

THE INFLUENCE OF SPECTRALLY FILTERED LIGHT ON MOTION PERCEPTION

by

JEFFREY W. NIGHTINGALE

(Under the Direction of Billy R. Hammond Jr.)

ABSTRACT

The ability to perceive motion is an integral part of visual perception. An individual's ability to discriminate motion has a marked influence on their survival and capacity to engage with the environment. Past studies on motion perception have been conducted primarily in a laboratory setting, however, limiting their ecological validity. Those that have not were limited in their control of the stimulus and psychophysical methods typically available within a laboratory. The present study implemented a novel, ecologically valid methodology of assessing motion perception performance under the following conditions: no veiling light, white (emulated daylight), and filtered (short-wave, medium-wave, long-wave veils). A xenon bulb was used as the light source, emulating the spectral characteristics of natural daylight; each of the 3 filtered conditions were chosen to isolate a band of the xenon light: short-wave (400nm-500nm), medium-wave (500nm-600nm) and long-wave (600nm-700nm). Motion perception thresholds were measured while these wavebands were interposed as a homogenous veil between the motion stimulus and the eye of the subject. In general, we found that varying spectral content did not change the motion thresholds for the subjects. Macular and iridial pigmentation were not covariates. These results suggest that motion perception is strongly resistant to degradation when tested using a variety of emulated ecological conditions.

INDEX WORDS: motion, motion perception, filter, spectral filters, light, daylight, veil,
ecological validity, macular pigment optical density, MPOD, vision

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Background

Lab-based Research Assessing Motion Perception

The fields of psychophysics, neuroscience, and psychology tend to use similar definitions of motion perception (and related terms), yet with nuanced differences between the disciplines. Due to the interdisciplinary nature of this topic area, the present study will define the terms used within. The most general condition for the perception of motion is the stimulation of a succession of neighboring retinal receptors by a visual stimulus. Retinal displacement does not occur, however, when tracking an object. Gregory (1977) was the first to describe two independent systems: the image-retina motion system (based on the former) and the eye-head motion system (based on the latter). In this study, we are testing the image-retina system. The image retina system is typically tested while subjects fixate a central point (say the middle of a display screen). Movement is registered at the level of the retina by the sequential activity of neurons that align with the path of the moving object. This study focused on the image-retina system because it is more low-level (ocular) than the eye-head motion system (Gorea et al., 1993, Edwards et al., 1988, Yan et al., 2023) and, hence, might be expected to be more influenced by optical issues (Liebowitz et al., 1972) like ocular light scatter (e.g., diffusing light could interfere with differential activation of closely spaced receptors).

In order to assess motion perception performance, the present study uses a random dot kinematogram (RDK) as its stimulus. An RDK, as used in the present study, is an array of

randomly placed dots on a 2-D stimulus display that move in the same direction. RDK's are commonly used to study the properties of low-level motion processes (Erkelens et al., 1985) like speed and velocity. These terms are not perfectly interchangeable. Speed, as a scalar quantity, is operationally defined as the magnitude of the change in position of an object over time; velocity, as a vector quantity, is operationally defined as the rate of change in position of an object. Much of the preeminent work on the study of motion perception – including the refinement of terms and definitions – has been conducted within the field described here as “motion psychophysics” and so the terms and definitions used by the present study will remain consistent with that body of literature.

Two excellent reviews of the motion perception literature by Nakayama (1985) and Burr & Thompson (2011) cover its advancement from the early 1960's to 2010, and so, for a complete history of the field of motion perception those resources are recommended; however, a brief overview of laboratory research relevant to the present study will be provided here.

Motion perception as a topic of interest and research has been studied since the early 20th century but did not reach a point of significant traction until the 1960's and 1970's. In this early foray into the study of “visual motion”, it was still debated whether or not motion perception was a fundamental biological sense in the same way that color vision and stereopsis are immediate experiences (Nakayama, 1985). It was the advent of more advanced stimuli presentation methods, such as the oscilloscope, that allowed motion studies to reach a point where behavioral research on humans could be conducted. Some of the earliest behavioral studies of motion utilized random dot stimuli, such as Braddick's (1974) seminal study on the distinction between apparent and real “movement.” The results of his study provided evidence for a “short-range process” meaning a mechanism for the perception of real and continuous motion (Nakayama,

1985). Additionally, this study was one of the first to measure the maximum amount of displacement that could be detected by the visual system and still be determined as an object in motion. Braddick (1974) and Nakayama & Tyler (1981) measured the other extreme, minimum displacement (Nakayama, 1985).

This early study by Braddick not only set the stage for future studies that would go on to use random-dot stimuli but would create the framework for an architecture of motion perception systems. This early framing, describing motion as distinct visual subsystems, was later refined into the current prevailing motion perception architecture: a feature-tracking motion system (Ullman, 1979), a first-order motion system (Braddick, 1974), and a second-order motion system (Lu & Sperling, 1995) as described by Derrington et al. (2004). It is because of these early laboratory studies that motion perception was determined to be a distinct anatomical and physiological system (Nakayama, 1985) that formed the basis of a perceptual system focused on motion (Marr & Ullman, 1981; Marr, 1982).

Despite the importance of this early work in the field of motion psychophysics, these studies were not without their limitations; namely, the ecological validity of the methods and the significant hardware limitations of the technology used to present the stimuli. The laboratory conditions used in the vast majority of these studies were not able to accurately recreate naturally occurring conditions. Many of these foundational studies also used an oscilloscope, which was not advanced enough to assess the more complex aspects of motion perception, as it could not present sufficiently complex stimuli. While ecological validity and hardware limitations may have been unavoidable for Braddick (1973, 1974) and other early motion researchers (Anstis & Moulden, 1970; Banks & Kane, 1972; Tyler, 1973) advances in computer displays and related technologies would soon make better methods available.

The 1960's and 1970's laid the groundwork for what would come to be known as the golden age of "motion processing" research in the 1980's (Burr & Thompson, 2011). Laboratory studies on motion could now utilize computers with much greater processing power than those afforded to their colleagues a decade prior. Before this advancement in technology, laboratory researchers were limited to two-frame random dot stimuli, but now with computers capable of higher framerates, this limitation would no longer be an issue (Burr & Thompson, 2011).

Some researchers would take advantage of this improved processing power and continue their research on motion perception, following up their earlier work. One such researcher was Braddick (Baker & Braddick, 1982a) who revisited the earlier topic of short-range, first-order motion processes once again using random-dot stimuli, but now looking at limiting displacement as a function of retinal angle and number of pixels – ultimately making the determination that it is not the number of pixels but, rather, retinal angle that determines the limiting displacement of short-range apparent motion. Again using RDK's, Baker & Braddick (1982b) also investigated the correspondence problem of segregated dots, finding that the problem is solved by short-range motion detection processes acting on each segregated region separately.

These studies continued to work within the previously described architecture that had come out of the past decade of research, but landmark publications early on in the new decade would rapidly evolve this framework. Marr (1982) would change the landscape of motion perception research by presenting computational models of visual processing, in addition to his earlier work in a paper on early visual processing (Marr & Ullman, 1981). The majority of studies in the field of motion research to follow would continue to work within this information processing conceptualization of the visual system, and continue to progress the field of motion psychophysics. Bonnet (1984) was one such study, which was one of the early studies assessing

velocity discrimination thresholds. In their work, they found that stationary references improved velocity discrimination and longer exposure times result in velocity discrimination thresholds that are independent of a motion phase; the determination was also made that velocity discrimination decreased with eccentric viewing (Bonnet, 1984).

This conclusion was expanded upon by Johnston & Wright (1985) as they investigated the impact of eccentricity and contrast on the lower threshold of motion (LTM). Their study added to the work by earlier researchers investigating perceived velocity under different eccentric viewing conditions (Tynan & Sekuler, 1982) with the narrowed focus on LTM. Subsequent studies have shown that an increase in the LTM has been demonstrated systematically with a reduction in perceived velocity with eccentric viewing (Lichtenstein, 1963; Tynan & Sekuler, 1982). Johnston et al., however, extended these findings by evidencing support for the ratio model of velocity coding – a standardized model of representing LTM's constant cortical velocity for grating contrasts below 0.05 (Johnston & Wright, 1985).

Whereas the work of Marr and other neurophysiologists would do much to illuminate the field of motion research by presenting a detailed and working framework for it to operate within, it would further the separation between behavioral laboratory research on motion perception and environmental validity. The prevailing cognitivist approach implemented by Marr and others during this time would eclipse the earlier sentiments provided by ecological psychologists like Roger Barker and J. J. Gibson, who argued against the information-processing model of cognition and advocated for a theory of direct perception and direct realism (Gibson, 1979). The philosophical concerns of the ecological integrity and environmental applicability of behavioral research being conducted in the field of motion psychophysics would go largely unheard

throughout the 1980's and 1990's, while technology continued to advance and methods of stimulus presentation became more complex.

Some laboratory studies throughout the 1990's continued the earlier work on LTM's (Wright & Gurney, 1992), now with more advanced stimulus presentation techniques allowing for precise control over the presentation parameters and new dimensional options for more complex stimuli. Other studies advanced the literature on the neurophysiology of motion processing (Albright & Stoner, 1995; Anderson et al., 1995), making such contributions as further evidence for the involvement of the P pathway in motion processing. Research using RDK's has also continued (Eagle & Rogers, 1997), advancing the body of literature in the field using this particular stimulus. Eagle & Rogers (1997), specifically, helped expand the field's understanding of spatial displacement using a RDK and direction discrimination task. In their study, they assessed the effect of dot density, patch size, and contrast on the upper spatial limit (dMax) of observers using a direction discrimination paradigm. They found that for all contrasts tested, decreasing the dot density below 5% led to an increased dMax; though, the rate of increase for this effect was slower for low-contrast stimuli (Eagle & Rogers, 1997). This study's use of RDK's, as well as others preceding it (Braddick, 1974; Baker & Braddick, 1982a; Baker & Braddick, 1982b) would help solidify the template for RDK's use in assessing motion perception, while introducing more levels of complexity to the experimental design, pushing the boundaries of what form motion studies could take in a laboratory setting. Studies such as these would later influence even more methodologically complex studies able to capitalize on further advanced technologies, such as Ma et al. (2021) and the present study.

The advancement of technology throughout 2000-2010s allowed researchers to begin revisiting topics like LTM and spatial and temporal limits of motion perception but with greater

emphasis on independent variables and their influence on these thresholds. Now that decades of research on the fundamentals of motion perception had been conducted, studies on motion perception could now begin looking at such influences as age, coherence, speed, eccentricity, and other variables that could have an effect on an individual's experience of motion. Snowden & Kavanagh (2006) conducted a study on the between group differences of minimum motion, motion coherence, and speed discrimination thresholds between older and younger adults. They found that older adults experience greater losses in motion perception for slow motion random-dot patterns and gratings, motion coherence at slow to medium speeds, and discrimination thresholds at all speeds tested. Lappin et al. (2009) tested the spatial and temporal limits of motion perception in individuals varying speed, eccentricity, and low vision. They found evidence to support the claim that thresholds for very slow motion are limited by spatial resolution, while thresholds for fast motion are limited by temporal resolution.

These laboratory-based studies, as well as other contemporary lab studies of motion perception, culminated in the current body of literature in the field of motion psychophysics that is situated on a sturdy foundation of neurophysiological, psychological, and psychophysical research. Although the body of work generated by these laboratory-based studies is mathematically and computationally sophisticated using advanced methodological practices and precise stimulus-presentation designs, the question of how well these models describe vision within the complexity of the real world is unclear.

Field-based Research Assessing Motion Perception

Lab-based research dominates the body of literature in the field of motion psychophysics, and these studies all share in common a marked lack in ecological validity. Although the stimulus presentation techniques such as RDK's and the advanced computer systems

implemented to display these stimuli are effective at isolating the variable, the question of how well randomly moving dots capture the intricacies of a chromatic and dynamic real world scene that requires a precise motor response is open to question. In addition to lab-based studies, however, there are some field-based studies that attempt to address this gap. It should be noted, however, that in comparison to lab-based studies, field research on motion perception is sparse and still struggles to capture motion perception performance on behavioral tasks in diverse environmental conditions (e.g., spectrally variant daylight, atmospheric “blue” haze).

Anderson & Holliday (1995) were some of the earlier researchers to begin to take motion perception research into the field, encouraged by a rising interest in the impact of disability glare – such as that caused by vehicle headlights – on motion perception. Their study was conducted outside, at night, with participants seated in a car on an empty road. A stimulus display was situated 23 m down the road. A car was parked next to the stimulus display with its headlights on, simulating an oncoming vehicle; their study included three conditions: oncoming headlights off (control), low-beam, and high-beam. They found that standard measures of visual acuity do not accurately represent visual performance under night driving conditions; specifically, simulated lens opacities severely impair the directional discrimination of low-contrast targets (Anderson & Holliday, 1995).

Wilkins & Gray (2015) utilized a hybrid lab/field-based study design where thirty athletes were given stroboscopic visual training via a ball-catching task (field component) and then assessed on a variety of visual tasks including motion perception via the Motion in Depth Sensitivity test (MIDS), administered via a computer display (lab component). They found that changes in catching performance – determined by the total number of balls caught – from pre-training to post-training were significantly correlated with changes in scores for the MIDS test;

these results provide evidence for improved catching performance if perceptual-cognitive improvement training in the field is also observed (Wilkins & Gray, 2015). With that said, the lab-based assessment of motion perception (MIDS) component of the study was not conducted under the same environmental conditions as the field-based stroboscopic training component. Being outside, the participants would have experienced variable phases of daylight, atmospheric haze, and other potential environmental influences.

The lack of motion perception studies under natural environmental conditions is primarily due to the difficulty of carrying out a study outside with the same degree of precision and accuracy as laboratory studies (e.g., isolating the variable and controlling conditions). Recently, however, some studies have attempted to bring the outside world into the lab by simulating environmental conditions. Driving simulators are a popular alternative to the earlier methods of Anderson & Holliday (1995), as the researcher no longer has to acquire all of the materials necessary to conduct a driving study in the field. Instead, they can simulate the car, road, and environmental conditions all within the lab. Wilkins et al. (2013) implemented the use of a driving simulator to investigate the relationship between motion perception and driving performance. They trained participants using a battery of motion perception tests and then measured their emergency braking performance, finding that motion perception training results in faster braking responses.

Riecke et al. (2006) tested whether cognitive factors influence self-motion perception. Their design put the participant in a simulated experience where they were seated in front of a curved projection screen displaying a scene of an outdoor marketplace. Participants would press a button to initiate clockwise or counter-clockwise movement of the scene in the image, and then were instructed to move a joystick in the direction of their perceived self-motion. Their results

hinged on the believability of the visual stimulus (e.g., coherent pictorial depth cues and spatial reference frame). When participants viewed the stimulus as a stable/realistic scene, they were more able to judge the visual motion as self-motion rather than object motion.

