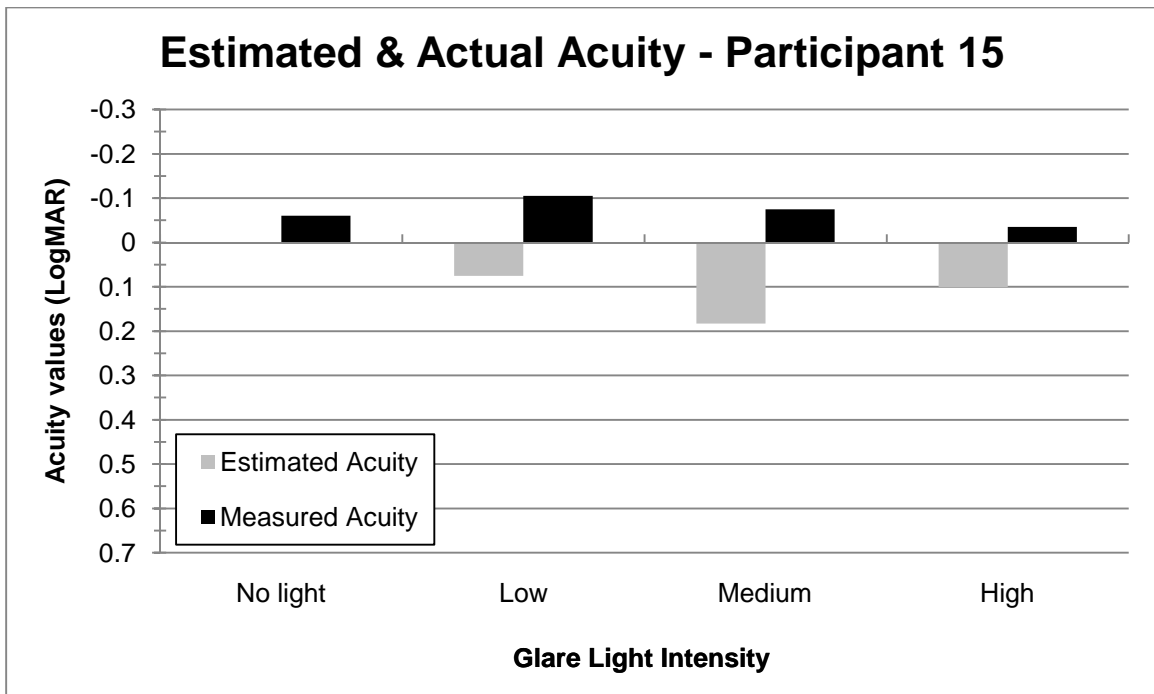
Appendix C; Figure 15. Participant 15 estimated and actual acuities.
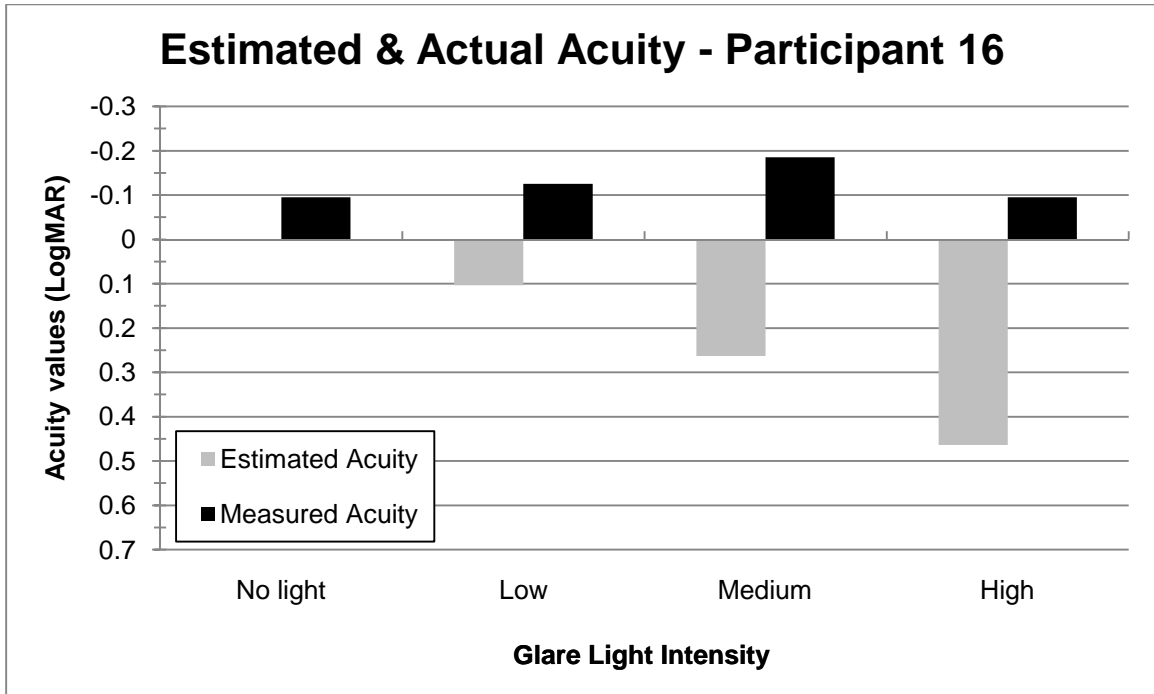
Appendix C; Figure 16. Participant 16 estimated and actual acuities.
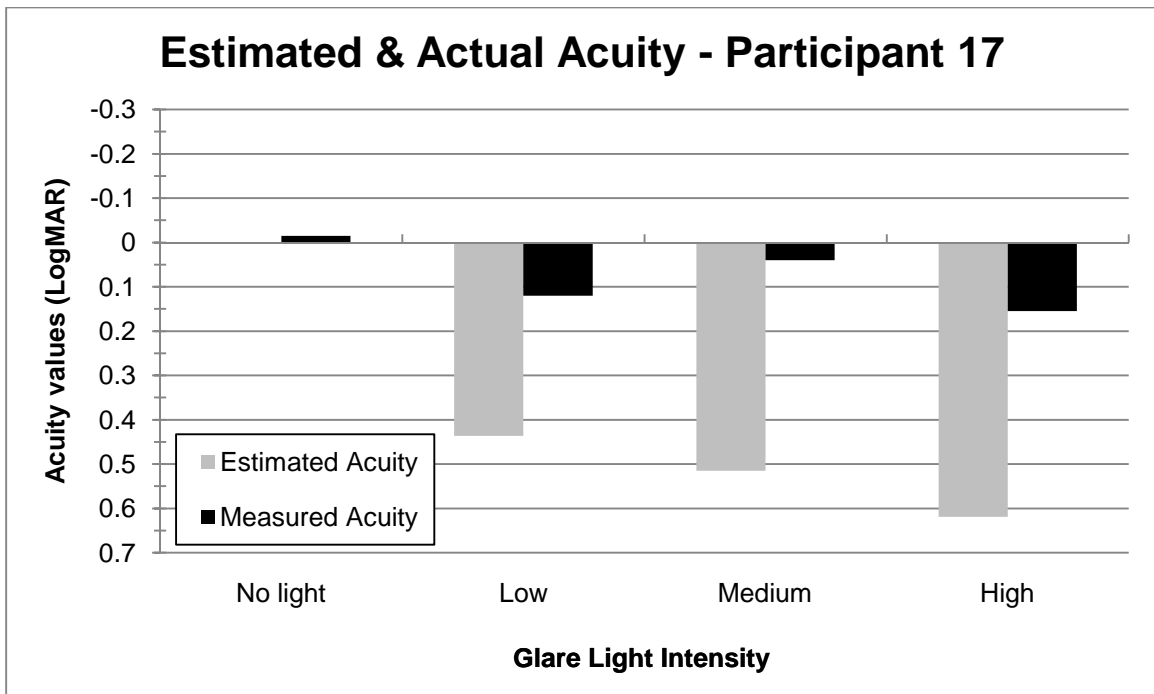
Appendix C; Figure 17. Participant 17 estimated and actual acuities.
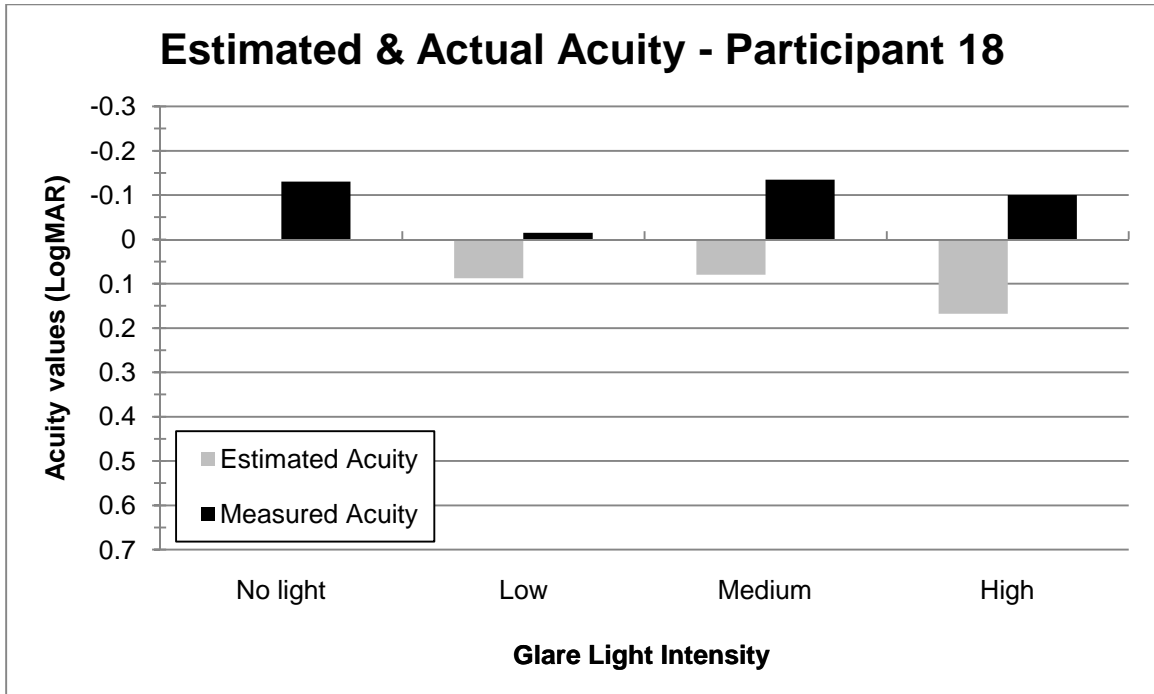
Appendix C; Figure 18. Participant 18 estimated and actual acuities.
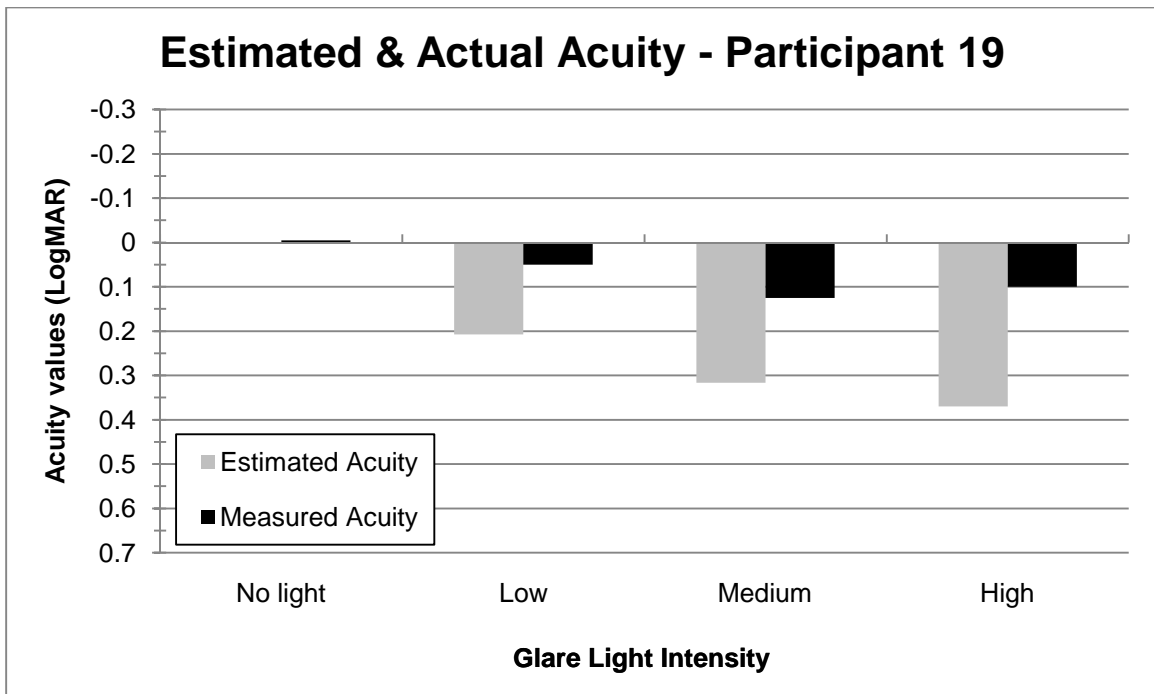
Appendix C; Figure 19. Participant 19 estimated and actual acuities.

145
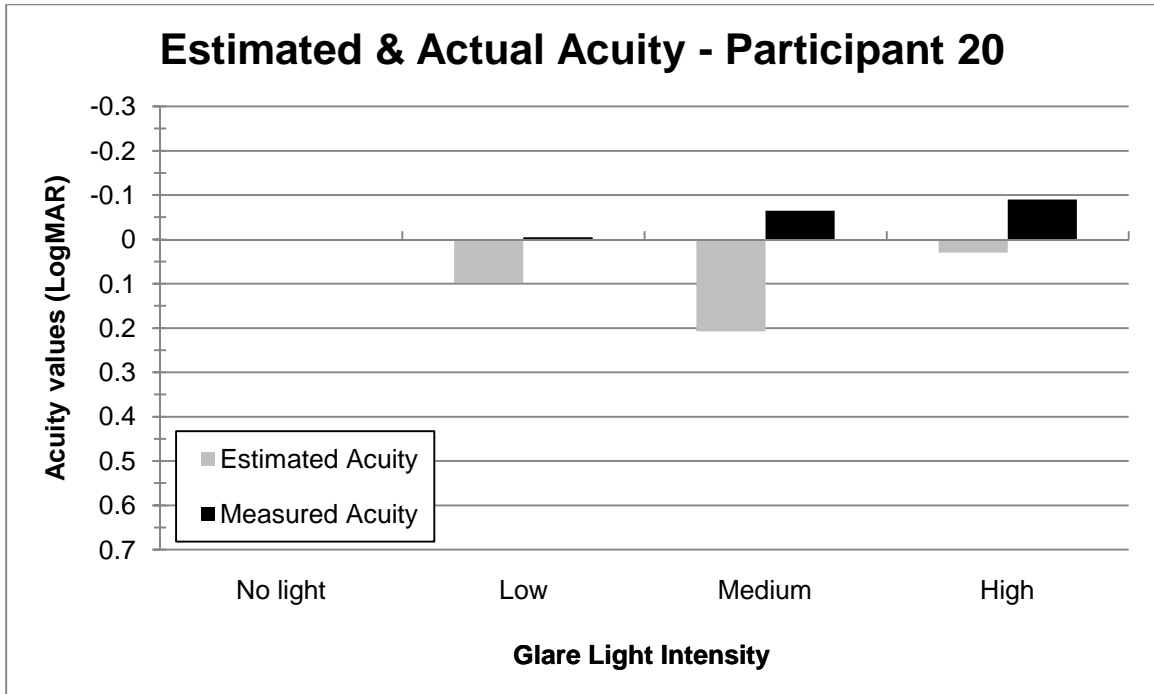
Appendix C; Figure 20. Participant 20 estimated and actual acuities.
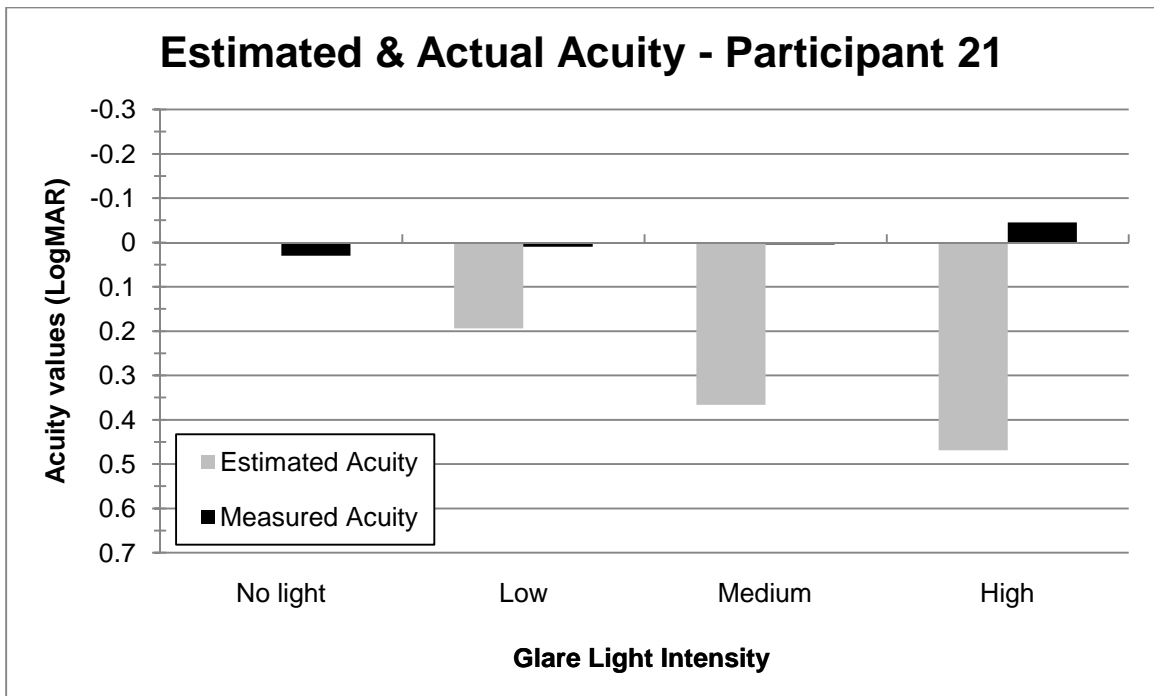
Appendix C; Figure 21. Participant 21 estimated and actual acuities.

