THE EFFECTS OF STIMULUS MOTION ON CONTRAST SENSITIVITY: DYNAMIC SENSITIVITY FUNCTIONS

by

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ABSTRACT

Static Visual Acuity (SVA) has been called into question for some time as a measure of overall visual system function and as a predictor of performance on real-life tasks requiring vision (i.e., operating an automobile). Specifically, it has been pointed out that the targets employed in most SVA testing (high contrast, stationary letters) are an insufficient analog to actual targets encountered in everyday activities, which are often in motion and/or of less-than-perfect contrast. In addition, the size-threshold methodology typically used to measure SVA is incongruent with current theories of a multi-channel visual system.

Dynamic Visual Acuity (DVA) and Contrast Sensitivity have been suggested as alternatives to SVA, but while each mitigates specific weaknesses of the SVA measure, neither addresses the shortcomings completely. Traditional DVA measures employ moving targets, but these targets are usually of perfect contrast and a size-threshold methodology is used to specify acuity levels. Contrast Sensitivity employs a contrast-threshold methodology and allows measurement of specific visual channels, but stationary targets are utilized.

The present study combined the DVA and Contrast Sensitivity measures in an effort to retain the unique qualities of each while addressing their shortcomings, resulting in a more detailed picture of the human visual system and functioning than has yet been possible. By measuring contrast sensitivity to targets at a set of spatial frequencies spanning the human "window of visibility" and under conditions of motion representative of that encountered in everyday activities, it was hoped that a more powerful predictor of actual visual performance would be created. In addition, normative data was established for two separate age populations, in the hopes of learning more about specific changes that occur to the visual system during the aging process.

Indeed, several effects and interactions among the three main variables (spatial frequency, velocity, age) were uncovered, which appears to indicate that the new test may provide more information about the visual system than DVA or contrast sensitivity by themselves. The ramifications of this effort to human factors and visual performance research are discussed along with recommendations for the continuation and application of this line of research.

Dedicated to my wife Erika, my son Corien, and my parents, William and Rosalie Zavod. Without their constant love and support, this accomplishment would not have been possible.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

During a routine visual screening or eye examination (e.g., for acquiring a driver's license), what is typically measured is the smallest size of high-contrast target that can be correctly resolved, also known as Static Visual Acuity or SVA. While SVA may be a useful tool for measuring the refractive errors of the eyes, it does have some limitations which call into question its usefulness as a diagnostic device, and as a predictor of actual performance in everyday activities (Committee on Vision, 1985; Miller & Ludvigh, 1962). When an individual's SVA is measured, both the individual and the test target(s) remain stationary throughout the duration of the test. During many normal human activities however, the individual, the visual stimulus, or both, are in some type of motion during viewing. For example, if an individual is engaged in an athletic activity, he or she may be presented with a situation in which they remain stationary, but must resolve a dynamic target (e.g., baseball). On the other hand, if the individual is flying an airplane, he or she faces the task of resolving stationary objects on the ground while they themselves are in motion. Finally, an individual operating an automobile may encounter both of these situations at different points during the driving task, in addition to the added situation of viewing moving targets (e.g., other automobiles) while they themselves are in motion in the same or a different direction.

Besides its motion-related shortcomings, SVA is typically measured with targets of perfect 100% contrast (black targets on a white background). However, such high contrast targets are once again a rarity in the real visual world and in everyday human life. For instance, the contrast of letters or symbols to their background on a road sign may be affected by a number of variables including the environmental conditions (weather, time of day, etc.) and viewing conditions (background scenery, etc.), as well as the physical condition of the sign itself (materials, age, dirt, etc.). Therefore, it is much more likely that individuals will encounter targets of less than 100% contrast during everyday life activities. This once again calls into question the ability of the SVA measure to predict real human performance that requires target resolution.

An additional drawback of SVA measurement is that typically, an individual's acuity score is determined by the smallest target that he/she can correctly identify. With this methodology, it seems that SVA purports to measure the functioning of a single entity that is responsible for perception of all visual stimuli. However, according to current theories of human spatial vision, the visual system does not rely on any single entity, but rather, is composed of a number of distinct "channels" (see Graham, 1992; Regan, 1982). Each of these channels is tuned to process a particular attribute or feature of the visual scene, including the size of particular features. When speaking of "size" however, what is really meant is the size of the image that the feature projects on the retina and its associated spatial frequencies. If this theory is correct, then when measuring SVA, we are actually measuring performance across various visual channels as targets decrease in size (or increase in spatial frequency). In addition, this "size-threshold" methodology inherently tends to focus more on those channels tuned to smaller (high spatial frequency) targets than to those tuned to larger (low spatial frequency) ones.

Since the weaknesses of the SVA measure listed above have been apparent for some time, there have been various attempts at creation of alternate forms of visual measurement which purport to alleviate or at least attenuate some of them. Two alternative measures in particular have proven to be quite successful, though each targets a different area of weakness associated with SVA measure.

Dynamic Visual Acuity or DVA, a term first coined by Ludvigh (1947), refers to a test of the ability to resolve a stimulus under conditions of relative motion between the observer and the stimulus. A DVA test typically consists of an observer attempting to identify a stimulus that is moved across his/her field of view in a vertical, horizontal, or circular motion. It has been argued that the DVA test may be a better test than SVA for measurement of overall visual functioning because the resolution of a moving target requires the coordinated functioning of the entire occulomotor system, rather than simply refraction of the lens. This includes not only optical and neural resolution, but also the tracking ability of the eye as well as factors such as attention, expectation, and practice (Burg & Hulbert, 1961; Committee on Vision, 1985; Long & Rourke, 1989; Miller & Ludvigh, 1956). It would seem that a test such as DVA would therefore provide a much higher level of predictability of human performance in everyday activities involving moving stimuli, such as those discussed above.