Although closer, especially according to context and complexity, simulated environmental conditions are not the same as the environments from which they derive. A participant moving through a virtually simulated environment is not receiving the same visual experience as someone outside. Computer displays cannot simulate many real-world factors such as atmospheric turbidity, real motion in depth, spectral content, etc. For example, white rendered on a digital device is usually the combination of blue, green and red phosphors and does not match the flat spectral emissions of white sunlight. As a result, behavioral studies using simulation technology do not have the same level of ecological validity as field studies, and do not have the same generalizability to environmental conditions as a result. For example, although high-level flight simulators are a useful aide for pilot training, they are not a substitute for actual flight training (Malmquist et al., 2023).

Simulation technology has advanced significantly over the past decade, and while the simulation of environmental conditions still has limitations, the use of simulation technology such as virtual reality headsets could have valuable methodological and clinical applications in research on motion perception (e.g., Fortes et al, 2020). Ma et al. (2021) were the first to introduce a VR-based RDK proposing its use as a diagnostic tool for visual motion perception and neurodegenerative disorders. Their research demonstrates the feasibility of this design and shows how simulation technology can be used as an alternative to more traditional stimulus-presentation displays, where spatial and environmental constraints are a concern. Nonetheless, virtual reality and head-mounted stimulus displays have their own constraints. For example,

some users (e.g., with poor stereoscopic vision) will get nauseous when using VR (so called cybersickness, Palmisano et al., 2020). This is not an insignificant percentage (Saredekas et al., 2020). These displays also share the same criticisms as their precedents (e.g., inability to recreate real spectral content). What is needed is the precision of computer-controlled displays (this allows stimulus control and sophisticated psychophysical procedures) with the introduction of real-world ecological stress. To that end, we used a high-end computer display (the Metropsis system) with ancillary optics designed to emulate real world light stress.

The Metropsis System

The Metropsis research system is a test suite with a variety of assessment applications: clinical research, applied vision research, sport science, and others. The test suite implements an advanced IPS (in-plane switching) LCD (liquid-crystal display) monitor (Display++) to present visual stimuli, designed and developed by Cambridge Research Systems. The Metropsis Display++ monitor, and the test suite as a whole, have been used by a large number of researchers investigating diseases of the eye and brain (Fernandes et al., 2019, Hammond et al., 2023) in addition to behavioral changes in visual functions. In this section, a brief overview of the Display++ monitor will be given and its use in clinical and applied vision research will be described – detailed hardware specifications and the calibration procedure of the monitor are covered at length in the Method section.

The Display++ is a 32” 1920x1080 IPS LCD monitor with a 120 Hz refresh rate that has been designed and calibrated specifically for visual stimulus presentation in cognitive, psychophysical, and neurophysiological research. Display++ has been used in a diverse range of studies investigating visual function (Puell et al., 2013; Yang et al., 2017; Kumaran et al., 2018; Radhakrishnan & Ramasubramanian, 2021). Most of these studies were clinical research

investigating the impact of certain eye diseases such as age-related macular degeneration (Puell et al., 2013) and glaucoma (Yang et al., 2017), however the stimuli being presented were still the same as would be conducted in applied vision research on visual perception.

Display++ is capable of presenting visual stimuli consistent with that seen in vision research, including visual motion perception. As part of the Metropsis test suite, the dedicated visual psychophysics experiment builder, Psykinematix, allows for the development of fine-tuned, complex stimuli such as the RDK's and discrimination tasks commonly found in the motion perception literature (Braddick, 1974; Baker & Braddick, 1982a; Eagle & Rogers, 1997; Bach et al., 2010; Ma et al., 2021). Each study listed previously uses a different method of display in presenting the stimulus: tachistoscope, oscilloscope, CRT, projection screen, and VR (Oculus Rift S - 115° field of view LCD, 80 Hz) respectively. Most of these forms of stimulus presentation have their own limitations and some are of questionable precision in their suitability for vision research, with the standard in the field being CRT monitors since their inception.

The Display++ monitor is an LCD and there are some notable differences between LCD and CRT displays that are relevant in considering which to use to present stimuli for vision research. The two most prevalent limitations noted in the literature on LCDs are the speed (temporal characteristics) and accuracy (spatial precision) (Wang & Nikolić, 2011). CRT's are largely unaffected by the limitations of LCDs, but they do have their own set of limitations, namely their difficulty in presenting continuous images without flicker, lack of independence between neighboring pixels in generating luminance, electromagnetic noise, and sparse availability (Wang & Nikolić, 2011). Despite these limitations, CRT's remain the standard even today due to their overall superior performance when compared to LCDs (Elze & Tanner, 2012);

however, some LCDs, such as the Display++, are calibrated with vision research in mind and directly address the limitations found in consumer-grade LCDs.

Ghodrati et al. (2015) tested the suitability of 5 LCD monitors (one of which being Display++) for use in vision research. They found that Display++ was less affected by the spatial and temporal limitations found in consumer-grade LCDs. The only limitations still affecting Display++ in their tests of its suitability were spatial imperfections resulting in luminance drops in the periphery during central fixation and unreliable luminance patterns when stimuli were presented for a single frame. Their conclusion was that Display++, as well as the other specialized LCD display, were suitable for all vision research applications and could be used as alternatives to CRT's in experimental designs where the spatial and temporal limitations would not be an issue. The present study does not implement central fixation and stimuli are presented for more than one frame, so the minor limitations inherent in the LCD Display++ will not have a meaningful impact on the presentation of stimuli.

The Present Study

An Ecological Approach Using a Laboratory System

The concept of ecological validity has been referred to a number of times throughout this review but has yet to be defined. Holleman et al. (2020), in their critique of ecological validity, challenge the evolving definition of ecological validity from the original definition of the term as coined by Brunswik (1949). Brunswik's initial definition referred to the cue-to-object relationship of a distal stimulus; this was later adapted by Orne (1962) who extended the definition to include a component of the experimental methods accurately reproducing elements of the natural environment in a laboratory setting. Orne's definition of ecological validity did not corrupt or supplant Brunswik's original definition, rather extending it in such a way so as to

encourage researchers (especially psychologists and behavioral researchers) to better consider their methodological practices.

An excellent discussion of ecological validity that addresses the criticisms of the definition's specificity can be found by Kihlstrom (2021). In the style of Orne, the present study will define ecological validity as the generalizability of experimental findings to real-world environmental conditions, with these environmental conditions (and cues) being reproduced in a laboratory setting.

The laboratory system used in the present study is Metropsis, which uses the Display++ monitor for stimulus presentation, as described previously. The stimulus being presented, an RDK, conveys the same ecologically valid cues about their direction of movement as would be available in a real-world situation. The participant will indicate the perceived direction of movement of the RDK using only these cues, with no elements of deception/masks or other cues present. In the trials where the participant views the stimulus through a veiling light source – produced by an ancillary optical bench setup and using a xenon bulb – the same cues conveyed by the stimulus will be what would be available to the participant if they were in a real-world situation.

One of the criticisms outlined in Holleman et al. (2020) was that researchers aiming to implement ecological validity in their methodology and experimental design should specify the contexts of behavior they are interested in investigating. This can help to more clearly define the context-generalizability of the behavior being studied. The fields of motion psychophysics and visual perception have much more context-generalizability due to the simple nature of the behavior being studied (vision), when compared with research on more complex behaviors, such as in the fields of social and cognitive psychology. Visual motion perception, the behavior being

investigated in the present study, applies to most contexts where visual perception itself takes place – with notable specific contexts being driving and sports activities.

Environmental Influences on Motion Perception: Light

The environmental conditions the present study recreates in a laboratory setting are spectral variations of daylight. This was achieved by spectrally filtering a white light source, producing wavebands in three distinct brackets: short-wave, medium-wave, and long-wave. This veiling source of light is distinct from glare, and acts to serve a different purpose with respect to its effect on the visual system. Numerous studies have investigated the effects of glare (photostress recovery, glare disability, glare discomfort) in relation to driving performance (Anderson & Holliday, 1995; Theeuwes et al., 2002; Babizhayev, 2003). Others have looked at the effects of glare on detection (Hwang et al., 2019) and recognition acuity (Nightingale & Hammond, 2021). Some have specifically looked at the effects of glare on visual motion perception (Barraza & Colombo, 2000; Sepulveda et al., 2022). These studies share a common finding: if light intensity is sufficiently high, it will degrade visual function. These studies, however, also overlook a key characteristic of natural light in the environment – the spectral qualities of the light itself. This is important since we know that the human visual system is not simply a flat light detector. For example, absolute thresholds to isolated wavelengths in the 400-700 nm region show a distinct gaussian shape with peak sensitivity in the central wavelengths and dramatically reduced sensitivity at the ends (the human spectral sensitivity function, V_l). In contrast, Vernier acuity is unrelated to chromatic content (Kraupsof, et al, 1991). We also know that motion perception is influenced by an object's color and chromatic surrounds (Kraupsof et al., 1990). What is not known is how spectral conditions (seeing through veils of different spectral content) influence object motion perception. This is not a trivial question. Objects seen

in the real world are seen, often at some distance, and through intervening atmosphere (Wooten & Hammond, 2002).

The human system for motion perception is tuned to the environment and the natural lighting conditions of the outside world, but these conditions are not static. The time of year, time of day, weather, atmospheric conditions, and outdoor temperature all influence the spectral characteristics of daylight and, as a result, visual perception of objects in the environment (Granzier & Valsecchi, 2014). For example, correlated color temperature (CCT) is used as an index of the spectral phases of the sun (the higher the number, the more blue the spectrum). Typical noon daylight is a CCT of 5000-6500 K. Northern skylight, however, can reach a CCT of 20,000 K. Incandescent or halogen bulbs range from a CCT of 2000-3000 K are more heavily red-shifted. Although the differences in objects as a result of these changing lighting conditions may be corrected for via color constancy, it is possible that the change in spectral quality of daylight may have a more nuanced effect on perception, specifically, motion perception. A study by Chapman et al., 2004 found that motion coherence thresholds were degraded in red light. Near sunset, the spectral distribution of daylight shift to the long-wave end of the spectrum as the descending sun's rays pass through an increasingly thick atmosphere (Granzier & Valsecchi, 2014). Based on these findings, it is possible that the spectral phases of daylight could have an influence on the motion perception system (e.g., motion processing could be different at different times of the day). Additionally, researchers Ali et al., 2021 found that by filtering out blue light, the perceived speed of achromatic test stimuli decreased by 6-20% with the strongest filters resulting in the greatest detriments to motion perception. These findings suggest that the filtration of white light (even filtering out "hazardous" short-wave light) can result in poorer motion perception capability. Because there are naturally occurring, environmental conditions

that can result in similar changes in the spectral characteristics of daylight (e.g. seasonal changes, time of day), investigating how these different lighting scenarios influence the motion perception system is a topic worthy of interest.

The present study incorporates a centrally fixated source of veiling light, homogeneously diffused using a large glass diffuser. Three unique bandpass filters were selected and interposed between the white light source and veiled glass surface to emulate spectrally variant daylight conditions ranging from short-wave to medium-wave and long-wave. Due to the homogenous nature of the veiling light as it appears on the glass surface, all discriminations of motion direction in the veiled conditions are made under equivalent luminance.

Addressing the Implications: Spectral Filtering

While the distribution of natural daylight's spectral characteristics naturally shift, there are cases where spectral filtering has been used purposefully in an attempt to improve visual performance. Glare, and the deleterious effects of light scatter: spokes, halos, starbursts, 2-point light scatter (Hammond et al., 2019; Nightingale & Hammond, 2021), are present in the real-world environment. Whether driving, engaging in outside physical activities like sports, or simply walking across the street, glare has significant implications for an individual's visual perception of the environment (Theeuwes et al., 2002; Babizhayev, 2003; Vos, 2003), and this includes the visual perception of motion (Anderson & Holliday, 1995; Barraza & Colombo, 2000; Sepulveda et al., 2022).

The deleterious effects of glare and their degrading impact on an individual's perception of the environment is not a newly discovered phenomena; humans since ancient times have sought ways to mitigate the effects of bright light, with the two principal methods of doing so being filtration and brightness reduction (Sloney, 1983). For some sources of light, and in some

environmental conditions (interior lighting, high/low beam headlights, phone/computer screens) brightness reduction is a feasible course of action for reducing the deleterious effects of the light source. In the case of intraocular and extraocular light scatter resulting from natural daylight, brightness reduction is not possible, and so filtering must be used. Many studies have looked at filtering methods for reducing the effects of glare (Sloney, 1983; Steen et al., 1993; Hammond et al., 2019), and they have found that removal of short-wave (400-500nm), high-energy frequencies improve visual performance under glare conditions.

Macular pigment optical density (MPOD) is a measurement of the density of the macular pigments (meso-zeaxanthin, lutein, and zeaxanthin) found within the eye. The macular pigments form a naturally-occurring intraocular filter that absorbs wavelengths between 400nm and 520nm, with an absorption peak of 460nm (Hammond et al., 2019). This natural, intraocular filter produced by these pigments is found in humans and functions the same as any other spectral filter would, being capable of filtering out short-wave, high-energy in the 400-520nm zone. Because some of the most significant deleterious effects of glare result from energy in this frequency range (Algvere et al., 2006; Hammond et al., 2014), macular pigment (MP) is well-suited to act as a natural filter for glare. Studies have shown that macular pigment does in fact improve visual performance under glare conditions (Stringham & Hammond, 2007; Stringham & Hammond, 2008), including such atmospheric conditions as “blue haze” and Rayleigh scattering. Due to macular pigment’s role as an intraocular filter and its evidenced role in the filtration of certain wavelengths present in naturally occurring daylight, the present study included it as one of the “filters” that were assessed.

While studies such as the ones mentioned have contributed to the larger body of literature on the influence of filtering light (in lieu of brightness reduction) on visual performance, none

have looked at the influence of the wider range of spectral filters (including MP) on motion perception using an ecologically valid approach. The present study implemented a novel, ecologically valid methodology of assessing motion perception performance with and without a veiling source of spectrally filtered light, under a variety of emulated environmental conditions. The design of the study was primarily functional in nature, and set out to determine individual differences in the perception of motion under veiled conditions, when viewed through different spectrally filtered lenses. This design addresses the limitations of both laboratory and field-based studies in the motion perception literature, no previous study has measured motion perception realistically in this way – in a controlled laboratory setting under real-life, spectrally variant environmental conditions.

The primary research question of the present study was whether there are individual differences in the perception of motion under varying veiling light conditions. The light conditions were chosen to emphasize short, mid, and long wavebands. Past studies (Chapman et al., 2004; Granzier & Valsecchi, 2014) have found that motion perception is influenced by the spectral properties of the light source. Motion perception was degraded in the presence of long-wave, red light and similarly degraded with the removal of short-wave, blue light. Based on this type of data, it was hypothesized that there would be differences in average motion perception under spectrally variant daylight conditions. Importantly, we used light levels that did not simply wash out the stimulus based on undifferentiated glare mechanisms. Rather, we focused on light levels that subjects would likely encounter over most of a normal day (being blinded by glare is relatively rare).

Motion perception thresholds were based on two measurements: performance (the percent correct responses out of the total number of trials) and LTM speed threshold (the lowest

recorded speed in degrees per second for a correct response over the total number of trials). We also measured slow motion as opposed to fast (i.e., the lower threshold) (Gorea et al, Van de Grind et al., 2011). This was based on the general finding that fast thresholds are limited primarily by the processing speed of the brain (Lappin et al., 2009; Yan et al., 2023), whereas slow thresholds are dominated by optical factors within the eye itself (Lieberman et al, 1972; Lappin et al., 2009). If normal variation in ambient spectra influence motion, we hypothesized it would likely have a larger impact on optical-based thresholds relative to brain-based thresholds.