146
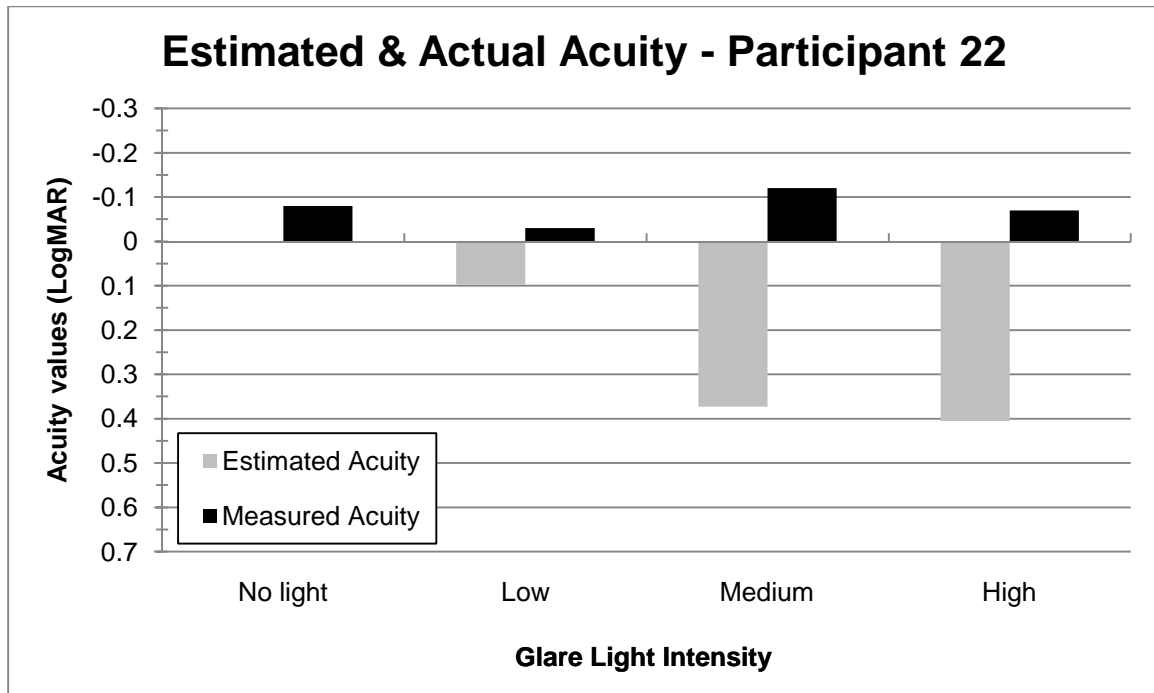
Appendix C; Figure 22. Participant 22 estimated and actual acuities.
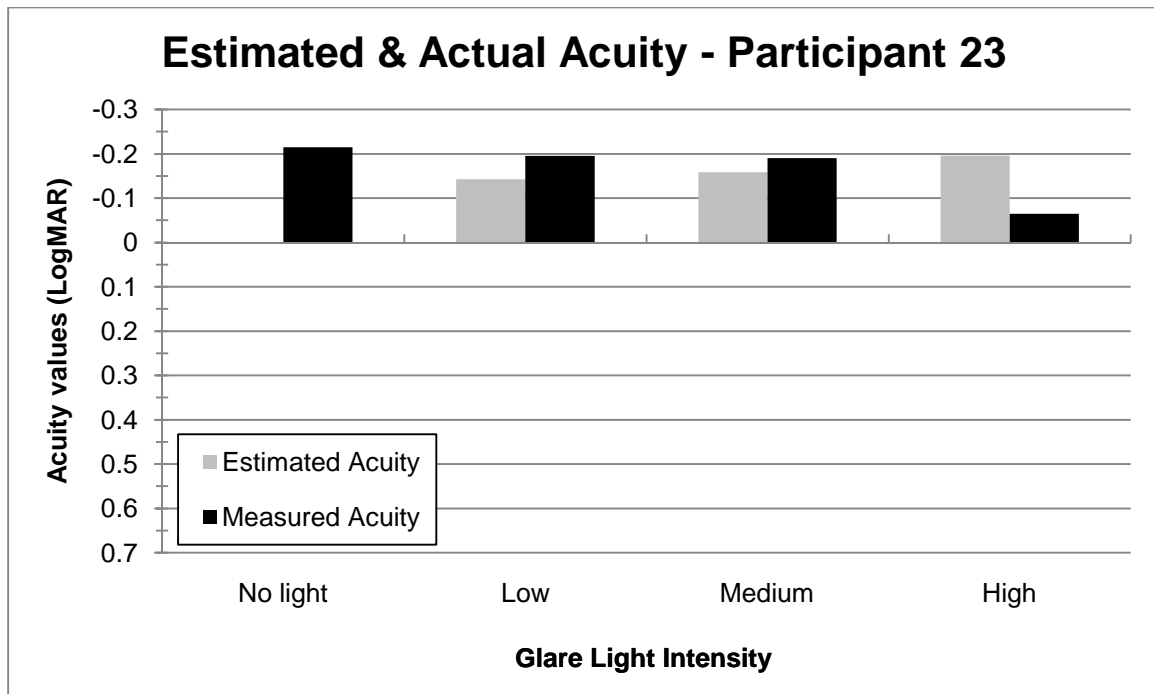
Appendix C; Figure 23. Participant 23 estimated and actual acuities.
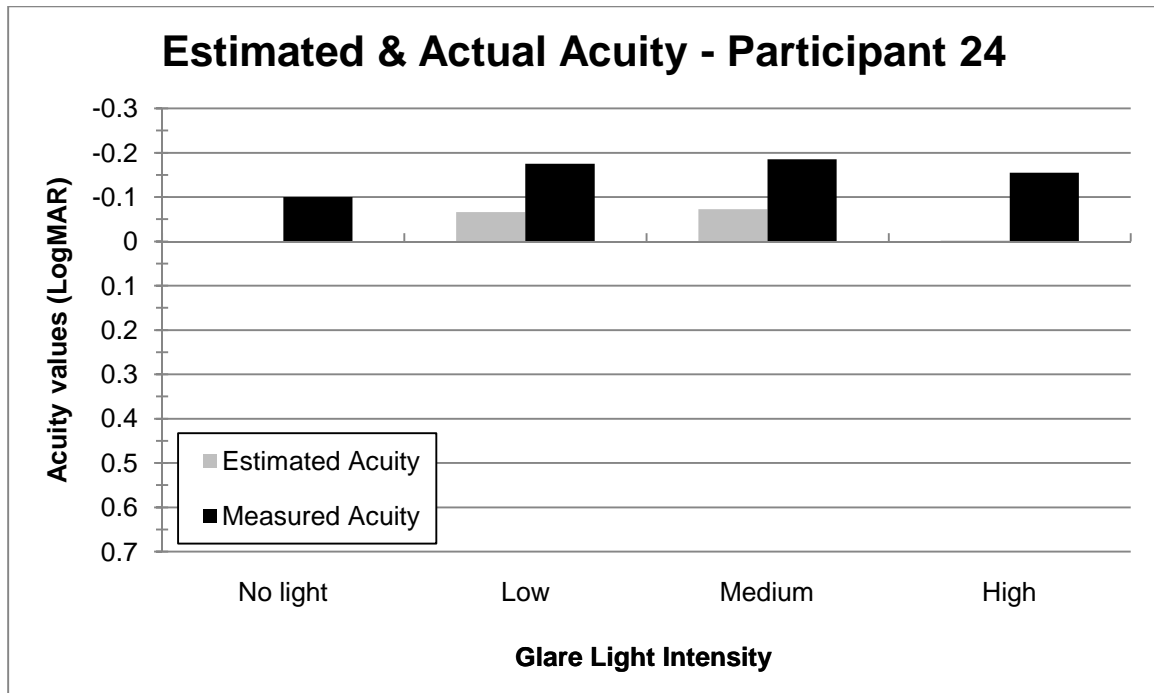
Appendix C; Figure 24. Participant 24 estimated and actual acuities.

Appendix D

Individual participant R^2 values for both the relationship between deBoer ratings of glare light discomfort and acuity estimates as well as the relationship between deBoer ratings of glare light discomfort and actual acuity.

Participant Number	R^2 DeBoer and Estimated Acuity	R^2 DeBoer and Actual Acuity
1	0.99	0.72
2	0.77	0.06
3	0.87	0.00
4	0.59	0.47
5	0.86	0.60
6	0.10	0.04
7	0.10	0.94
8	0.74	0.34
9	0.96	0.88
10	0.95	0.98
11	0.33	0.07
12	0.67	0.98
13	1.00	0.84
14	0.37	0.92
15	0.17	0.93
16	0.98	0.25
17	0.88	0.00
18	0.07	0.83
19	0.96	0.43
20	0.15	0.95
21	0.98	0.82
22	0.34	0.00
23	0.91	1.00
24	0.48	0.25

Graphs depicting individual participant estimated and actual acuity data +
corresponding deBoer ratings of discomfort in Experiment 1
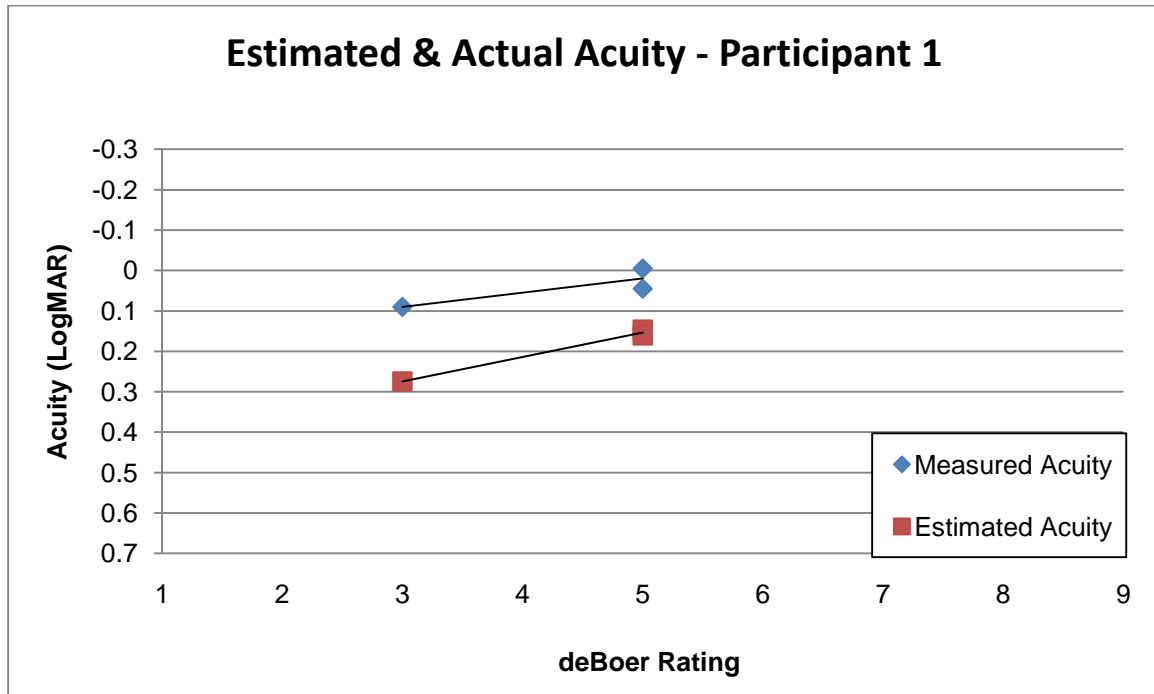
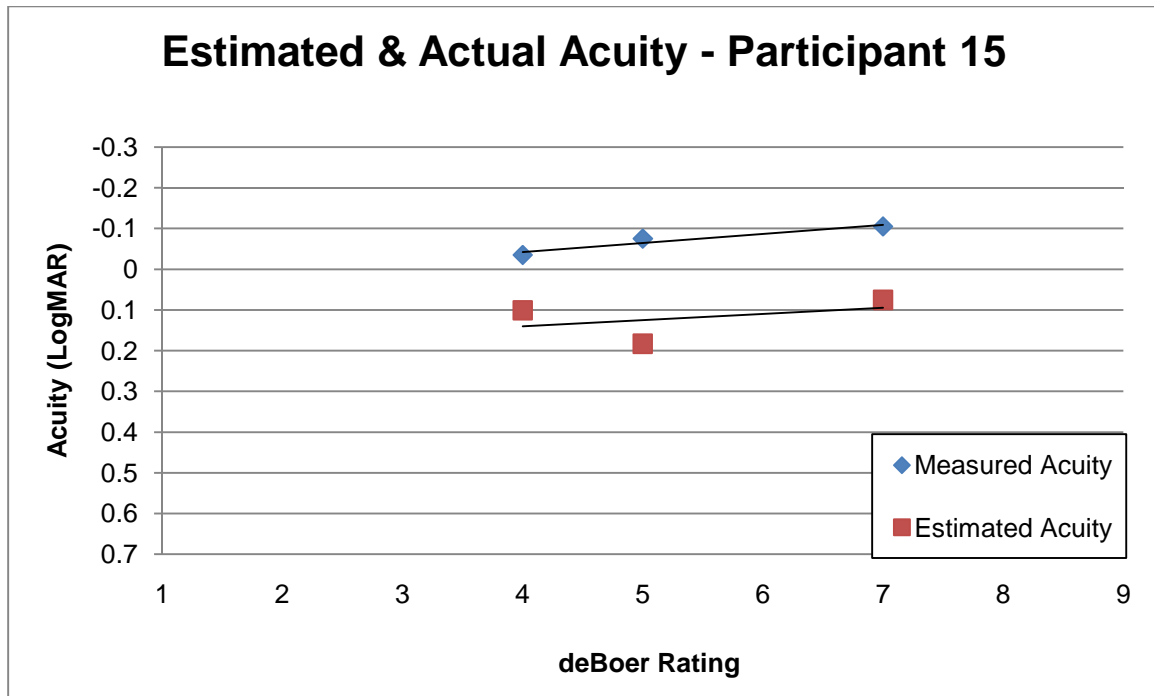