A second test that has gained notoriety in the field of vision research is known as Contrast Sensitivity and involves the measurement of one's ability to resolve targets of varying contrast to their background. This type of visual test speaks not only to the problem of unrealistic perfect-contrast targets associated with the SVA measure, but also to the above-mentioned problem of measuring visual ability across various size-specific channels. Since the dependent variable in the Contrast Sensitivity test is the contrast of the target relative to its background, the size of the target can be kept constant thereby isolating a single size-specific channel in the visual system. Furthermore, by repeating the procedure for targets of multiple sizes (or spatial frequencies), one can produce a Contrast Sensitivity Function, a term first coined by Campbell and Robson (1968), which provides a graphic comparison of the functioning of various channels of the visual system.

Dynamic Visual Acuity

Definition and History

The ability to see objects in motion was first formally studied in the 1930's when Blackburn (1937) reported that a fixed-size object was visible at a velocity of 25 deg/sec but invisible at 50 deg/sec. It was not until 1947, however, that Ludvigh (1947) carried out the first systematic investigation to attempt the determination of visual acuity of a moving object, which he referred to as Dynamic Visual Acuity (DVA). Rather than the observer simply trying to determine whether an object was present, he employed Snellen letters as moving targets so that observers were required to resolve the detail of the stimulus in order to identify the target.

Based on that early work, DVA has been formally defined as the ability to resolve a stimulus under conditions of relative motion between the observer and the test stimulus (see Miller & Ludvigh, 1962 and Morrison, 1980, for reviews). For the formal measurement of DVA, a test stimulus such as a Landolt-C is moved across the field of view of the observer in either a horizontal, vertical, or circular motion; it is the task of the observer to identify some characteristic of the stimulus (e.g., the location of the gap in the Landolt-C). This relative motion may also be obtained by holding the stimulus in a stationary position and setting the observer in motion (Miller, 1958). Furthermore, many different variables including angular velocity, target size, target luminance, target position, and duration of exposure may be manipulated in order to obtain a measure of one's DVA under a range of stimulus and viewing conditions (see Miller & Ludvigh, 1962).

Importance of the DVA Measure

Over the past 50 years, it has been suggested repeatedly that DVA may be a better test for overall visual functioning than SVA, because resolution of a moving target requires the coordinated functioning of the entire occulomotor system. By testing how well the entire system works under dynamic conditions, we are better able to mimic real-life situations in which targets are in relative motion and, it is hoped, eventually predict actual performance in such situations.

The above argument is supported by research that has attempted to correlate individuals' SVA scores with their DVA scores. Most studies have found low correlations between the two measures, which would seem to indicate only a weak relationship between the two abilities being measured (see Ferguson & Suzansky, 1973; Ludvigh & Miller, 1954; Miller & Ludvigh, 1955; and Miller & Ludvigh, 1956). Furthermore, Hulbert, Burg, and Mathewson (1958) found that, while small correlations between the two measures exist at low velocities, they tend to disappear altogether at higher (but still modest) velocities. Burg and Hulbert (1958) reported that the critical velocity at which these correlations approach zero is approximately 60 deg/sec. This finding is particularly noteworthy since this value is very low in terms of typical target velocities we routinely encounter. For example, an automobile traveling at 30 mph and moving past a stationary observer at a distance of 30 ft has a retinal velocity for that observer of approximately 84 deg/sec. Hence, it is not surprising that both early (e.g., Ludvigh & Miller, 1953, 1954, 1954, 1958) as well as more recent research (e.g., Long & May, 1992; Long & Penn, 1987) has found that participants with similar ability on the SVA task show widely different abilities on the DVA task. Such findings have led to the widespread recognition of the potential of the DVA test. The Committee on Vision (1985) concluded that "dynamic visual acuity is often more predictive of real-world task performance than are static acuity measurements of vision" and that DVA "has real potential for the assessment of vision" (p. 24).

DVA and Performance

As discussed above, visual stimuli encountered in everyday life are often in motion relative to the observer, either due to motion of the object, motion of the observer, or a combination of the two. Everyday activities such as driving an automobile or participating in sports involve rapidly moving stimuli. In order for tasks such as these to be performed safely and correctly, a person must be able to resolve the moving stimuli. Failure to do so could result in decreased performance as well as potentially hazardous situations.

Driving

When an individual applies for a driver's license, he or she is tested for SVA to ensure that their static acuity is within acceptable limits at least with the aid of corrective lenses. While this type of acuity test demonstrates that a person is able to resolve static targets at specified distances, it may not predict other types of visual performance that are critical to operating an automobile. The act of driving requires the ability to resolve targets such as road signs, upcoming hazards, pedestrians, and other automobiles. While these targets may sometimes be encountered in static situations, more often they will be moving at various velocities and will require dynamic acuity for their adequate resolution. Since only low correlations have been found between acuity in static and dynamic situations, a person who rates "normal" on the static driver's test may or may not perform "normally" in a dynamic situation (i.e., while driving). Hulbert et al. (1958) and more recently Long and Kearns (1996) found higher correlations between the ability to read highway signs and DVA scores than with SVA scores. Burg (1971) reported that, when comparing various visual tests with actual driving performance records, "…binocular dynamic acuity is by far the most consistent contributor to prediction, followed at some distance by binocular static acuity…" (p. 83). From this evidence, it seems that including a test for DVA on a driver's test might well help in the screening process for competent drivers.

Flying

As with driving, the act of operating an aircraft also requires the ability to resolve targets in motion. Goodson and Miller (1959) found that when targets located on the ground were viewed from the air, a significant loss of acuity occurred in the same manner as when a stationary observer views a moving target. De Klerk, Eernst, and Hoogerheide (1964) also reported that DVA may be related to both night flying and formation flying performance.