As a secondary objective, due to the strong body of literature on macular pigment's relationship with filtering out certain wavelengths of naturally occurring daylight (e.g. short-wavelengths), the question of MPOD's influence on motion perception was also addressed. In line with the study by Ali et al., 2021, it was hypothesized that higher MPOD would result in poorer motion perception under the white veiled condition when compared to those with lower MPOD, as more short-wave light would be filtered out.

This study has a number of practical outcomes. One is simply that it will provide guidance on how to design filters (goggles, glasses, windshields, etc.) that optimize motion perception in ever-changing common daylight conditions (not just in glare). The design of light sources would also be informed (e.g., weighting some areas of the visible spectrum may be called for with certain tasks). Many jobs require accurate motion detection and simply broad-band light may not be optimal for some tasks.

CHAPTER 2

METHOD

Subjects

The sample size for this study was determined by an a priori power analysis (conducted using RStudio) and participants were primarily recruited using the UGA SONA Systems website. The target population for the present study consisted of healthy, young adults (ranging from 18 to 30) with normal or corrected to normal vision. Normal vision was set as 20/30 or better visual acuity in both eyes – first determined by self-report, and then again verified using a wall-mounted Snellen chart. Additionally, as inclusion criteria, the subject needed to be fluent in English and able to both read and understand the consent document. Exclusion criteria broadly included subjects with ocular diseases, corneal or laser-corrective surgery, significant scotomas, hard-contact use, or astigmatism greater than 0.75 diopters. All study procedures and materials were approved by the University of Georgia Institutional Review Board prior to initiating the study. All participants gave both written and verbal informed consent prior to participation and the tenets of the Declaration of Helsinki for research on human subjects were followed.

Design

The study implemented a within-person, cross-sectional design with between-group comparisons for descriptive and MPOD variables. Measurements from five different tasks were recorded: demographics questionnaire, iris color, visual (Snellen) acuity, MPOD, and motion perception. Demographic information (e.g., age, gender) was collected using a self-report, laboratory questionnaire. Iris color – both hue and lightness – was also recorded (scale provided

in Figure 1). Visual acuity was measured using a wall-mounted Snellen chart, with participants standing a fixed distance (~6 meters) away from the chart and instructed to read the chart with both eyes open.

Measurement of MPOD

MPOD was measured using heterochromatic flicker photometry (HFP) using a tabletop device as described in Wooten et al. (1999). Participants were instructed to look through an eyepiece using their right eye, where a flickering target disk was presented. The disk varies in size, and the different sizes correspond to different retinal eccentricities (10' was used for a central measurement; 7° was used for a peripheral measurement). The target disk is composed of two monochromatic lights – 460nm, strongly absorbed by MP, and 570nm, not absorbed by MP – presented in counter-phase. The researcher was seated opposite to the participant, on the side of the device equipped with a touchscreen panel, and guided the participant through the central and peripheral experimental conditions. The participant, seated on the other side of the device, was instructed to press a button when their perception of flicker stopped – indicating that the participant perceived a luminance-match between the short-wave and medium-wave, counter-phase lights. A number of trials were recorded for the central and peripheral conditions to obtain an accurate measure of MPOD.

Measurement of Motion Perception

Motion perception thresholds were measured using a forced-choice direction discrimination task via a hybrid laboratory system (Metropsis) and optical bench setup. A conceptual schematic of the apparatus is shown in Figure 2. For Trial 1, participants experienced the motion perception task with no veil. For Trial 2, participants experienced the motion

perception task with a white, unfiltered light (emulated daylight). For Trial 3, participants experienced three filtered conditions of veiling light: short-wave, medium-wave, and long-wave.

Metropsis. The Metropsis system was controlled by an iMac desktop computer and remotely operated by an iPad which was used by the researcher to begin the experiment and monitor the participant's performance. The psychophysical task was an RDK built using the Psykinematix software program. The RDK consisted of 100 white dots of maximum luminance (350 cd/m^2) at 100% coherence, displayed on a black background of minimum luminance (0 cd/m^2); the dots were presented in a random direction (up, down, left, or right) at a random speed (between 0.01 and 5 degrees/second) for one second, and each dot had an asynchronous decay period over the duration of the presentation time. The participant was seated in a dark room, at a fixed distance from the stimulus display (~ 1.5 meters); their head was placed in a chinrest and they viewed the stimulus using binocular vision. A clear pane of glass was situated in the participant's line of sight, such that the display could only be viewed looking through the glass – for Trial 1 the presence of the glass did not obscure viewing of the stimulus; for Trials 2 and 3, the thin glass served as a beam-splitter, transmitting light from the veiling light source to the participant's view. The participant, once seated, was instructed to determine the direction of the dots in the RDK. Their responses were recorded by a button press using a Cedrus response box – a top button press indicating a determination of upward movement, bottom button press corresponding to downward movement, left button press corresponding to leftward movement, and right button press corresponding to rightward movement. The experimental design incorporated a staircase methodology, and so participants completed a number of trials for this task until their threshold was determined. Their performance on the direction discrimination task was recorded.

Optical Bench. For Trial 1, an optical bench setup was not necessary (the no veil control condition), but for Trials 2 and 3, an optical bench setup was utilized. The system begins with a bright, white light source, emulating daylight using a 300 Watt Xenon bulb and fiber optic cable. Light from this source was then passed through a collimating lens and then passed through a focusing lens, from which the light was focused into a mirror. The mirror reflected the light onto a large diffuser which created a homogenous, veiling light source on the surface of the glass pane. Now, when looking at the stimulus display, the participants were looking through this veil of light when making their direction determinations. For Trials 2 and 3, the participants repeated the same protocol as Trial 1.

Instruments

The laboratory demographics questionnaire used in the present study consists of standard screening questions (ex. age, gender) and collects basic, self-report optical information (ex. glasses/contact use). This information was collected because certain demographic and optical characteristics could influence performance on the motion perception task under different lighting conditions and/or under certain spectral conditions; the demographic data collected are addressed in the analysis. The format of the specific questionnaire used was selected to address the exclusion criteria discussed previously, and ensure a diverse representation of subjects. A standardized iris color scale was used to measure the hue and lightness of the subject's iris color (shown in Figure 1). A Snellen acuity chart was used to measure visual acuity; this was measured to address exclusion criteria, mentioned previously. The tabletop HFP device used to measure MPOD was the same as that used in Wooten et al. (1999), though with an updated housing and more advanced interface, and uses the same psychophysical and methodological design. The device has proven to be both highly accurate and efficient in measuring MP (for

further information regarding the device and its validity, refer to Wooten et al., 1999). The hybrid optical bench setup and direction discrimination task are a novel, ecologically valid design based on prior methods used in the field of motion perception research (Braddick, 1974; Baker & Braddick, 1982a; Eagle and Rogers, 1997; Bach et al., 2010; Ma et al., 2021).

An ILT960-BB Spectroradiometer was used to measure the spectral characteristics of the light source and the wavebands for each filter condition. Figures 3 through 6 show the spectral graphs for the light source, short-wave, medium-wave, and long-wave measurements. A LED light meter with color temperature compensation (CTC) was used to ensure light levels were consistent across conditions. The light meter was placed at the position of the eye when taking measurements of the energy levels, and these levels were consistent across conditions ($M = 87$ lux).

Procedure Description

Since the method used in the present study is novel, a small control group of ten participants was used to verify the reliability of the method and demonstrate the replicability of the results. These ten participants completed the procedure described below and then completed the procedure again on a later date (within a week of the first visit). A table of their scores demonstrating the reliability of the method is provided in Table 1 of the Tables and Figures section of this manuscript. Figures depicting the method's ability to replicate performance and LTM scores are also provided.

Before beginning an experimental session, it was confirmed that all optical elements in the system were correctly aligned, light intensity of the Xenon source was correct, the stimulus display was precisely calibrated with the Display++ real time calibration procedures (with no error reports), and the subject's head was properly seated in the chinrest. The task (direction

discrimination) was then explained to the participant and the stimuli were presented. The goal of the experimental design was to obtain motion perception performance scores (as a percentage correct out of the total number of trials completed) and LTM speed thresholds (the lowest speed in degrees/second for a trial with a correct response) for the direction discrimination task. This was done for all three trials and all three filter conditions for Trial 3. The procedures and psychophysical methods that were used in the present study are outlined below.

Procedure

1. Participants were recruited using the University of Georgia's SONA Systems website; participants entered the lab and reviewed the consent form.
2. After obtaining consent, the researcher provided the participant with a standardized demographics questionnaire where they gave self-report demographic and optical information.
3. The researcher then assessed the iris color (hue and lightness) of the participant, using a standardized iris color scale.
4. Visual acuity was then assessed using a wall-mounted Snellen chart. The participant was instructed to stand ~6 meters away from the wall-mounted chart, and their binocular acuity was recorded by the researcher.
5. Following, MPOD was measured using a tabletop HFP device. The researcher, seated on one side of the device, controlled the experimental measures and walked the participant through the task. The participant, seated on the other side of the device, was instructed to press a button to indicate when the target disk composed of counter-phase blue and green wavelengths appeared fused. This was done for foveal vision and parafoveal vision. MPOD and the corresponding standard deviation were then recorded.

6. Motion perception was measured next. A staircase method was used to determine motion perception performance and to obtain LTM speed thresholds for the direction discrimination task. Direction of the RDK was randomized and speed was varied using the staircase method to obtain performance and threshold values.
7. The participant was seated and situated in a chin rest at the end of an optical table. The stimulus display (Display++) was placed in a fixed position ~1.5 meters away from the participant, at the other end of the table. The researcher described the direction discrimination task to the participant before beginning.
8. A random number generator was used to determine the starting trial (1, 2, or 3) and the order of spectral filters (1-3).
9. Consistent with the order of trials and conditions determined by the random number generator, the researcher turned off the lights and started the experiment using the remote (an iPad).
10. Participants then completed the direction discrimination task for each trial. Their responses were recorded using directional buttons on a response box, corresponding to the perceived direction of motion. The performance and threshold data were then collected by the Metropsis software, filed electronically in an encrypted folder, and printed out.
11. After all conditions for each trial were completed, the participant would be debriefed and credit for their participation would be given.
12. All participants were given a unique identifier and all data collected was stored electronically in an encrypted folder and physically in a locked filing cabinet.

CHAPTER 3

RESULTS

Power Analysis

A power analysis was conducted using RStudio to assess the sample size necessary to obtain an 80% or greater likelihood of finding a significant association between filter type and performance as well as filter type and LTM speed threshold. Because three filter types are being assessed, a One-way repeated measures ANOVA was performed for both filter type and performance (Cohen's $f = 0.437$) and filter type and LTM speed threshold (Cohen's $f = 0.366$). It was found that a sample size of $n = 53$ would be needed to reach $\beta = .80$ at $\alpha = .05$ for filter type and performance; a sample size of $n = 75$ would be needed to reach $\beta = .80$ at $\alpha = .05$ for filter type and LTM speed threshold. Based on this a priori power analysis and the previous literature on motion perception, it was decided that a sample size of $n = 60$ would be used.

A second set of power analyses were conducted, also in RStudio, to assess the sample size necessary to obtain an 80% or greater likelihood of finding a significant association between MPOD and motion perception performance as well as MPOD and LTM speed threshold under veiling light conditions ($\beta = .80$). Pearson product moment correlations were performed for both MPOD and performance ($r = -0.223$) and MPOD and LTM speed threshold ($r = 0.526$). It was found that a sample size of $n = 155$ would be needed to reach $\beta = .80$ at $\alpha = .05$ for MPOD and performance; a sample size of $n = 24$ would be needed to reach $\beta = .80$ at $\alpha = .05$ for MPOD and LTM speed threshold. The present study is not powered to assess the relationship between MPOD and motion perception performance, but could still give an indication (i.e., the size is

sufficient to indicate the nature of the trend) of the relationship between MPOD and LTM speed threshold; as MPOD's influence on motion perception is a secondary objective of the present study, these analyses will be included but future research is likely necessary to fully address the relationship.

Internal Reliability

A control group of $n = 10$ participants was used to verify the reliability of the method and demonstrate the replicability of the results. Bivariate Pearson correlations were used to analyze the reliability of performance and LTM scores from visit 1 to visit 2 for all filter conditions.

Among participants in this sample, there was no significant correlation observed between visit 1 and visit 2 based on their performance scores for any filter condition: no veil, $r(8) = -0.43$, $p = 0.22$; white veil, $r(8) = -0.17$, $p = 0.64$; short-wave, $r(8) = 0.12$, $p = 0.74$; medium-wave, $r(8) = 0.59$, $p = 0.07$; long-wave, $r(8) = -0.36$, $p = 0.30$. Pearson correlation results for performance can be seen in Table 1. While performance scores between visits were not strongly or significantly correlated, scores across filter conditions were relatively similar; due to this similarity, performance scores across all filter conditions were averaged and the average performance score for each visit was plotted to give a visual representation of performance reliability. This visual representation is provided in Figure 7.

There was also no significant correlation observed between visit 1 and visit 2 based on their LTM scores for any filter condition: no veil, $r(8) = 0.10$, $p = 0.79$; white veil, $r(8) = 0.02$, $p = 0.97$; short-wave, $r(8) = -0.41$, $p = 0.24$; medium-wave, $r(8) = 0.37$, $p = 0.29$; long-wave, $r(8) = 0.29$, $p = 0.42$. Pearson correlation results for LTM can be seen in Table 2. While LTM scores between visits were not strongly or significantly correlated, scores across filter conditions were relatively similar; due to this similarity, LTM scores across all filter conditions were averaged

and the average LTM score for each visit was plotted to give a visual representation of LTM reliability. This visual representation is provided in Figure 8 – data has been Winsorized due to an outlier 3 standard deviations from the mean.

Descriptive Statistics

Descriptive statistics are provided for all demographic variables in Table 3. The present study was composed of a relatively homogenous sample of young (Age; mean = 19, SD = 1.88), healthy (MPOD; mean = 0.48, SD = 0.19) adults. Despite this homogeneity, there was wide variance observed across all filter conditions for both visual measures, as shown in Figures 9a-e and 10a-e.

Within-Subjects: ANOVA

A one-way, within-subjects ANOVA was used to analyze the influence of spectral filtering on motion perception performance in no veil, white veil, short-wave, medium-wave, and long-wave conditions. There was not a significant effect of filtering on performance scores $F(4, 236) = 0.87, p = 0.48$. Another one-way, within-subjects ANOVA was used to analyze the influence of spectral filtering on LTM speed thresholds in no veil, white veil, short-wave, medium-wave, and long-wave conditions. There was not a significant effect of filtering on LTM scores $F(4, 236) = 0.63, p = 0.61$. Box plots of performance and LTM mean scores, organized by filter condition, are shown in Figures 11 and 12.