Appendix E; Figure 1. Participant 1 estimated and actual acuities with
corresponding deBoer ratings of discomfort.
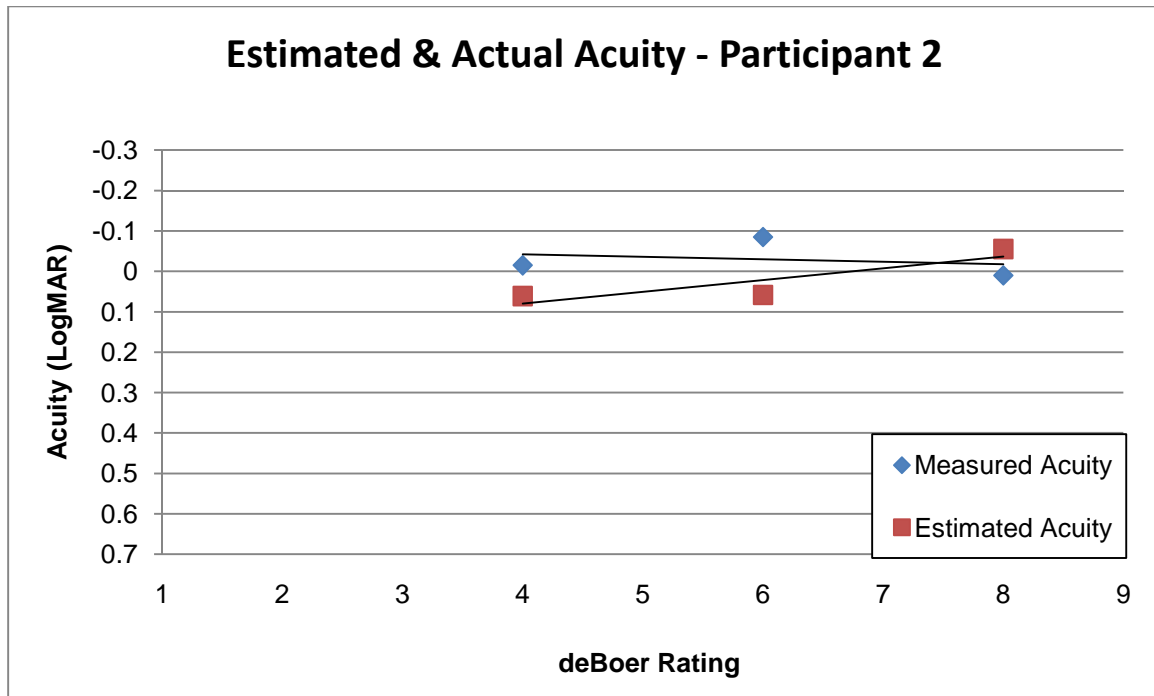
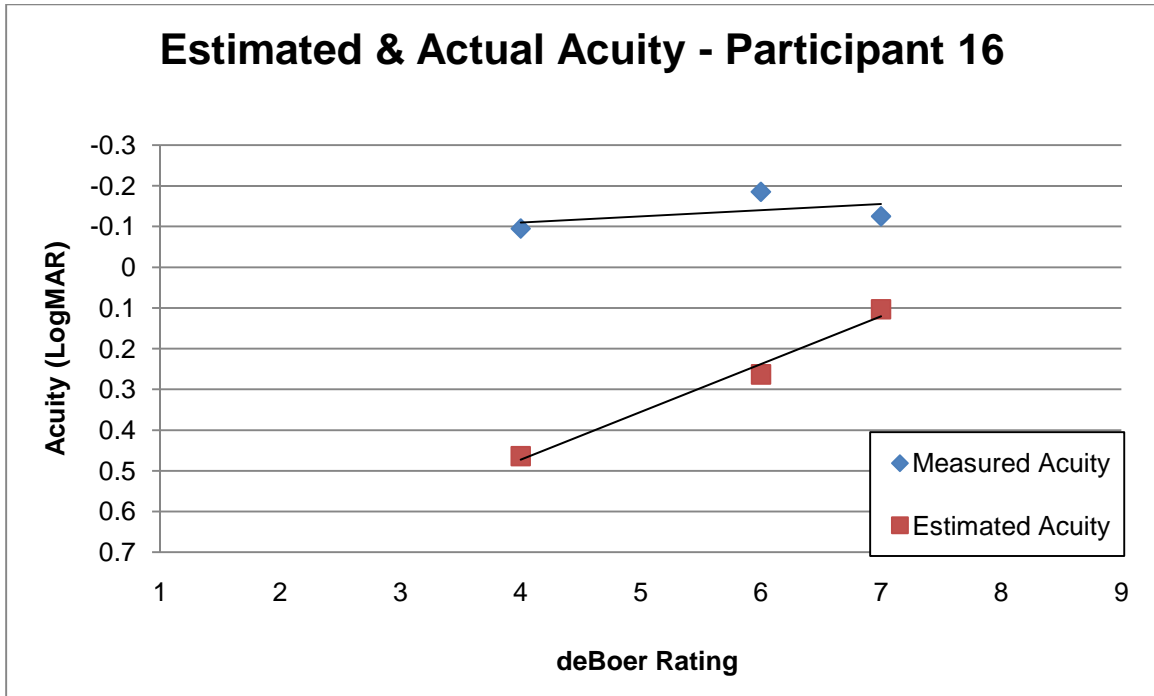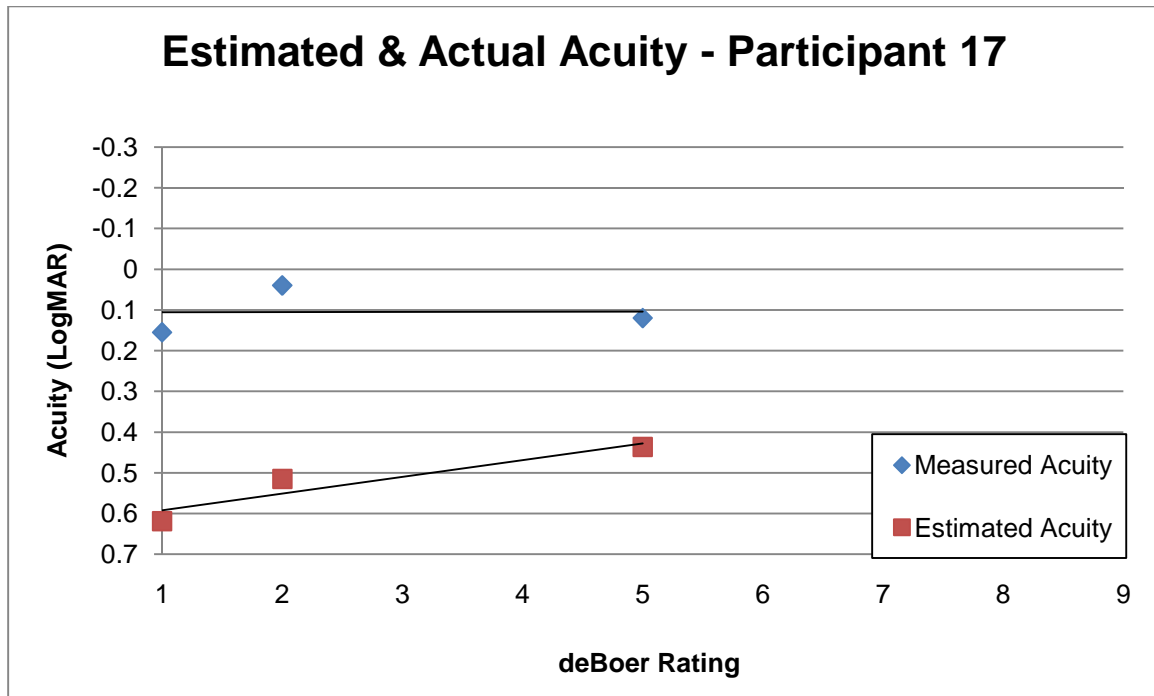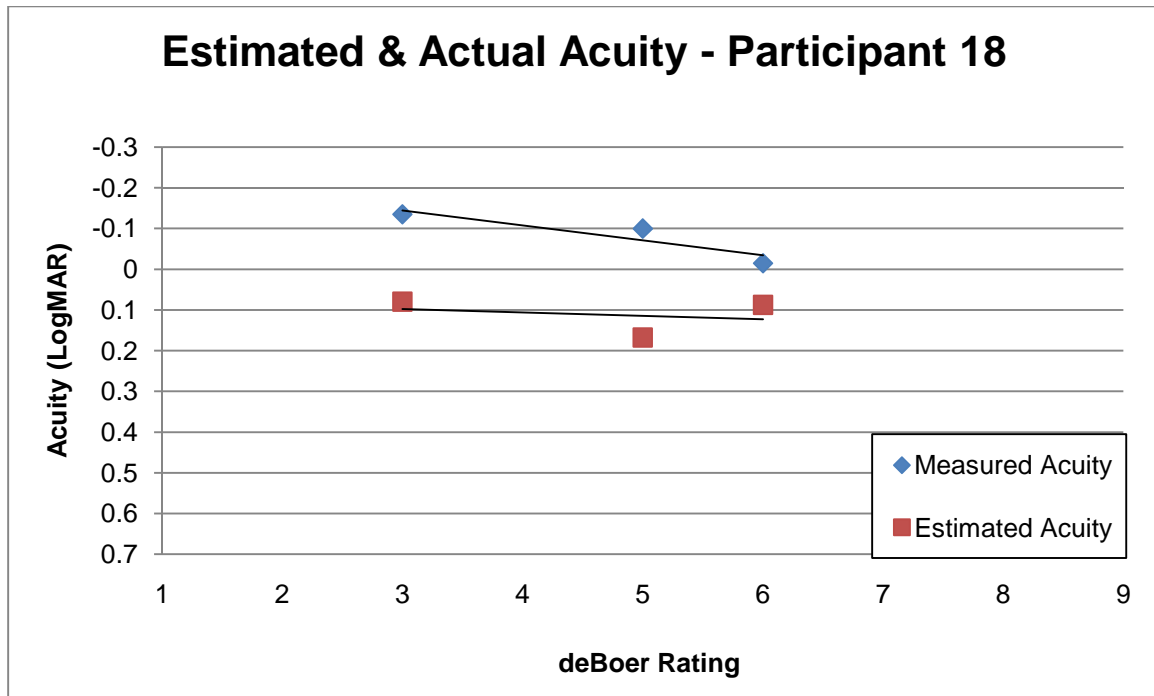Appendix E; Figure 2. Participant 2 estimated and actual acuities with corresponding deBoer ratings of discomfort.
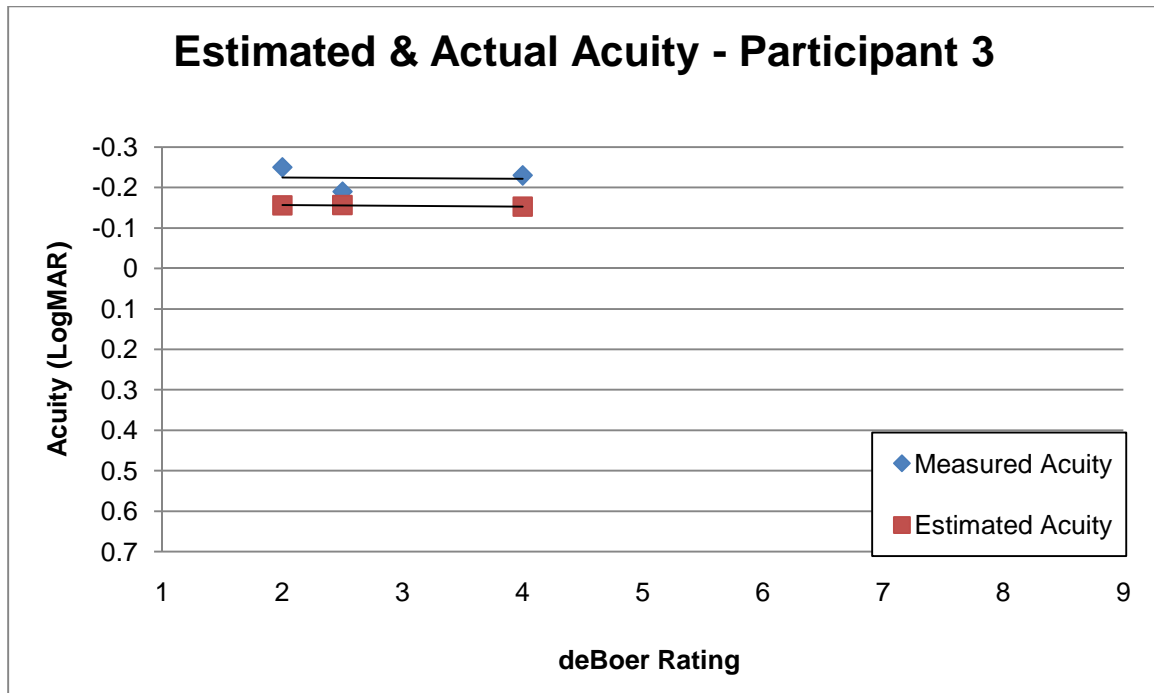
Appendix E; Figure 3. Participant 3 estimated and actual acuities with corresponding deBoer ratings of discomfort.
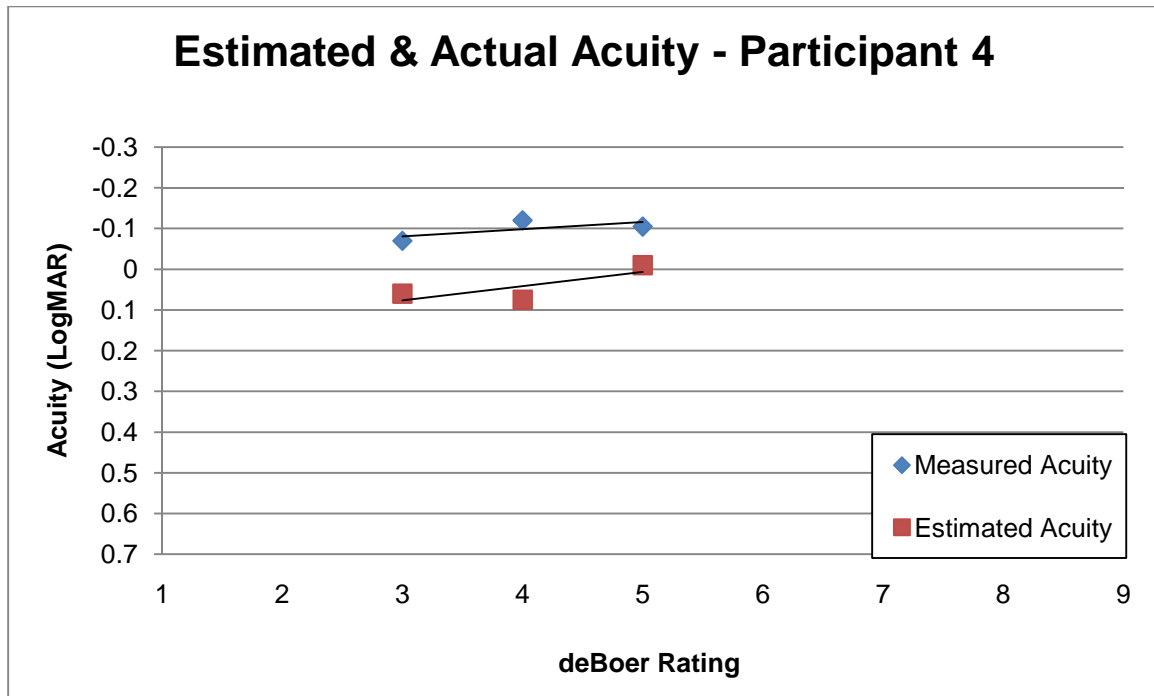
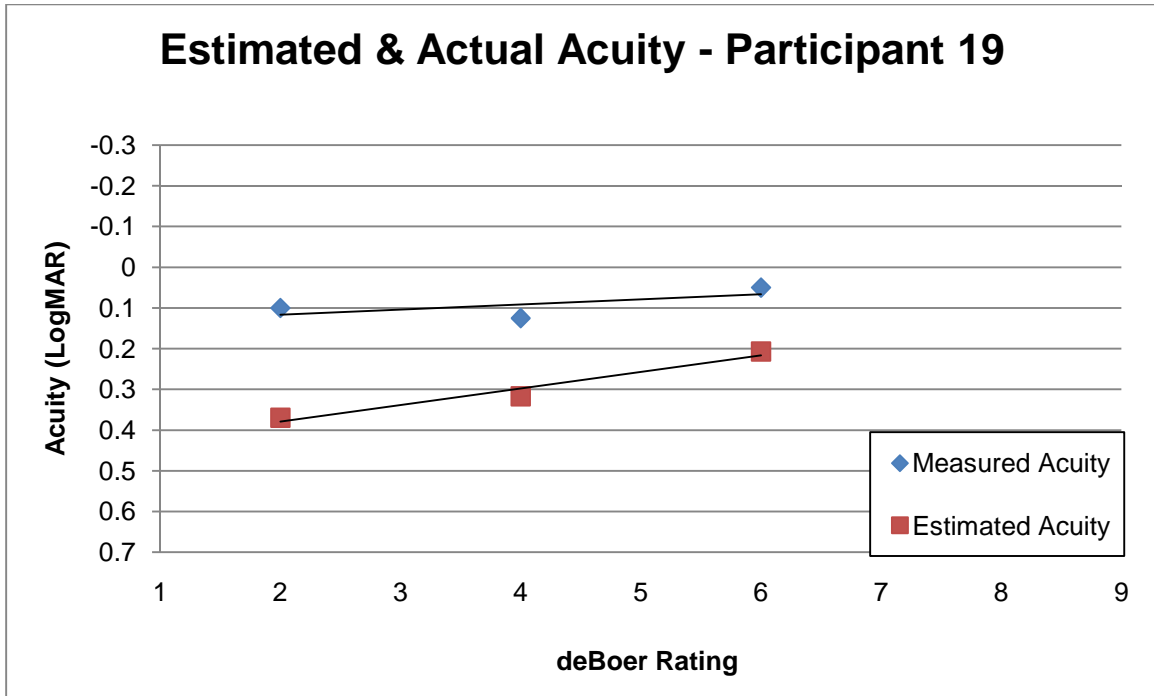Appendix E; Figure 4. Participant 4 estimated and actual acuities with corresponding deBoer ratings of discomfort.
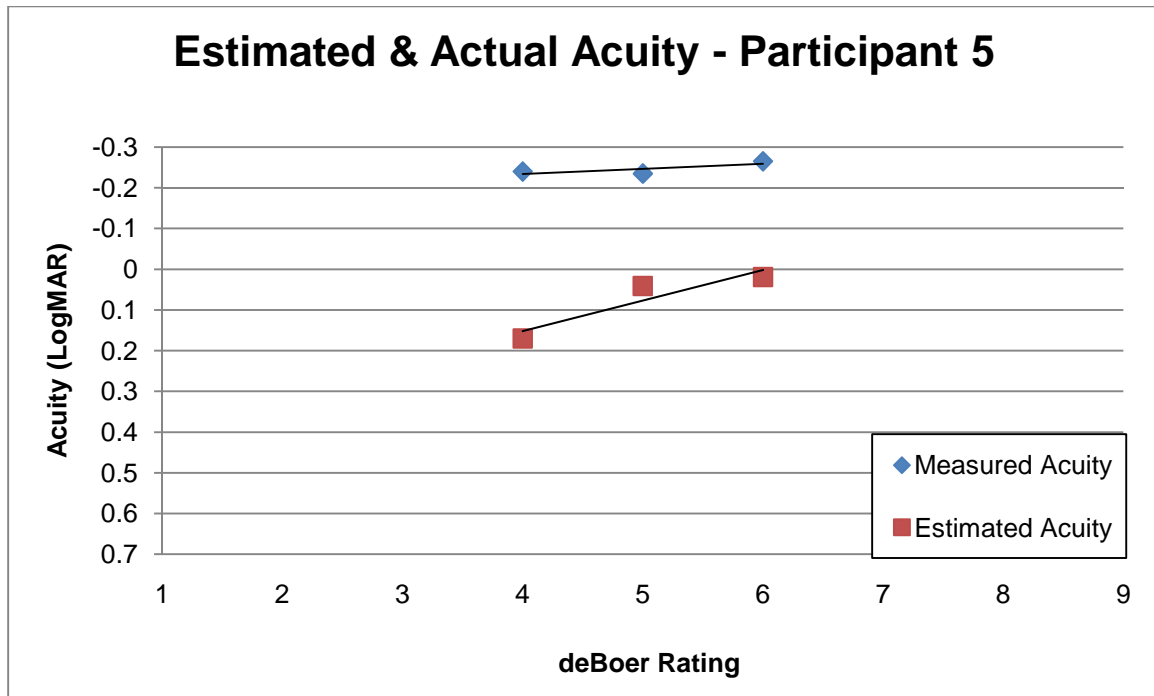