Athletics

In many sports, the ability to track and resolve moving targets is an obvious requirement for adequate performance. For example, a baseball player must be able to follow a baseball moving at very high speeds in order to hit or catch it. In sports such as hockey, lacrosse, or soccer, a goaltender must be able to follow a ball or puck traveling at high speeds in order to block it. Many believe that the better an athlete's DVA, the better he or she will be able to perform in sports. Beal, Mayyasi, Templeton, and Johnston (1971) found a high correlation between accuracy of field shooting in basketball and DVA, while significantly lower correlations were found between shooting accuracy and SVA (Foul shooting, which does not require the resolution of moving targets, was not related to DVA.) In addition, they found that the player with the best free throw accuracy and field accuracy had the best DVA on the team. Rouse, DeLand, Christian, and Hawley (1988) found that, when compared to a control group of college nonathletes, a group of college baseball players performed significantly better on a DVA task. Furthermore, Ishigaki and Miyao (1993) found that athletes had an advantage over their nonathlete counterparts in the resolution of smaller targets at higher velocities. Other studies have shown that a player's performance may actually be improved through training with a dynamic task. White (cited in Sherman, 1980) found that college baseball players were able to improve their batting average as well as pitching and defensive abilities after just 12 hr of vision training. In an article by Christenson and Winkelstein (1988) which describes an attempt to develop a sports vision testing battery, the authors list DVA as a vision skill which "should be further developed and investigated" (p. 672).

Stimulus Variables

Angular Velocity

From the early days of DVA research, it has been known that the angular velocity, or the speed at which the target is moved across the visual field, will have a marked effect on acuity. In an early applied study determining acuity for objects seen from a moving automobile, O'Hara (1950) found that as the automobile increased its speed, acuity scores became progressively worse. Rose (1952) also determined that as Morse code characters were moved across the horizontal plane at different velocities ranging from 3.6 to 360 deg/sec, marked detriments in visual acuity occurred between the velocities of 20 and 100 deg/sec.

After obtaining results similar to those mentioned above, Ludvigh (1949) attempted to formulate a mathematical equation to describe the relationship between angular velocity and visual acuity. This equation was later modified by Ludvigh and Miller (1953) to the form: $Y = a + bx^3$ in which Y = visual angle in min of arc, a = an individual's measured SVA level in min of arc, b = a dynamic acuity component, and x = target angular velocity in deg/sec. This equation fit their empirical data very well for targets presented for 400ms, and they assumed that approximately 200ms was required for initial target acquisition and 200ms for subsequent pursuit and resolution. It should be noted that in the above equation, when the angular velocity is 0, the equation becomes $Y = a$. For large angular velocities though, the Y value is determined primarily by the bx^3 term (Ludvigh & Miller, 1953). This is consistent with the data described earlier that revealed a significant correlation between SVA and DVA for low velocities only.

Duration of Exposure

In more recent research (e.g., Long & Penn, 1987), the variable of target duration during a test has been examined. It has repeatedly been found that at longer exposure times (600ms as compared to 200ms), higher levels of DVA performance are achieved. These results may be explained by the known fact that the human eye has a latency period of about 200ms before it can react to a stimulus. After this period, the eye makes an initial saccade, or high-speed eye movement, which resets the position of the eye in a single jerky movement, followed by smooth pursuit movements which attempt to maintain the target on the fovea by matching eye movement velocity to target velocity (e.g., Rashbass, 1961). Therefore, with a 200ms duration, the eye only has the opportunity to make its initial saccade; the target disappears before the eye is able to initiate smooth movements. With a 600ms duration, however, the eye can make an initial saccade and then proceed with one or more smooth pursuit movements as well as multiple saccades to maintain the image on the fovea.

Illumination

It is well known through past research (e.g. Hecht, 1934; Sloan, 1968; Wilcox, 1932) that increasing illumination to the level of about 5 ft-c will result in improvements in SVA, but these improvements attain asymptote at illuminations beyond this level. Ludvigh (1949) compared the beneficial effects of increasing target luminance under both static and dynamic conditions. He found that while increases above 10 ft-c had little effect on SVA, acuity for an object moving at 90 deg/sec still showed improvement at levels as high as 505 ft-c. Similar illumination effects were also found by Miller (1958) in studies where the observer was put in motion and the target remained stationary. Under static conditions, he concluded that 5 to 10 ft-c provided adequate illumination, while under dynamic conditions, performance continued to improve as illumination exceeded levels 10-20 times the static level. Finally, Van Den Brink (1957) also found that a higher level of illumination is required for acuity of moving targets than is needed for stationary ones. He determined that at a 250ms duration, for every 1 to 4 deg/s increase in velocity of the target, illumination must be greatly increased in order to maintain an equal level of acuity.

Procedural Variables

Fixed-head vs. Free-head Movement

Another procedural variable that has come into play in the development of methods for the measurement of DVA is whether or not the observer should be able to move his/her head while following a target during a trial. The main difference between the two procedures is that in a condition of free-head movement, the observer is able to obtain foveal fixation over about 180 deg of the visual field, while in the case of the fixed-head condition, foveal fixation is limited to about 90-100 deg (Burg & Hulbert, 1961). Crawford (1960, cited in Morrison, 1980) compared the two conditions at various velocities and exposure durations. He found that DVA was better under the free-head condition, and this advantage increased in magnitude with faster speeds and longer exposure durations. Furthermore, Long and Riggs (1991) compared DVA measurements taken under free-head conditions with a similar study conducted by Long and Rourke (1989) which employed fixed-head viewing. They found that resolution thresholds were significantly lower under the free-head condition than under the fixed-head condition both before and after training on the DVA task.

