Practical Electronic Instrumentation For Psychophysical Testing Of Visuomotor Performance

by

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(Under the direction of Billy R. Hammond, Jr.)

Abstract

The technological barriers to new methods of vision testing are continuously being eroded. As instrumentation becomes more accessible and user friendly, methods that were previously only available in select research laboratories become more practical for broader experimentation and eventual clinical application. To further examine complex visuo-motor phenomena (e.g. coincidence anticipation timing under glaring conditions) instruments capable of performing six psychophysical tests (coincidence anticipation timing, reaction timing with fixed and variable target locations, flicker fusion testing, glare disability testing, and photostress recovery timing) were constructed and 12 subjects were tested on all six tasks at two testing sessions. Test-retest reliability was generally high ($r > 0.8$, $p < 0.05$) and all tests had ecological validity. These experiments demonstrate that complex laboratory experiments can be performed with practical equipment while still retaining high experimental standards.

Index words: Psychophysics, Coincidence Anticipation Timing, Reaction Timing, Critical Flicker Fusion, Glare Disability, Photostress Recovery

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Dedication

To my wonderful parents, Suzanne and John O'Brien, for their love and support and to my grandfather, Dr. Pennti A. Honkanen, who was my earliest inspiration to pursue the highest levels of formal education.

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Chapter 1

Overview

Vision, both as a biological phenomena and a personal experience, has been a substantial area of study within psychology since the field was a subdivision of philosophy. The evolution of psychophysics the study of the relationship between objective physical stimuli and the subjective sensations and perceptions they elicit permitted the study of psychology to progress beyond indeterminate introspection. Psychophysics and the approaches to experimental psychology rooted therein allowed experimental psychology to arise from the fields of philosophy and physiology, which, previously, were largely separate or irreconcilable. Much of psychophysical experimentation is focused on precision instrumentation which has the effect of confining a method of testing to academic laboratories and other large research facilities. The complexity and sensitivity of psychophysical instruments is often a major hurdle to expanding the scope of research or transitioning to practical applications.

As technology progresses, the methodologies and instrumentation available to researchers expands. With the rise and improvement of computerized displays, many experimenters transitioned away from traditional, large optical systems. While there are clear advantages to the use of modern digital displays for vision research, this trend did not come without limitations. For example, the spectra and intensity of even the best research monitors will not effectively replicate natural lighting, but an optical system built around a xenon source can produce stimuli of similar spectrum and a far wider range of intensities. Many of the functional limits of displays and practical limitations of traditional optical systems can be surpassed by modern light-emitting diodes (LEDs).

LED based systems provide the ability to custom-tailor spectrum and intensity just as lamp-based systems have for decades, but do so with the stability and precision of computerized displays. It here that a fusion of two largely incompatible traditional methods of producing stimuli can occur and practical instrumentation can be achieved for generating the precision stimuli necessary for visual psychophysics experimentation. When properly harnessed, this permits methodologies and knowledge developed over generations of psychophysical research to both expand research and transition tests which were previously constrained to laboratories to progress to clinical application. This dissertation describes the development of apparati for testing visual and visuo-motor performance. Ideally, one outcome is to create equipment with the precision necessary for laboratory environments and the practicality necessary for clinical environments.

Chapter 2

Introduction

2.1 Stimulus Considerations

In psychophysics, the nature of the stimulus is critical to the experiment. If two instruments produce identical stimuli, the differences in the mechanisms of those apparatuses are of little consequence. Historically, the challenge for many experimenters has been to create precise, stable, consistent, accurate stimuli with a minimum of instrumentation error. Although the resulting stimulus is of primary importance, there are further design considerations to be made when creating an apparatus for psychophysical experimentation. Every approach has its own limitations and drawbacks, but there may be substantial gains that outweigh these negatives.

Many properties of a stimulus must be carefully controlled to ensure consistency between presentations in visual psychophysics. Any combination of chromatic composition, luminance, contrast, direction and speed of movement (if the stimulus is a moving target), size, exposure time, frequency (if the target is non-static), and any relevant rates of change (e.g. luminance increases or decreases) may need to be carefully controlled and adjusted depending on the nature of the experiment. Often the equipment used to create a stimulus is selected for either a high degree of precision and ease of adjustment of the static (such as chromatic composition) or dynamic characteristics (such as frequency) of the stimulus. The natural consequence of this is that while one characteristic of the stimulus may be readily adjustable, another may be difficult or impossible to alter during the course of an experiment.

Large, custom-built, optical systems have been at the heart of much of the early exploration of the visual system. In these systems, the lighting from a lamp (or lamps) is directed to the subject after being run through appropriate filters, lenses, mirrors, etc. to create the final stimulus. Careful set-up of such an apparatus can allow adjustments of nearly any static characteristic. When configured for Maxwellian view (a method of projecting an imagine onto the retina most well explained in Westheimer, 1966), it is even possible to minimize the impact of refractive errors in the subject's eye. Although such optical systems frequently have great flexibility for generating static stimuli, creating dynamically varying stimuli is often difficult with such equipment (for information on the integration of modern electronic controls into traditional optical systems, see Osaka, 1979, 1985). The more common methods for creating temporal variations in stimuli in such optical systems is the use of shutters (in which an electromechanically actuated iris is opened and closed) or choppers (sectored disks which rotate to alternatively permit or interrupt the path of a beam of light).

The advent of the cathode ray tube (CRT) greatly increased the ability of experimenters to generate visual stimuli with temporally varying stimuli (in addition to permitting spatial flexibility in producing stimuli, such as in Kelly & Savoie, 1973). Oscilloscope traces and computerized displays made it possible to adjust the shape, luminance, position, and other characteristics of a stimulus in real-time (computerized displays were an evolution of the previous tachistoscope displays, as evidenced in Mezrich, 1973). This allowed for greater ease of examining the temporal components of the visual system. Although these systems have improved dramatically over time (e.g. displays are no longer monochromatic and refresh rates have increased significantly), there are still significant limitations. Even for the more modern liquid crystal display (LCD) systems (a general improvement over CRTs, as per Lagroix, Yanko, & Spalek, 2012), flexibility in controlling luminance and chromatic composition are far lower than traditional optical systems.

Bridging the gap between the spatial strengths of classical optics and the temporal abilities and flexibility of computerized displays, dedicated electronic equipment for vision testing has become more prevalent, often venturing out of the laboratory and into the clinic. The original methods for electronic control (including electromechanical controls in shutters and choppers) of stimuli were largely analog in design (though this did not necessarily diminish the sophistication of resulting stimuli, as per Jones & Tulunay-Keesey, 1975). The most noteworthy issues regarding these designs are two-fold. First, analog components often suffer issues in stability, especially when dealing with the high currents necessary to drive light sources. Analog component parts become increasingly difficult to find (and expensive) with both improved manufacturing tolerance and improved thermal stability. Precision components reduce the instability of the circuits required for presenting stimuli for precise durations and improved thermal stability is necessary for one to be able to drive the high currents needed for light sources without deviations caused by the heat of use. This generally must be offset by either constant manual adjustment of the equipment or a feedback circuit, which can greatly increase design complexity.

Secondly, with the need for high precision with analog electronic hardware, changing the stimuli becomes increasingly difficult and time consuming. The ability to switch between stable, precise settings with purely analog components usually requires a number of similar circuits in parallel with some sort of switching device. Given the downsides of performing this switching by hand, as soon as digital logic circuitry progressed to the point of integrated circuits (ICs) being able to replace large volumes of analog components, vision researchers have been producing stimuli using digital electronics to control light sources (such as in Spydell, 1983).

The rise of digital circuitry has dramatically improved the stability and precision of vision testing equipment. It became possible to take a single high precision analog device (a quartz crystal in many cases) and specify useful time periods with great precision. The light emitting diode (LED), a digital component which generates light, increased flexibility in producing light for vision testing stimuli (e.g., Nealis, Engelke, & Massaro, 1973; Nygaard & Frumkes, 1982; Fadda & Falsini, 1996). Compared to traditional lamp systems, LEDs have high stability for both brightness and chromatic content over long periods of time. In addition, they have short rise and fall times for producing or ceasing to produce illumination, meaning they can be pulsed at high frequency without negatively impacting stability. Even the readouts of equipment have improved as analog meters, which have precision limited by the precision of the observer, have been replaced with digital measurements for time, intensity, chromatic composition, etc.

Despite the fact that the advent of discrete digital ICs created a wide range of new options for digital electronics, the ability to control stimuli using either an microcontroller[1] or a microcomputer[2] allow for control options that cannot readily be matched by systems without such controls (or miniaturization from older designs requiring a full general purpose computer, such as the one used by Yates & Harding, 1974). The use of a purpose built microcontroller or microcomputer based system to operate components with real-time priority makes them ideal for vision testing apparatuses in the laboratory, and the ability to produce them en masse with reduced expense and a high degree of precision makes them well suited for clinical equipment. This arrangement is frequently described as an "embedded system", and it offers the ability to generate stimuli in ways that would have been difficult, if not impossible, prior to their development.

The use of embedded systems in scientific equipment allows for stimuli presentations

[1]Microcontrollers are a subset of microcomputers.

[2]Full-featured microcomputers are becoming more common in embedded applications.

which would otherwise be difficult, if not impossible. Stimuli can be presented at precise frequencies or exposed for exact durations spanning from microseconds to minutes (or longer, although it's rarely practical in vision experiments) and timing systems can even be fed into one another. In addition to the ability to generate stimuli with extreme precision, time sensitive dependent measures (e.g. reaction timing) can be made with greater precision than is practical with stopwatches or even the timing precision on non-embedded microcomputers. There may always be a place in vision research for the elegance of the optical table and the unique spatial and temporal characteristics of a computerized display, but embedded systems are becoming easier to integrate into both of these and have been used to explore new aspects of human vision as well as move psychophysics out of the laboratory.

Like optical systems and computerized displays, there are some circumstances where only an embedded system is appropriate for testing a particular aspect of vision. Knowing when to select the appropriate equipment for creating a new vision testing apparatus or method is difficult in some cases, but very clear in others. Some testing environments or other requirements may necessitate a form factor that is more practical. Although initial means of testing vision are often not subject to such considerations, the form factor (i.e. enclosure dimensions, user input ergonomics, etc.) of the necessary equipment for an experimental or clinical application may force the selection of an embedded system approach.

2.1.1 Form Factor Considerations

The form factor for laboratory equipment is often an afterthought. In many lab environments, form factor is primarily a consideration regarding the space a piece of equipment occupies. With regards to vision testing, the subject is brought to the instrument, and as long as the stimulus is appropriate, the details of the form factor are of less importance (for an examination of the non-effect of response method, see Algom, Marks, & Wiesenfeld, 1991). Novel equipment for vision testing often begins either as a quick prototype or as a series of modifications to existing equipment and becomes optimized after initial testing. As the equipment develops through successive iterations the form factor becomes a more and more prominent consideration. However, in some circumstances, knowing the expected usage of an instrument drives form factor considerations from the early prototypes.

Vision testing stimuli with motion other than flicker are difficult to generate within a traditional optical system. The movement of a target is limited to within the area of the path of light between optical components. It is possible to create a moving target by precisely adjusting mirrors, but this method often necessitates electromechanical control for each axis of motion and is difficult to keep stable over repeated trials or between testing sessions. In addition, planar mirrors will cause non-linear distortions in the final stimulus with variations in angular eccentricity unless the path length from the mirror to the subsequent optical component is sufficiently long (which is difficult even in many laboratory settings due to finite available space). An opaque material adhered to a thin piece of glass may be moved to create a dark target in an illuminated field or to remove all extraneous illumination to create a lighted target, but moving this in an optical system also necessitates precise electromechanical controls. Even producing simple flicker usually requires either a rotating chopper or an electromechanical shutter. While the rotating chopper often makes smooth frequency adjustments easy, relative durations of each temporal component of a flickering stimulus are difficult to adjust during an experiment. Varying the duty cycle with a chopper system usually requires changing the sectored disks used to interrupt the light path. Likewise, though many electromechanical shutter drivers make precise adjustment of duty cycle simple, shutters can be prone to failure if driven at high or even moderate frequencies.

Although it would be preferable, from the perspective of constructing instrumentation, to be able to permanently establish equipment in a single location, instruments often need to be moved around a laboratory or shipped to another location. In instances where equipment must be moved, even within a laboratory, optical systems are often difficult to keep in alignment. As a result optical systems are frequently disassembled before shipping, and must be rebuilt and realigned on location. The fragility of many optical components further compounds the difficulty of deploying such equipment outside of the originating laboratory. While the ease of portability for software makes computerized displays ideal in some circumstances, if there are relevant luminance or chromatic differences between displays, this either has to be corrected for during a calibration procedure or requires transporting a full computer system.