Appendix E; Figure 5. Participant 5 estimated and actual acuities with corresponding deBoer ratings of discomfort.
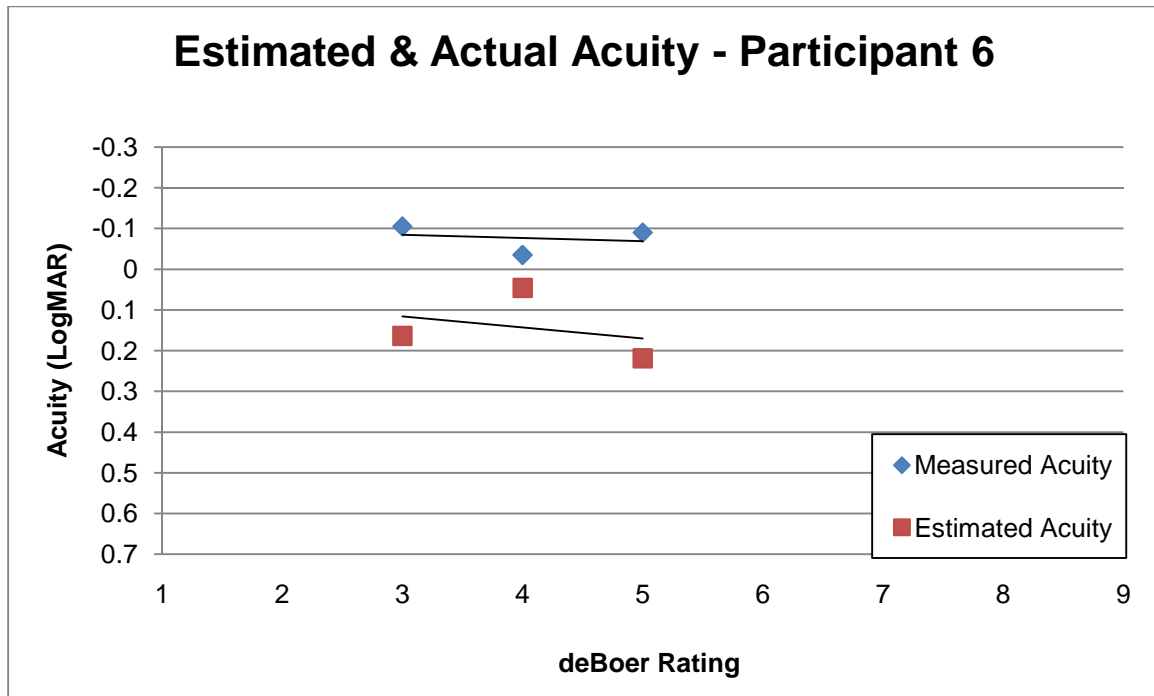
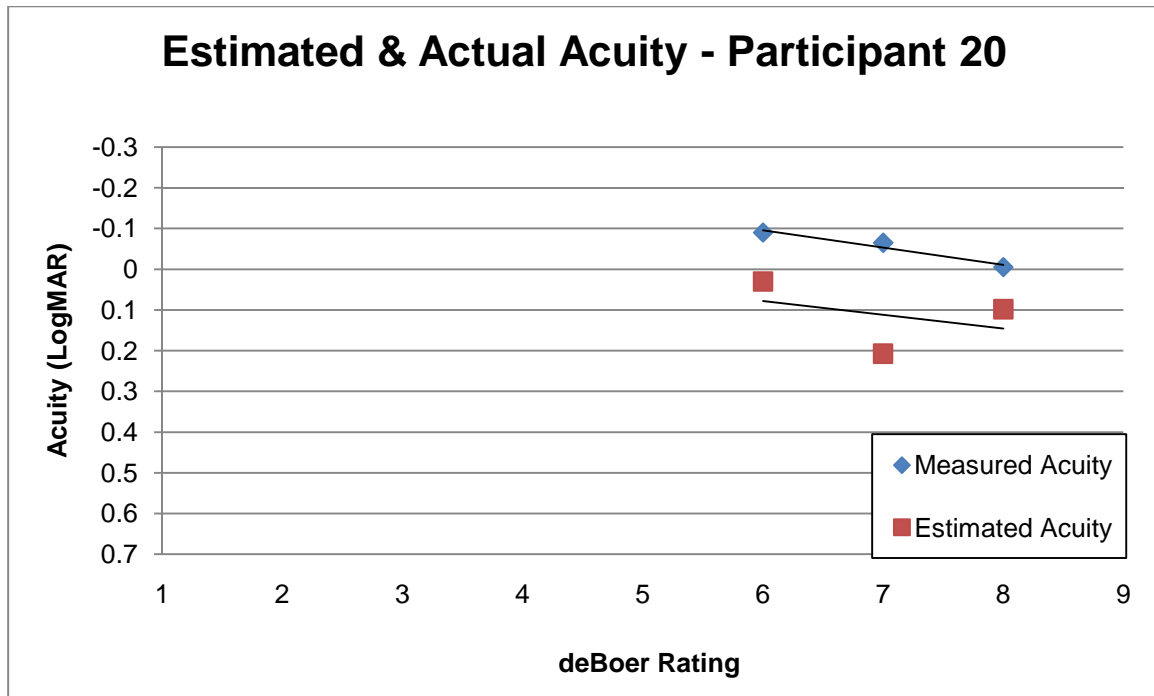Appendix E; Figure 6. Participant 6 estimated and actual acuities with corresponding deBoer ratings of discomfort.
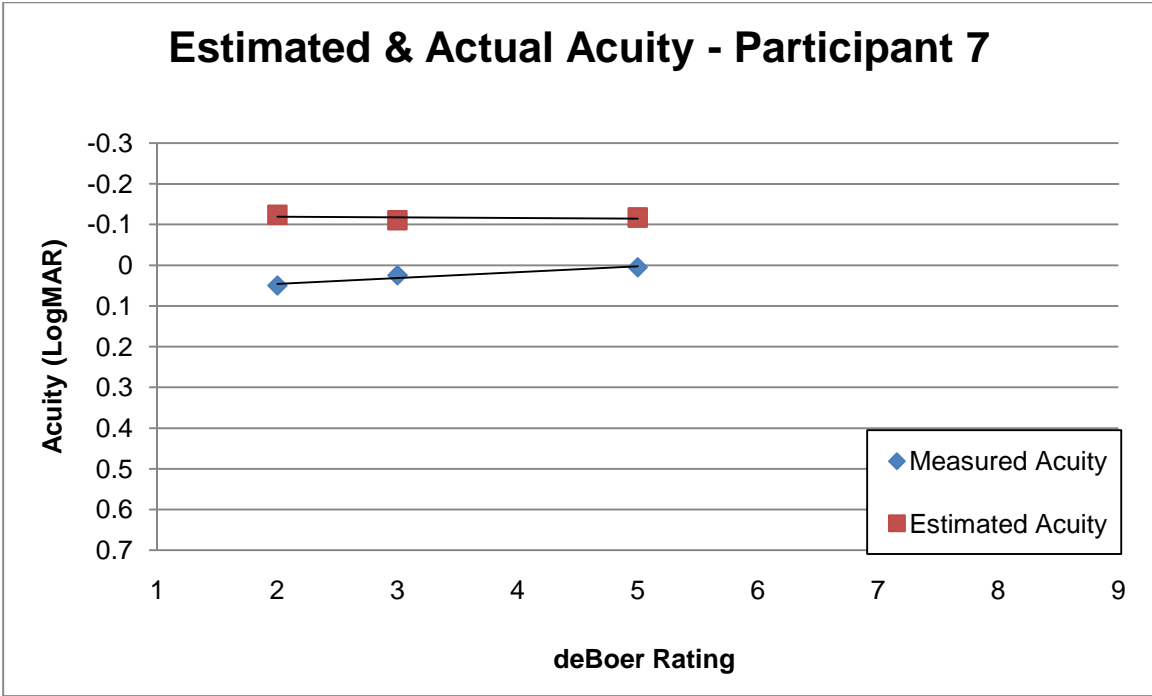
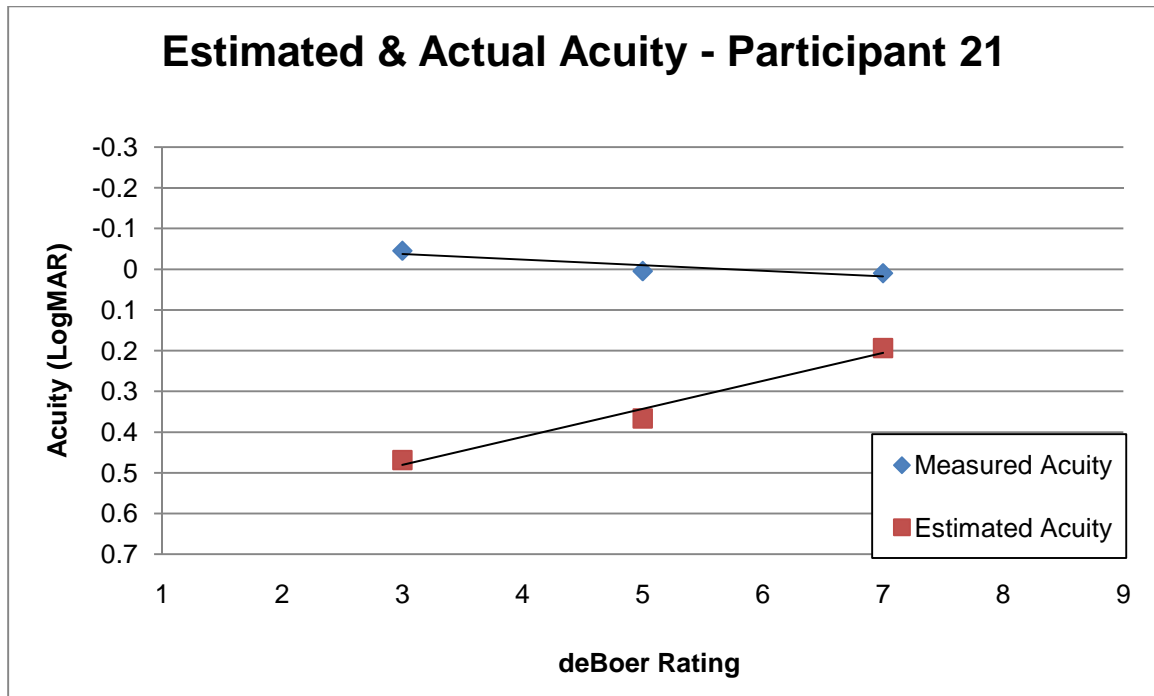Appendix E; Figure 7. Participant 7 estimated and actual acuities with corresponding deBoer ratings of discomfort.
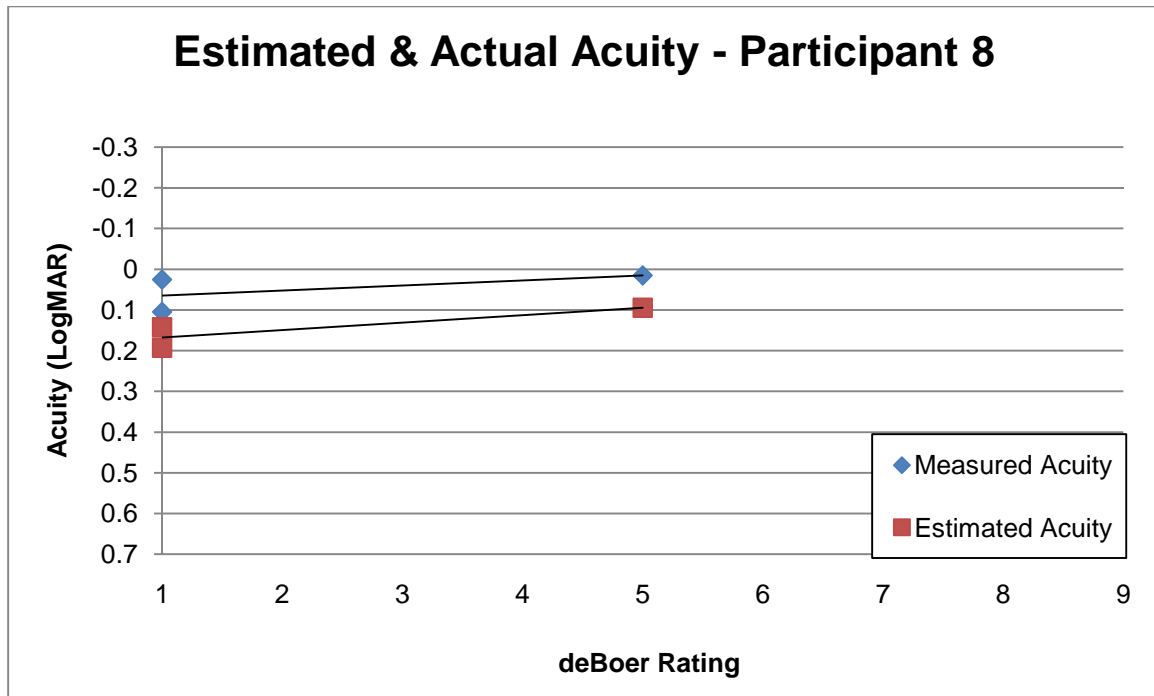
Appendix E; Figure 8. Participant 8 estimated and actual acuities with corresponding deBoer ratings of discomfort.
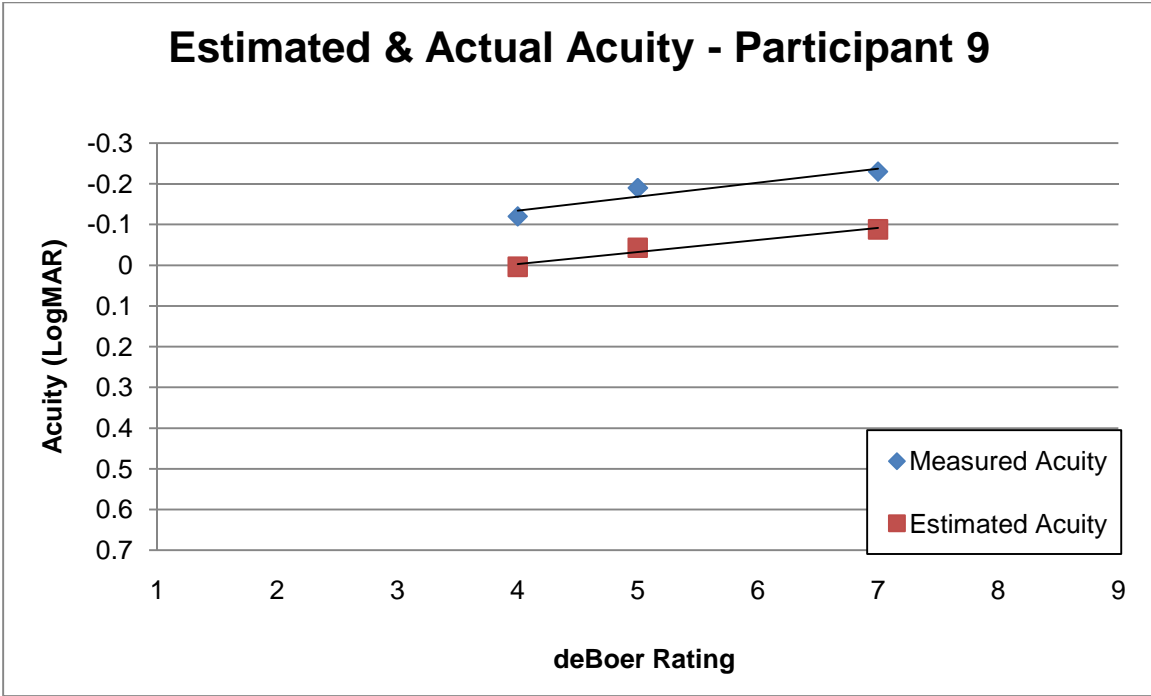
Appendix E; Figure 9. Participant 9 estimated and actual acuities with corresponding deBoer ratings of discomfort.
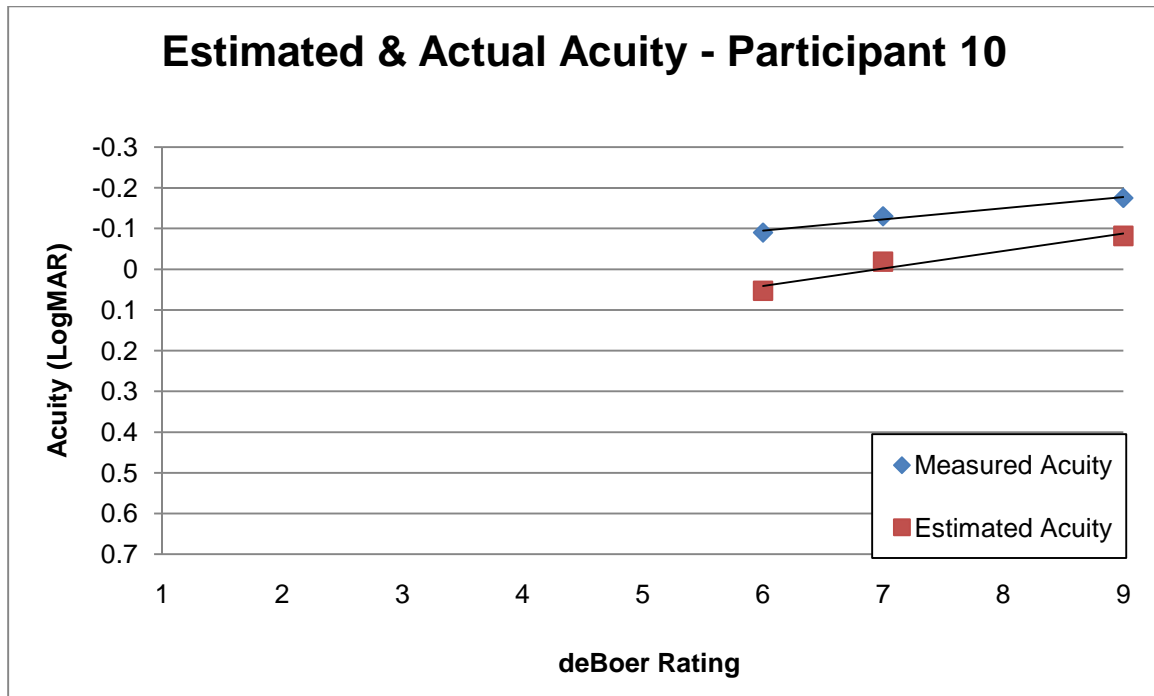