Between-Subjects: T-Tests

Independent-samples T-tests were conducted to find between-group differences in performance scores for iris color (light and dark), ethnicity (white and not white), and visual correction (correction and no correction). Independent-samples statistics for performance can be seen in Table 4. There was no significant difference found between light irises and dark irises for

any filter condition: no veil, $t(35) = 1.45, p = 0.16$; white veil, $t(35) = 1.65, p = 0.11$; short-wave, $t(35) = 0.80, p = 0.43$; medium-wave, $t(35) = 0.89, p = 0.38$; long-wave, $t(35) = -1.05, p = 0.30$.

There was also no significant difference found between white and not white participants for any filter condition: no veil, $t(35) = 0.72, p = 0.47$; white veil, $t(35) = 1.27, p = 0.21$; short-wave, $t(35) = 0.87, p = 0.39$; medium-wave, $t(35) = 1.38, p = 0.18$; long-wave, $t(35) = -0.11, p = 0.92$.

There was a significant difference found between correction and no correction for the short-wave filter condition, $t(35) = -2.76, p = 0.01$, but no significant differences were found for the other conditions: no veil, $t(35) = -1.49, p = 0.15$; white veil, $t(35) = -1.44, p = 0.16$; medium-wave, $t(35) = -0.32, p = 0.75$; long-wave, $t(35) = -0.72, p = 0.48$.

Independent-samples statistics for LTM can be seen in Table 5. There was no significant difference found between light irises and dark irises for any filter condition: no veil, $t(35) = -1.82, p = 0.07$; white veil, $t(35) = -1.29, p = 0.21$; short-wave, $t(35) = -1.07, p = 0.29$; medium-wave, $t(35) = -1.19, p = 0.24$; long-wave, $t(35) = -0.75, p = 0.46$. There was also no significant difference found between white and not white participants for any filter condition: no veil, $t(35) = 0.72, p = 0.47$; white veil, $t(35) = -0.99, p = 0.33$; short-wave, $t(35) = -0.97, p = 0.34$; medium-wave, $t(35) = -1.33, p = 0.19$; long-wave, $t(35) = -0.88, p = 0.38$. There was a significant difference found between correction and no correction for the medium-wave filter condition, $t(35) = 1.99, p = 0.05$, but no significant differences were found for the other conditions: no veil, $t(35) = -1.49, p = 0.15$; white veil, $t(35) = 1.23, p = 0.23$; short-wave, $t(35) = -1.18, p = 0.24$; long-wave, $t(35) = 1.16, p = 0.25$.

Between-Subjects: Pearson Correlations

Bivariate Pearson correlations were used to analyze the influence of MPOD on motion perception performance and LTM speed thresholds. Among participants in this sample, there was

no significant correlation observed between MPOD and performance scores, $r(55) = 2.15, p = 0.66$. There was also no significant correlation established between MPOD and LTM scores, $r(55) = -0.11, p = 0.82$. These correlations were controlled for age, iris color (lightness), and visual correction. For a visual representation of the subjects' performance and LTM scores organized by MPOD, refer to Figures 13 and Figure 14, respectively.

Additional Findings

Due to the high variability in scores across filter conditions for the relatively homogenous sample, additional Pearson correlations were conducted for all combinations of filter pairs. The results of these correlations can be seen in Table 6 for performance scores and Table 7 for LTM scores. While weakly correlated, nearly all of these correlations are strongly significant.

CHAPTER 4
TABLES AND FIGURES

Table 1

Internal Reliability Control Study (Performance, n = 10)

Variable	Df	Correlation	Significance
No Veil	8	-0.43	0.22
White Veil	8	-0.17	0.64
Short-wave	8	0.12	0.74
Medium-wave	8	0.59	0.07
Long-wave	8	-0.36	0.30

Table 2

Internal Reliability Control Study (LTM, n = 10)

Variable	Df	Correlation	Significance
No Veil	8	0.10	0.79
White Veil	8	0.02	0.97
Short-wave	8	-0.41	0.24
Medium-wave	8	0.37	0.29
Long-wave	8	0.29	0.42

Table 3*Descriptive Statistics (n = 60)*

Variable	Average	SD	Range	n Analyzable
Age	19.25	1.88	8, 18 to 26	60
MPOD (10')	0.48	0.19	1, 0 to 1	60
Race	Asian – 21.7% Black – 6.7% Hispanic – 21.7% White – 65.0%	N/A	N/A	60
Sex	Female – 63.3% Male – 36.7%	N/A	N/A	60
Vision Correction	Correction – 35% No Correction – 65%	N/A	N/A	60
Iris Color (Hue)	Blue – 28.3% Brown – 43.3% Gray – 3.3% Green – 15% Hazel – 10%	N/A	N/A	60
Iris Color (Lightness)	Dark – 33.3% Light – 28.3% Medium – 38.3%	N/A	N/A	60

Table 4

Between-groups Analyses (Performance) based on iris color classification, race, and visual

correction: T-tests

	No Veil			White Veil			Short-wave		
Variable	df	T	p	df	t	p	df	t	p
Light and Dark	35	1.45	0.16	35	1.65	0.11	35	0.80	0.43
White and Not White	35	0.72	0.47	35	1.27	0.21	35	0.87	0.39
Correction and No Correction	35	-1.49	0.15	35	-1.44	0.16	35	-2.76	0.01**
	Medium-wave			Long-wave					
Variable	df	T	p	df	t	p			
Light and Dark	35	0.89	0.38	35	-1.05	0.30			
White and Not White	35	1.38	0.18	35	-0.11	0.92			
Correction and No Correction	35	-0.32	0.75	35	-0.72	0.48			

Table 5

Between-groups Analyses (LTM) based on iris color classification, race, and visual correction:

T-tests

	No Veil			White Veil			Short-wave		
Variable	df	T	p	df	t	p	df	t	p
Light and Dark	35	-1.82	0.07	35	-1.29	0.21	35	-1.07	0.29
White and Not White	35	0.72	0.47	35	-0.99	0.33	35	-0.97	0.34
Correction and No Correction	35	-1.49	0.15	35	1.23	0.23	35	1.18	0.24
	Medium-wave			Long-wave					
Variable	df	T	p	df	t	p			
Light and Dark	35	-1.19	0.24	35	-0.75	0.46			
White and Not White	35	-1.33	0.19	35	-0.88	0.38			
Correction and No Correction	35	1.99	0.05*	35	1.16	0.25			

Table 6*Pearson Correlations (Performance) for each condition*

Variable	Df	Correlation	Significance
No Veil/White Veil	58	0.36	0.005**
No Veil/Short-wave	58	0.36	0.004**
No Veil/Medium-wave	58	0.31	0.01**
No Veil/Long-wave	58	0.18	0.16
White Veil/Short-wave	58	0.49	< 0.001***
White Veil/Medium-wave	58	0.27	0.04*
White Veil/Long-wave	58	0.37	0.003**
Short-wave/Medium-wave	58	0.17	0.20
Short-wave/Long-wave	58	0.38	0.003**
Medium-wave/Long-wave	58	0.26	0.05*

Table 7*Pearson Correlations (LTM) for every combination of conditions*

Variable	Df	Correlation	Significance
No Veil/White Veil	58	0.65	< 0.001***
No Veil/Short-wave	58	0.59	< 0.001***
No Veil/Medium-wave	58	0.46	< 0.001***
No Veil/Long-wave	58	0.56	< 0.001***
White Veil/Short-wave	58	0.97	< 0.001***
White Veil/Medium-wave	58	0.42	< 0.001***
White Veil/Long-wave	58	0.45	< 0.001***
Short-wave/Medium-wave	58	0.32	0.01**
Short-wave/Long-wave	58	0.34	0.008**
Medium-wave/Long-wave	58	0.72	< 0.001***

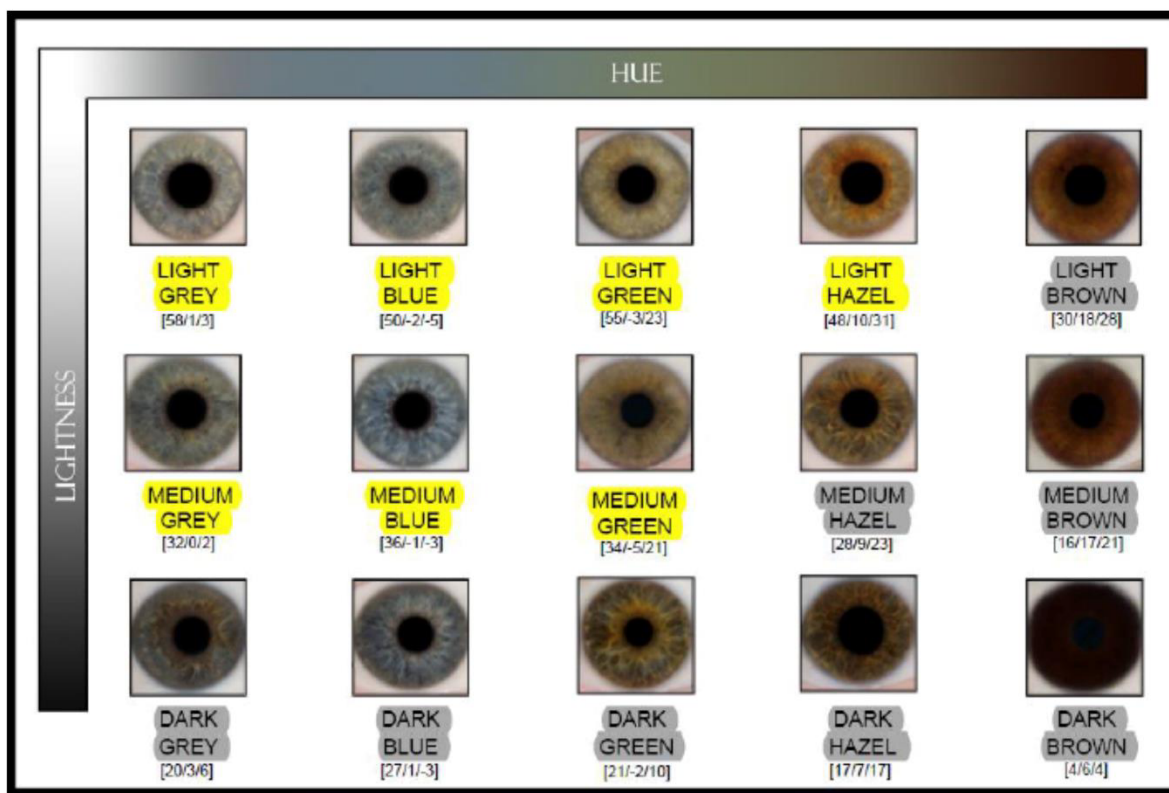


Figure 1. Iris Color Scale.

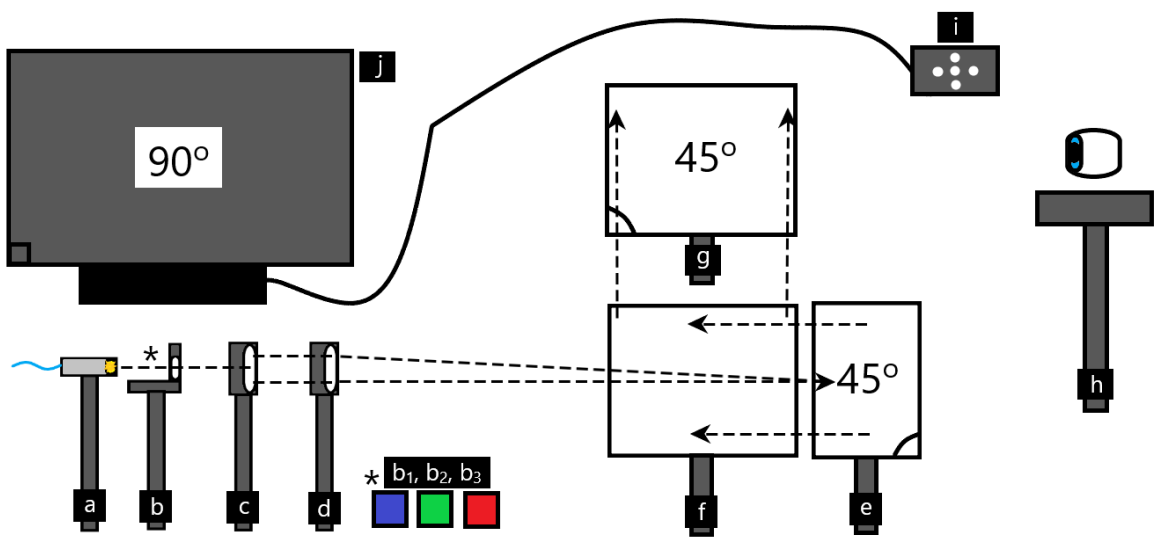


Figure 2. Motion Perception Schematic including (a) xenon light source (b) filter holder and (b1, b2, b3) filters (c) collimating lens (d) focusing lens (e) mirror (f) diffuser (g) glass pane (h) chin rest (i) response box (j) stimulus display.