2.2 Subject Interface Considerations

Traditionally, a psychophysical stimulus is adjusted by an experimenter who records responses from the subject. While this may be an inevitable necessity for some psychophysical tests, in some circumstances, removing the need for the experimenter to collect subject responses is preferable or essential. Creating a response or adjustment interface for the use of the subject in psychophysics instruments may permit improved accuracy (as this eliminates the recording errors from the experimenter) and speed (which consequently can reduce fatigue created by long testing sessions). Removing the experimenter from the entry of subject responses may decrease transcription errors caused by any perceived ambiguity in the subject's response. In addition, if there is a time-sensitive component to the response variable, a response directly recorded from the subject does not include any delay or measurement error from the experimenter, improving accuracy.

Classical psychophysics experiments have largely used young, healthy adults for subjects in initial testing. Special populations are often screened out of exploratory experiments but become of interest later, especially as research extends into areas such as developmental or clinical research. Given that the means for adapting equipment for vision testing cannot be addressed exhaustively, there are several general considerations for some of the more common special populations which warrant examination.

2.2.1 Considerations For Special Populations

For certain subject populations, changes may be required in the interface, stimuli, or testing methodology for psychophysical instruments. Assuming the subject is readily communicative to the experimenter, it is often possible to place the controls for stimulus adjustment into the hands in the experimenter instead of the subject. This method is useful for testing elderly subjects who are either uncomfortable with the interface and prefer to respond verbally or who have difficulty with fine motor control.

For visual stimuli, the presentation frequency for any temporally varying stimulus may need to be reduced for elderly or very young subjects. Likewise, luminance may need to be adjusted either due to reduced sensitivity, reflexive aversion, or a combination of the two. In addition, for infants, stimulus size may need to be dramatically increased to account for the disparity between infant and adult acuity. (For an example of an extremely specialized design of psychophysical testing equipment for use with infants, see Chin, Taylor, Menzies, & Whyte, 1985)

Changes to testing methodology, separate from interface or stimuli accommodations, are often necessary for special populations (for example, a testing method for visual psychophysics in infants was developed by Mayer and Dobson (1980)). In the laboratory, well-trained subjects are often able to use the method of adjustment (in which the subject adjust the stimulus to meet a testing criterion), but this frequently needs to be adapted to the method of limits (in which the experimenter adjusts the stimulus to satisfy a criterion for the subject) for inexperienced subjects or for subjects with difficulty adjusting the controls. In some populations, adaptive psychophysical methods are generally preferable to the method of constant stimuli (in which stimuli are presented in random order to characterize the underlying psychophysical system) as they require significantly fewer trials, and this makes them ideal for testing infants, the elderly, or anyone who is likely to suffer from attentional or fatigue issues during testing. Many adaptive procedures are also well suited to multiple testing sessions, which can be a necessity with infants or subjects with cognitive impairments. Although traditional tests in visual psychophysics require a verbal or manual response, these adaptive procedures are often well suited to the preferential looking technique, in which changes in gaze direction as measured by an observer are used to determine a binary response for threshold estimation. Despite the fact that the particulars of the necessary accommodations may vary, it is essential to take the limitations of subject populations into account when both designing psychophysics instruments and deciding on testing methodologies.

2.3 Data Output Considerations

Whereas the input of information for vision testing equipment is highly dependent upon the aforementioned considerations, the optimal form factor for data output is most influenced by two factors: the presence or absence of a computer and the volume of data. For small systems with relatively few data points, a display with the relevant information is often sufficient and aides both portability and simplicity. This may also be preferable if the collected data is going to be added to a paper record rather than a digital record. If the data collected is of large volume or the device already uses computerized controls, storing the information digitally offers several advantages. Larger volumes of data can be collected with digital storage methods (whether the information is sent to a computer or stored on removable media is of little consequence) without risking transcription errors. Automating data collection allows the experimenter or clinician to focus on the subject or patient, ensuring that the psychophysical task is being completed properly. In addition, if a psychophysical instrument is outputting data electronically, it can provide a larger volume of information which may be useful in monitoring instrument stability over time, examining fatigue effects of the task, or looking for other predictive or confounding factors. Digitally stored output data can also be paired readily with other instrumentation such as electro-physiologic or video recordings of the subject.

If the data from each trial for a task is easily transcribed by hand, that may be preferable with faster tests. In such a case, the output display should be designed for simplicity of use for the experimenter or clinician. For more time consuming tests, or for equipment where the output data is large, an ideal form factor for the output data is a comma separated value (CSV) file. CSVs are readable by human beings but are also readily processed by virtually every electronic device capable of receiving an input file. As a result, a CSV file provides the greatest compatibility for future software or hardware and is well suited to automated data processing techniques.

Chapter 3

Coincidence Anticipation with a Glaring Stimulus: An Example Of Design For Visual Psychophysics Instrumentation

Coincidence anticipation timing (CAT) is the measurement of the ability of a subject to correctly gauge the trajectory of a moving stimulus toward a target and to coordinate a response (usually a motor response) to its arrival at the target. Earlier research into this visuo-motor task described the phenomena as the "transit reaction" (e.g., W. Hick & Bates, 1950; Slater-Hammel, 1960), but the terms "coincidence anticipation" (e.g., Dunham Jr, 1977, 1989; Brady, 1996), "anticipatory timing" (e.g., Isaacs & Finch, 1983), and "coincidence anticipation timing" (e.g., Millslagle, 2000; Ak & Koçak, 2010; Sanders, 2011) have become more common descriptions. The task requires a subject to track a moving stimulus (or, as will be discussed later, a stimulus with apparent motion) as it approaches a stationary target and to coordinate a response (most commonly a button press) to coincide with the stimulus's arrival at the target.

Previous coincidence anticipation experiments are largely centered around three general topics: describing and validating apparati (usually collecting normative data in the process), examining sex and/or age differences in coincidence anticipation performance, and comparing the performance of groups of individuals with different amounts of athletic practice. W. Hick and Bates (1950) described and modeled the relation of the "transit reaction" to the act of tracking and coordinating a motor response to a moving target. As was common of much state sponsored psychophysics research of the time[1], there was clear military interest, so the models generated by Hick & Bates heavily use examples of aiming artillery or anti-aircraft weapons. There are two relevant consequences of this beginning framework. The internally obvious consequence is that the models presented by Hick & Bates include several elements which are not directly relevant to the majority of subsequent research in coincidence anticipation (i.e. subjects having to compensate for the lag in the rotation of a turret and the time-of-flight of a shell when coordinating their response to a moving target). The comparatively externally relevant consequence is that their models were generated using unpublished[2] experimental data, so no experimental methodology or apparatus[3] for quantifying the transit reaction is described. Slater-Hammel (1960) notes[4]:

> However, except for such generalizations, it appears that few experimental investigations have been concerned with the characteristics and limitations of performance in transit reactions. About the only published material on these reactions has been presented by Hick and Bates (2). These investigators, citing an unpublished study by Bates, state that an experiment on coincidence anticipation in

[1] I.e. shortly after the second World War

[2] Slater-Hammel (1960) notes that unpublished data collected by Bates was used to generate the models.

[3] The apparatus was likely a British tank, but for obvious reasons such information would not have been disclosed at the time of publication.

[4] After referring to the ubiquitous observation that people are regularly able to successfully coordinate motor responses to moving targets in athletic performance

tank gunnery "showed that reaction time variations could account for practically the whole of the errors."

Slater-Hammel (1960) sought to characterize the reliability and accuracy of the transit reaction using a modified analog clock, thus measuring the phenomena in a radial configuration. Test-retest reliability was found to be high and performance was not found to vary with knowledge of results. This appears to be the first instance of an attempt to characterize the transit reaction with a published experimental apparatus and methodology. This was followed shortly thereafter by Belisle (1963) whose apparatus was designed around that of Slater-Hammel (1960). Belisle (1963) used the term "coincidence-anticipation" to describe an experiment using a population of university students who were all former athletes (reflective of a general trend in subsequent research). Despite not including any experimental data, Haywood and Singleton (1977) describe a method for generating coincidence-anticipation timing stimuli electronically (rather than electromechanically). This is representative of a distinct change in the measurement of coincidence-anticipation timing - the transition from mechanical and electromechanical apparati to purely electronic ones. Ultimately the CRT display that Haywood and Singleton (1977) designed their circuit around would not become the predominant method for assessing coincidence-anticipation performance, and as instrumentation for quantifying this phenomena improved, new experiments would examine finer aspects of inter-subject performance differences.

Coincidence anticipation timing performance differences between age groups or by sex has been a frequent subject of consideration. These differences are often examined simultaneously (in a factorial design). The earliest research focused on the performance of male subjects who were military personnel or collegiate athletes, but this focus soon broadened. Dunham Jr (1977) found performance in 7 year olds to be less accurate than older children, and found higher accuracy in boys than girls (in the 7 to 12 year age range). Similar age and sex differences have been found by other experimenters (e.g., Bard, Fleury, Carrière, &

Bellec, 1981). In contrast to the unsurprising (and consequently less frequently examined) age differences, these suggested sex differences are by no means universal. Brady (1996) found improved coincidence anticipation accuracy by sex only in "open skill" athletes and, in contrast, Harrold and Kozar (2002) found no significant differences in performance by sex. It is possible that any sex differences in coincidence anticipation performance are due to socialization and prior experience (as suggested by Petrakis (1985) as an explanation for found sex differences between male baseball and female softball players) or may be indicative of some underlying general difference in physiology or cognition (as suggested by Sanders (2011) in a review of prior experiments examining sex differences in coincidence anticipation performance). Given that sex differences in coincidence anticipation performance appear to be more pronounced in earlier experiments, this may be reflective of unintended sampling biases, similarity of measurement tasks to sex-normed activities[5], or the changing sex distribution of competitive athletics. This would be of particular interest, as athletic performance is a mainstay of coincidence anticipation experiments.

Examinations of coincidence anticipation differences between athletes of different sports and between athletes and non-athletes has largely focused around collegiate and high school athletics (probably due to the comparative convenience of testing collegiate athletes over professional athletes and the difficulty of testing young children). Brady (1996) examined differences between "open skill" athletes, "closed skill" athletes, and non-athletes and found "open skill" athletes had reduced variability. Isaacs and Finch (1983) demonstrated that intermediate level tennis players had higher accuracy in predicting the trajectory of a target with limited visual information than beginning players. Dunham Jr (1989) found earlier and more consistent coincidence anticipation timing responses in adolescent baseball players than non-players. Millslagle (2000) did not find significant difference in coincidence antici-

[5]E.g. Some instrument interfaces may have shared similarity to electronic games which were more commonly played by male than female children at the time of the experiment.

pation performance between experienced and inexperienced female fast pitch college softball players. Ripoll and Latiri (1997) determined that expert table tennis players had superior performance on a coincidence anticipation task while the target was decelerating. While results between experiments have been mixed, the general trend in coincidence anticipation experiments with athletes suggests that greater levels of experience in athletic competitions requiring the participant to track the trajectory of a moving object. This is likely indicative of both a difference in reaction timing (e.g. Youngen, 1959) and differences in motion processing due to practice effects.

Apparati for assessing performance of coincidence anticipation have evolved over time as technology has improved and experiments have become more focused. Although the earliest systems were electromechanical ones made from modified analog clocks (e.g., Slater-Hammel, 1960; Belisle, 1963), some purely mechanical systems were used in early experiments. Dunham Jr and Glad (1976) constructed a wooden track to create a gravity-propelled moving target by attaching a foam ball to a toy car[6]. Despite the fact that there have been other mechanically driven systems (e.g., Schmidt, 1969), the majority of stimuli for coincidence anticipation experiments have been electronically generated. Although the earliest description of a purely electronic system is likely that of Haywood and Singleton (1977), a commercially available coincidence anticipation timing system (and similarly constructed apparati) using LEDs in sequence to generate apparent motion would eventually come to predominate the literature. The Bassin Anticipation Timer produced by Lafayette Life Sciences is the most ubiquitous single instrument for coincidence anticipation timing experiments (e.g., Brady, 1996; Millslagle, 2000; Petrakis, 1985; Molstad et al., 1994; Harrold & Kozar, 2002; Kuhlman & Beitel, 1991; Ak & Koçak, 2010) and systems of a similar function (whether custom-built or simply not explicitly named) have also been popular (e.g., Ripoll

[6]While timing was performed electronically, the stimuli itself was generated without electronic components. This method was also used by Dunham Jr (1977) in a subsequent experiment.

& Latiri, 1997; Benguigui & Ripoll, 1998). These linear LED track systems sequentially turn on and off LEDs to create the perception of a moving stimulus which moves toward a designated target on the track.