Appendix E; Figure 10. Participant 10 estimated and actual acuities with corresponding deBoer ratings of discomfort.
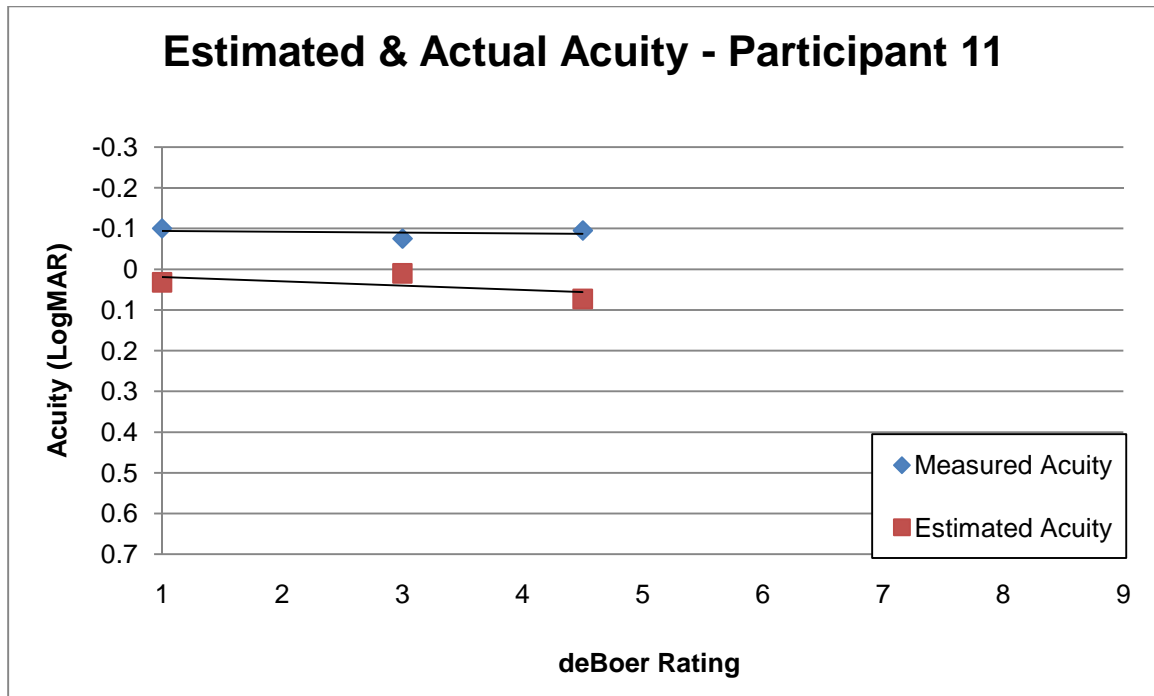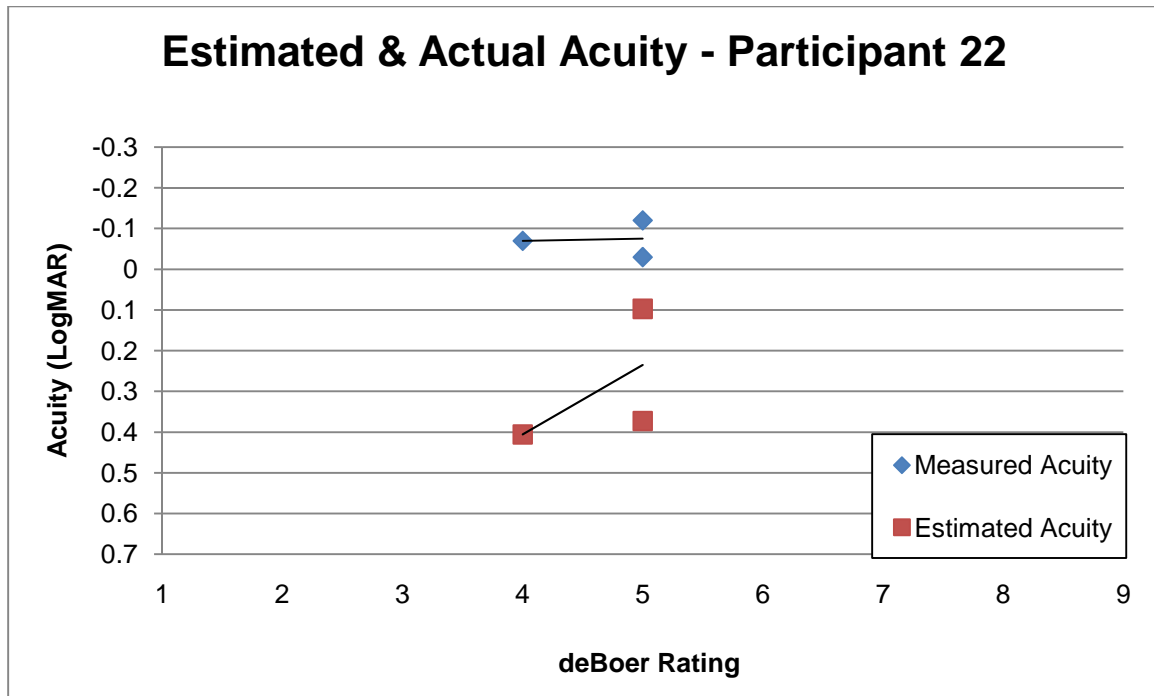
Appendix E; Figure 11. Participant 11 estimated and actual acuities with corresponding deBoer ratings of discomfort.
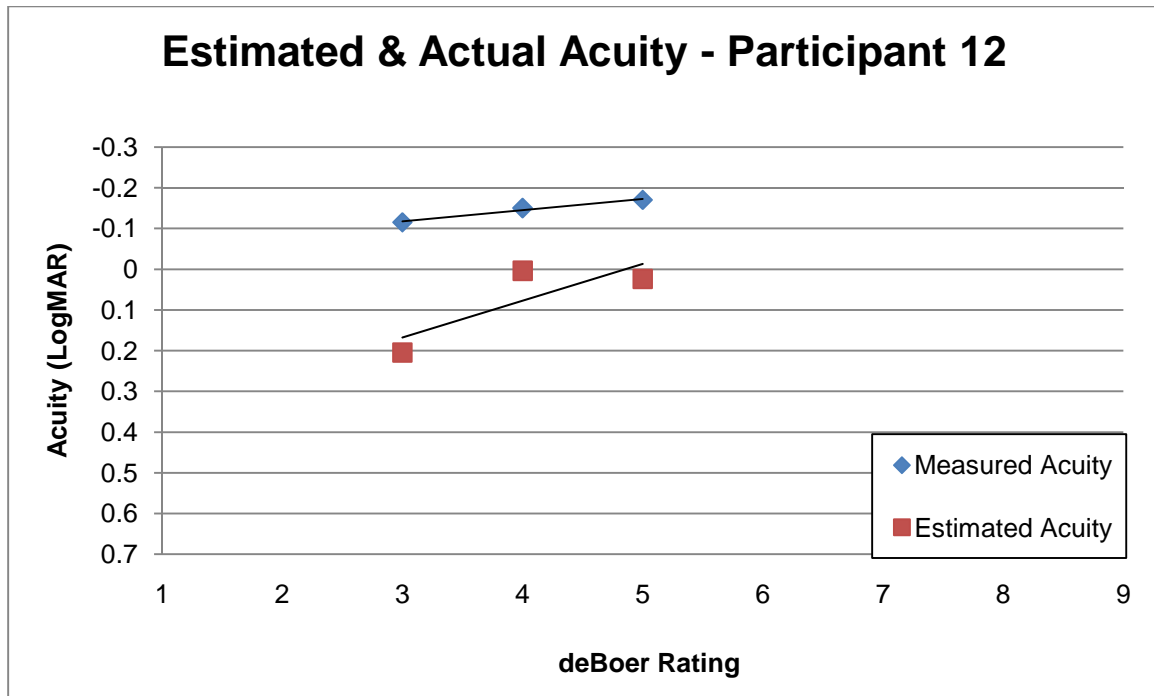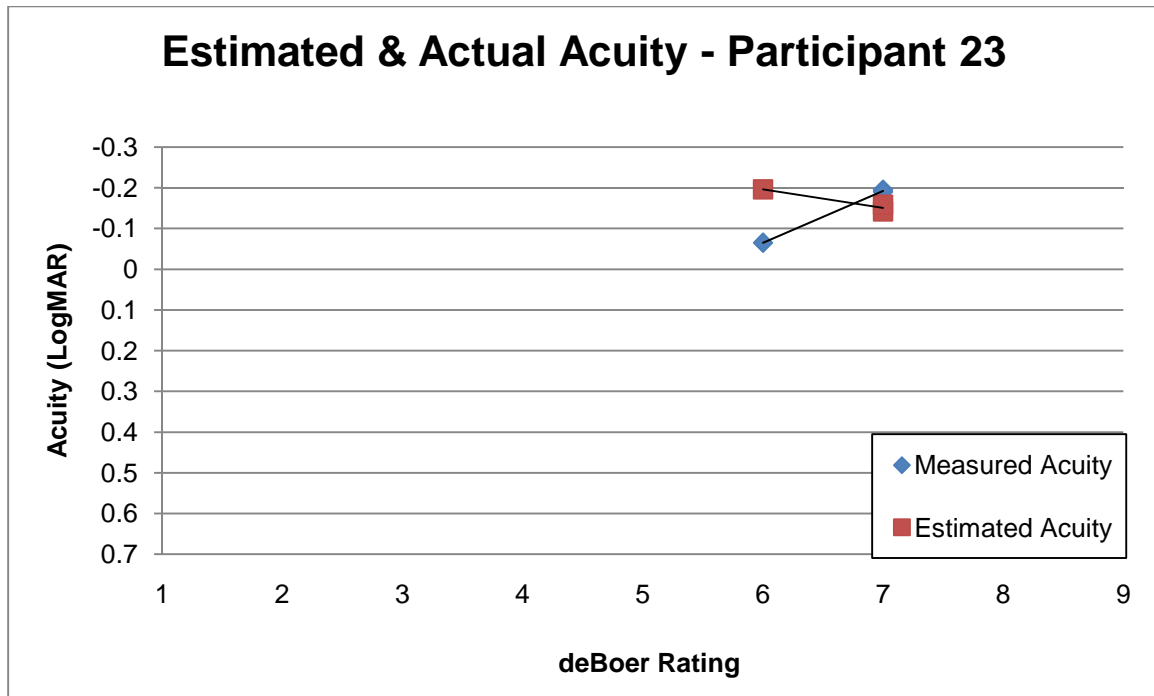
Appendix E; Figure 12. Participant 12 estimated and actual acuities with corresponding deBoer ratings of discomfort.
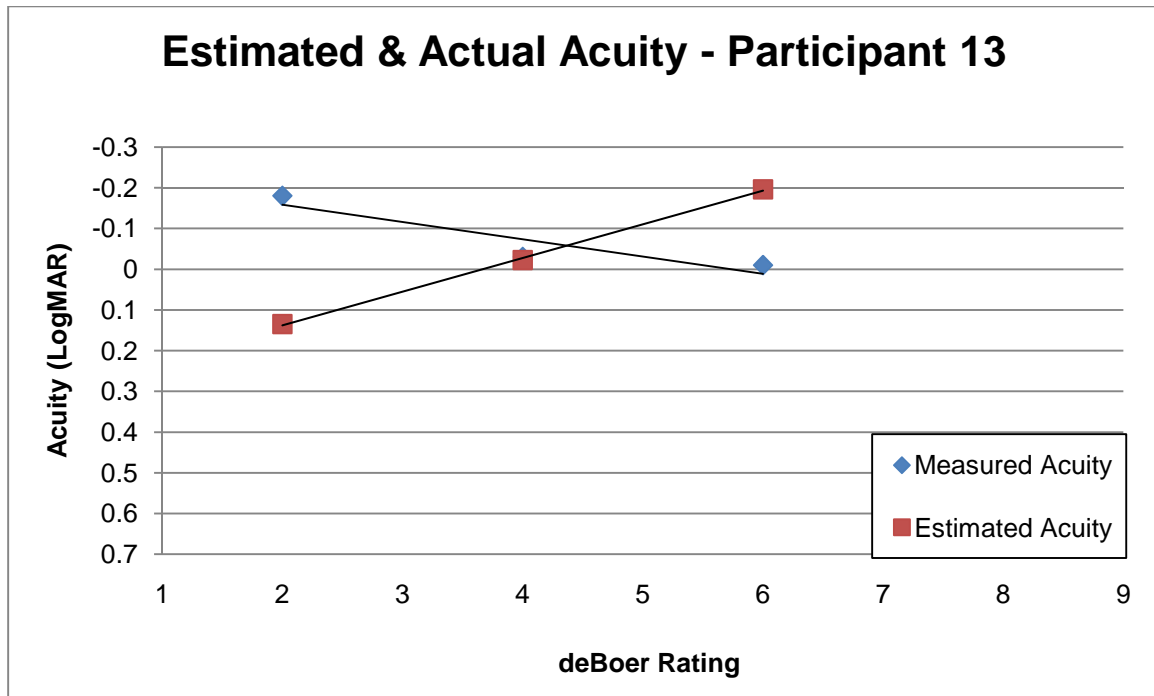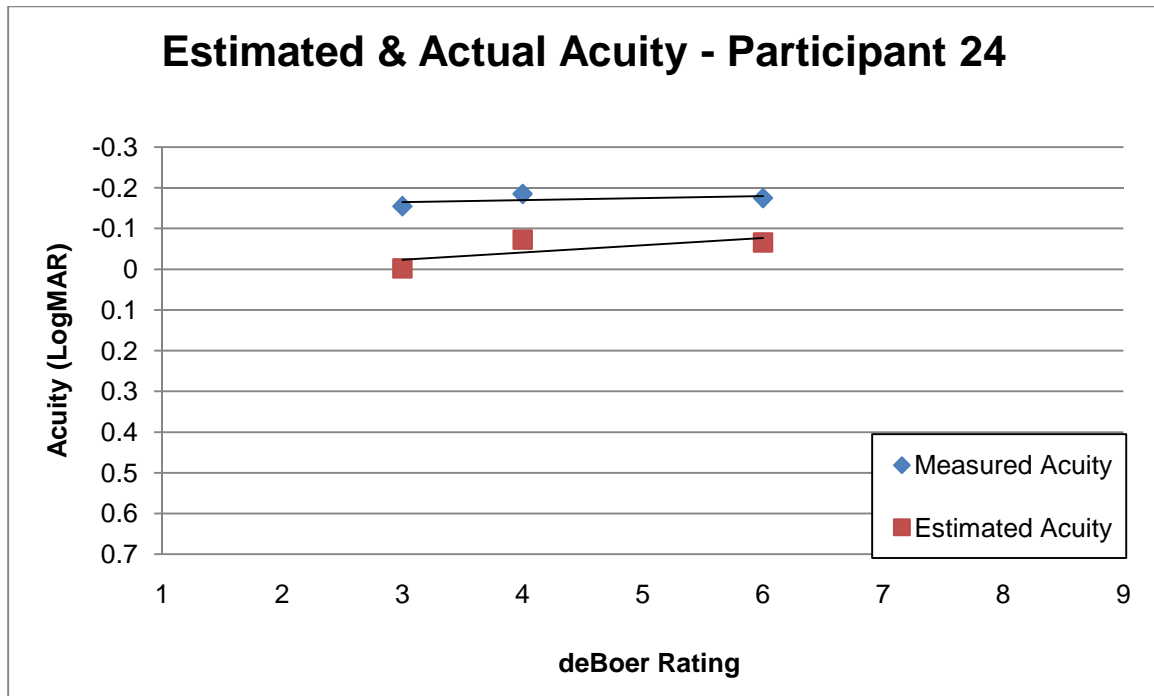
Appendix E; Figure 13. Participant 13 estimated and actual acuities with corresponding deBoer ratings of discomfort.
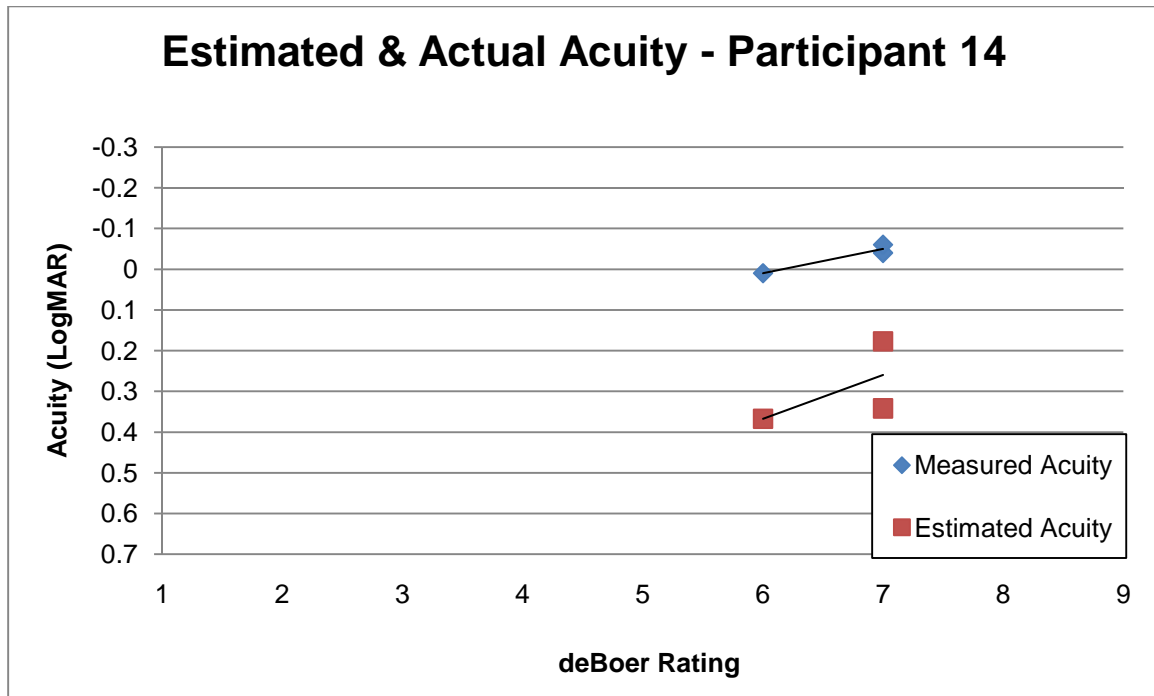
Appendix E; Figure 14. Participant 14 estimated and actual acuities with corresponding deBoer ratings of discomfort.