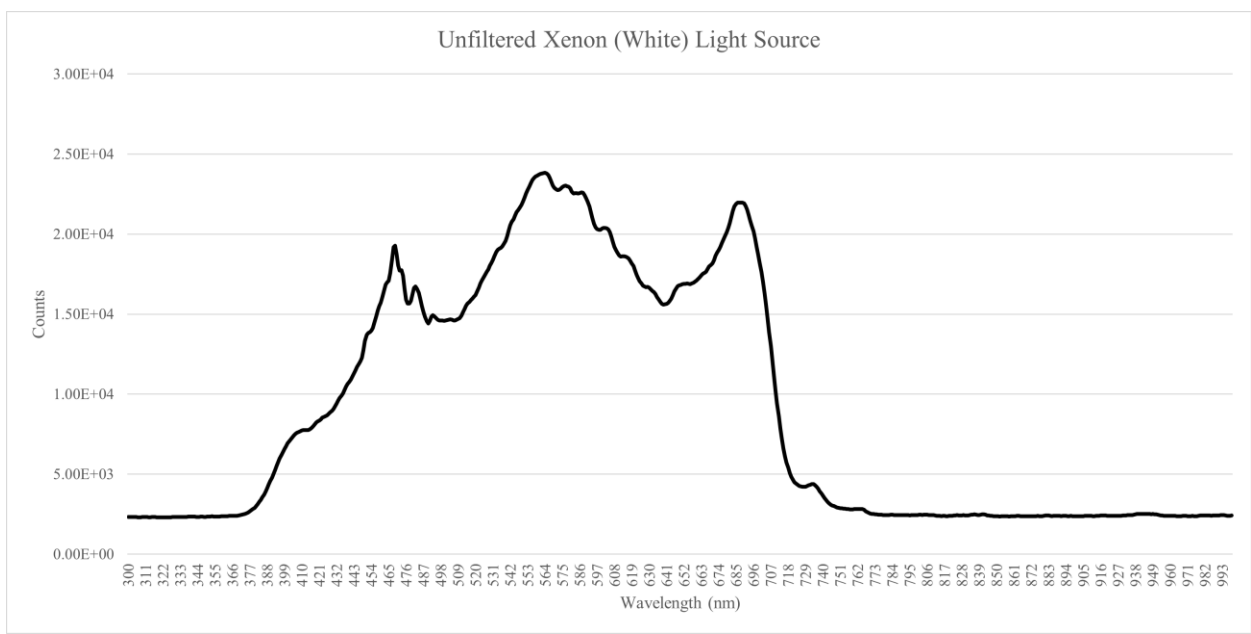


Figure 3. Spectral Graph: Unfiltered Xenon (White) Light Source

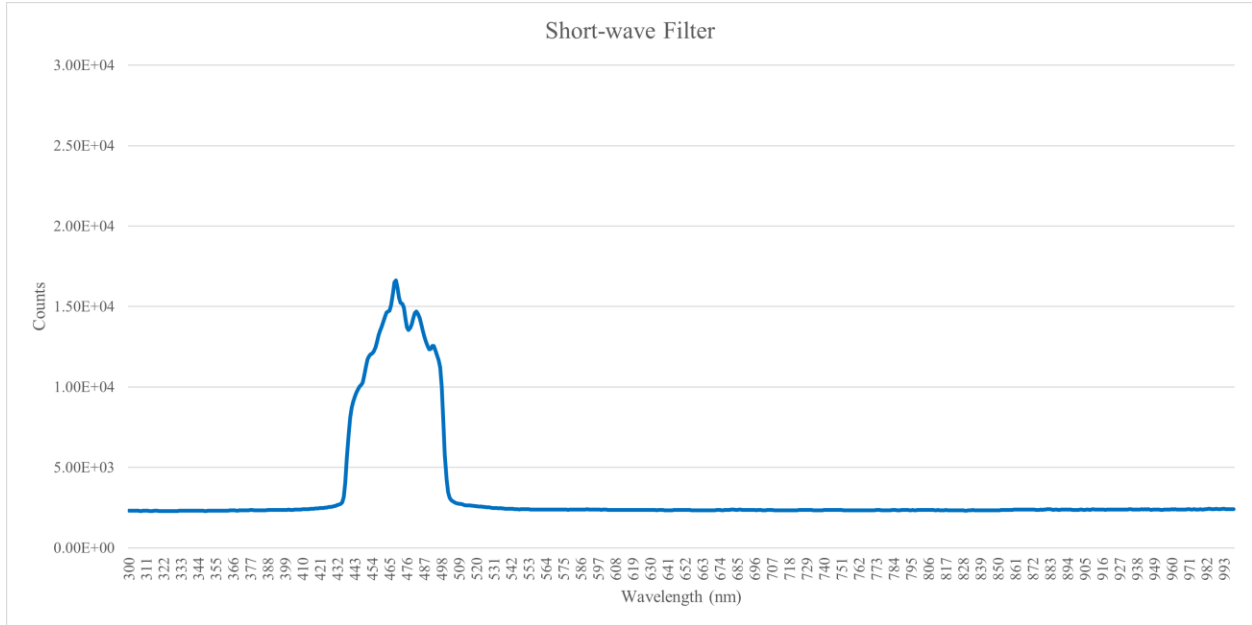


Figure 4. Spectral Graph: Short-wave Filter

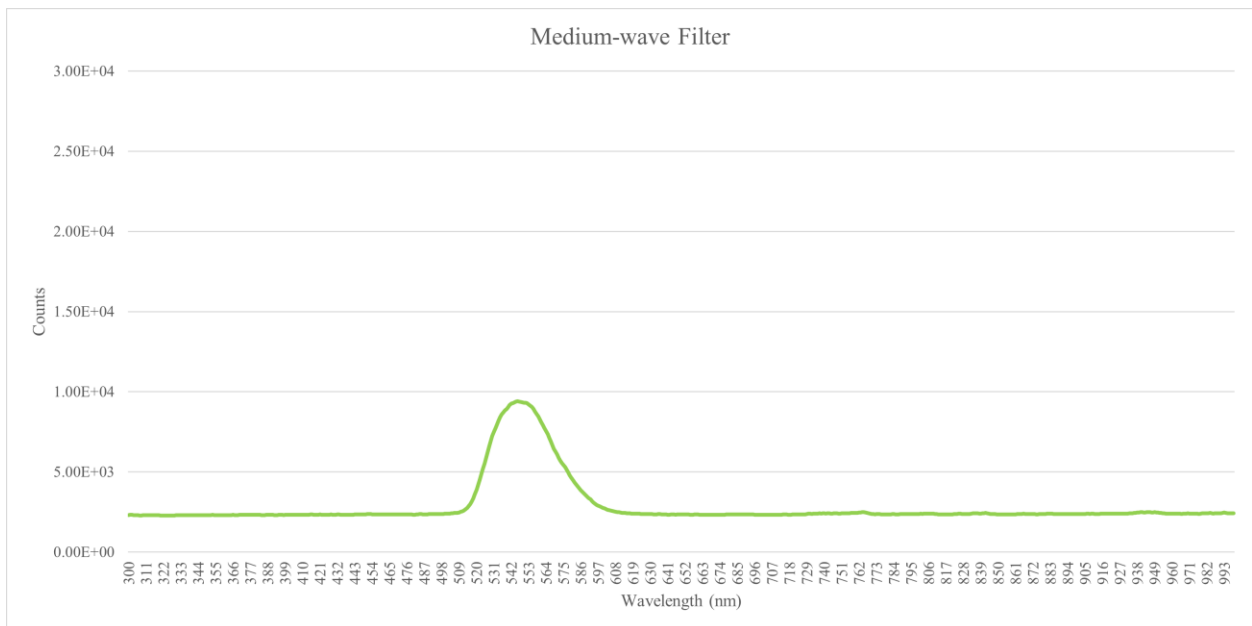


Figure 5. Spectral Graph: Medium-wave Filter

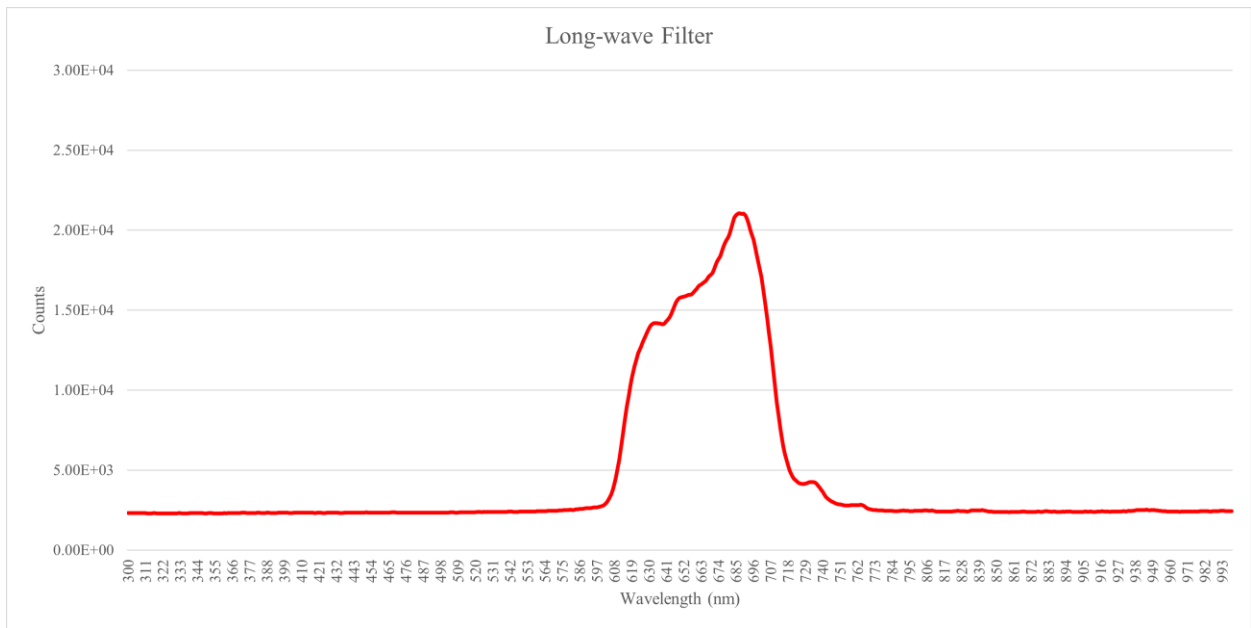


Figure 6. Long-wave Filter

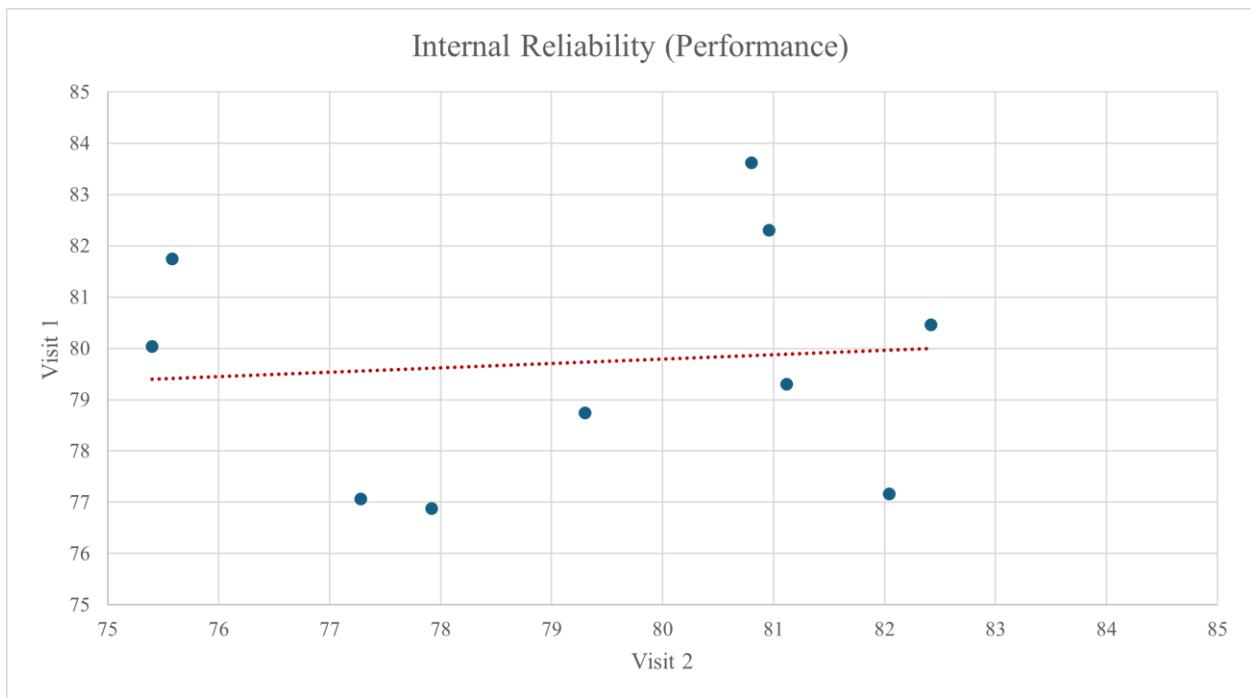


Figure 7. Internal Reliability Control Study (Performance).

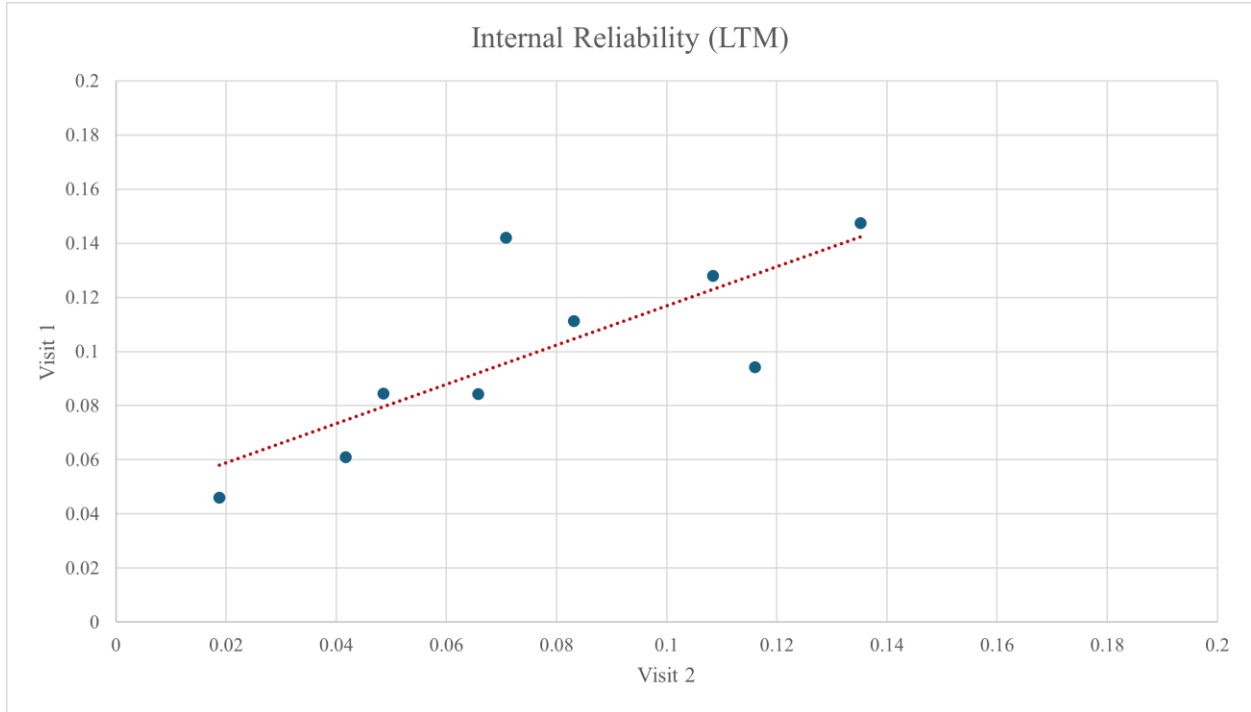


Figure 8. Internal Reliability Control Study (LTM). *Note: n = 9, data has been Winsorized.