In stark contrast to these more common LED based systems, there have been a few experiments conducted with real-world stimuli. Isaacs and Finch (1983) had subjects respond to serves from a tennis instructor. Dunham Jr (1989) moved away from the mechanical gravity-propelled systems and used a pitching machine to throw baseballs at controlled velocities; even having subjects throw a ball at a moving target has been tried in the laboratory (Bard et al., 1981). Despite the clear improvements in ecological validity, such experimental methods raise several issues. Having a human directly move the target (as in Isaacs & Finch, 1983) leads to variability in the velocities presented, and standard pitching machines will present acoustic cues to the subject (as velocity of the projectile is dependent upon rotary motion in the equipment). Variability in the path of motion provides another variable for consideration, and this is inevitable with any system that is not confined to a single axis of motion for the stimulus. Although LED track systems have lower ecologic validity than these apparati with real-world stimuli, they have greatly improved flexibility for presenting various velocities (without wide error ranges, acoustic cues, or travel-path deviations) and have a high level of consistency.

Despite these LED track systems offering a high degree of precision and being well suited to the laboratory, there is a notable difference between the stimuli they produce and the real-world visual tasks they are intended to replicate. The Bassin Anticipation Timer (and nearly all apparati using LED tracks to generate a moving stimulus) uses red LEDs[7] to generate the moving stimulus. There are few, if any, instances in which the athletic performances such equipment is intended to model and predict occurs with long-wave heavy lighting.

[7] It is worth mentioning that red LEDs were the most commonly manufactured color when LEDs first came to the consumer market, and for many years, it was difficult to source reliable, high-brightness LEDs in any other color.

Most athletic activities today (in which coincidence anticipation is needed skill) occur either under natural lighting (which is short-wave dominant during the majority of the day) or artificial lighting, which is most commonly produced by a xenon source (which also provides significant amounts of short-wave light). While the long-wave heavy sources typical of prior experiments using LED tracks are less noxious to the subject, a short-wave heavy white LED produces a spectrum which is more representative of natural or artificial outdoor lighting and better replicates any produced visual fatigue, glare disability, photostress, or photodiscomfort which would be experienced by athletes under normal performance.

Although short-wave visible light has been rather lacking in most prior experiments of coincidence anticipation timing, it is abundant in both natural and artificial lighting used in most competitive athletics. Eye black[8] has been used in competitive sports for decades to reduce the impact of glare, so the glare component of visual performance in athletics has been widely recognized by players and coaches. Glare disability has been found to be greater at shorter wavelengths (i.e. Flannagan, Sivak, Ensing, & Simmons, 1989) and these shorter wavelengths, in addition to comprising a large portion of sunlight, have been been incorporated into stadium lighting for decades to allow for improved filming (see Kühl, 1972). The most common method of achieving this short-wave heavy illumination with artificial stadium lighting today is the use of xenon lamps, but only recently have advances in LED technology made short-wave heavy (cool) white LEDs widely available in high intensities. Despite the low or moderate intensity long-wave sources used in most LED track systems for coincidence anticipation assessments avoiding the added variable of glare disability, this missing glare would be an expected part of much of the athletic performance modeled in coincidence anticipation. Consequently, to model the coordination of a motor response to a moving visual stimulus in most modern athletic competitions, having a stimulus which is

[8]A dark grease applied underneath the eyes for the reduction of glare (and psychological effects) in sports such as baseball, softball, football, etc.

high in both overall luminous intensity and short-wave energy may improve ecologic validity and be more representative of real-world conditions.

When attempting to any complex perceptual phenomena, it is worthwhile to attempt to decompose the perception into individually testable components. Given that coincidence anticipation timing involves elements of motor response and reaction speed, a simple reaction time assessment as well as an assessment of reaction time with a variable stimulus location may provide predictive insights into coincidence anticipation performance. If this coincidence anticipation is performed under glaring conditions or with a glaring stimulus, assessments of glare disability may prove useful in the decomposition of this phenomena. In addition, the amount of recovery from the glaring stimulus between trials could possibly be predicted by photostress recovery times, thus it warrants examination. Lastly, while the general visual processing speed of a subject may be difficult to quantify, the frequency of critical flicker fusion may be a suitable proxy measurement and has the benefit of being relatively easy to assess.

The following is a series of experiments conducted for the purpose of creating a predictive model for coincidence anticipation timing performance with a glare-inducing stimulus. In the first experiment, coincidence anticipation timing performance is assessed along with measurements of reaction time. By using the same equipment, the motor component of the response to these tasks is held constant, and the stimuli are directly comparable. In the second experiment, estimates of flicker sensitivity (taken as the threshold estimate for the frequency of a subject's experience of the fusion of flicker) with a stimulus of similar spectral composition to provide a predictive proxy measurement of global visual processing speed. In the third experiment, glare disability and photostress recovery are assessed, again using stimuli of similar spectral composition to the coincidence anticipation apparatus. These two measures, respectively, are attempts to predict the impact of the glaring nature of the target during and between trials. Test-retest reliability assessments will also be conducted for all of the measures. It would stand to reason that one should be able to expect that faster reaction speeds, higher flicker fusion thresholds, higher resiliency to glare and shorter photostress recovery times would each contribute to improved performance on a coincidence anticipation timing task with a glaring stimulus. Collecting such data on the same subjects allows comparison between measures to assess any individually predictive components of coincidence anticipation under glaring conditions, the possibility of a globally predictive model composed of all of these measures (or some subset of measures) and demonstrate the utility of a testing battery of practical instrumentation for exploratory research in visual psychophysics.

Chapter 4

Hypotheses

Assumptions For a coincidence anticipation timing (CAT) task, the following metrics are considered to be indicators of superior CAT performance when comparing two subjects under the same (velocity) condition:

1 Lower average absolute timing errors (i.e. the arithmetic mean of the absolute value of the difference between the subject's response time and the time at which the stimulus was coincident with the reference target).

2 Fewer missed trials (i.e. the number of trials in which the subject's motor response was late enough that the trial had finished and the stimulus had reached the end of the track).

Hypotheses Regarding data that will be collected:

Hypothesis 1 Using the intercept and slope coefficients of the Hick-Hyman law, derived empirically from average reaction times for both the fixed position (FRT) and variable position reaction time (VRT) tasks, performance on a coincidence anticipation task can be predicted, as both of these coefficients are expected to positively correlated with both average absolute timing error and number of missed trials.

Hypothesis 2 Critical flicker fusion (CFF) thresholds are a metric of visual processing speed (without the motor component of CAT, VRT, or FRT). As faster visual processing is expected to improve CAT performance, CFF thresholds are expected to negatively correlate with both average absolute timing error and number of missed trials.

Hypothesis 3 Average glare disability thresholds (i.e. the quantity of glaring light required to obscure a target for a subject) are expected to positively correlate to performance on a CAT task that uses a high-intensity stimulus. Average photostress recovery times (i.e. the duration after exposure to a photostress source required for a target to become visible again) are predicted to negatively correlate to CAT performance using a high-intensity stimulus. Higher glare disability thresholds and lower photostress recovery times are indicative of a greater resilience to the negative perceptual effects of high intensity light sources, and thus subjects with greater resilience to these effects should have less difficulty in performing a visuo-motor task with a glaring stimulus.

Hypothesis 4 The intercept and slope coefficients of the Hick-Hyman law (as described in hypothesis 1), CFF threshold frequency (as described in hypothesis 2), and average glare disability and photostress recovery times (as described in hypothesis 3) can be used additively to create a predictive model for CAT performance with a high-intensity stimulus.

Hypothesis 5 For all 5 metrics, test-retest reliability is high (i.e. Pearson's $r \geq 0.7$) between testing sessions.

Chapter 5

Experiment 1 - Coincidence Anticipation Timing and Reaction Timing

5.1 Introduction

The speed with which individuals are able to make motor responses to stimuli has been a historic mainstay of psychological research (e.g. Donders' 1869 account of mental processing speed was re-published in an English translation in 1969). Although initial psychological experiments with reaction timing reflect the field's divergence from physiology (e.g. Poffenberger (1912) mentions that understanding the speed of neural transmission is no longer the sole interest of the physiologist), the ability to provide an objective measurement of the speed of mental processing, even if indirectly, was eventually the driving factor for continued research in the area (e.g., Berkson, 1960; Broadhurst, 1958; Goodenough, 1935). As technological improvements allowed for the presentation of progressively more complex and sophisticated stimuli, so too did the precision of measurements improve. A robust model for the impact of number of possible target locations on the time required for a reaction was first proposed by W. E. Hick (1952) and then improved by Hyman (1953) to create the Hick-Hyman Law. This law models reaction time (T) as a function of the number of possible target locations (n) and an empirically determined slope coefficient (b).

$$\text{The Hick-Hyman Law: } T = a + b * log_2(n + 1)$$

Of particular interest in the above equation is the slope coefficient (b). Assuming simple (single target location) reaction timing is a proxy measurement of an individual's visuo-motor processing speed, b should be indicative of how well that individual can monitor multiple, discrete targets in parallel. When the targets in question are equal in size, luminance, spectral composition, etc. and are equally spaced, it would stand to reason b is a representation of how well one is able to monitor a restricted area of visual space for the appearance of a target.

If the Hick-Hyman Law slope coefficient is an indicator of one's ability to monitor visual space, it may be of use in predicting performance on a coincidence anticipation timing task. The most common method of measuring a subject's ability to anticipate coincidence involves an array of discrete stimuli with apparent motion generated over a linear pathway and a motor response used to indicate anticipated spatial coincidence between the moving stimulus and a stationary target (e.g., Petrakis, 1985; Molstad et al., 1994; Brady, 1996; Ripoll & Latiri, 1997; Benguigui & Ripoll, 1998; Millslagle, 2000; Ak & Koçak, 2010). Tracking a stimulus moving along a linear path to a predetermined target requires continuously updating the region of visual space that is being monitored (inclusively bounded by the stimulus and the target). Given that lower values of b are indicative of improved performance in monitoring larger areas of visual space for a reaction timing task, and there is a motor-reaction component to coincidence anticipation timing, b may correlate to one's performance in coincidence anticipation timing.

If one is investigating the relationship between the Hick-Hyman Law slope coefficient and coincidence anticipation timing performance, it would be desirable to keep as many stimulus characteristics between the anticipation timing and reaction timing tasks identical. Using the same equipment to generate both of the reaction timing tasks (as a minimum of 2 values of n are required to calculate b) and the anticipation timing task would be preferable. This would allow the motor response component to be held constant between all tasks as well as the visual properties of the stimulus (save the induction of beta motion in the anticipation timing task).

Given that much of the previous research on coincidence anticipation timing has been centered around either the prediction of (or making predictions from) athletic performance (e.g., Brady, 1996; Ripoll & Latiri, 1997; Millslagle, 2000) or attempts to isolate some of the perceptual components of athletic performance (e.g., Dunham Jr, 1977; Petrakis, 1985; Harrold & Kozar, 2002; Ak & Koçak, 2010), it would be inappropriate to overlook the practical applications of equipment capable of measuring both reaction time (whether with a single or multiple targets) and anticipation timing. Such an apparatus may be useful in comparing the visuo-motor performance of athletes for the purposes of selecting team members, identifying promising recruits, etc. In addition to diagnostic use, such equipment may be useful in training athletes for improved visuo-motor performance[1]. Reaction speed is important in the majority of competitive sports and coincidence anticipation with contrived stimuli would be expected to require the same mental faculties as those for striking or catching a moving ball. If b is correlated to anticipation timing performance, then it may be possible to improve performance on one task by training on the other or improve athletic performance by training for improved reaction time or anticipation timing.

For the purpose of exploring the potential relationship between coincidence anticipation and reaction speed (simple reaction speed, reaction speed with multiple target locations,

[1] A review of experiments testing the effects of practice on reaction time may be found in Laws Of Visual Choice Reaction Time (Teichner & Krebs, 1974)

and the Hick-Hyman Law slope coefficient), a custom-built electronic apparatus capable of performing reaction timing with a single or multiple targets as well as performing coincidence anticipation timing was constructed and an experiment was conducted.

5.2 Apparatus Overview

121 bright, cool-white LEDs were embedded into a track with 2 cm center-to-center spacing. The left-most LED was connected independently to a microcontroller while the remaining 120 were connected to 15 8-bit shift registers[2]. The independently connected LED was used as an indicator to mark the beginning of a new trial for the coincidence anticipation task while the remaining 120 LEDs were used for creating apparent motion for coincidence anticipation and for presenting a stimulus for the reaction timing tasks.