Appendix E; Figure 15. Participant 15 estimated and actual acuities with corresponding deBoer ratings of discomfort.

Appendix E; Figure 16. Participant 16 estimated and actual acuities with corresponding deBoer ratings of discomfort.

Appendix E; Figure 17. Participant 17 estimated and actual acuities with corresponding deBoer ratings of discomfort.

Appendix E; Figure 18. Participant 18 estimated and actual acuities with corresponding deBoer ratings of discomfort.

Appendix E; Figure 19. Participant 19 estimated and actual acuities with corresponding deBoer ratings of discomfort.

Appendix E; Figure 20. Participant 20 estimated and actual acuities with corresponding deBoer ratings of discomfort.

Appendix E; Figure 21. Participant 21 estimated and actual acuities with corresponding deBoer ratings of discomfort.

Appendix E; Figure 22. Participant 22 estimated and actual acuities with corresponding deBoer ratings of discomfort.

Appendix E; Figure 23. Participant 23 estimated and actual acuities with corresponding deBoer ratings of discomfort.

Appendix E; Figure 24. Participant 24 estimated and actual acuities with corresponding deBoer ratings of discomfort.
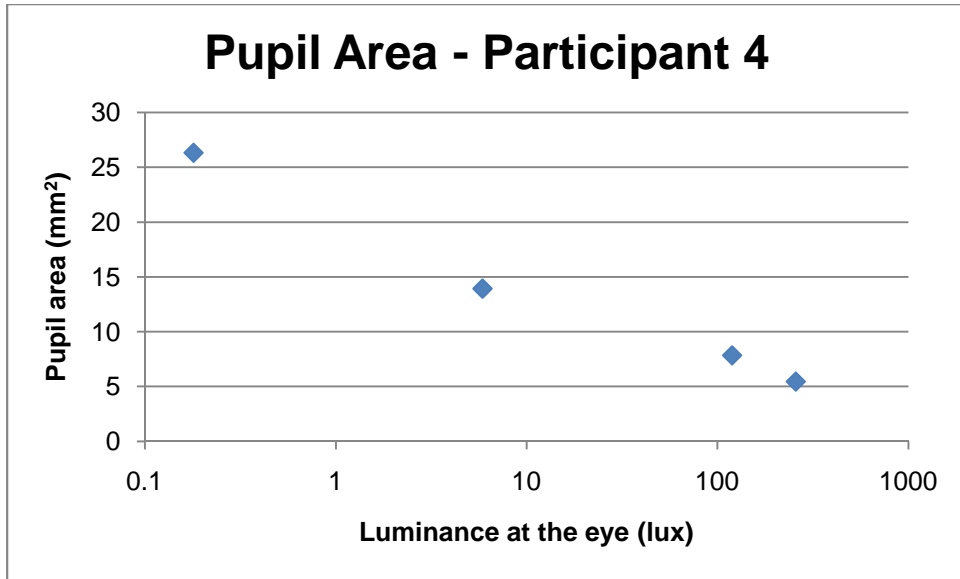
Graphs depicting individual participant pupil area.
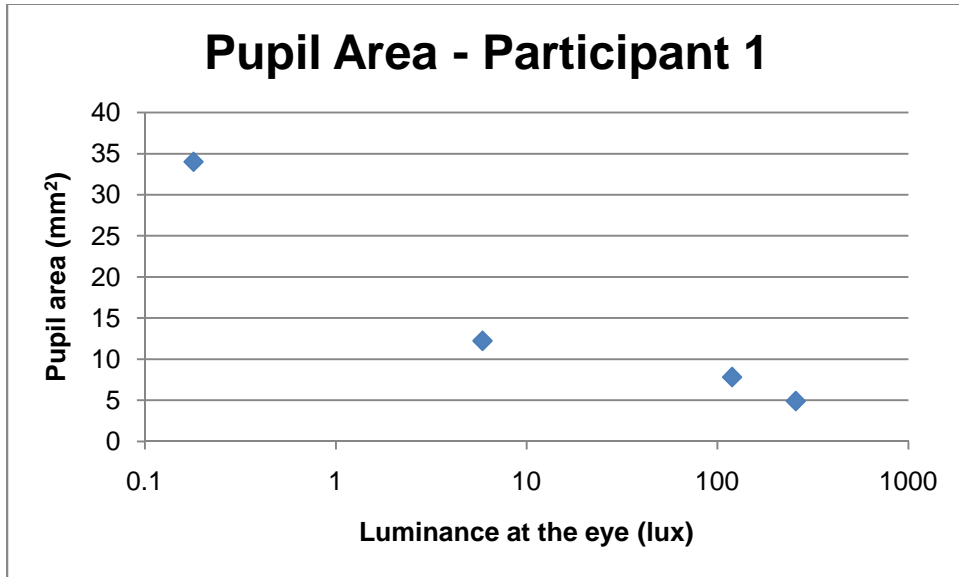
Appendix F; Figure 1. Participant 1 pupil area (mm^2) at no light, low glare, medium glare, and high glare.
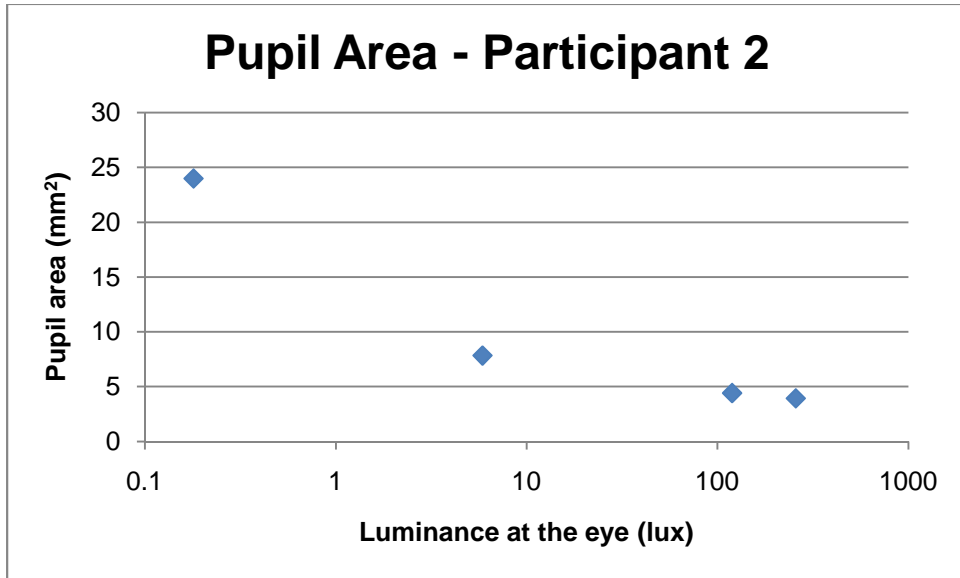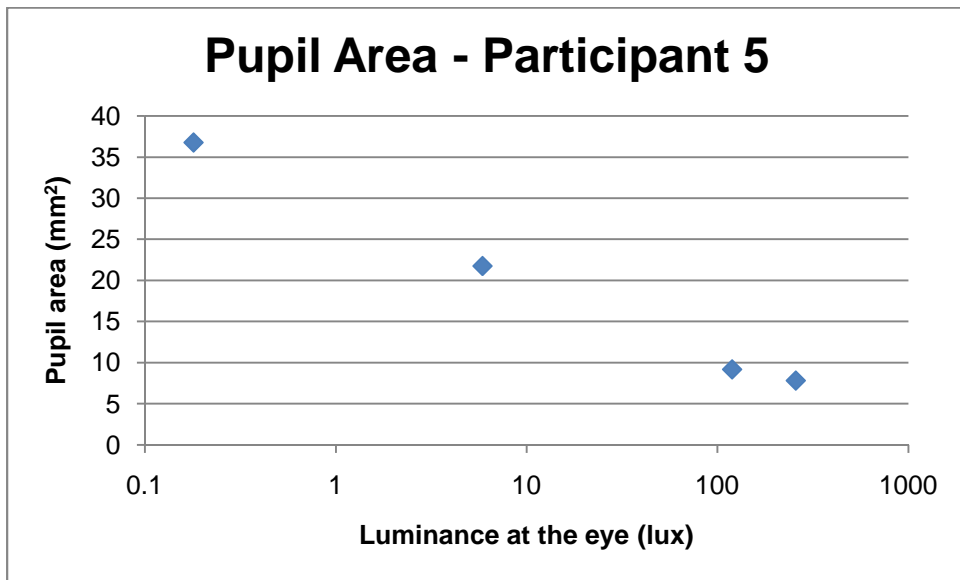
Appendix F; Figure 2. Participant 2 pupil area (mm^2) at no light, low glare, medium glare, and high glare.
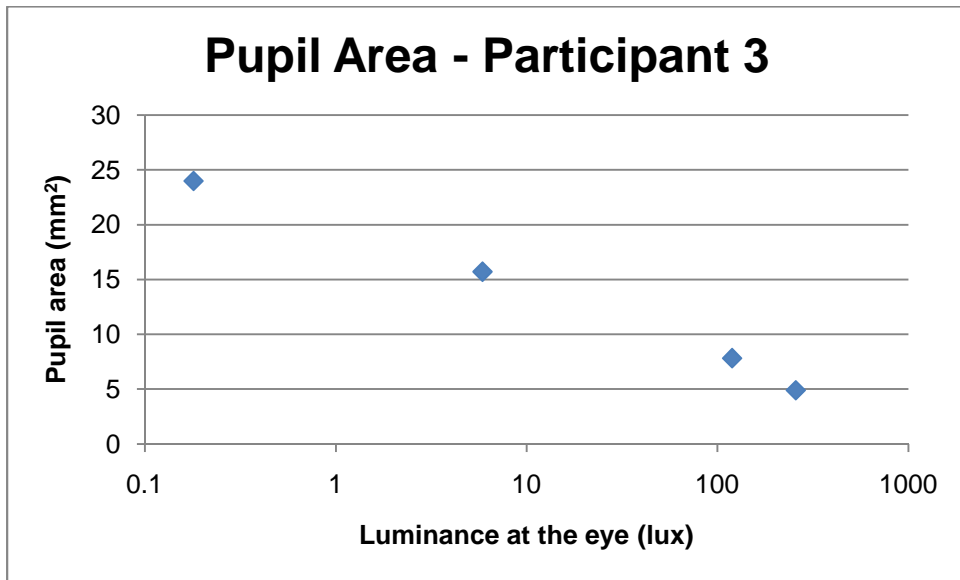
Appendix F; Figure 3. Participant 3 pupil area (mm^2) at no light, low glare, medium glare, and high glare.
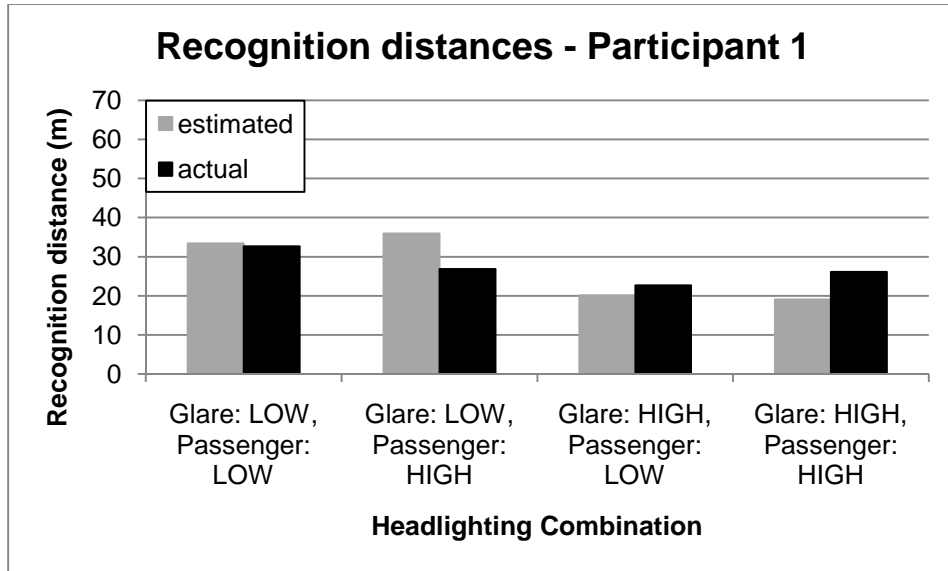
175