Practice and Transfer Effects

Ludvigh and Miller (1954) and Miller and Ludvigh (1957) examined the effects of practice on DVA for 200 naval aviation cadets at two different target velocities by determining 20 successive acuity thresholds at each velocity. They found that while a substantial practice effect could be seen at a target velocity of 110 deg/sec, only a slight effect was evident at the lower velocity of 20 deg/sec. The results also showed that a large amount of the improvement found at the higher velocity took place in the very early trials. Furthermore, they discovered that large individual differences in practice effects appeared among the participants. They found that "…there are a large number of individuals who demonstrate a negligible amount of improvement in dynamic acuity as a result of practice. Likewise, there are those individuals who show a considerable amount of improvement in acuity and seem to learn with exceptional rapidity" (Miller & Ludvigh, 1962, p. 102).

A further finding of these studies has been called into question in more recent research. Ludvigh and Miller (1954) and Miller and Ludvigh (1957) reported that those naval cadets who began the trials with the best initial DVA performance showed a much larger improvement through the first half of the trials than the cadets who began the trials with the poorest DVA performance. Long and Riggs (1991) and Long and Rourke (1989), however, obtained opposite results. They determined that the initially poor performers benefited more from practice on the DVA task than their counterparts who were initially better performers. The authors hypothesized that the reason for the differing results may have been due to the fact that Ludvigh and Miller (1958) used naval cadets as participants, and these cadets had been extensively prescreened on a host of variables. In contrast, Long and Riggs (1991) and Long and Rourke (1989) utilized college student volunteers as participants, who probably represented a much less homogeneous sample of subjects.

The effect of transfer of training on DVA has also been examined. Ludvigh and Miller (1955) found that when participants were given practice with a 20 deg/sec target, no significant improvement was evident at the 110 deg/sec target velocity. Furthermore, when given practice at the 110 deg/sec target velocity, no significant improvement at the 20 deg/sec velocity was reported. Results such as these would seem to provide further evidence that different visual processes are employed for targets of low and high velocity.

Organismic Variables

Age

Burg's (1966) DVA study of 17,500 California drivers allowed him to determine whether a person's age was related to DVA performance. He found that, indeed, DVA scores decline as a function of age, but follow a somewhat different pattern of degradation to that of SVA scores. Up to the approximate age of 44 years, he found a gradual decline for both SVA and DVA. Beyond this age, however, the decline in DVA became quite pronounced, and this decline was more noticeable at higher target velocities.

Later research sought to examine possible causes for the decline in DVA performance with increasing age. Sharpe and Sylvester (1978) measured smooth eye movements during pursuit of targets and found that these movements were closer to the actual target speeds for the younger participants than the older ones. They concluded that this data suggested an age-related decline in motor functioning. Long and Crambert (1990) hypothesized that age-related decline in DVA may be due, at least in part, to changes that occur within the eye itself as the individual ages, such as a thickening of the lens and smaller pupil size, both of which allow less light to enter the eye. This theory was supported by the finding that if the luminance of the target was increased by a factor of 3 to allow roughly equal amounts of light to enter eyes of the older group as to the younger group, the age effect virtually disappeared. Hence, although there is clearly a decrease in DVA ability with increasing age, the complete basis for this effect is not yet certain.

Gender

Burg and Hulbert (1961) measured DVA for 236 male and female participants in seven age groups at five target speeds. Out of 30 comparisons made between males and females at a specific velocity, mean male thresholds were lower (i.e., indicative of superior acuity) than those of females in 24 of them. In a later study cited above, Burg (1966), utilized a much greater number of participants (17,500) to study gender effects on DVA. Fourteen age groups and four target velocities were employed yielding a total of 56 possible comparisons. It was found that 49 out of the 56 comparisons yielded lower thresholds for male groups than female groups. More recent studies (e.g., Long &

Homolka, 1992; Long & May, 1992) have found similar male superiority in DVA ability among college students.

Limitations of the DVA Measure

The popular current theory of spatial vision suggests that rather than a single entity that processes all visual stimuli, the visual system is actually composed of a number of “channels”, each of which is tuned to process a particular attribute or feature of the visual scene (see Graham, 1992; Regan, 1982). For example, it is known that some of these channels are tuned to stimuli of specific sizes or spatial frequencies. Therefore, using the traditional “size-threshold” methodology for the assessment of DVA would mean that rather than measuring the functioning of a single visual channel, measurement would be carried out across channels, which could yield ambiguous information about visual functioning. This suggests that the methodology employed by studies such as those by Ishigaki and Miyao (1994) and Rouse et al. (1988) which hold target size constant and determine velocity thresholds may yield more precise information about the individual components of the overall spatial visual system. Using this methodology, velocity sensitivity is being selectively measured for different parts of the system by using different-sized targets to tap the abilities of the different types of channels.

What is important here is that these different channels also have varying degrees of involvement in eye-movement control systems as well as different temporal tuning characteristics such as latencies and speed of conduction (see reviews by Graham, 1992; Regan, 1982). Therefore, stimuli that differentially activate these various channels might engage different levels of eye movement control. Long and Garvey (1988) sought to demonstrate that this situation could affect DVA and its measurement by adding a set of borders of constant size and energy above and below the target. It was their hypothesis that these borders served to keep the overall stimulus energy relatively constant across trials even as the target was decreased in size. In addition, these borders would provide a constant low-spatial frequency input to the visual system. The authors proposed that the differential processing of two different types of channels known as "transient" and "sustained" in the visual system would be revealed by these new targets. Since the sustained channels are tuned to high spatial frequencies (smaller targets), it is more likely that these channels alone are dominant when a small target is employed. The transient channels, on the other hand, are tuned to low spatial frequencies (larger targets). When the borders are added to the target, this creates a corresponding input to the transient channels under all target conditions regardless of the size of the Landolt-C. Because the transient channels prefer stimuli in motion while the sustained channels prefer stationary stimuli, the added input to the transient cells by the borders may cause the improvement in performance on the DVA task only when small targets are used. This is precisely what they found.