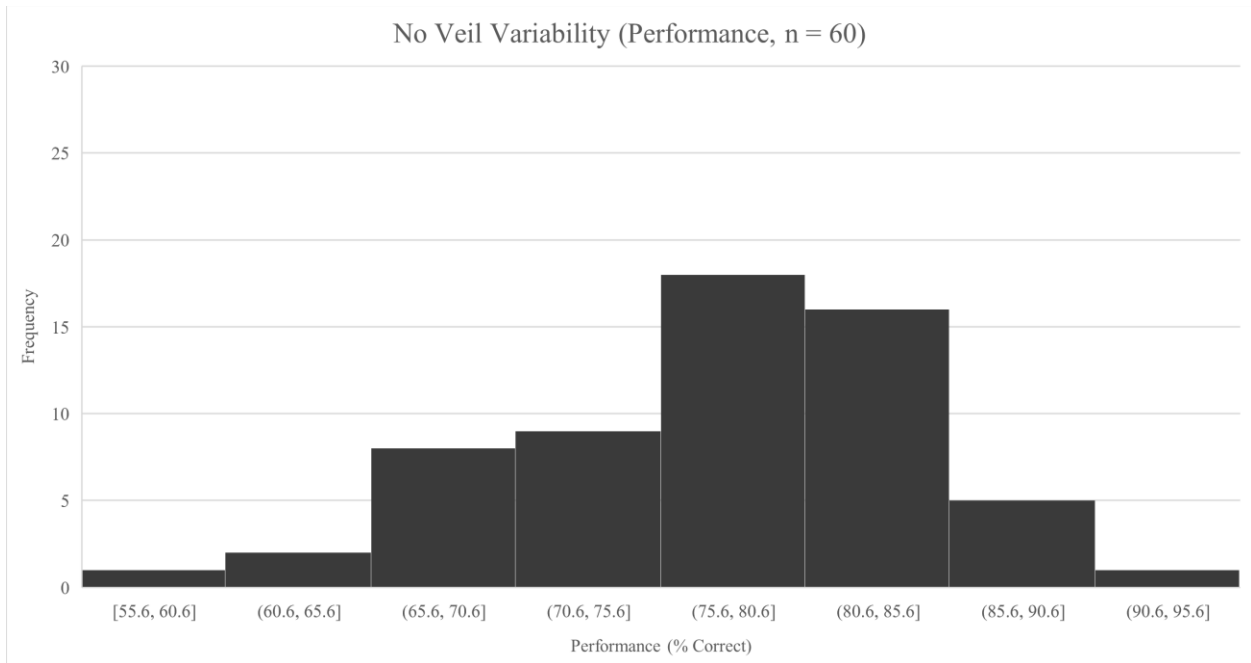


Figure 9a. Variation in Performance of All Subjects (No Veil)

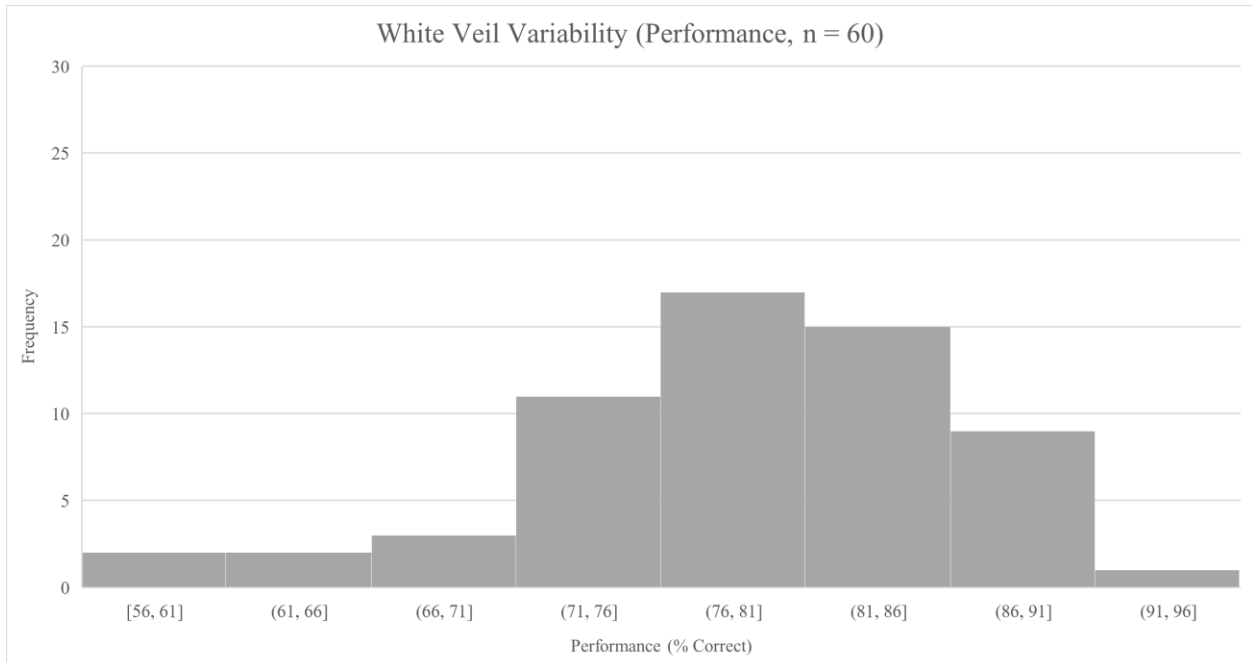


Figure 9b. Variation in Performance of All Subjects (White Veil)

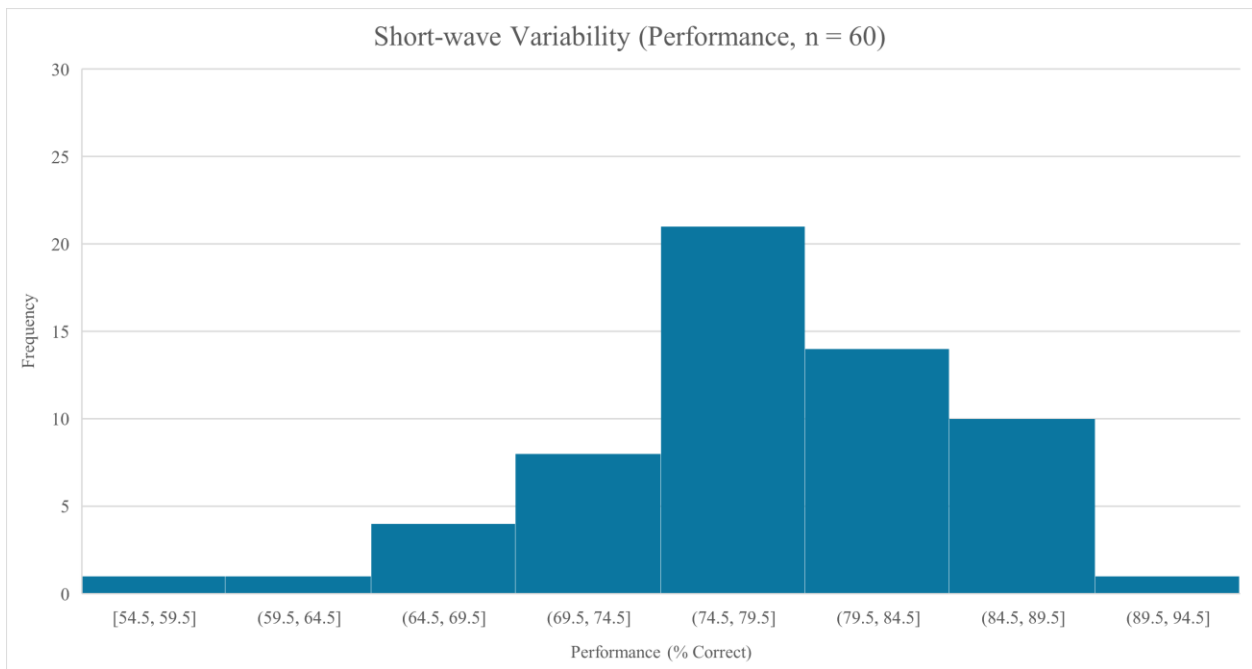


Figure 9c. Variation in Performance of All Subjects (Short-wave)

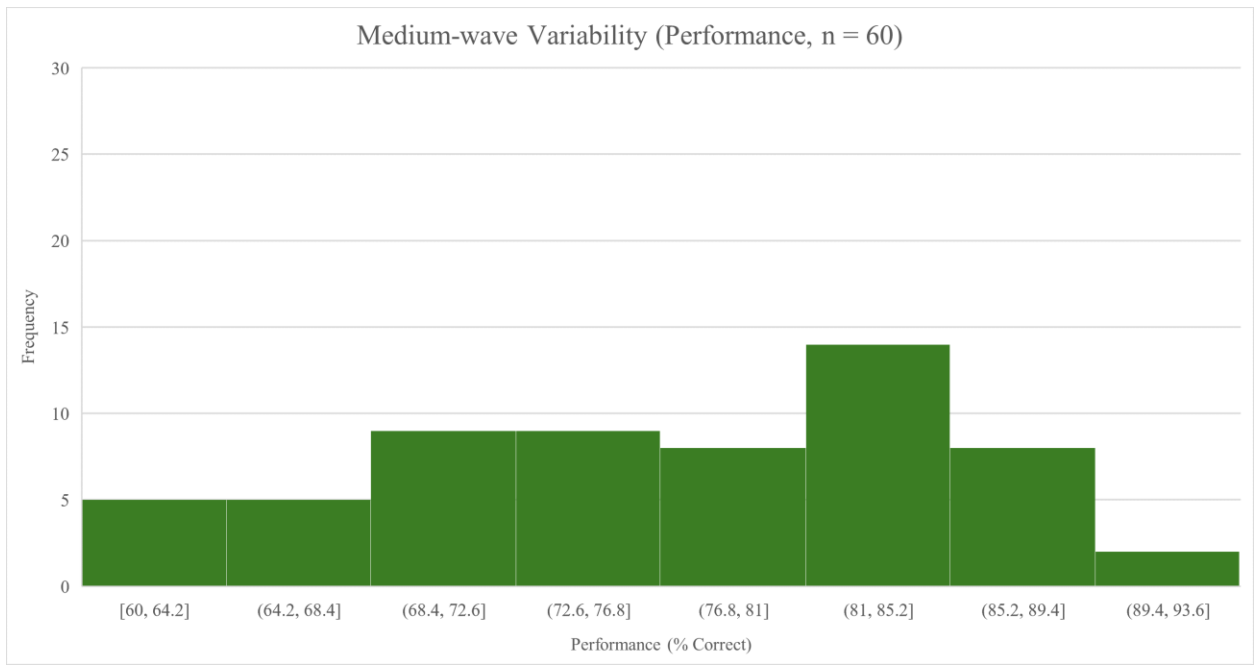


Figure 9d. Variation in Performance of All Subjects (Medium-wave)

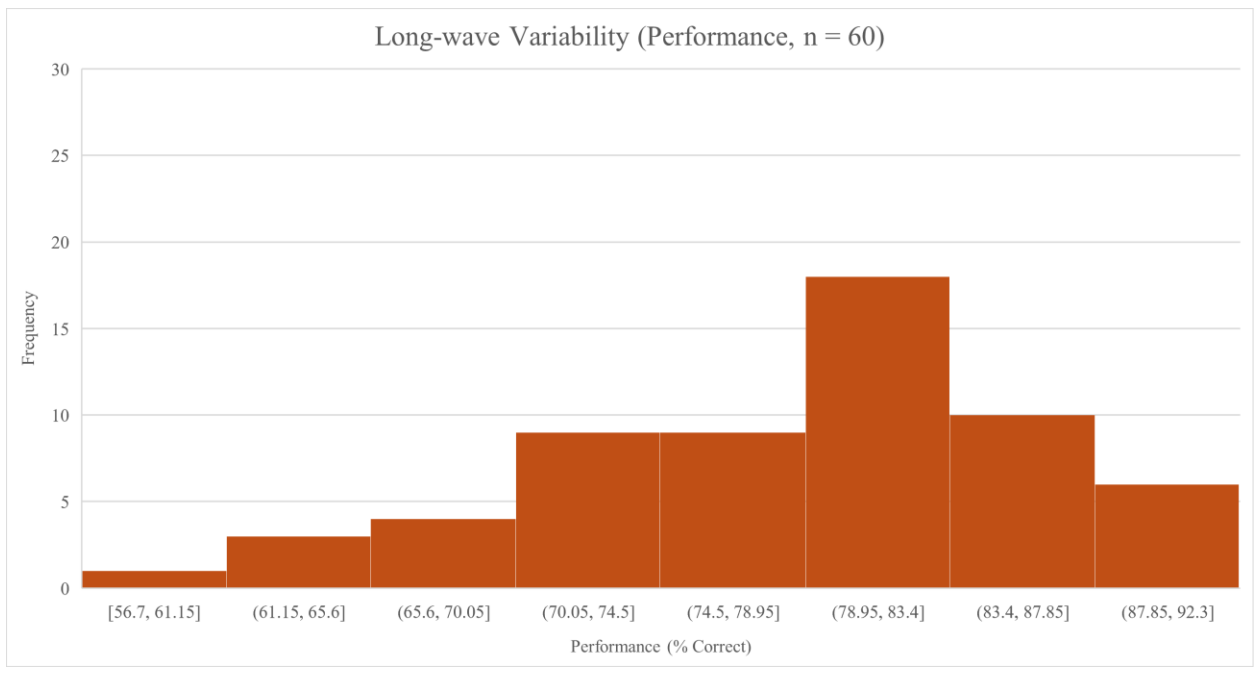


Figure 9e. Variation in Performance of All Subjects (Long-wave)

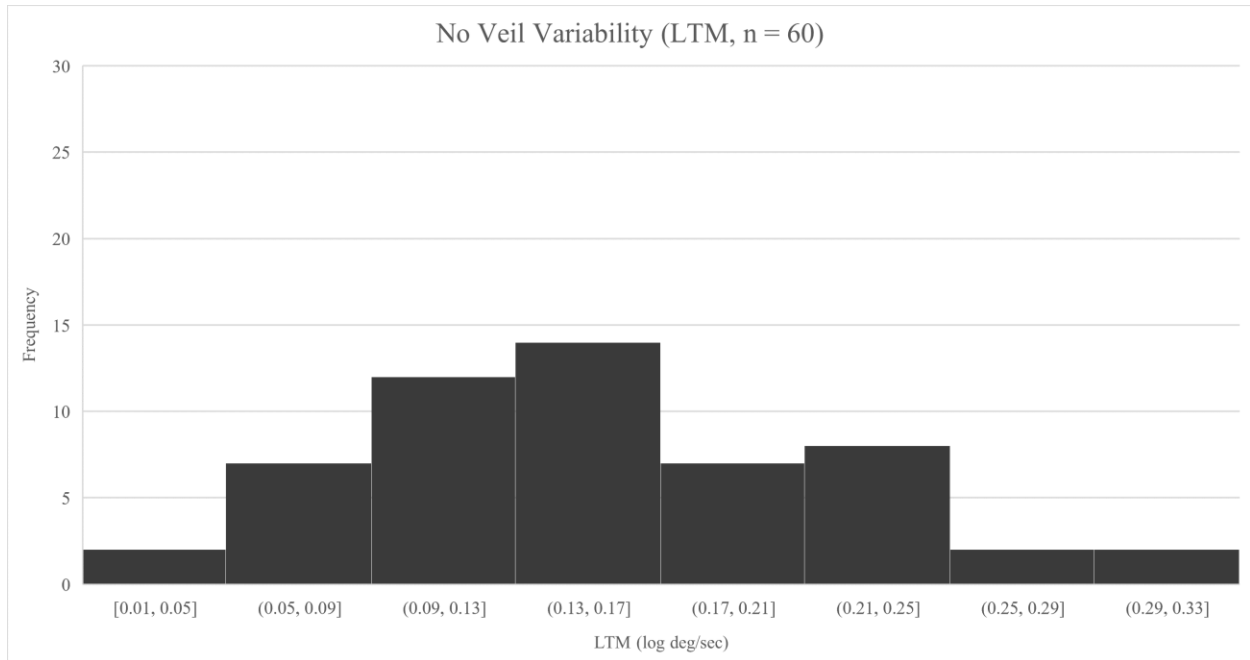


Figure 10a. Variation in LTM of All Subjects (No Veil)