Appendix F; Figure 4. Participant 4 pupil area (mm^2) at no light, low glare, medium glare, and high glare.

Appendix F; Figure 5. Participant 5 pupil area (mm^2) at no light, low glare, medium glare, and high glare.
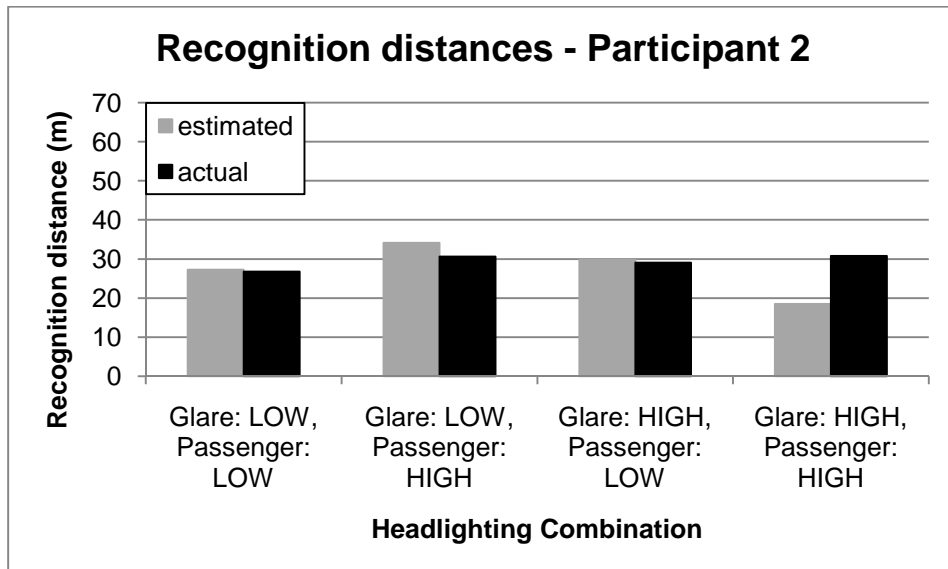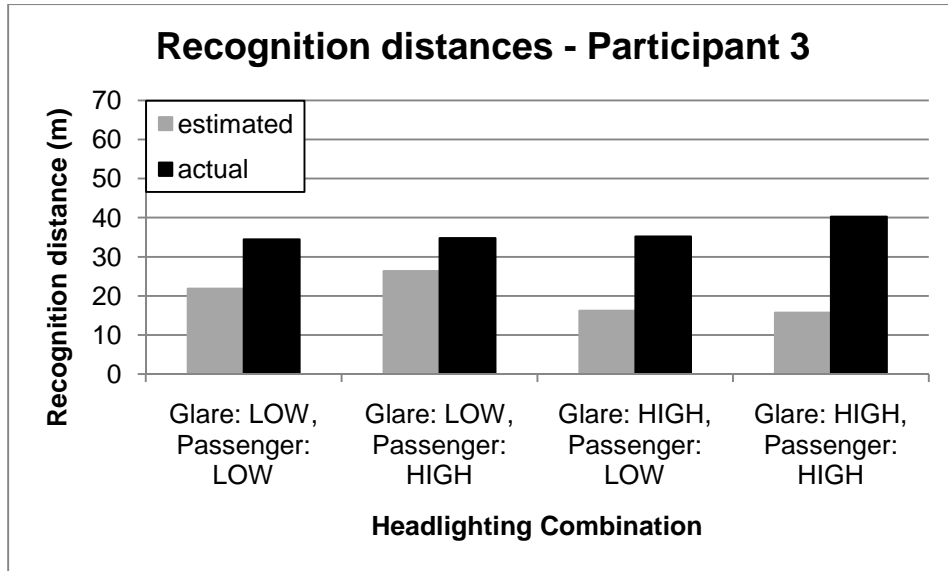
Experiment 2 participant estimated and actual recognition distances

Appendix G: Figure 1. Participant 1 estimated and actual Landolt C recognition distances.

Appendix G: Figure 2. Participant 2 estimated and actual Landolt C recognition distances.

Appendix G: Figure 3. Participant 3 estimated and actual Landolt C recognition distances.

Appendix G: Figure 4. Participant 4 estimated and actual Landolt C recognition distances.

Appendix G: Figure 5. Participant 5 estimated and actual Landolt C recognition distances.
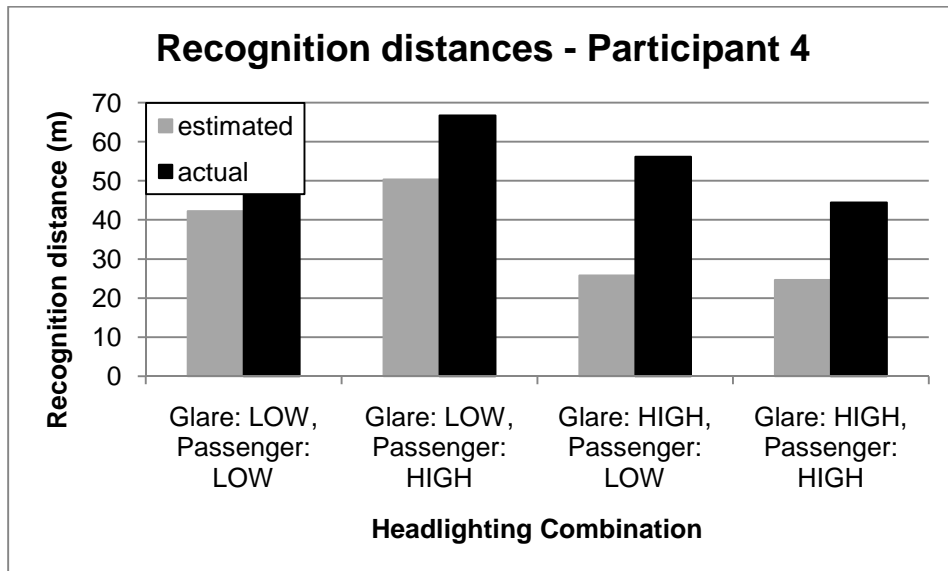

Appendix G: Figure 6. Participant 6 estimated and actual Landolt C recognition distances.
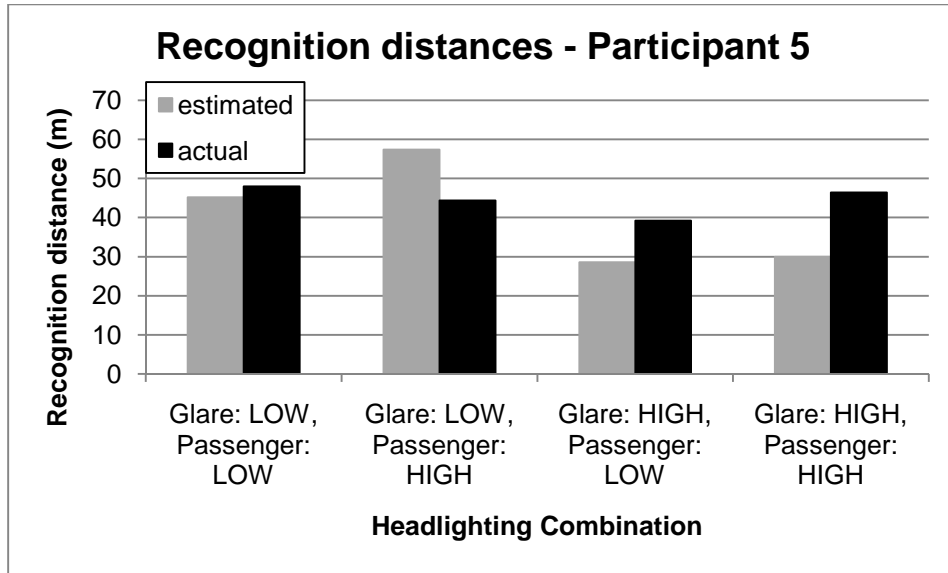
Appendix G: Figure 7. Participant 7 estimated and actual Landolt C recognition distances.

Appendix G: Figure 8. Participant 8 estimated and actual Landolt C recognition distances.
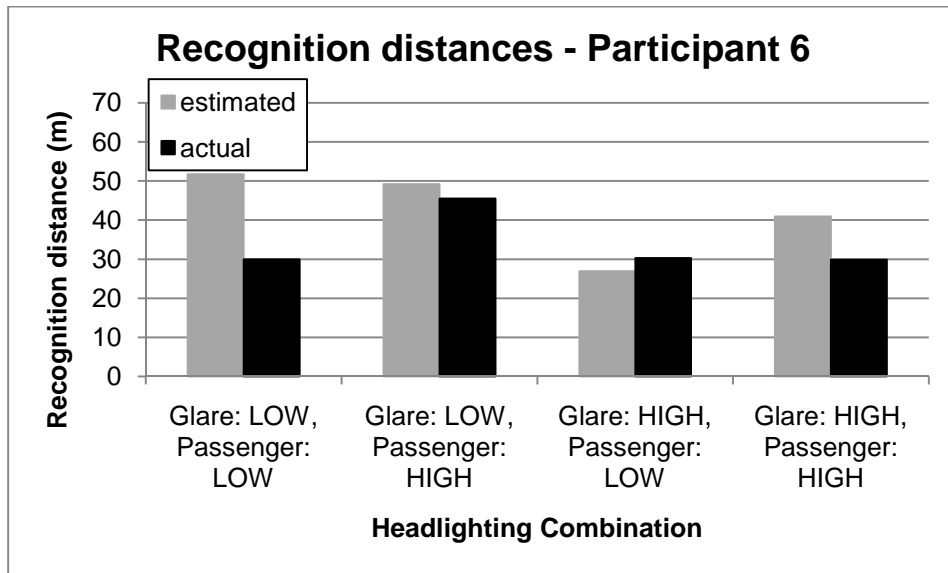
Recognition distances - Participant 9

Appendix G: Figure 9. Participant 9 estimated and actual Landolt C recognition distances.

Recognition distances - Participant 10

Appendix G: Figure 10. Participant 10 estimated and actual Landolt C recognition distances.

Appendix G: Figure 11. Participant 11 estimated and actual Landolt C recognition distances.