In addition, as argued above, while traditional DVA measurement involves high-contrast targets, visual stimuli in the everyday world are often of much lower contrast to their background, calling into question the predictive ability of the standard DVA measure for actual visual performance.

Contrast Sensitivity

Definition and History

To examine the ancestry of modern contrast sensitivity measures, one must go back to the middle of the 18^{th} century. It was at this time that Pierre Bouguer performed an experiment in which he showed that a shadow of a rod cast by a distant candle on a white screen remained visible until the candle was between 7 and 8 times farther from the screen than a candle located one foot from it (Bouguer, 1760; cited in Robson, 1993). By all accounts, this was most likely the first successful measurement of the human visual threshold for light difference. As important as Bouguer's seminal findings now seem to be, it was not until the work of Masson (1845; cited in Robson, 1993) that this line of visual research would be continued. In this study, white paper discs marked with black sectors of various lengths were rotated rapidly, rendering the black sectors as gray stripes of varying contrast, depending on the size of the sector. Instead of varying the contrast of the stimuli itself, Masson varied the illumination under which the discs would be viewed. It was his finding that the threshold for contrast was independent of overall luminance. Although this finding was later questioned (e.g., Aubert, 1876; cited in Robson, 1993), the work of Masson was nonetheless essential in fostering the clinical study of contrast sensitivity.

While the utility of Masson's test for measuring a new aspect of visual functioning was realized by many others in the field, the problem of the convenience of such a test for widespread use became a major stumbling block in its progress. It was pointed out that compared to other visual tests, such as the Snellen chart for visual acuity, Masson's test required a much more complicated apparatus and the task itself was difficult for a participant to understand. It was these methodological problems that prompted many attempts to create a more quick and convenient measure of contrast sensitivity. The first such effort was carried out by Ole Bull (1881; cited in Robson, 1993), who created a chart to measure contrast sensitivity which was similar to the Snellen chart, but which used letters of various shades of gray on a black background as the visual stimuli. This effort was followed a few years later by another attempt by Bjerrum (1884; cited in Robson, 1993). Bjerrum also saw the utility in mimicking the design of the Snellen chart for a contrast sensitivity measure. However, he took this idea a step further and created a set of Snellen charts, each with a different contrast ratio of the targets to their white background. Bjerrum's contrast charts seem to represent the first widely accepted method of contrast sensitivity measurement.

The next major advance in contrast sensitivity measurement did not occur until 1918, when George Young developed another technique he considered to be easy and rapid (Young, 1918a, 1918b; cited in Robson, 1993). In a precursor to contrast sensitivity tests still in use today, Young created a series of ink spots of varying contrast on pages of a book by simple dilution of the ink. He measured an individual's sensitivity threshold as the dilution level of the first spot detected when beginning at high dilution (invisible) and working towards low dilution (high contrast). A problem with this test, however, was that since the individual had to simply report the detection of the spots, there was no way of assuring that they actually did detect it. This problem was tackled when a commercial version of Young's test was released by a company called Raphael's (Robson, 1993). This version of the test incorporated a "forced-choice" methodology in which the ink spots were placed were placed in random positions, thereby forcing the individual to not only report the detection of the spot, but also to identify its location. This was another major advance still found in testing today in order to attenuate the effects of participant guessing.

During World War II, Hecht, Hendley, Frank, and Shlaer (1946; cited in Robson, 1993) devised a device meant to measure visual detriments associated with the condition known as hypoxia. Instead of spots or letters, they used Landolt rings as targets in order to measure contrast thresholds while controlling guessing rates. More importantly, these targets were produced photographically by varying exposure time and then calibrated with a photoelectric cell and galvanometer system. This approach marks the first time that targets for measuring contrast sensitivity were produced by a controlled process and then validated to assure their accuracy.

The Second World War also led to another major milestone in contrast sensitivity measurement. E.W.H. Selwyn was working for Kodak Research Laboratories looking for ways to improve aerial reconnaissance photographs that would need to be visually interpreted (Robson, 1993). It was during this effort that he suggested that sine wave gratings could be used as simple and accurate targets for contrast sensitivity (Selwyn, 1948; cited in Robson, 1993). According to Robson (1993, p. 259), a sine wave grating can be defined as “a target whose luminance varies in one direction as a sinusoidal function about its mean level, but is invariant in the direction at right angles to this”. Selwyn found that such gratings would be an optimal target for contrast measurement since they possess the property that when photographed, they produce an exact image of lower contrast, which would allow a set of targets of varying contrast steps to be easily produced.

In this same effort, Selwyn also became the first person to examine the effects of target spatial frequency on contrast sensitivity. Using an optical system that allowed for variation of apparent size and contrast of test gratings, Selwyn was able to produce visual targets containing bars of varying width, which would subtend to varying angles of the eye (Selwyn, 1948; cited in Robson, 1993). He became the first to witness what would eventually become known as the human “Contrast Sensitivity Function”, as he observed that not only did contrast threshold increase with very high spatial frequencies, but with very low spatial frequencies as well, a fact that he could not explain at the time.

While working for RCA on television systems, Otto Schade needed a way to measure effectively measure human contrast sensitivity (1956; cited in Robson, 1993). He found that he could use a cathode ray tube to create sine wave gratings to be used as test targets. Using this method, he was able to produce targets of varying contrast both quickly and accurately.