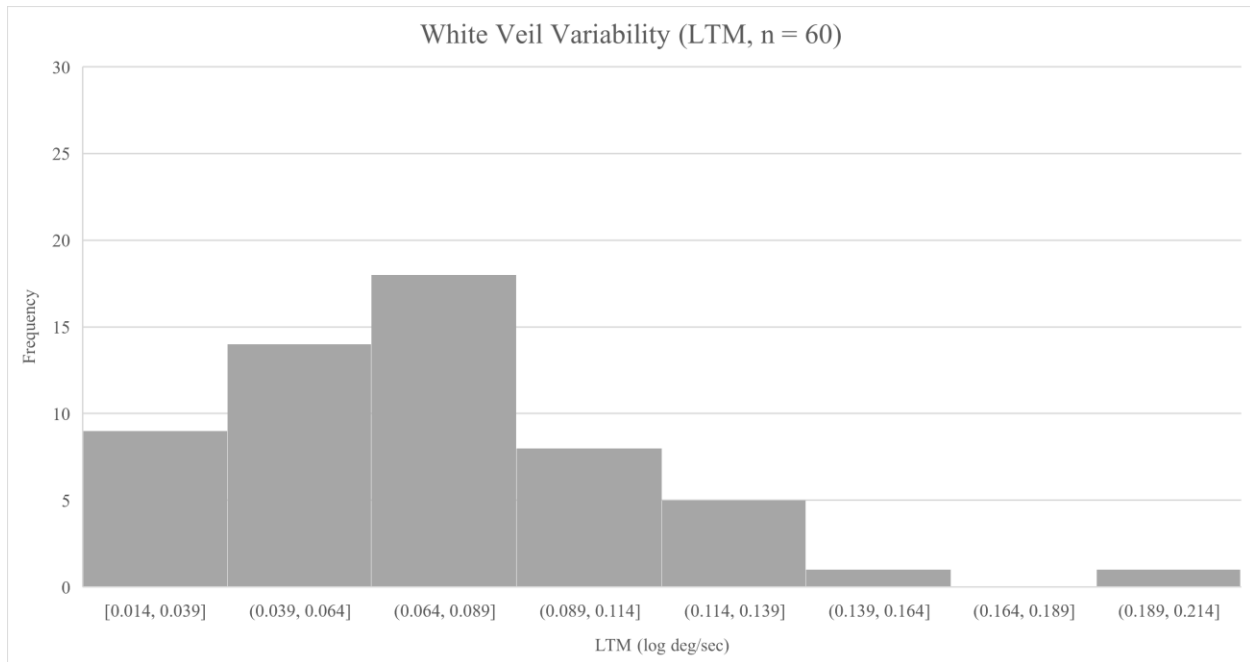


Figure 10b. Variation in LTM of All Subjects (White Veil)

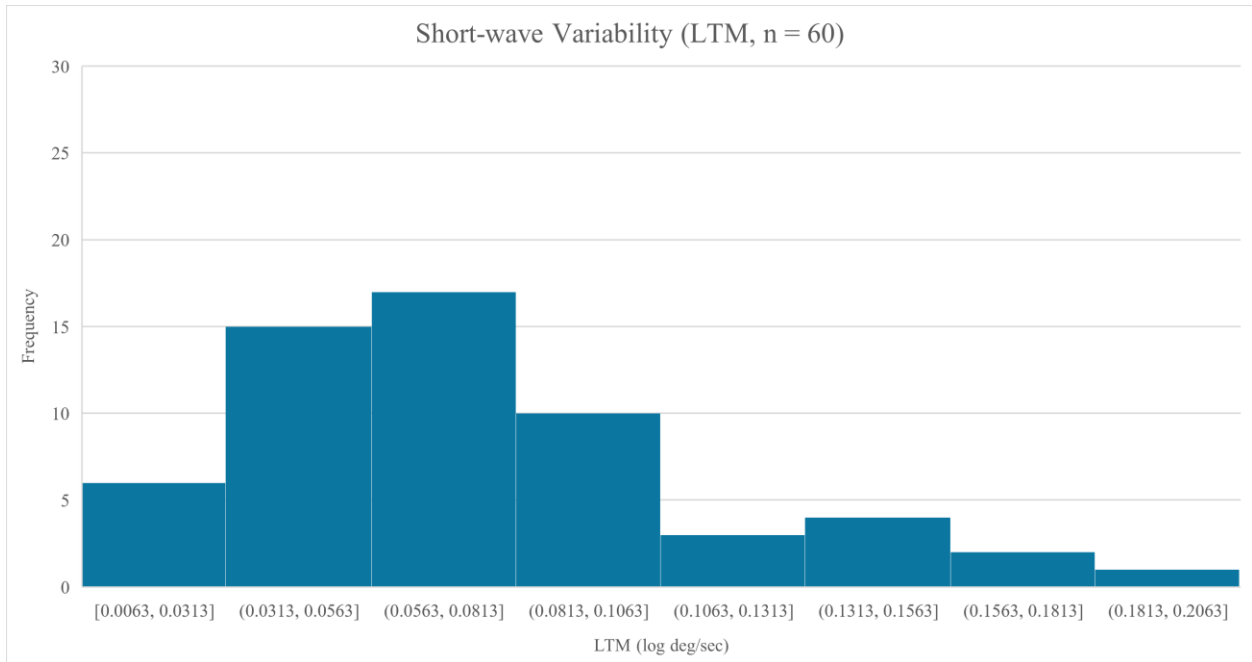


Figure 10c. Variation in LTM of All Subjects (Short-wave)

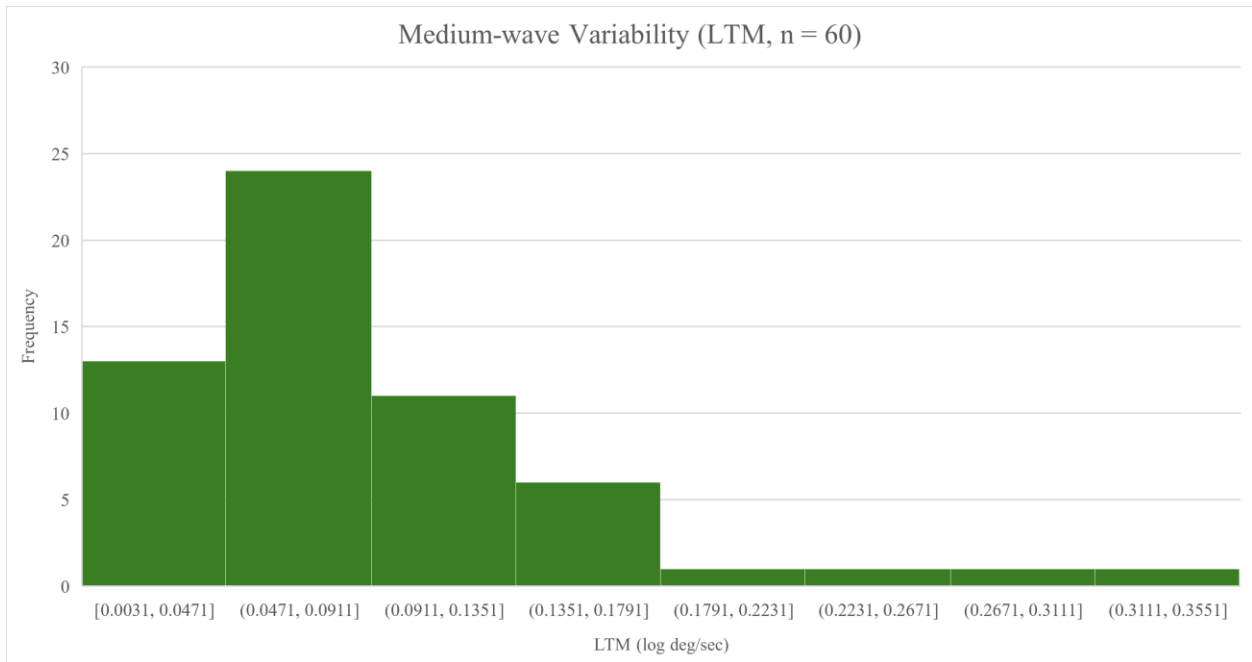


Figure 10d. Variation in LTM of All Subjects (Medium-wave)

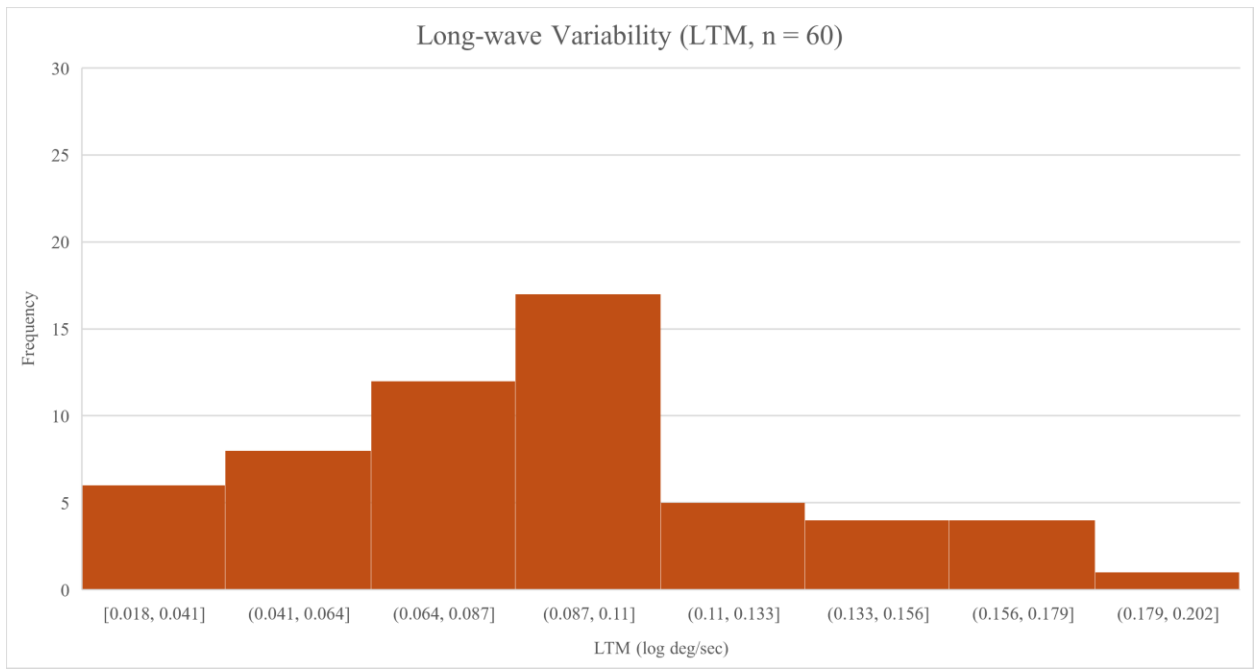


Figure 10e. Variation in LTM of All Subjects (Long-wave)

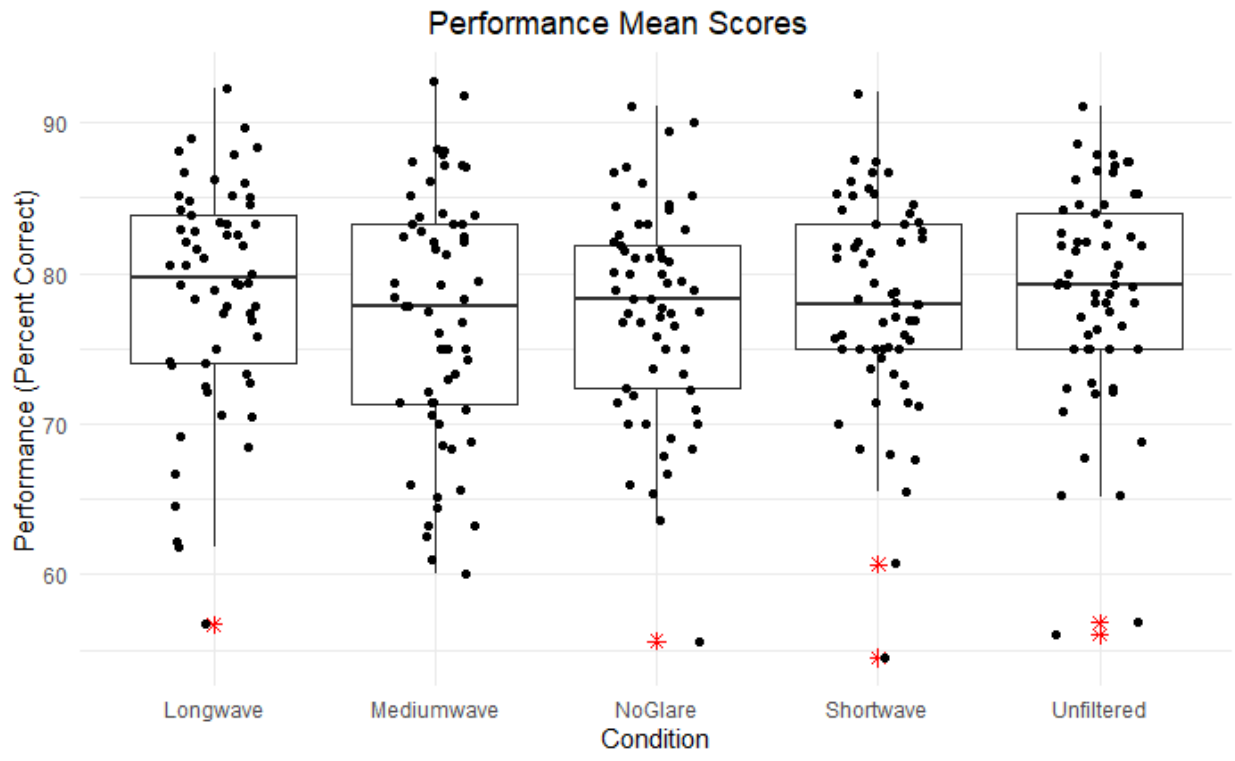


Figure 11. Box Plots of Performance Mean Scores, Organized by Filter Condition

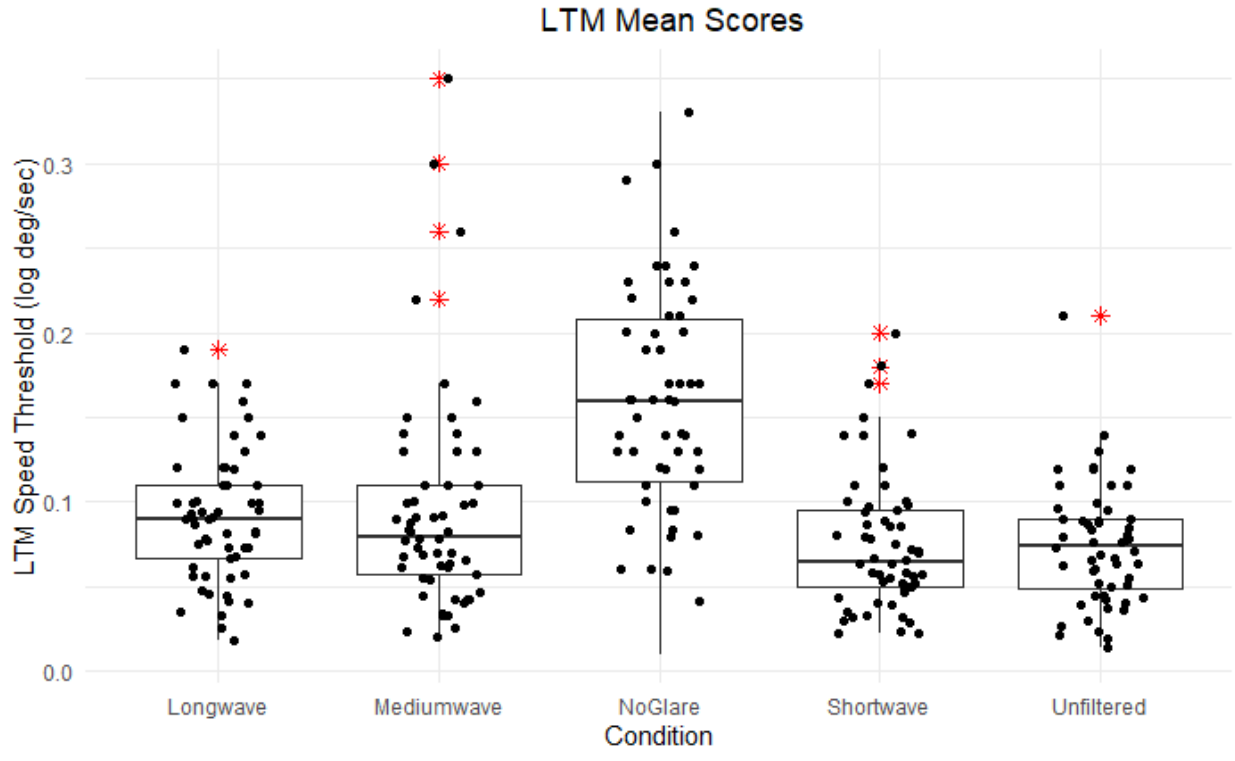


Figure 12. Box Plots of Performance Mean Scores, Organized by Filter Condition. *Note: Some outliers are not pictured due to axis scaling, but are still included in the analysis.