Subject responses were recorded via a button press. To improve timing accuracy for the responses, a hardware interrupt was used on the driving microcontroller. In contrast to the more common polling procedure to look for button presses (in which signals are searched for at regular intervals within the main control program), the use of a hardware interrupt allowed the main program to run until interrupted by a hardware signal. This abruptly halts the main control program, but allows for simple procedures (such as recording the time of a button press) to be performed with an extremely high degree of precision.

For all three tasks performed by this apparatus, data was output to a computer via a serial connection and was formatted during output into a table for the creation of a CSV file. The automatic data logging should eliminate experimenter error and reduce total testing time (in the hopes of minimizing fatigue effects) while the CSV format permits easier automatic processing of summary data for statistical analysis.

The apparatus was mounted on a wall with the LED track 66 inches above the floor and

[2]74HC595 parallel output shift registers via a Serial Peripheral Interface connection

subjects stand 68 inches[3] from the front surface of the track. A standard CAT-5 ethernet cable connected the push button used for CAT, VRT, and FRT responses by the subject to the microcontroller driving the device. Seed values for randomization were automatically selected by a combination of random electrical noise in the environment[4] and the time (in microseconds) at which the experimenter first provided serial input to the microcontroller.

5.3 Coincidence Anticipation Timing Functionality/Operation

After the experimenter explained the task to the subject, the CAT testing procedure began with a single low velocity (approximately 2.5 MPH) reference trial (which is not included in the data analysis) before normal testing begins. For each trial, the left-most LED is turned on to indicate a trial was about to begin and wass held on for a duration between 500 and 2500 milliseconds randomly selected from a uniform distribution. After this pre-trial delay, each LED wass turned on and held for a pre-determined delay before being turned off and the subsequent LED turned on. This method creates apparent motion of the light source toward (and then through) a target location on the track (corresponding to the 105$^{\text{th}}$ LED) marked with white tape (for contrast against the black housing of the LED track). After the final (i.e. right-most) LED is turned off, a post-trial delay of 1000 ms provided a brief recovery period for the subject to reduce fatigue effects. Trials in which response lagged sufficiently to where the final LED was illuminated before the response was recorded were treated as missing data for magnitude information[5].

[3] The subjects stood 72 inches from the wall onto which the track was mounted, but enclosure for the LEDs left the end of each LED 4 inches from the wall.

[4] Assessed using an analog-to-digital converter with no input.

[5] The current firmware does not allow timing to continue after the last LED has been illuminated, as continuing to keep time would interfere with the sub-routine which generates the smooth motion of the stimuli.

The length of the pre-determined delay for which each LED (after the first one) is kept on determines the apparent velocity of the light source. Four velocities (5, 10, 15, and 20 MPH) were used for 15 trials per velocity (for a total of 60 trials in addition to the initial low-velocity trial, which is discarded). The order of these trials was randomized[6] for each subject.

The time of the subject's button press (with a resolution of +/- 4 microseconds) was recorded and compared to the time of the "moving" light source first matching the target location (i.e. the "on" time for the LED). The numeric sign of the difference between these two times determines if the trial was "lagging" (subject response occurred after the target LED was illuminated) or "leading" (subject response occurred before the target LED was illuminated). The magnitude of the time difference between lag or lead is also recorded.

5.4 VRT Functionality/Operation

For the VRT task, the same track system and subject position was used as in the CAT task. 120 (all but the left-most) LEDs are used as potential target locations. After being instructed on how the task is performed, subjects were told that the position of the target was randomized between trials. After a pre-trial delay of 1000 to 3000 milliseconds, a randomly selected LED was turned on until a button press is detected. Upon the detection of a button press, the microcontroller calculated the time difference (with a resolution of +/- 4 microseconds) between the onset of the stimulus and the button press and turned off the LED at which point another randomized pre-trial delay began. After data collection, trials with reaction times of under 100 milliseconds (representing an errant button press prior to the beginning of the trial, as that is well under reasonable reaction time for the task) or

[6] To avoid straining limited memory resources on the microcontroller, a linear congruential generator (LCG) is used. The code for the LCG is a modification of code written by William E. Whiteside and used with permission.

over 500 milliseconds (representing either an attentional lapse or a button press that was insufficient to generate an appropriate electronic signal to be registered) were pulled from the dataset and then ending trials (in which fatigue is more likely) were removed until 150 trials remained for averaging.

5.5 FRT Functionality/Operation

For the FRT task, the apparatus and procedure used in the VRT task were repeated, but with a fixed position for the target location rather than a randomly selected target location. Instead of the variable position, the 105$^{\text{th}}$ LED (which corresponds to the target location for the CAT task) was always used. Post-collection data processing was identical to that in the VRT condition. Due to the stimuli intensity and spectra, as well as its consistent position, subjects in previous experiments have reported an afterimage after the FRT task, so it was performed after the CAT and VRT tasks to prevent visual after-effects from the FRT task altering performance on the CAT and VRT tasks.

5.6 Experiment 1

After being run through the informed consent procedure, subjects filled out a brief screener questionnaire to ensure they were free of visual or motor conditions which would likely influence the experiment as well as to screen for possible safety concerns (i.e. epilepsy). The purpose and design of the experiment were explained to them (there was no deception or blinding to conditions). Subjects in this experiment were also in experiments 2 and 3, and each subject was tested on two separate occasions 20-48 hours apart.

12 subjects (n=12) were tested for this experiment (and experiments 2 and 3). Subjects had an average age of 25.6 years and the sample was 75% female. At each of the two testing

sessions, subjects were first tested using the previous described CAT routine. After CAT testing, each subject was tested using the previously described VRT routine and approximately 160 trials were collected (which was trimmed during analysis to an even 150 for every subject after filtering). After VRT, the subjects were tested through the previously described FRT routine for approximately 160 trials (which, again, were trimmed during analysis to an even 150 for every subject after filtering).

The processing of coincidence anticipation timing data (even prior to statistical analysis) presents several challenges. The current firmware for the aforementioned apparatus records trials in which the subject's response occurred after the last LED in the track was illuminated as being missing. Because of this, missing trials can be treated as "lagging" trials, but there is no corresponding magnitude data to accompany them. Data may be subset into individual velocities (or some combination of velocities) or aggregated together. Additionally, unless trials are independent (which is almost certainly an inappropriate assumption) there exists the possibility of subject responses being related to not only the velocity of a given trial, but the velocities of the trials before it. Ultimately, the testing routine in any coincidence anticipation timing paradigm is a series of compromises. Randomizing velocities likely biases subject responses toward a lagging or leading response depending on whether the current trial's velocity is lower or higher (respectively) than the previous trial, but failing to randomize velocities increases the risk that the task becomes a direct analogue to a simple reaction timing task. A small number of trials increases the influence of early observations in which the subject is not yet acclimated to the task, but a large enough number of trials will induce a fatigue effect. The aforementioned testing routine for coincidence anticipation timing is referred to by the author as the Georgia Paradigm (named after the University of Georgia) and represents one possible set of compromises in the pursuit of a better understanding of a complex visuo-motor phenomena.

Ideally, data from these measures would have been compared to previous experiments using the same equipment, but this presented several issues. First, in previous experiments with the same equipment, test-rest sessions were substantially further apart (usually on the order of months). Secondly, the number of trials for both reaction timing tasks were substantially lower (usually around 80) in previous experiments. Thirdly, in previous experiments, the order of the reaction timing tasks was typically reversed (VRT before FRT). Consequently, subjects in previous experiments would likely have afterimages from the FRT task increasing their average VRT, while in this experiment, fatigue from a long VRT testing session is likely to have increased FRT averages. Finally, in previous experiments with matching equipment, the majority of the subjects were either younger (i.e. an primarily undergraduate population of 18-22 year olds) or far older (i.e. over 50) or were special populations (e.g. athletes or subjects suffering from Alzheimer's Disease or other neuro-degenerative conditions).

Chapter 6

Experiment 2 - Flicker Sensitivity

6.1 Introduction

Although it is difficult to identify the origins of the study of flicker sensitivity in the human visual system (as initial studies of such phenomena arose in "natural psychology" before the advent of modern science), psychophysical investigations into flicker sensitivity were being conducted in the 19th century (e.g., Sherrington, 1897; Grünbaum, 1897). Flickering and otherwise temporally varying visual targets had been created prior to the advent of motorized stimuli (an annotated bibliography of publications of flicker fusion phenomena beginning in 1740 can be found in Landis, 1953), but controlling such targets with a high degree of precision was prohibitively difficult. With the spread of electric motors into laboratories, it became possible to create sectored discs (a.k.a. choppers) and sectored mirrors to interrupt or alternate the channels of an optical system presented to the subject. The speed of the produced flicker in such systems can be controlled by changing the disc (or mirror arrangement), changing the gearing of the motor, or adjusting the speed of the motor. Despite these first two methods changing the produced flicker frequency in a very predictable fashion, adjusting the frequency usually requires stopping the experiment to make mechanical adjustments (the issue of having a set number of discrete flicker settings available is discussed by Ferree & Rand, 1925). By adjusting the motor speed, flicker frequency can be changed both on-demand (without having to stop the experiment) and over a continuous range which permits a wider variety of threshold estimation procedures (e.g. the method of adjustment).

With the advent of precision electronic controls for producing flicker, psychophysical investigations of flicker sensitivity were more readily able to branch into a wide variety of topics such as examinations of sensitivity between different retinal eccentricities (e.g., Creed & Ruch, 1932), adaptation effects in flicker sensitivity (e.g., Craik, 1940), flicker sensitivity by spectral composition (e.g., Riggs, Berry, & Wayner, 1949) and even investigations of flicker sensitivity in non-human animals (e.g., Crozier, Wolf, & Zerrahn-Wolf, 1937). Eventually, psychophysical investigations into flicker sensitivity largely settled on using thresholds of critical flicker fusion (CFF), the phenomena of flicker ceasing to be detectable by a subject after a certain threshold frequency (for a thorough review of many early experiments in critical flicker fusion, see Landis, 1954). For a period in 1960s, there was extensive interest in CFF thresholds as a dependent variable in examinations of and experiments with individuals with psychiatric health issues (in particular, CFF was used widely to investigate schizophrenia such as King, 1962; Clark, Rutschmann, Link, & Brown, 1963; Clark, Brown, & Rutschmann, 1967; Watson, Thomas, Felling, & Andersen, 1969). Given the comparative ease of estimating CFF thresholds over other measures of temporal vision, this focus on special populations is unsurprising and is reflective of a trend to attempt to integrate psychophysical measurements into clinical assessments as both the body of prior research and the availability of suitable instrumentation increases.

Clinical assessments of CFF thresholds have typically focused on either identifying (or quantifying) a pathology or comparing broad effects of psychopharmaceutical treatments. Group differences in CFF thresholds have been examined to differentiate normal aging from age-related degenerative neurological disorders. (e.g., Goldenberg, Wimmer, Auff, & Schnaberth, 1986; Curran, Wilson, Musa, & Wattis, 2004). Flicker sensitivity has been suggested as a method for identifying visual pathologies (most commonly progressive degenerative visual disorders) for several decades (e.g., Tyler, 1981; Tyler, Ernst, & Lyness, 1984; Falsini et al., 2000). Examinations of CFF thresholds are commonly used to compare the degree of excitation or inhibition of the central nervous system between different drugs or examine dosage-effect relationships (e.g., Turner, 1968; Hindmarch & Parrott, 1977; Grundström, Holmberg, & Hansen, 1978) Given that CFF threshold estimates in clinical settings are most commonly used as proxy measurements for central nervous system activity, hardware for these assessments needs to be precisely controllable and highly stable over time. A high degree of stability through the duration of a clinical trial or between testing sessions in a normal clinical environment improves the reliability and sensitivity of these threshold estimates.

The use of flicker fusion as a non-invasive, proxy measurement for processing speed in the central nervous system (e.g., McGuire, 1958; Berchou & Block, 1983) permits both the comparison of individuals to themselves over time (or under different experimental conditions) and the comparison of individuals to one another. Beyond the traditional clinical applications, CFF may be a reasonable parameter for the deconvolution of visual processing speed from performance in certain visuo-motor tasks. If CFF correlates with a complex visuo-motor task (e.g. coincidence anticipation timing) it may be possible to control for the effects of visual processing speed statistically and, in conjunction with other reaction timing measures (to allow for analogous control for motor processing speed) isolate the mental processes specifically associated with performance on that visuo-motor task.

6.2 Hardware Overview

Hardware used in this experiment for measuring CFF was custom-built to provide high-brightness white stimuli of similar spectrum to the CAT/VRT/FRT testing equipment (as well as the equipment in experiment 3)[1]. The apparatus was driven using 3 microcontrollers. A master microcontroller communicated with the two slave microcontrollers as well as the user interface on a traditional computer. For subject input, a slave microcontroller was used to detect changes to a rotary encoder as well as two push buttons (only one of which was used for this experiment).