It was about this time that J.G. Robson and Fergus Campbell, realizing the utility of contrast sensitivity measurement, began to examine it more closely. During their research on sensitivity functions, they put forth what would become a very important theory in visual science. They suggested that the changes observed in contrast sensitivity as a function of target spatial frequency was due to the fact that the human visual system is actually made up of a number of independent processing channels (Campbell & Robson, 1968). Certain channels are tuned to process specific spatial frequencies, causing the fluctuations in sensitivity that make up the human contrast sensitivity function. Now that this function became the focus of contrast sensitivity research, the challenge was to find a method of its rapid and accurate measurement.

Though Campbell and Robson (1964, 1968) did suggest some possible measurement methods, it was Arden (1978) who was the first to introduce a test for measuring contrast sensitivity across multiple spatial frequencies. On each of six cards, he printed a grating of a specific spatial frequency. On each of these cards, the actual contrast of the grating varied from very low at the bottom to very high at the top. An individual's sensitivity at each spatial frequency was measured by incrementally revealing the grating of each card from bottom to top. Sensitivity was defined by the point at which the individual reported detection of the grating. An obvious problem with this method, however, is that like many of its predecessors, it left itself wide open to the possibility of participant guessing and there was no assurance that the participant did in fact detect the grating.

The culmination of modern contrast sensitivity measurement seems to have occurred in 1984, when Ginsburg introduced what would become known as the "Vistech" chart (Ginsburg, 1984). The Vistech chart purports to measure contrast sensitivity at 5 different spatial frequencies, ranging from 1.5 c/deg to 18 c/deg of visual angle. The chart consists of a 5 x 9 matrix of round patches, each containing a grating of a specific spatial frequency and contrast. The chart is arranged so that each horizontal row contains 9 gratings of the same spatial frequency, but which decrease in contrast from the left to the right. Each grating can have one of three possible orientations: vertical, tilted 15 deg to the left, or tilted 15 deg to the right. During an evaluation, the participant is asked to specify the orientation of each grating at each spatial frequency. The participant's sensitivity at a particular frequency is defined as the lowest contrast level at which he/she can correctly specify the orientation of the associated grating. A participant's measured sensitivity at each frequency can then be plotted together on a chart in order to graphically display his/her contrast sensitivity function. The Vistech chart remains one of the most popular methods for assessing contrast sensitivity as its administration is fast and easy for both the participant and the experimenter. In addition, it provides a range of spatial sensitivity broad enough to capture the unique shape of human contrast sensitivity function.

Importance of the Contrast Sensitivity Measure

Static acuity is typically measured by determining the smallest, high-contrast target that can be identified by the observer. Since small sizes correspond only to the high end of the visible spatial frequency spectrum, it stands to reason that such acuity tests only measure a portion of the observer's entire Contrast Sensitivity Function (CSF) (Committee on Vision, 1985). According to Ginsburg (1981), targets in a typical static acuity test only tap a spatial frequency range of about 18 to 30 c/deg. It can be assumed then, that according to Campbell and Robson's (1968) "multiple-channel" theory, that static acuity scores would be unable to predict sensitivity to targets of lower spatial frequencies. This assumption has been supported by research that has found that individuals may have very similar sensitivities to high spatial frequencies while having widely varying sensitivities to lower frequencies (e.g., Bodis-Wollner, 1972; Regan, et al., 1981). In addition, studies with cataract participants have found that the impairment often reveals itself in the form of decreased contrast sensitivity scores, while leaving static acuity largely unchanged (e.g., Long & Zavod, 2002; Wood & Troutbeck, 1995). Ginsburg (1981) provides compelling evidence of the advantage of contrast sensitivity measurement in his analogy that "…testing audition in a manner similar to that in which we presently test spatial vision would provide a measure of the ability to hear a wide range of sound frequencies at only one high level of intensity…" (pp. 4-5) The conclusion that can be drawn is that the CSF can provide more detailed information about the overall functioning of the visual system than standard acuity measures since it measures sensitivity for a much wider range of spatial frequencies (and associated visual channels).

Empirical Findings – Target Variables

Spatial Frequency (Contrast Sensitivity Functions)

Selwyn (1948; cited in Robson, 1993) was the first researcher on record to document the fact that human sensitivity to contrast actually varies as a function of the spatial frequency of targets. As testing procedures and target fidelity improved over the years, researchers were able to obtain an increasingly clearer picture of the relationship, which eventually became known as the contrast sensitivity function (CSF) (see Campbell & Robson, 1964, 1968). In particular, it was found that normal adult humans have a "window of visibility" that stretches from spatial frequencies of approximately .1 to 100 c/deg (Sekuler & Blake, 1994). However, a more important finding was that across this window, the contrast required for the various frequencies to be visible to the observer varied. When contrast thresholds for frequencies across the visible spectrum are plotted together, the resulting function forms a distinct inverted-U shape. Specifically, at the low and high ends of the visible frequency spectrum, sensitivity is very low (i.e., between 1.0 and .1 threshold contrast), while middle frequencies form the high peak of the curve (i.e., between .01 and .001 threshold contrast). This function and its distinct shape have become very important in contrast sensitivity research as they form the “baselines” against which functions produced through other experimental procedures or variables are compared.

Illumination

As would be expected, illumination has an effect on sensitivity to contrast. However, it is the particular nature of this effect that is most interesting and helpful in gaining insight into real-life visual performance. It has been found that under mesopic (i.e., twilight) conditions, sensitivity to the lowest spatial frequencies is the same as that found under normal (photopic) conditions (see Sekuler & Blake, 1994). However, at a spatial frequency of approximately 1.0 c/deg, sensitivity begins to rapidly fall from the normal CSF. Under scotopic (i.e., nighttime) conditions, sensitivity functions still follow the inverted-U shape, but are dramatically lowered across the entire spectrum from the normal CSF.