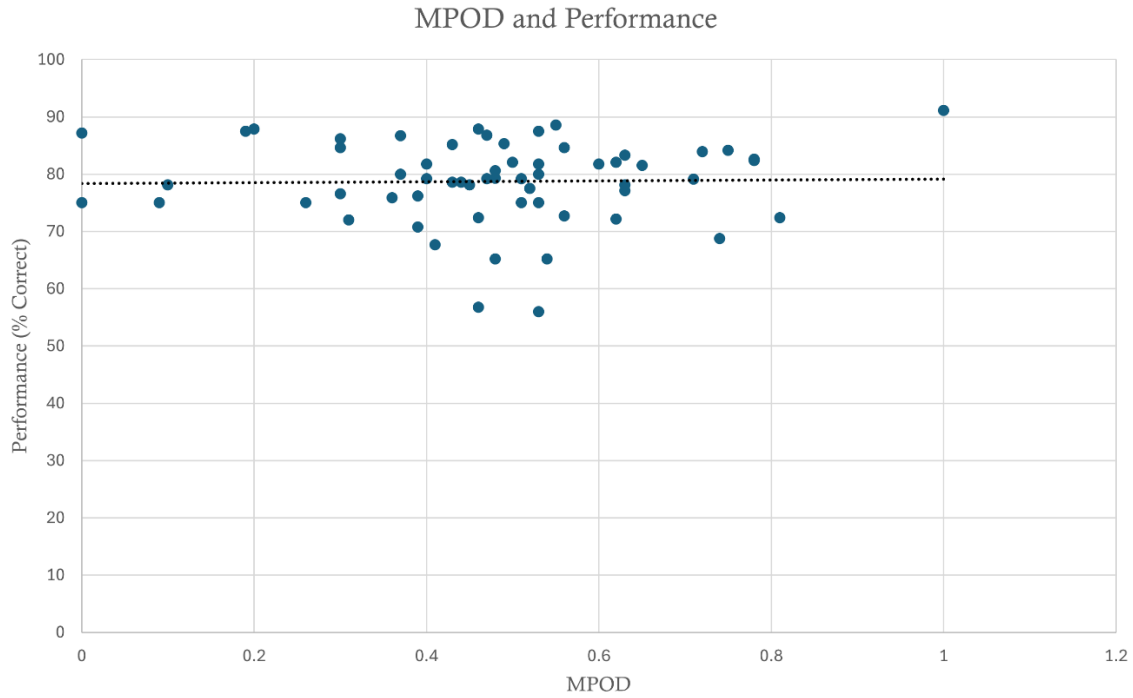


Figure 13. Distribution of Performance Scores, Organized by Subjects' MPOD.

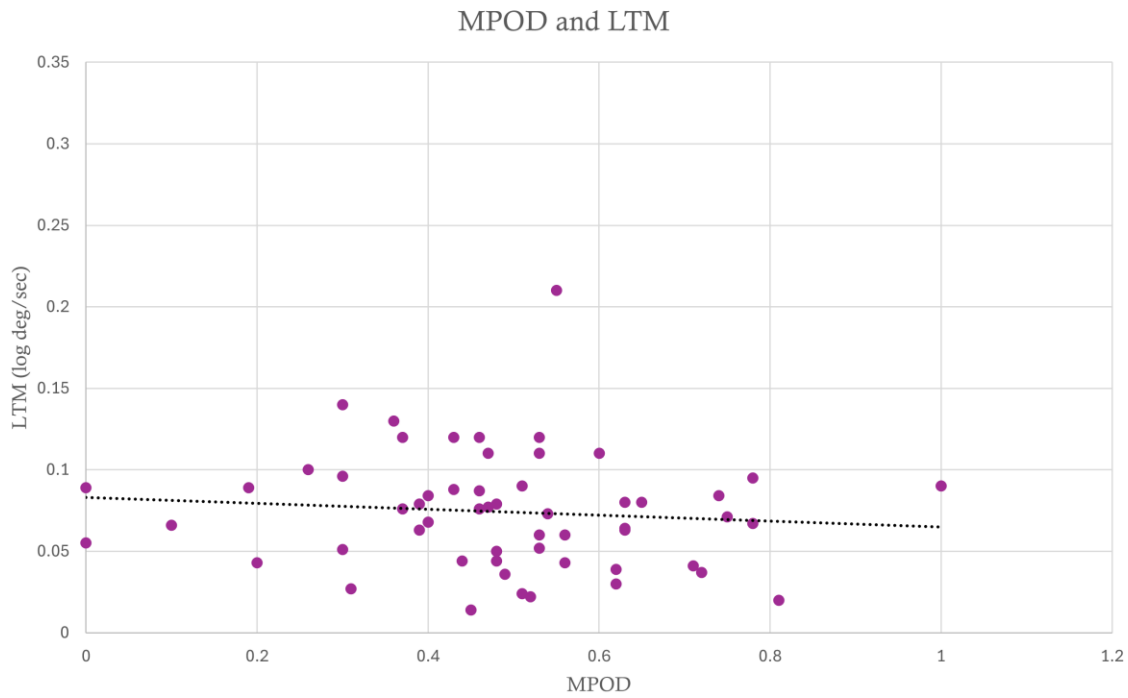


Figure 14. Distribution of LTM Scores, Organized by Subjects' MPOD.

CHAPTER 5

DISCUSSION

Glare, and the deleterious effects produced by this kind of light scatter, has a demonstrated negative effect on many aspects of visual perception. Although past studies have thoroughly investigated a limited number of visual functions influenced by glare, the literature on motion perception – specifically, the lower threshold of motion – is sparse. Additionally, there are only really two approaches to reducing the deleterious effects of light scatter, one has to either change the nature of the light source or use filtering lenses. The latter is the only method for reducing the effects of glare produced by environmental sources like natural daylight. No data currently exists regarding the effects of changing the ambient spectral conditions of light on the perception of motion. Moreover, no data also exists on these effects under normal (non-glaring) conditions (i.e., bright light that an individual would likely experience most of the time). To this end, we designed a task that would strongly impact the image-retina system with a veiling source of bright light, putting stress on the slow-motion system and using band-pass filters to change the spectral characteristics of the veil. 60 subjects were assessed and the study was sufficiently powered to test the relationship between the filter conditions and motion perception. We did not find a significant difference in mean scores for performance or LTM speed thresholds across the five (no veil, white veil, short-wave, medium-wave, and long-wave) experimental conditions.

The present study implemented a novel, ecologically valid methodology of assessing motion perception performance under the following conditions: no veiling light, white (emulated

daylight), and filtered (short-wave, medium-wave, long-wave veils). This methodology was used to test the influence of spectral filtering on motion perception. Our hypothesis was directional as it was expected that there would be individual differences in motion perception (performance and speed thresholds) across the varying filtered conditions. An analysis of variance indicated that there were no significant differences in motion perception performance ($F = 0.87, p = 0.48$) or LTM speed thresholds ($F = 0.63, p = 0.61$). Both of these statistics indicate that there were no significant mean differences across the five different conditions. The box plots produced in Figures 11 and 12 illustrate this lack of effect. Using this same methodology, the influence of MPOD on motion perception (performance and speed thresholds) was also assessed. MPOD did not significantly correlate with performance ($r = 2.15, p = 0.66$) or LTM speed thresholds ($r = -0.11, p = 0.82$). Both correlations being relatively weak and nonsignificant indicate that MPOD had no effect on motion perception performance. The scatterplots produced in Figures 13 and 14 illustrate this lack of effect.

An unanticipated finding of the present study is the high, and consistent, variability in motion perception performance and LTM speed thresholds for a relatively homogeneous sample of young, healthy adults across all filter conditions. This variability is shown in the box plots of Figures 11 and 12 but is best represented by Figures 9a-e and 10a-e, where one can see a large range of scores (some approaching 2-3 SD apart) with a similar distribution across filter conditions. We used an RDK and implemented an ecological approach for our measures of motion perception performance and LTM. Hence, it seems likely that this high variability across testing sessions reflects true natural variability. Spectral conditions change throughout the day and in different seasons, weather conditions, and environments (Thorne et al., 2009; Granzier & Valsecchi, 2014). Although slow motion tends to be relatively front-end (i.e., strongly influenced

by anterior optics), it is still a visual-motor task (meaning it requires the entire system). Hence, the ultimate behavioral response is likely influenced by both optics and the underlying, strongly dynamic, physiology. Detecting motion involves a network of neural computations and, as such, may be susceptible to natural variations in the system (Hedge et al., 2020). A common limitation of reliability assessment in vision studies is that the testing is done on the same day often within a single session (Fenandes et al., 2019; Rubin, 1988); i.e., when the system is more stable. The present data suggest that when subjects are tested across days (perhaps in differing physiological/computational states), reliability is reduced. Another interpretation is simply that the measures are difficult and may be noisy (despite the high performance values, see Figure 9a). For the ten subjects we tested, when we collapsed across spectral conditions, the correlation across sessions was relatively high. Motion may be similar to other dynamic features of the body in that it must be assessed over days/states to obtain a representative threshold. For example, blood pressure varies by time of day, physiological state, sleep patterns, caffeine use, etc.; many measures are needed to obtain a representative value.

In the present study each filter condition (save for no veiling light) outputted nearly the same amount of energy ($M = 87$ lux). It is also possible that there was not enough light reaching the eye to sufficiently stress the slow motion system enough to see a difference in the visual measures across the varying conditions.¹ Our ability to see motion is an integral part of visual perception and has been finely tuned to promote our survival in the unpredictable natural

¹ For comparison, automotive halogen headlights typically emit around 55 lux (at their most intense) and the new LED headlights emit around 100 lux (at their most intense) (Rammohan et al., 2017). Often the lux levels for headlights are specified at the source (measured directly at the light itself) but, of course, the light levels are strongly attenuated by the time they reach the eye itself. 87 Lux would be considered extremely bright if measured at the plane of the eye in a nighttime driving scenario (Pulling et al., 1980).

environment. Our motion system, specifically our slow motion system, may simply be robust enough that veiling sources of light at energy levels around 100 lux are not stressful enough on the system to degrade our ability to see motion. This is an important observation. For example, glare disability, as typically defined, is based on light interfering with visual function (Aslam et al., 2017). In most cases, however, visual function is tested using static spatial targets. For example, in a typical scenario, an intense annulus encircles a sine wave grating and the subject increases the intensity of the annulus until light scatters and veils the target (Hammond et al., 2013, 2014). In our study, light of varying spectral content was used. In all conditions, however, the average LTM was no different from any light stress at all. This suggests that full field motion may be more resistant to degradation than the simple one-degree static targets often used in glare disability experiments. This makes sense. The high survival value of perceiving motion may have granted this system considerable priority (e.g., an entire extrastriate area, V5 devoted to motion processing). It would be useful in the future to compare different types of visual function (from static to moving targets) to determine how glare disables specific categories of vision.

A secondary objective of this study was to investigate the relationship between MPOD and motion perception; it was found that MPOD was not correlated with motion perception performance or LTM speed thresholds. Previous studies (Stringham & Hammond, 2007; Stringham & Hammond, 2008; Stringham et al., 2011) have demonstrated the positive effects of MPOD with respect to its influence on visual functions under environmentally stressed conditions. In the present study, we do not see the same benefits of MPOD for motion perception. Whereas the study was sufficiently powered to investigate the relationship between filter conditions and motion perception, more participants would have been needed to sufficiently power a study dedicated to investigating the relationship between MPOD and motion

perception – an a priori power analysis for this interaction gave an n closer to 120 participants. This is more in line with the prior literature on the relationship between MPOD and sources of environmental stress (Hammond et al., 2013), but because the primary objective of the present study was on spectral filtering, the sample size was capped at 60 so as to not be overpowered. As shown in Figure 14, the relation between MPOD and LTM appear to show a slight trend but the magnitude of the effects appears to be relatively small.

The results from this work indicate some clear future directions. If motion perception is resistant to optical degradation, how intense must the light be in order to reduce motion thresholds? T-tests revealed that participants with correction had lower performance scores ($t = -2.76, p = 0.01$) compared to participants without correction for the short-wave condition. Additionally, participants with correction had higher speed thresholds ($t = 1.99, p = 0.05$) compared to participants without correction for the medium-wave condition. This suggests that there may be some negative effect of refractive state on motion perception in the shorter-wave spectral conditions. Future studies could investigate this effect further by focusing on the effect of spectrally-filtered sources of light for participants with and without visual correction.

In sum, detecting slow motion appears to be an especially hardy aspect of our normal visual repertoire. One, however, that is highly variable both for a given subject (across sessions) and across subjects (even when testing young healthy adults). The implications are significant. For example, children with autism often have normal fast-motion thresholds but impaired slow-motion (Manning et al., 2013). Brain damage can selectively reduce the perception of slow motion (Ma et al, 2015), particularly amblyopia (Meier et al., 2019). Losses due to aging appear to be particularly strong for the slow-motion system (Snowden et al, 2006). Understanding the system as it normally operates will help us understand these types of deficiencies.

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