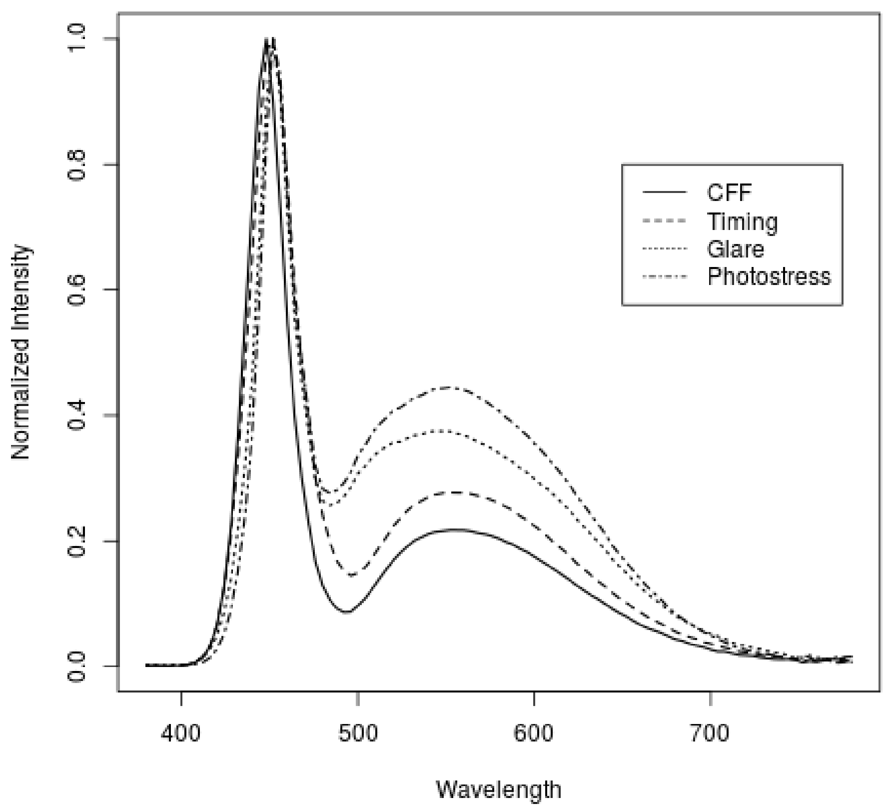

Figure 6.1: Spectral Comparison of Testing Apparati

[1]See Figure 6.1 for a spectral comparison of apparati.

For the stimuli production, another slave microcontroller was used to toggle the lines of an AND gate connected to a transistor driving the LED ring. One of two input lines of the AND gate was fed a signal from the microcontroller corresponding to the selected flicker frequency (software limited from 0.25 Hz to 100.00Hz) and the other received a high-frequency (approximately 1KHz) 8-bit pulse-with modulation[2] (PWM) signal used for brightness control. In this configuration, the LEDs were in their on-state only when both lines were high, meaning that while the visible flicker line was held low, the LEDs were off, and while it was held high, the LEDs toggled at at a frequency well outside of visual detection to create a stable but adjustable luminance.

The LED ring used to create the stimulus was built into a circuit board which was attached to an acrylic diffuser[3] using bolts. The distance between this diffuser and the LEDs was carefully adjusted under light tension (provided by small segments of vinyl tubing placed on the shaft of the bolt) to create a uniformly illuminated surface. This was then masked by a piece of acetate, painted matte black, to create a circular target. A 52mm hole was placed in this acetate prior to painting (along with holes to accommodate the mounting bolts) to create a 1 degree diameter target at a viewing distance of 30 cm. This diffuser-circuitry assembly was mounted into an acrylic frame onto which an eyepiece was mounted to hold a 3 mm diameter artificial pupil and ensure a 30cm viewing distance. The artificial pupil was made from a thin sheet of copper-laminated fiberglass[4]. A second ring of (identically controlled) LEDs was also included in the construction of the equipment, but the internal reflector geometry of the LEDs necessitated that the distance of the diffuser be increased, meaning both LED rings had overlapping projections. Thus the mask on the diffuser was modified to only permit a single stimulus, which had the unfortunate side effect

[2] Pulse-width modulation is a method of switching a constant voltage supply on and off to create an adjustable duty cycle voltage source.

[3] Light diffusion was created on the acrylic with repeated passes from a random orbital sander.

[4] This material is identical to that traditionally used in making circuit boards except the fiberglass layer is substantially thinner.

of eliminating the possibility of using certain threshold estimation methodologies.

A device of similar functionality was constructed previously for experimentation with infants. In that device, two channels of LED rings were controlled by a microcontroller with both flicker and brightness control, but instead of the use of an AND gate to drive a single transistor, two transistors in series were driven independently. This has the unfortunate side-effect of doubling the voltage drop across the transistor and is not recommended for use by anyone considering this against the AND gate method for creating CFF testing hardware.

6.3 Firmware Overview

Since the input device only handled subject input, the firmware was rather minimal. The state of both buttons were polled in a continuous loop and changes in the rotation of a rotary encoder were handled using a hardware interrupt routine (which would prevent adjustments from being missed). When requested by the master controller, the slave input controller would send two bytes to indicate the magnitude and direction of rotation of the rotary encoder as well as which, if any, of the buttons had been pressed since the last request.

The master controller would poll the slave input device at regular intervals, and if a change was detected, relay this back to the experimenter's user interface over a serial connection. Any changes to the stimulus (whether in response to adjustments made by the subject or ones made by the user interface for the experimenter) were received by the master controller and relayed to the slave stimuli controller. Despite this arrangement slightly increasing the delay between a subject's adjustment and the stimuli's response, it allows for improved modularity in future experiments, hot-swapping[5] of input devices, and allows for modular replacement of components in the event that hardware is damaged. This method of separating hardware and serial inputs from stimulus production also minimizes interference with the generation

[5] Adding, removing, or replacing hardware while a device is in use.

and maintenance of precision flicker.

The slave controller driving the stimuli LEDs used a timer interrupt to precisely toggle a digital line (one of the ones connected to the AND gate driving the LEDs' transistor) at an adjustable frequency. This provides the advantage of removing flicker control from the main loop, allowing the main loop to continuously search for instructions from the master controller to alter frequency or brightness. Brightness control was performed using the microcontroller's onboard PWM abilities and allow the experimenter to precisely set a stable brightness.

Each microcontroller's firmware was written to minimize computational intensity (which is easier to handle in the experimenter's GUI) and respond as rapidly as possible. This approach to developing psychophysical instruments, in contrast to previous attempts minimize GUI development by having more extensive firmware, shows promise and is likely to allow for the production of superior testing equipment in the future. While there is a certain appeal to the simplicity of stand-alone embedded systems for vision testing equipment, increased difficulty in development and a lack of portability of the collected data (especially in comparison to any computer-based method which allows for data to be easily saved) will outweigh the drawbacks in many situations.

6.4 Interface Overview

A custom-made graphic user interface was developed for use with this equipment. The GUI allows the experimenter to rapidly control the target's brightness and flicker frequency as well as turn it off (or on without flicker, which is useful for taking calibration measurements). The master controller has bidirectional communication with the GUI. This allows the master controller to send information regarding the state of the buttons and any rotational information from the subject's controls to be sent to the GUI, and for a selection in the GUI to allow the incrementation (decrementation) of the flicker frequency of the target to be changed to 1.00Hz, 0.10Hz, and 0.01Hz per detected change of the rotary encoder. When a button press to indicate the satisfaction of a threshold condition is detected by the GUI, it turns off the target and outputs stimuli variables (i.e. frequency, PWM value, system time at which the button press was detected, etc.) to a CSV file for storage.

6.5 Experiment 2

After the testing from experiment 1, the same subjects were given instructions explaining how to use the CFF testing apparatus. The stimulus was set to a PWM value corresponding to approximately 4000 lux[6]. Measurements were taken using the method of limits with alternating ascending and descending thresholds. For ascending thresholds, subjects were instructed to increase the frequency until the stimulus first appeared to fuse (and if they felt they had exceeded that threshold, to back the frequency down until flicker was detected and slowly adjust until the point of fusion). For the first ascending trial, the starting frequency for each subject was set to 20 Hz (a value well below expected thresholds for young, healthy subjects with a stimulus) and for subsequent ascending trials the starting frequency was set to an arbitrary value at least 15 Hz below their last descending threshold. For the first descending threshold, the starting frequency was set either to 60 Hz or a value of at least 15 Hz above their first ascending threshold. Subjects were instructed decrease the frequency until flicker was first apparent, and if they believed they had exceeded this first flicker frequency, to increase the frequency until fusion was detected again and decrease the frequency more slowly. For subsequent descending thresholds, the starting frequency was set to an arbitrary frequency of at least 15 Hz above the subject's last ascending threshold. Subjects were tested for a total of 10 trials for each of the two testing sessions (with 5

[6] As measured with a Photo Research SpectraScan PR-650

ascending and 5 descending trials).

Subjects were instructed to blink several times after they felt the ascending or descending threshold condition was met to minimize any possible effects from afterimages or flicker adaptation. Subjects wore an eye patch over their left eye and made judgments with their right eye. The height of the equipment and the height of the subject's seat was adjusted as necessary to ensure comfortable viewing of the stimulus.

Chapter 7

Experiment 3 - Glare Disability and Photostress Recovery

7.1 Introduction

Though visual psychophysics often concerns the minimum limits of human perception, quantifying visual performance at the upper limits of stimulus intensity presents a different challenge. With improvements in artificial lighting (i.e. the advent of bulbs which could produce stable, high intensity light for long enough durations to be practical in a laboratory settings), it became possible to examine the impacts of glare and photostress, which previously would have been experienced only in uncontrolled, natural settings. The comparatively lower intensities of light required (and thus lower technological barriers) for assessing glare disability may explain why it was readily studied well in advance of photostress recovery (e.g. glare disability was being modeled in the 1920's (see Stiles, 1929) while photostress recovery studies largely began in the 1960's as the phenomena of "flash-blindness", experienced after witnessing explosions, was better understood (e.g., Severin, Alder, Newton, & Culver, 1963; Severin, Newton, & Culver, 1963)).

Glare disability occurs when the presence of a high intensity light source (typically sunlight, vehicle headlights, stadium lighting, etc.) prevents an individual from resolving sufficient visual detail in a scene (during naturalistic viewing) or a target (during testing conditions). In contrast, photostress occurs when a brief exposure to high intensity light causes a disruption of normal photopic vision for some period of time before the visual system recovers (this period being the "photostress recovery time"). From a photochemical perspective, a photostress event is analogous to an extreme glare event. An obtrusive light source at intensities sufficient for glare will cause a veiling scatter in the eye that reduces contrast and diminishes visual discrimination (when this intensity is just sufficient to eliminate the discrimination of a target, the glare disability threshold has been reached). The same obtrusive light source, above some particular intensity, will dissociate (or "bleach") photopigments faster than they can be regenerated. If the product of intensity and time (more specifically, the integral of intensity over time) is high enough, nearly all of the photopigment will be dissociated and some duration without this exposure (the photostress recovery time) will be required for the photopigments to regenerate and vision to return to the levels required to detect or discriminate a stimulus. As a result, if a photostress source can be run for long durations and at a reduced intensity, it should be sufficient for the creation of a glare source.

The majority of glare disability research is focused on clinical issues that increase a patient's susceptibility to glare. Most prominent among these are intraocular lens implantation (e.g., Nadler, Jaffe, Clayman, Jaffe, & Luscombe, 1984; Koch, Emery, Jardeleza, & Franklin, 1986; Masket, 1989) and corneal surgical procedures (e.g., Ghaith, Daniel, Stulting, Thompson, & Lynn, 1998; Wachler, Durrie, Assil, & Krueger, 1999). More recently, there has been an increased interest in the impact of glare disability on driving performance (e.g., Shinar & Schieber, 1991; Babizhayev, 2002; Gray, Perkins, Suryakumar, Neuman, & Maxwell, 2011). Glare disability is of particular importance to driving ability in the elderly and in individuals who have undergone corneal or lens surgeries, but reduced driving performance from glare is a potential safety issue for all drivers.