Target Type

Ginsburg’s chart of sine-wave grating patches introduced a method that allowed for relatively quick, easy, and accurate measurement of the sensitivities of multiple visual channels (i.e., multiple spatial frequencies). Though grating targets are still used today for contrast sensitivity measurement, the last 20 years or so have also seen a divergent path of testing methodology. Regan and Neima (1983), among others, suggested that instead of measuring sensitivity for several spatial frequencies, a measure of acuity for a high-contrast target coupled with a second measure of a lower contrast target should act as a sufficient measure of contrast sensitivity. Specifically, they suggested that these acuity measurements be made with two letter-charts of varied contrast. The advantage of such a test over grating-type tests was not only that it would be quicker and easier to administer, but also that the use of letters could augment the forced-choice methodology by increasing the number of possible alternatives.

Pelli, Robson, and Wilkins (1988) took this idea a step further when they designed a contrast sensitivity test that would use a single letter chart. This chart consisted of a series letters that decreased in contrast incrementally. The size of the letters, however, did not vary and was tuned to tap the middle range of the visible spatial frequency spectrum. It was their thought that such a test would be a fast and simple way to augment standard acuity letter charts in measuring overall visual functioning.

Other Empirical Findings - Organismic Variables

Age

The variable with perhaps the most clearly defined (albeit not fully understood) effect on contrast sensitivity is that of the age. It has been well-documented that the contrast sensitivity function of a human being undergoes a series of defined and predictable changes in shape and breadth throughout the various stages of life. For example, Banks & Salaptek (1978) measured contrast sensitivity functions for a set of 2-month old babies. They found that while the infants' CSFs took the classic inverted-U shape, their contrast thresholds were much higher at all spatial frequencies than that of an adult. In addition, while the infants' window of visibility extended to approximately the same point as that of adults on the lower end of the frequency spectrum, their cutoffs on the high frequency end came sooner than those of adult observers.

Bradley and Freeman (1982) studied the changes that occur to the CSF during childhood. They found that between age 2.5 and 4.5, children have gained a window of visibility approximately equal to that of adults. However, contrast thresholds across the function are still higher than those of adults, with the effect being somewhat more pronounced at the lower frequencies. They also found that from this time until about the age range of 8-16, these thresholds gradually decrease for all spatial frequencies until the CSF matches that of an adult.

Though the typical shape and breadth of the normal adult CSF has been documented time and again, it has been found that contrast thresholds and the window of visibility will still undergo some normal changes during adulthood, especially at the later stages of life. Early studies into the effects of advanced age on the CSF revealed contradictory results. For example, Arden (1978) measured sensitivities for low and intermediate spatial frequencies for participants ranging age from 11 to 70 years and found no differences. However, Arundale (1978) and Derefeldt, Lennerstrand, and Lundh (1979) both found decreases at only high spatial frequencies with advanced age, while Sekuler, Hutman, and Owsley (1980) found reductions at only lower spatial frequencies. While these varying sets of results provided no solid answer to the question of the effect of advanced age on the CSF, Owsley, Sekuler, and Siemsen (1983) performed a thorough review of these and other similar studies up to that point. They concluded that various methodological difficulties such as small number of participants and lack of control over extraneous variables led to the wide range of results. With these difficulties in mind, they performed their own study, measuring sensitivities of a group of 91 adults between the ages of 19 and 87 years for spatial frequencies of .5, 1, 2, 4, 8, and 19 c/deg. They found that while sensitivity for low spatial frequencies remained unchanged across all ages, sensitivity for higher spatial frequencies (i.e., 2 c/deg and higher) began to decrease at around the ages of 40-50. The magnitude of these losses was also found to increase somewhat steadily with more advanced age. The authors postulate that the observed reductions in sensitivity to higher spatial frequencies may be attributed to lower levels of retinal illuminance in older observers due to natural changes in the lens of the eye, as well as possible age-related neural changes in the visual system. Most recently, Higgins, Jaffe, Caruso, and deMonasterio (1988) obtained results similar to those of Owsley et al. (1983) when using a forced-choice methodology. More importantly, they were able to control for age-related pupillary changes, providing further evidence that a neural component is involved with declines in contrast sensitivity with age.

Pathology

Perhaps the most compelling area of contrast sensitivity research has been that which has focused on the effects of various pathologies on individuals' sensitivity functions. In some of the earliest work in the area, Bodis-Wollner (1972), while studying patients with cerebral lesions, found that not only did the patients suffer decrements in contrast sensitivity while maintaining normal (20/40) acuity, but the losses were characterized by three distinct patterns. Some patients experienced decreased contrast sensitivity over the entire range of spatial frequencies, while others only experienced losses at the high end of the spectrum. A small number of patients also showed a "notch" in their sensitivity function, indicating a loss in the middle frequencies, while low and high frequencies were left largely unaffected. Later research by Regan and Neima (1983) into individuals differences in contrast sensitivity functions found that four main types of distortion may occur, including a loss of sensitivity at high spatial frequencies, a loss at intermediate frequencies, a loss at low and intermediate frequencies, and a general loss across the frequency spectrum.

Studies such as these have led researchers over the past 30 years to examine the effects of various pathologies (both visual and non-visual) on the contrast sensitivity function. Abnormal CSF patterns such as those described above, have been found in patients with diseases or conditions such as multiple sclerosis (Kupersmith, Seiple, Nelson, & Carr, 1984), amblyopia (Hess & Howell, 1977), albinism (Loshin & Browning, 1983), macular degeneration (Loshin & White, 1984), glaucoma (Atkin, Bodis-Wollner, Wolkstein, Moss, & Podos, 1979), and cataracts (Hess & Woo, 1978). Results such as these provide further support for the utility of contrast sensitivity as a useful measure of the functioning of the visual system and as a device to augment current screening techniques for certain pathological conditions.