Appendix G: Figure 12. Participant 12 estimated and actual Landolt C recognition distances.
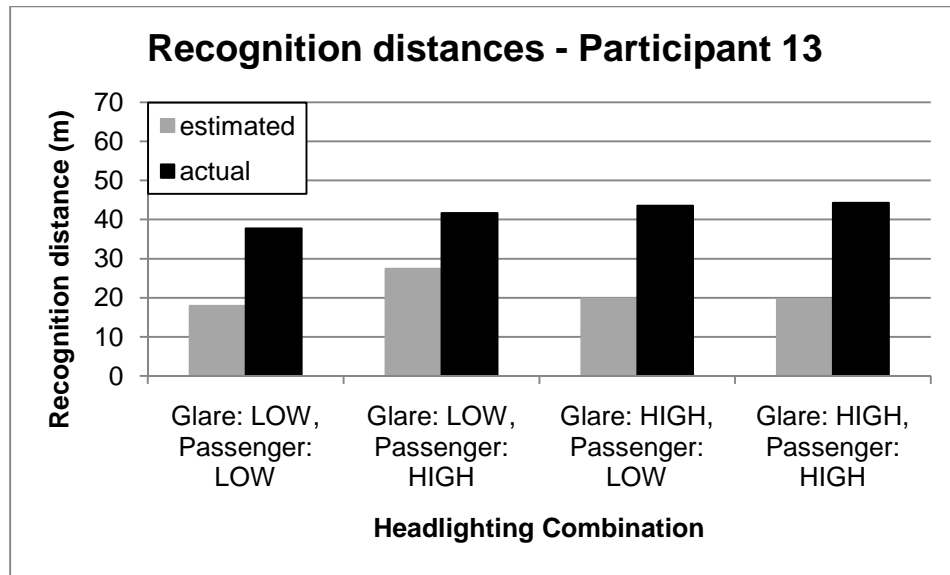
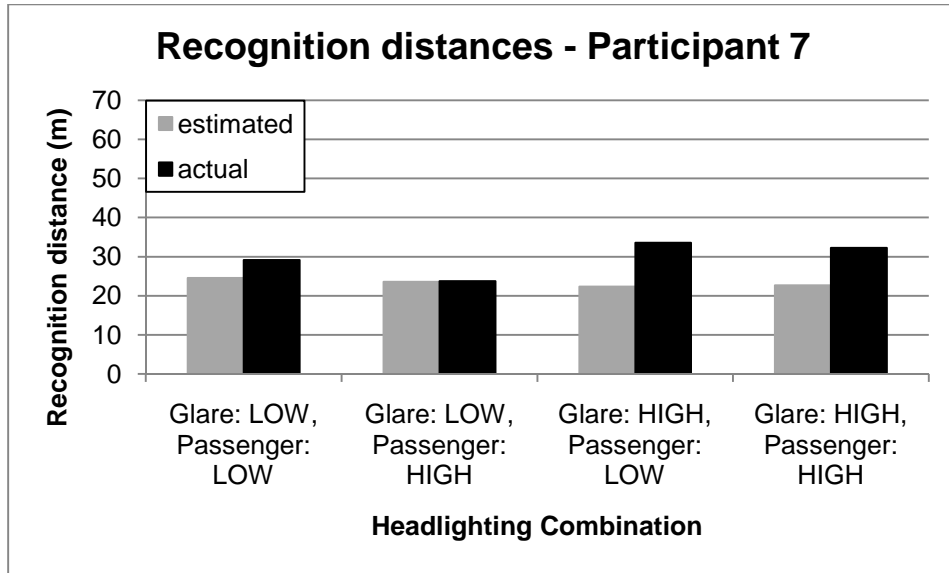Appendix G: Figure 13. Participant 13 estimated and actual Landolt C recognition distances.
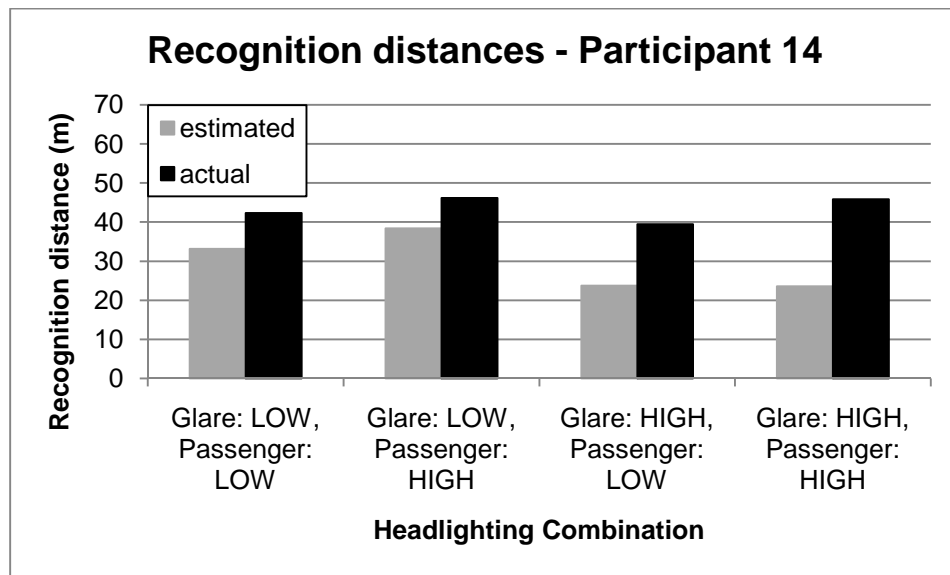
Appendix G: Figure 14. Participant 14 estimated and actual Landolt C recognition distances.
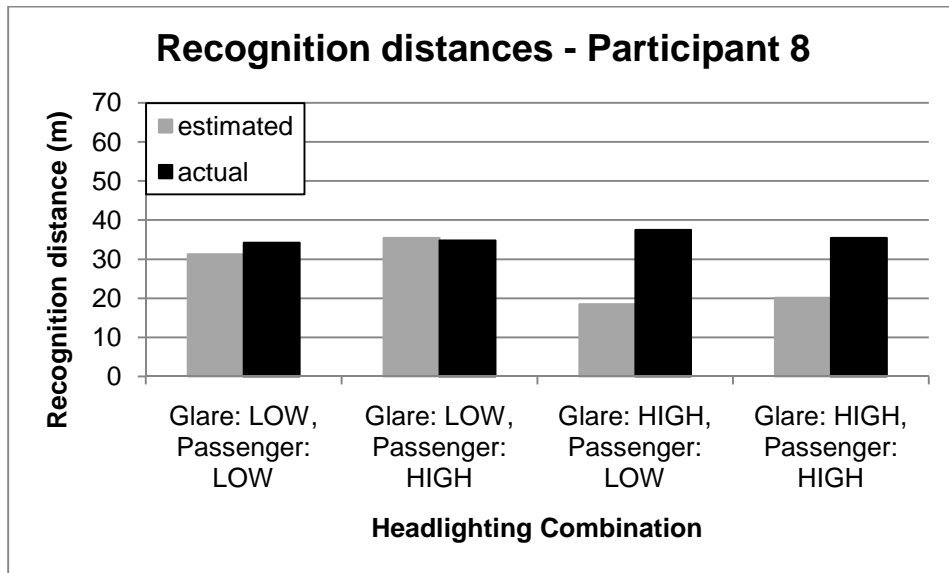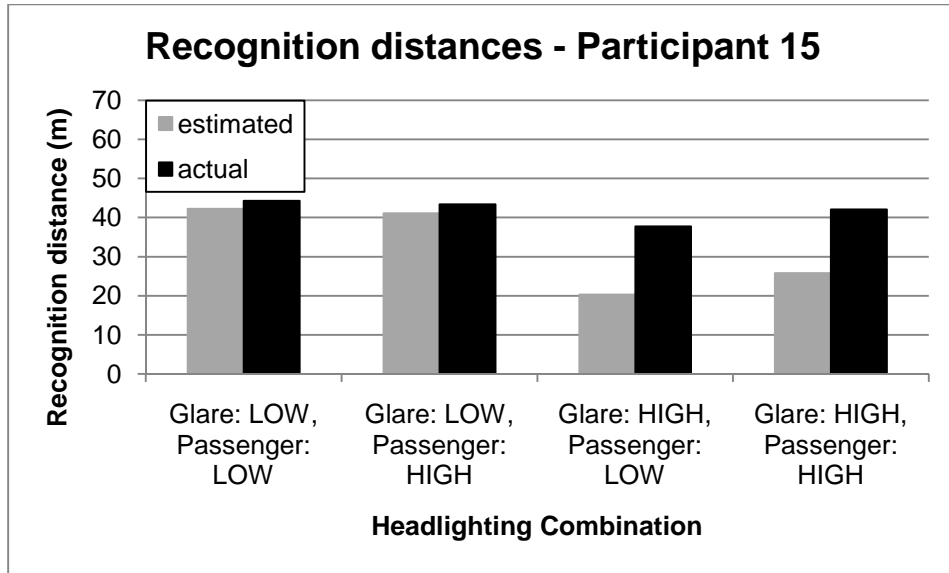
Appendix G: Figure 15. Participant 15 estimated and actual Landolt C recognition distances.
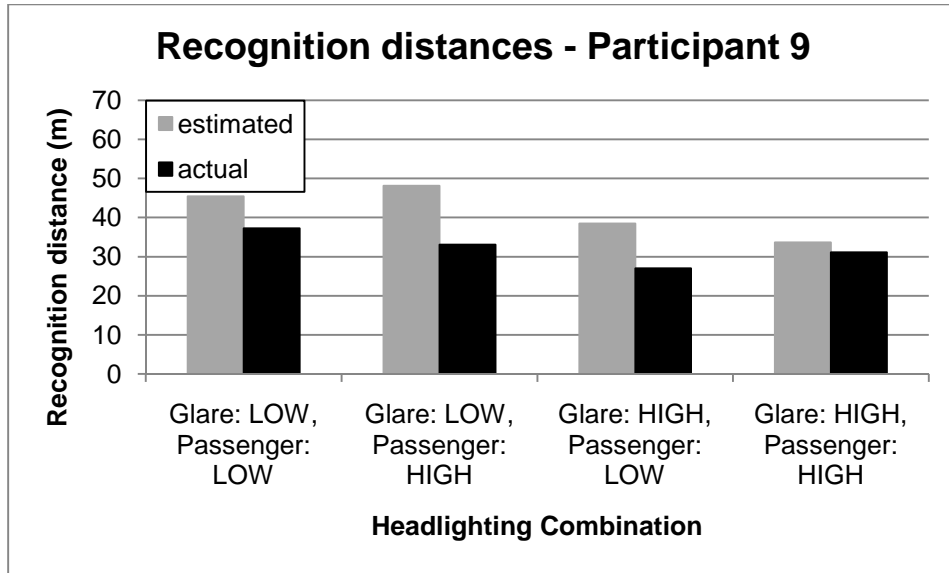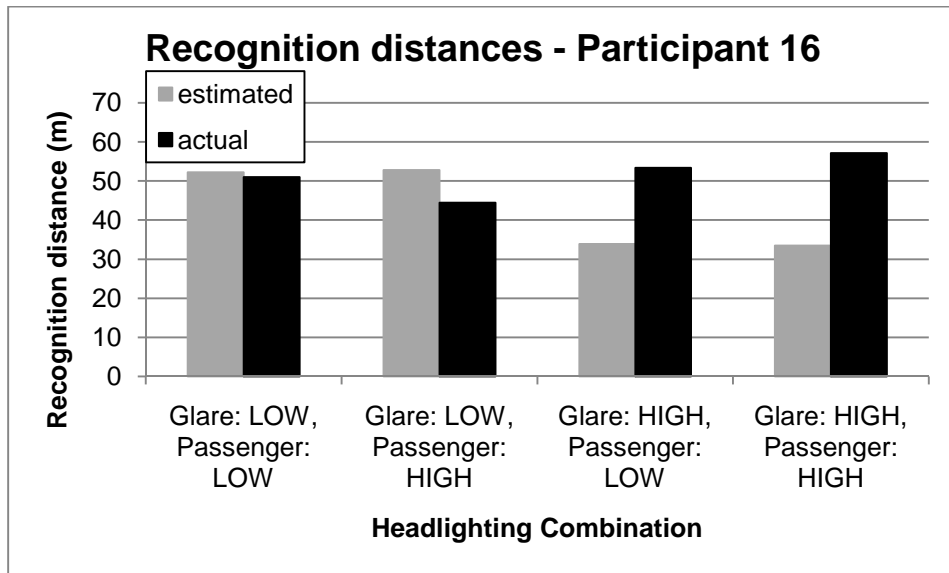

Appendix G: Figure 16. Participant 16 estimated and actual Landolt C recognition distances.
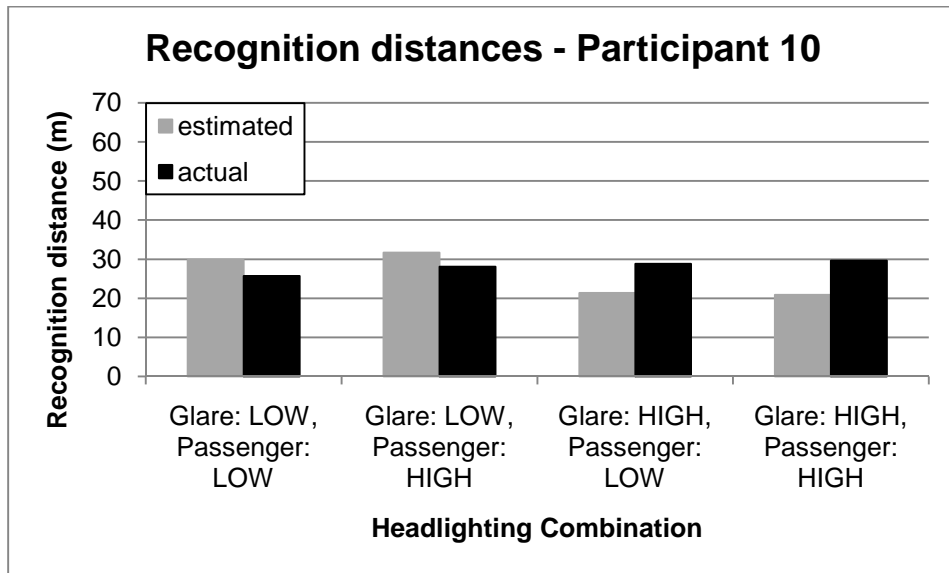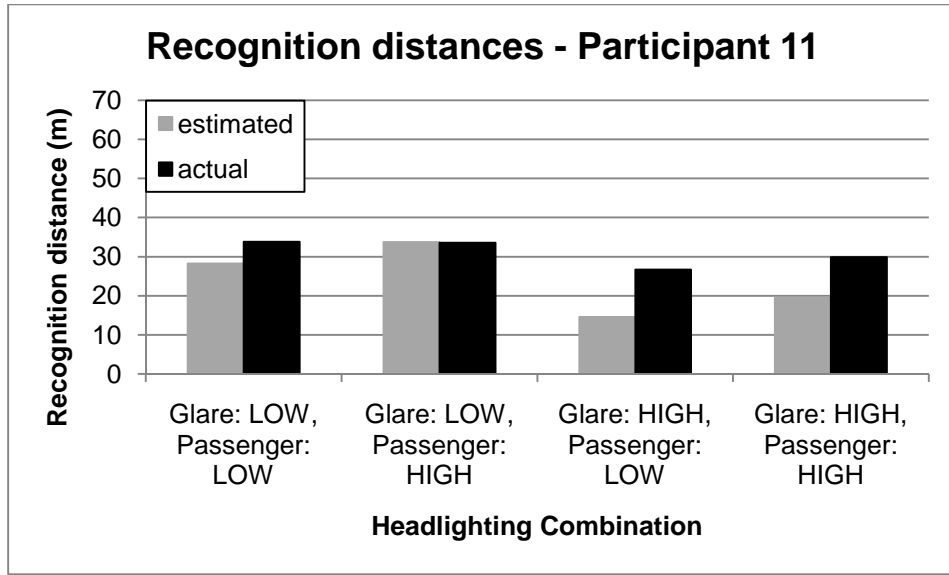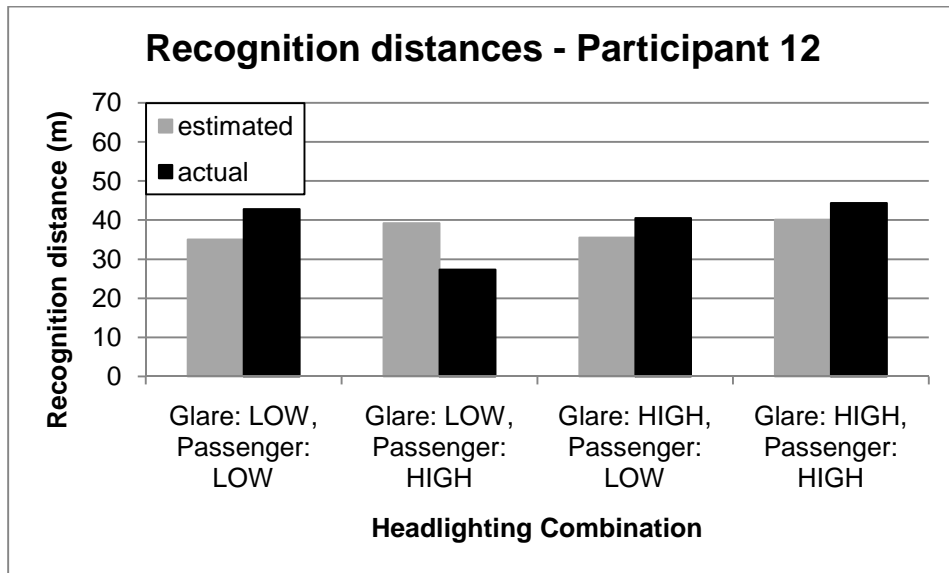
Appendix H

Individual participant R^2 values for both the relationship between deBoer ratings of glare light discomfort and estimated Landolt C recognition as well as the relationship between deBoer ratings of glare light discomfort and actual recognition distance of the Landolt C.

Participant Number	R^2 DeBoer and Estimated Distance	R^2 DeBoer and Actual Distance
1	0.94	0.66
2	0.27	0.09
3	0.82	0.11
4	0.93	0.78
5	0.85	0.00
6	0.94	0.31
7	0.83	0.71
8	0.97	0.36
9	0.84	0.49
10	0.98	0.39
11	0.90	0.94
12	0.00	0.12
13	0.33	0.70
14	0.93	0.25
15	0.84	0.62
16	1.00	0.06

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