Photostress recovery research is comparatively scarce (which is unsurprising, as glare is experienced in natural settings far more frequently than photostress) but published research primarily focuses on recovery times in individuals with retinal health issues such as macular degeneration (e.g., Sandberg & Gaudio, 1995; Wolffsohn et al., 2006) and glaucoma (e.g., Sherman & Henkind, 1988; Horiguchi, Ito, & Miyake, 1998). The advent of improved methods for generating photostress testing sources that are lacking in the potentially hazardous infrared and ultraviolet which would have been present in traditional halogen and xenon sources may aide in the expansion of photostress research. LED-based systems are now capable of producing the high intensities of visible wavelengths required for photostress testing without many of the energetic drawbacks (i.e. spectral emission outside of desired wavelengths, heat production, and power consumption) of older lighting technologies and have begun to emerge in photostress testing research (e.g., Stringham, Garcia, Smith, McLin, & Foutch, 2011) as a result. With the goal of improving the accessibility of equipment for both glare and photostress testing, a novel apparatus was developed.

7.2 Hardware Overview

A custom apparatus for assessing glare disability and photostress recovery time was created to provide sufficient intensity of light and a uniform spatial distribution with minimal reliance on optics. A microcontroller provided a PWM signal to permit the glare and photostress sources to be held at an adjustable intensity for any needed duration while maintaining a high degree of linearity and stability in adjustment. For the glare source, a ring of 47[1] high-intensity cool-white LEDs were placed on a circuit board with a viewing hole in its center. Following the geometric guidelines of Moreno, Avendaño-Alejo, and Tzonchev (2006), the

[1]Spacing was equivalent to a 48 LED design, but one LED was removed to allow a ground connection trace to be made without the addition of wire.

110 degree beam-angle LEDs were arranged in a circular pattern with a 20 mm radius to create a plane of uniform illumination at the pupil when held approximately 25.5 mm from the subject's pupil. The photostress source was created by using 45 of the same high-intensity cool-white LEDs arranged in an approximately square pattern[2] with 5 mm center to center spacing of the LEDs. The arrangement was used to create a uniform illumination pattern on an acrylic diffuser[3] which was apertured and placed placed in the path of a beam-splitter[4] for the subject to view. The driving microcontroller was given commands over a serial connection to coordinate the intensity of the glare and photostress sources with a custom-made program that also produced visual targets for the subject.

7.3 Software Overview

The control software was written in Processing[5] to allow visual targets generated on a computer monitor to be coordinated with serial commands sent over USB to the microcontroller driving the glare and photostress sources. Targets were generated procedurally (rather than being pre-rendered images) to allow the experimenter to select testing conditions by editing a configuration file. The glare target consisted of two square gratings with a radial alpha gradient[6] tilted 45 degrees from vertical (one tilted left and one tilted right) which alternated at 0.5 Hz to minimize adaptation and fatigue effects. The same targets were used for photostress recovery testing, but were either oriented "left" or "right" and did not alternate (other than in the randomization between trials).

The glare disability testing routine allows the subject to adjust the intensity of the glare

[2] The arrangement was 5 rows of 7 LEDs with a row of 5 LEDs on each side. This was done to soften any luminance corners.

[3] Light diffusion was created on the acrylic with repeated passes from a random orbital sander.

[4] This was accomplished with a short series of lenses. While a lens-free set-up would be desirable, this arrangement avoided the need to move the photostress source between trials.

[5] Processing is a Java derivative.

[6] This configuration loosely approximates a Gabor patch but permits greater control over contrast than would be possible with a sine grating.

source using a mouse. While a slider-bar was available, more precise adjustment and more intuitive adjustment for the subject was achieved using the scroll wheel of the mouse. In the glare disability testing routine, when the spacebar key was pressed, the luminance of the glare source was halved and the PWM value at the time of the key press, along with configuration information for the stimulus and current system time, was sent to a CSV file for storage.

The photostress recovery testing routine consisted of turning on the photostress source for a pre-defined duration when the subject indicated they were ready to begin a trial (via a press of the space bar key), then turning the source off, starting a timer, and placing a grating on screen. While otherwise identical (unless configured differently by the experimenter) to the glare disability testing grating, the stimulus for the photostress recovery testing routine did not alternate in orientation but remained static. It was randomly tilted left or right. When a subject indicated they were able to correctly detect the direction of the tilt of the grating (by pressing the respective arrow key on the keyboard) the timer stopped, a text prompt appeared on screen, and recovery time as well as stimulus settings and current system time were written to the same CSV file as in the glare disability testing routine.

7.4 Experiment 3

Glare disability and photostress recovery assessments were be performed using the same 12 subjects from experiments 1 and 2. Testing was performed on two occasions per subject. For both the glare disability and photostress recovery testing tasks, the subject was seated approximately 60 cm from a Dell 1703FP monitor. First glare disability testing was performed using the right eye, then photostress recovery testing was performed using the left eye. While ideally glare disability and photostress recovery testing would be performed using the same eye, the use of alternating eyes offered two advantages. First, the glare disability and photostress recovery testing sources could both remain stationary during testing and this minimization of mechanical disturbance reduced risk of damage to the equipment or fluctuation of intensity for either source from expected values. Secondly, this method allowed for quick testing without glare disability testing biasing initial photostress recovery times via photobleaching.

During glare disability testing, the subject was presented with a target comprised of alternating right and left tilted square gratings (of approximately 9.25 cycles per degree with a software setting of 4.75% Michelson contrast). The target was viewed through the free-view glare source and, using the scroll wheel of a mouse, the subject adjusted the intensity of the glare source until the target was no longer visible before indicating this with a keyboard button press. The glare intensity (recorded as the PWM setting[7]) was output to a file, the glare source was reduced in brightness by 50% (to avoid jarring luminance changes but ensure the brightness had been reduced to sub-threshold values), and the next trial began. Subjects were told that any time they could reduce the intensity (even down to fully off) of the glare source if they had lost sight of the target location. Glare disability testing was performed using the subjects' right eyes and, during each of the two testing sessions, four trials were conducted.

Photostress recovery testing was performed after glare disability testing (in part because photostress recovery testing after-effects are more likely to taint glare disability assessments and in part because, of the two tasks, photostress recovery testing is more likely to leave the subject with the sensation of visual fatigue or discomfort). For photostress testing, the subject was exposed to the photostress source measured at 1000 lux from a distance of 10cm[8] for 8000 ms through a beam-splitter and timing begans after the photostress source

[7]Maximum intensity could not be measured due to the geometry of the source and the available equipment, but is expected to be of similar magnitude to the photostress source. Previous assessments of the circuitry used to adjust luminance have shown the PWM values to correspond linearly to photometric readings with precision that meets or exceeds the measurement capability of available equipment.

[8]As measured with a Photo Research SpectraScan PR-650.

was turned off and a target was drawn on the monitor. Subjects were instructed to keep the eye open for the entire photostress exposure time. The target was either a right or left tilted square grating (identical to that used in glare disability testing, but static rather than alternating) and recovery time was determined by the duration between the end of the photostress exposure and the time at which the subject presses a key corresponding correctly to the direction of tilt of the target. Subjects were instructed not to respond before they were able to determine the direction of tilt. After making a correct decision, the target was removed from the screen and text instructions appeared. Subjects were instructed to begin the next trial as quickly as possible after the end of each previous trial. Photostress recovery testing consisted of five trials during each of the two testing sessions for each subject.

Chapter 8

Results

8.1 Test-Retest Reliability

All five collected predictor variables (VRT, FRT, CFF, glare disability, and photostress recovery) demonstrated a high degree of test-retest reliability. While a summary of the reliability statistics for each of these tests can be found in Table 8.1, an interesting trend can be found by examining each of these measures independently.

Table 8.1: Test Retest Reliability For Predictor Variables

Measure	r	p
VRT	0.89	< 0.001
FRT	0.96	< 0.000001
CFF	0.85	< 0.001
Glare	0.92	< 0.0001
Photostress	0.85	< 0.001

In figures 8.1-8.5 results from the first testing session are visible on the x-axis and results from the second testing session are visible on the y-axis. The thick, solid line represents the best fit linear regression line (the equation of which can be found above each plot along with fitness statistics) and the thin, dashed line represents a hypothetical 1:1 correspondence between testing sessions.

Average variable position reaction times for the second testing session were lower than the first testing session for the majority of subjects (as can be seen from the number of observations below the dashed line). This is indicative of generally improved performance within the sample between the two sessions.

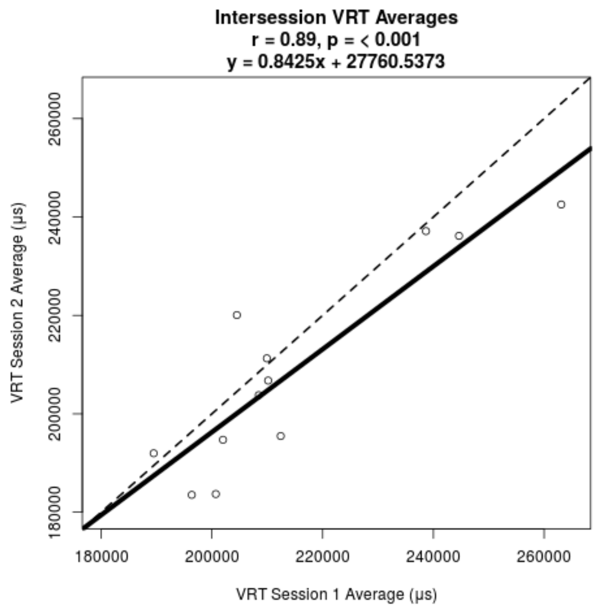

Figure 8.1: Test-Retest Reliability for VRT

Average fixed position reaction times for the second testing session were slightly lower than the first testing session for the majority of subjects (as can be seen from the number of observations below the dashed line). The closer correspondence of averages between the two testing sessions may indicate that fixed position reaction times were close to minimum possible average values for each subject even at the first testing session, and practice effects were likely smaller.

Average critical flicker fusion threshold frequencies for the second testing session were higher than the first testing session for the majority of subjects (as can be seen from the number of observations above the dashed line). An increase in the fusion threshold frequency for a subject is classically considered to be an "improvement", as higher threshold frequencies

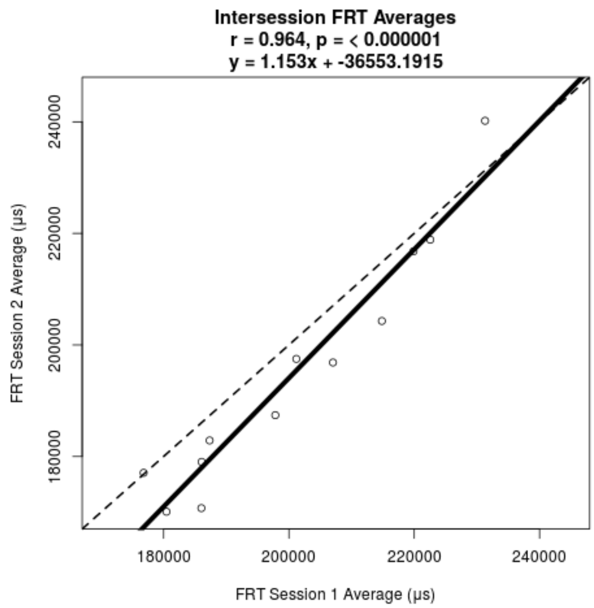

Figure 8.2: Test-Retest Reliability for FRT

are typically considered to be indicative of a faster visual system and a reduction in flicker sensitivity is associated with depression of the central nervous system.

Average glare disability brightness thresholds for the second testing session were higher than the first testing session for the majority of subjects (as can be seen from the number of observations above the dashed line). This is indicative of generally improved performance within the sample between the two testing sessions.

While photostress recovery times were the least related between all five of the predictor measures, test-retest reliability was still quite high. Average recovery times for the second testing session were lower than than the first testing session for the majority of subjects (as can be seen from the number of observations below the dashed line).

For all five of the predictor variables, the test-retest reliability was quite high and the most common change between testing sessions was in the direction of improved scores (either reduced times or higher thresholds). High test-retest reliability, such as in these measures, is

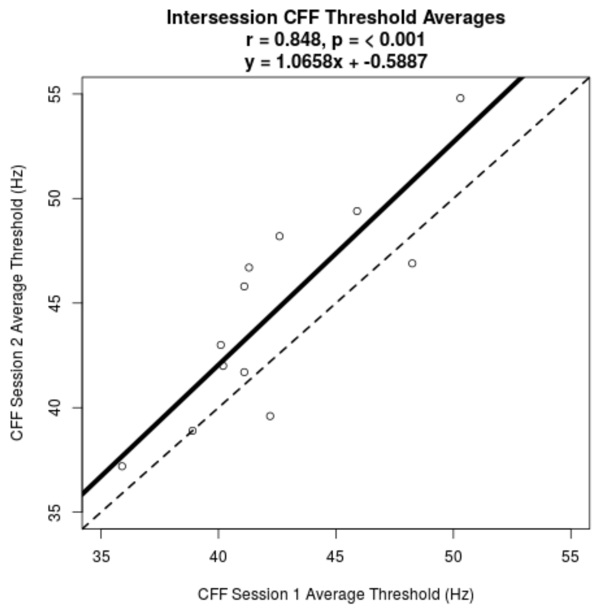

Figure 8.3: Test-Retest Reliability for CFF

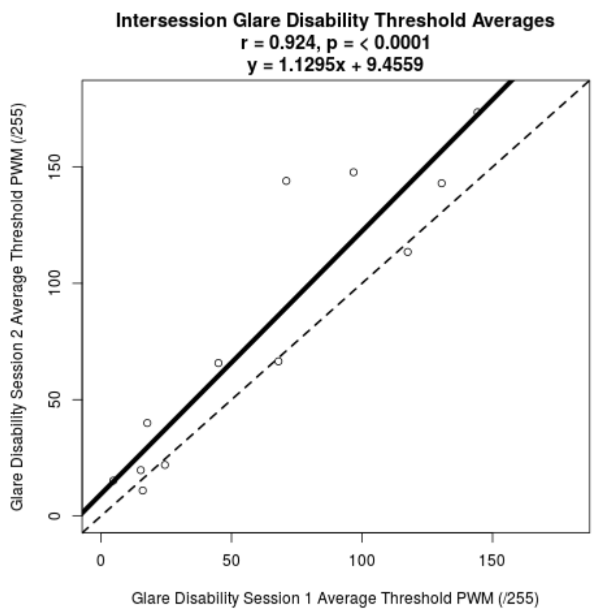

Figure 8.4: Test-Retest Reliability for Glare

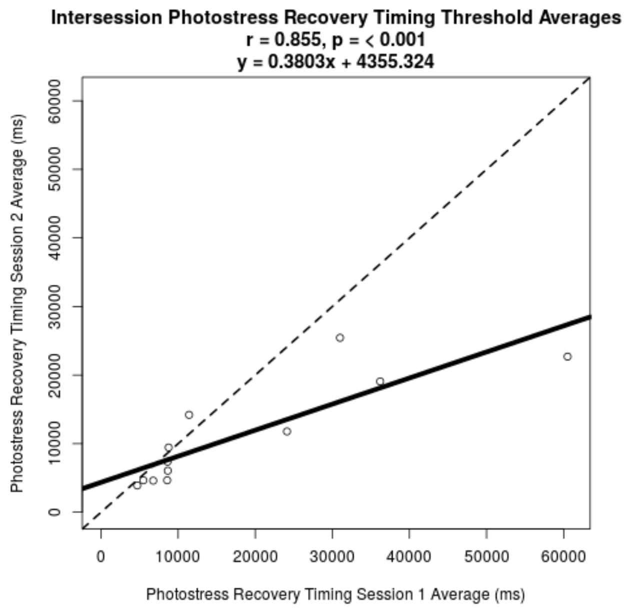

Figure 8.5: Test-Retest Reliability for Photostress

essential for any such measure to be suitable for a clinical environment or broader research use.

Coincidence anticipation timing scores are more difficult to assess for test-retest reliability metrics, as there are multiple velocities and the missed trials being treated as missing data creates an interesting effect. With regards to average timing error, as seen in Table 8.2, test-retest reliability decreases as velocity increases. Beyond performance differences, this may be a statistical artifact of the missed trials being treated as missing data. With regards to average number of missed trials, as seen in table 8.3, test retest reliability increases as velocity increases. Missed trials were virtually nonexistent in the 5 MPH condition (between both testing sessions and all subjects, only a single 5 MPH trial was missed). It is worth noting that test-retest reliability correlations for missed trials were calculated using Spearman's ρ instead of Pearson's r because the number of missed trials was discrete (while average timing error was continuous). This inverse pattern between these two test-retest reliability metrics suggests that some, if not most, of the reduction in test-retest reliability for average timing error is caused by missed trials being treated as missing data. Future iterations of the control firmware should be revised to address this issue.

Table 8.2: Test-Retest Reliability Of Average Timing Errors By CAT Velocity

Velocity	r	p
5 MPH	0.85	< 0.001
10 MPH	0.66	< 0.05
15 MPH	0.28	Not Sig.
20 MPH	0.56	Not Sig.

Table 8.3: Test Retest Reliability By CAT Velocity For Missed Trials

Velocity	Spearman's ρ	p
5 MPH	NA	NA
10 MPH	0.55	Not Sig.
15 MPH	0.58	< 0.05
20 MPH	0.89	< 0.0001

Test-retest reliability for the coefficients of the Hick-Hyman Law were reasonably high (the intercept was quite high, though slope was lower) and both were statistically significant (these values can be seen in table 8.4).

Table 8.4: Test Retest Reliability Of Calculated Hick-Hyman Law Coefficients

	Coefficient	r	p
1	Intercept (a)	0.94	< 0.00001
2	Slope (b)	0.67	< 0.05

8.2 Inter-assessment Relationships

Given the number of relationships being assessed within this dataset, inter-assessment correlations were assessed only using inter-sesson averages to reduce the probability of spurious correlations. Any true relationship between variables was assumed to be identifiable despite this limitation. As with any small sample size experiment (despite the fact that the data collected consisted of over 750 trials per subject) a conservative approach is advisable in interpreting any test statistics.

While the Hick-Hyman Law intercept coefficient for subjects correlated moderately ($r=0.65$, $p<0.05$) with average absolute timing error at 5 MPH, the slope coefficient did not and neither the intercept nor slope coefficient meaningfully correlated with any of the other velocities tested. Likewise, while the Hick-Hyman Law slope coefficient for subjects correlated moderately ($\rho=0.60$, $p<0.05$) with the number of missed trials for the 15 MPH condition, the intercept coefficient did not and neither the slope nor intercept coefficient significantly correlated with any of the other velocities. It is likely that both of these metrics, while being statistically significant, are spurious and if there is any actual relationship between the Hick-Hyman Law coefficients and CAT performance, it is not detectable in the CAT and reaction time testing methods used in this experiment.

At the risk of relationships between CAT performance and average VRT or FRT being missed by the arithmetic transformation of the Hick-Hyman Law, average intersessio VRT and FRT were compared to intersession CAT performance within each velocity. While average FRT and VRT did moderately correlate with average absolute timing error in the 5 MPH condition ($r=0.67$, $p<0.05$, and $r=0.63$, $p<0.05$), given that these variables did not correlate with performance on any other velocities, and absolutely no meaningful correlation between number of missed trials and FRT or VRT could be found, it is likely that these are spurious as well.

Intersession average critical flicker fusion threshold frequencies did not significantly correlate to intersession average CAT errors for any of the 4 velocities nor did they significantly correlate to the number of missed trials. Intersession average glare disability thresholds correlated moderately ($r=-0.62$, $p<0.05$) with average timing error for the 20 MPH condition, but given that there was no significant correlation with any other velocity, nor did glare disability correlate with the number of missed trials, this relationship is likely spurious. Average intersession photostress recovery times did not significantly correlate with either the average timing error nor the number of missed trials for any CAT velocity. Surprisingly, glare disability thresholds and photostress recovery times did not exhibit a correlation in inter-session averages (r=0.16, p=0.61).

Given the broad lack of correlation between either the average absolute timing error or average number of missed trials for every predictor variable tested at nearly every (if not every) velocity, no coherent predictive model for coincidence anticipation timing under glaring conditions can be made from this dataset.

Chapter 9

Conclusions and Future Directions

Ultimately, while test-retest reliability was high, there was no compelling evidence to suggest that any of the selected predictor variables are capable of predicting coincidence anticipation timing under glaring conditions. While there exists the possibility that an effect exists but the sample size in these experiments was insufficient to detect it, coincidence anticipation timing may be more related to some visual, motor, or visuo-motor phenomena not examined in these experiments than any of the aforementioned predictor variables. All previously stated formal hypotheses (save Hypothesis 5, concerning test-retest reliability) are considered to be unsupported.

If future experimentation is to be continued in this vein, a method of testing for coincidence anticipation timing which does not result in "missed" trials is likely a necessity, as evidenced by the seemingly complementary reliability statistics in tables 8.2 and 8.3. Likewise, the total number of trials per velocity for CAT testing likely warrants increases, especially if a large number of reaction timing trials are going to be used for a comparison. It is advisable to, whenever possible, ensure that glare disability and photostress recovery testing, if they're to be compared to one another, are either performed in the same eye or are both tested binocularly, as the lack of correlation between the two measures in this sample was unexpected and may have been influenced by any between-eye differences in optical aberrations of the subjects.

While the use of the Hick-Hyman Law in examining the two reaction timing tasks did allow for an alternative interpretation of the reaction timing data, the arithmetic transformation that can be performed with two conditions is likely of less use than the statistically derived results one would have from 3 or more conditions. Therefore it is recommended that in future experiments the use of this lens for viewing data be reserved for more complex reaction timing batteries.

The custom coincidence anticipation timing equipment (or, preferably a future iteration with improved firmware) should be compared to the commonly used Bassin Timer system to attempt to isolate the influence of spectrum from CAT performance. Additionally, given that some subjects reported fatigue during the reaction timing tasks, if the aforementioned reaction timing testing methodology is to be used in a future experiment, the number of trials corresponding to a diminishing degree of precision in the average should be assessed to minimize fatigue effects.

References

Ak, E., & Koçak, S. (2010). Coincidence-anticipation timing and reaction time in youth tennis and table tennis players 1. *Perceptual and Motor Skills*, *110*(3), 879–887.

Algom, D., Marks, L. E., & Wiesenfeld, D. (1991). Tapping the social psychology of psychophysical experiments: Mode of responding does not alter statistical properties of magnitude estimates. *Bulletin of the Psychonomic Society*, *29*(3), 226–228.

Babizhayev, M. A. (2002). Glare disability and driving safety. *Ophthalmic research*, *35*(1), 19–25.

Bard, C., Fleury, M., Carrière, L., & Bellec, J. (1981). Components of the coincidence-anticipation behavior of children aged from 6 to 11 years. *Perceptual and Motor Skills*, *52*(2), 547–556.

Belisle, J. J. (1963). Accuracy, reliability, and refractoriness in a coincidence-anticipation task. *Research Quarterly. American Association for Health, Physical Education and Recreation*, *34*(3), 271–281.

Benguigui, N., & Ripoll, H. (1998). Effects of tennis practice on the coincidence timing accuracy of adults and children. *Research Quarterly for Exercise and Sport*, *69*(3), 217–223.

Berchou, R., & Block, R. I. (1983). Use of computerized psychomotor testing in determining cns effects of drugs. *Perceptual and motor skills*, *57*(3), 691–700.

Berkson, G. (1960). An analysis of reaction time in normal and mentally deficient young men: I. duration threshold experiment. *Journal of Mental Deficiency Research*.

Brady, F. (1996). Anticipation of coincidence, gender, and sports classification. *Perceptual and Motor Skills*, *82*(1), 227–239.

Broadhurst, A. (1958). Experimental studies of the mental speed of schizophrenics i. effects of a stimulant and a depressant drug. *The British Journal of Psychiatry*, *104*(437), 1123–1129.

Chin, K., Taylor, M., Menzies, R., & Whyte, H. (1985). Development of visual evoked potentials in neonates. a study using light emitting diode goggles. *Archives of disease in childhood*, *60*(12), 1166–1168.

Clark, W. C., Brown, J. C., & Rutschmann, J. (1967). Flicker sensitivity and response bias in psychiatric patients and normal subjects. *Journal of Abnormal Psychology*, *72*(1), 35.

Clark, W. C., Rutschmann, J., Link, R., & Brown, J. C. (1963). Comparison of flicker-fusion thresholds obtained by the methods of forced-choice and limits on psychiatric patients. *Perceptual and motor skills*, *16*(1), 19–30.

Craik, K. (1940). The effect of adaptation on subjective brightness. *Proceedings of the Royal Society of London. Series B, Biological Sciences*, *128*(851), 232–247.

Creed, R., & Ruch, T. C. (1932). Regional variations in sensitivity to flicker. *The Journal of physiology*, *74*(4), 407–423.

Crozier, W., Wolf, E., & Zerrahn-Wolf, G. (1937). Critical illumination and flicker frequency in related fishes. *The Journal of general physiology*, *21*(1), 17–56.

Curran, S., Wilson, S., Musa, S., & Wattis, J. (2004). Critical flicker fusion threshold in patients with alzheimer's disease and vascular dementia. *International journal of geriatric psychiatry*, *19*(6), 575–581.

Donders, F. C. (1969). On the speed of mental processes. *Acta Psychologica*, *30*, 412–431.

Dunham Jr, P. (1977). Age, sex, speed, and practice in coincidence-anticipation performance of children. *Perceptual and Motor Skills*, *45*(1), 187–193.

Dunham Jr, P. (1989). Coincidence-anticipation performance of adolescent baseball players and nonplayers. *Perceptual and motor skills*, *68*(3c), 1151–1156.

Dunham Jr, P., & Glad, H. L. (1976). Simple coincidence-anticipation apparatus. *Research Quarterly. American Alliance for Health, Physical Education and Recreation*, *47*(3), 532–535.

Fadda, A., & Falsini, B. (1996). Instrumentation for electroretinography: a led-based stimulator. In *Engineering in medicine and biology society, 1996. bridging disciplines for biomedicine. proceedings of the 18th annual international conference of the ieee* (Vol. 1, pp. 152–153).

Falsini, B., Fadda, A., Iarossi, G., Piccardi, M., Canu, D., Minnella, A., … Scullica, L. (2000). Retinal sensitivity to flicker modulation: reduced by early age-related maculopathy. *Investigative ophthalmology & visual science*, *41*(6), 1498–1506.

Ferree, C., & Rand, G. (1925). The effect of speed of rotation of the disc on the disagreement of flicker and equality-of-brightness photometry for lights of different composition and intensity. *The American Journal of Psychology*, 178–187.

Flannagan, M. J., Sivak, M., Ensing, M., & Simmons, C. J. (1989). Effect of wavelength on discomfort glare from monochromatic sources.

Ghaith, A. A., Daniel, J., Stulting, R. D., Thompson, K. P., & Lynn, M. (1998). Contrast sensitivity and glare disability after radial keratotomy and photorefractive keratectomy. *Archives of ophthalmology*, *116*(1), 12–18.

Goldenberg, G., Wimmer, A., Auff, E., & Schnaberth, G. (1986). Impairment of motor planning in patients with parkinson's disease: evidence from ideomotor apraxia testing. *Journal of Neurology, Neurosurgery & Psychiatry*, *49*(11), 1266–1272.

Goodenough, F. L. (1935). The development of the reactive process from early childhood to maturity. *Journal of Experimental Psychology*, *18*(4), 431.

Gray, R., Perkins, S. A., Suryakumar, R., Neuman, B., & Maxwell, W. A. (2011). Reduced effect of glare disability on driving performance in patients with blue light–filtering intraocular lenses. *Journal of Cataract & Refractive Surgery*, *37*(1), 38–44.

Grünbaum, O. (1897). On intermittent stimulation of the retina part i. *The Journal of physiology*, *21*(4-5), 396–402.

Grundström, R., Holmberg, G., & Hansen, T. (1978). Degree of sedation obtained with various doses of diazepam and nitrazepam. *Acta pharmacologica et toxicologica*, *43*(1), 13–18.

Harrold, D., & Kozar, B. (2002). Velocity, occlusion, and sex of subjects in coincidence of anticipation. *Perceptual and Motor Skills*, *94*(3), 914–920.

Haywood, K. M., & Singleton, R. M. (1977). Circuitry for an electronic coincidence-anticipation device. *Research Quarterly. American Alliance for Health, Physical Education and Recreation*, *48*(2), 461–462.

Hick, W., & Bates, J. A. V. (1950). The human operator of control mechanisms.

Hick, W. E. (1952). On the rate of gain of information. *Quarterly Journal of Experimental Psychology*, *4*(1), 11–26.

Hindmarch, I., & Parrott, A. (1977). Repeated dose comparison of nomifensine, imipramine and placebo on subjective assessments of sleep and objective measures of psychomotor performance. *British journal of clinical pharmacology*, *4*(S2), 167S–173S.

Horiguchi, M., Ito, Y., & Miyake, Y. (1998). Extrafoveal photostress recovery test in glaucoma and idiopathic central serous chorioretinopathy. *British journal of ophthalmology*, *82*(9), 1007–1012.

Hyman, R. (1953). Stimulus information as a determinant of reaction time. *Journal of Experimental Psychology*, *45*(3), 188.

Isaacs, L. D., & Finch, A. E. (1983). Anticipatory timing of beginning and intermediate tennis players. *Perceptual and Motor Skills*, *57*(2), 451–454.

Jones, R. M., & Tulunay-Keesey, U. (1975). Accuracy of image stabilization by an optical-electronic feedback system. *Vision research*, *15*(1), 57–IN1.

Kelly, D., & Savoie, R. (1973). A study of sine-wave contrast sensitivity by two psychophysical methods. *Perception & Psychophysics*, *14*(2), 313–318.

King, H. (1962). Two-flash and flicker fusion thresholds for normal and schizophrenic subjects. *Perceptual and motor skills*, *14*(3), 517–518.

Koch, D. D., Emery, J. M., Jardeleza, T. L., & Franklin, D. (1986). Glare following posterior chamber intraocular lens implantation. *Journal of Cataract & Refractive Surgery*, *12*(5), 480–484.

Kühl, B. (1972). New discharge lamps for television and film lighting. *Journal of the Illuminating Engineering Society*, *1*(4), 300–304.

Kuhlman, J. S., & Beitel, P. A. (1991). Videogame experience: A possible explanation for differences in anticipation of coincidence. *Perceptual and motor skills*, *72*(2), 483–488.

Lagroix, H. E., Yanko, M. R., & Spalek, T. M. (2012). Lcds are better: Psychophysical and photometric estimates of the temporal characteristics of crt and lcd monitors. *Attention, Perception, & Psychophysics*, *74*(5), 1033–1041.

Landis, C. (1953). *An annotated bibliography of flicker fusion phenomena covering the period 1740-1952*. National Academies.

Landis, C. (1954). Determinants of the critical flicker-fusion threshold. *Physiological Reviews*, *34*(2), 259–286.

Masket, S. (1989). Reversal of glare disability after cataract surgery. *Journal of Cataract & Refractive Surgery*, *15*(2), 165–168.

Mayer, D., & Dobson, V. (1980). Assessment of vision in young children: a new operant approach yields estimates of acuity. *Investigative ophthalmology & visual science*, *19*(5), 566–570.

McGuire, F. L. (1958). A comparison of two kinds of flicker phenomena as indicators of cns involvement. *The Journal of nervous and mental disease*, *126*(6), 540–546.

Mezrich, J. J. (1973). Utility of the computer as tachistoscope in a particular psychophysical setting. *Behavior Research Methods*, *5*(2), 153–155.

Millslagle, D. G. (2000). Dynamic visual acuity and coincidence-anticipation timing by experienced and inexperienced women players of fast pitch softball. *Perceptual and Motor Skills*, *90*(2), 498–504.

Molstad, S. M., Kluka, D. A., Love, P. A., Baylor, K. A., Covington, N. K., & Cook, T. L. (1994). Timing of coincidence anticipation by ncaa division i softball athletes. *Perceptual and motor skills*, *79*(3f), 1491–1497.

Moreno, I., Avendaño-Alejo, M., & Tzonchev, R. I. (2006). Designing light-emitting diode arrays for uniform near-field irradiance. *Applied optics*, *45*(10), 2265–2272.

Nadler, D. J., Jaffe, N. S., Clayman, H. M., Jaffe, M. S., & Luscombe, S. M. (1984). Glare disability in eyes with intraocular lenses. *American journal of ophthalmology*, *97*(1), 43–47.

Nealis, P. M., Engelke, R. M., & Massaro, D. W. (1973). A description and evaluation of light-emitting diode displays for generation of visual stimuli. *Behavior Research Methods & Instrumentation*, *5*(1), 37–40.

Nygaard, R. W., & Frumkes, T. E. (1982). Leds: convenient, inexpensive sources for visual experimentation. *Vision research*, *22*(4), 435–440.

Osaka, N. (1979). A microprocessor-based real-time basic laboratory: A pulse motor-controlled visual stimulator. *Behavior Research Methods & Instrumentation*, *11*(6), 549–552.

Osaka, N. (1985). The maxwellian optics laboratory automation using a personal computer. *Behavior Research Methods, Instruments, & Computers*, *17*(2), 206–208.

Petrakis, E. (1985). Sex differences and specificity of anticipation of coincidence. *Perceptual and Motor Skills*, *61*(3f), 1135–1138.

Poffenberger, A. T. (1912). *Reaction time to retinal stimulation: with special reference to the time lost in conduction through nerve centers* (No. 23). The Science Press.

Riggs, L. A., Berry, R. N., & Wayner, M. (1949). A comparison of electrical and psychophysical determinations of the spectral sensitivity of the human eye. *JOSA*, *39*(6), 427–434.

Ripoll, H., & Latiri, I. (1997). Effect of expertise on coincident-timing accuracy in a fast ball game. *Journal of Sports Sciences*, *15*(6), 573–580.

Sandberg, M. A., & Gaudio, A. R. (1995). Slow photostress recovery and disease severity in age-related macular degeneration. *Retina*, *15*(5), 407–412.

Sanders, G. (2011). Sex differences in coincidence-anticipation timing (cat): a review 1. *Perceptual and Motor Skills*, *112*(1), 61–90.

Schmidt, R. A. (1969). Movement time as a determiner of timing accuracy. *Journal of experimental psychology*, *79*(1p1), 43.

Severin, S. L., Alder, A. V., Newton, N. L., & Culver, J. F. (1963). *Photostress and flash blindness in aerospace operations* (Tech. Rep.). DTIC Document.

Severin, S. L., Newton, N. L., & Culver, J. F. (1963). A study of photostress and flash blindness. *American journal of ophthalmology*, *56*(4), 589–595.

Sherman, M., & Henkind, P. (1988). Photostress recovery in chronic open angle glaucoma. *British Journal of Ophthalmology*, *72*(9), 641–645.

Sherrington, C. (1897). On reciprocal action in the retina as studied by means of some rotating discs. *The Journal of Physiology*, *21*(1), 33–54.

Shinar, D., & Schieber, F. (1991). Visual requirements for safety and mobility of older drivers. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *33*(5), 507–519.

Slater-Hammel, A. T. (1960). Reliability, accuracy, and refractoriness of a transit reaction. *Research Quarterly. American Association for Health, Physical Education and*

Recreation, *31*(2), 217–228.

Spydell, J. D. (1983). A low-cost light-emitting diode photic stimulator. *Electroencephalography and clinical neurophysiology*, *55*(4), 485–486.

Stiles, W. (1929). The scattering theory of the effect of glare on the brightness difference threshold. *Proceedings of the Royal Society of London. Series B, Containing Papers of a Biological Character*, 131–146.

Stringham, J. M., Garcia, P. V., Smith, P. A., McLin, L. N., & Foutch, B. K. (2011). Macular pigment and visual performance in glare: benefits for photostress recovery, disability glare, and visual discomfort. *Investigative ophthalmology & visual science*, *52*(10), 7406–7415.

Teichner, W. H., & Krebs, M. J. (1974). Laws of visual choice reaction time. *Psychological Review*, *81*(1), 75.

Turner, P. (1968). Critical flicker frequency and centrally-acting drugs. *The British journal of ophthalmology*, *52*(3), 245.

Tyler, C. W. (1981). Specific deficits of flicker sensitivity in glaucoma and ocular hypertension. *Investigative ophthalmology & visual science*, *20*(2), 204–212.

Tyler, C. W., Ernst, W., & Lyness, A. L. (1984). Photopic flicker sensitivity losses in simplex and multiplex retinitis pigmentosa. *Investigative ophthalmology & visual science*, *25*(9), 1035–1042.

Wachler, B. S. B., Durrie, D. S., Assil, K. K., & Krueger, R. R. (1999). Improvement of visual function with glare testing after photorefractive keratectomy and radial keratotomy. *American journal of ophthalmology*, *128*(5), 582–587.

Watson, C. G., Thomas, R. W., Felling, J., & Andersen, D. (1969). Differentiation of organics from schizophrenics with the trail making, dynamometer, critical flicker fusion, and light-intensity matching tests. *Journal of clinical psychology*.

Westheimer, G. (1966). The maxwellian view. *Vision research*, *6*(11), 669–682.

Wolffsohn, J., Anderson, S. J., Mitchell, J., Woodcock, A., Rubinstein, M., Ffytche, T., . . . Bradley, C. (2006). Effect of age related macular degeneration on the eger macular stressometer photostress recovery time. *British journal of ophthalmology*, *90*(4), 432–434.

Yates, J. T., & Harding, T. H. (1974). Computerized system for stimulus generation, control, behavioral data acquisition and summary for primate visual psychophysics. *Computers and Biomedical Research*, *7*(3), 200–212.

Youngen, L. (1959). A comparison of reaction and movement times of women athletes and nonathletes. *Research Quarterly. American Association for Health, Physical Education and Recreation*, *30*(3), 349–355.