Contrast Sensitivity and Performance

While it was pointed out above that DVA measures may have a significant advantage over standard SVA measures in terms of prediction of performance in everyday life activities due to the fact that such activities often involve non-stationary stimuli, a similar statement can also be made concerning contrast sensitivity measures.

While typical SVA tests measure the ability to resolve targets of perfect 100% contrast to their background, visual stimuli encountered in everyday life activities are often of much lower contrast, due to various viewing conditions such as inclement weather or darkness, as well as degradation of the stimuli themselves due to such factors as age or physical condition. It can therefore be suggested that contrast sensitivity measures would be better predictors of performance in such situations. There have been studies on various activities that seem to support this hypothesis. For example, Owsley and Sloan (1987) found through a multiple regression model that contrast sensitivity at middle to low spatial frequencies was a strong predictor of patients' ability to see faces, road signs, and commonplace objects. Equally important to the present argument, however, is the fact that they also found that the inclusion of static acuity as a predictor did not improve the model. Others examples of findings associated with contrast sensitivity and performance of specific activities follow.

Driving

There have been studies that have specifically examined the relationship between contrast sensitivity and various aspects of the task of operating an automobile. For example, Evans and Ginsburg (1985) found a significant correlation between individuals' contrast sensitivity scores and the distance at which they could discriminate highway signs. Later studies by Wood and Troutbeck (1994, 1995) examined a wider range of visual aspects involved in the driving task. In their studies, they simulated in participants the effects of cataractus vision in an attempt to determine the effects of the disease on elderly drivers. Cataracts occurs when the lens of the eye becomes clouded, reducing the transparency of the lens and increasing dispersion of light that passes through it. They found that their impaired participants showed poorer performance in identifying visual cues whiles driving, such as reading road signs, detecting other vehicles at intersections, and detecting pedestrians at the side of the road. They also found that the time taken to maneuver around test cones and to reverse into a parking bay was longer for the cataract condition than for the normal condition. Of equal importance, however, was the finding that although individuals in the cataractus condition still satisfied legal acuity requirements for driving (20/40 vision), their contrast sensitivity was found to be significantly decreased. Lastly, it was found that contrast sensitivity scores correlated highly with a "composite driving score", leading the authors to conclude that contrast sensitivity scores were a strong predictor of driving performance.

Flying

As already discussed, another activity involving multiple tasks highly reliant on visual performance is piloting of an airplane. Ginsburg, Evans, Sekuler, and Harp (1982) examined the ability of a set of pilots to detect small, semi-isolated air-to-ground targets in a flight simulator. They found that while the pilots' contrast sensitivity scores correlated highly with the distance at which the targets could be detected, their standard static acuity scores were a much poorer predictor.

Limitations of the Contrast Sensitivity Measure

Just as it was argued above that the predictive ability of the DVA measure must be called into question because of its use of high-contrast targets, the reverse argument can be made about the contrast sensitivity measure. While traditional contrast sensitivity assessments are made with static targets, such targets are rarely encountered in everyday life. Instead, an individual may be regularly faced with targets of varying velocity in motion relative to him or herself which must be perceived and resolved in order to function properly. Therefore, it is the aim of the current effort to draw upon the strengths of each test while attenuating the shortcomings in an effort to create a visual assessment tool that will offer a more complete picture of an individual's overall visual functioning and allow better prediction of actual performance than is currently available.

The Research: Dynamic Contrast Sensitivity Functions

The Committee On Vision (1985) has stated that "…it may be that combining measurement of the contrast sensitivity function with dynamic, moving-target testing conditions can lead to more powerful measures of visual assessment that are predictive of visual task performance" (p. 24). They further recommend that "a dynamic contrast sensitivity function be measured using grating targets moving with a range of angular velocities, and that it be compared with measurements of static contrast sensitivity function…" (p. 24).

There have been previous efforts to determine the effects of target motion on contrast sensitivity. Murphy (1978) reported that gratings in motion required higher contrast levels in order to be resolved. The findings of this study were severely limited, however, by the fact that only a single spatial frequency (5.14 c/deg) was employed, along with a maximum target velocity of only 7 deg/sec (typical velocities used in DVA work range from 30-150 deg/sec.) Scialfa, Garvey, Gish, Deering, Leibowitz, and Goebel (1988) compared the sensitivity to grating targets of different spatial frequencies by determining the maximum velocity at which they could be resolved. They reported that the spatial frequency for which the observer indicated greatest sensitivity was lower under dynamic than under static conditions. Again, caution must be taken when interpreting these findings for two reasons. First, only a very small range of low spatial frequencies (.9 to 3.7 cycles/deg) and rather low target velocities (0-70 deg/sec) were employed. Second, the targets were presented in a circular motion, a condition which has not been employed to a large extent in traditional DVA work due to its lack of any real-life analog to such motion. Long and Homolka (1992) examined CSF's at four velocities for gratings of three spatial frequencies (1.0, 3.0, and 10 c/deg). The measurements were taken at two different target durations, one which would allow only saccadic movement of the eye and a longer duration that would allow both saccadic and smooth pursuit movements. They reported that under the longer duration, the horizontal motion of the target caused reduction in sensitivity to the middle and, especially, the high spatial frequencies. Furthermore, they reported that sensitivity for the lowest spatial frequency actually improved at the lower target velocities (up to 60 deg/sec) as target velocity was increased. Under the shorter duration, however, a reduction in sensitivity occurred across all spatial frequencies as velocity was increased. While this study produced some very interesting and useful results, these results may have been limited by the range of spatial frequencies that was employed. First, only three spatial frequencies were used which were not enough to properly plot a typical CSF function. Second, the highest spatial frequency employed was only 10 c/deg, which is only slightly higher than the spatial frequencies usually found at the middle of the CSF function, at the top of the inverted-U. This restricted range of frequencies did not allow measurement of contrast sensitivity at the higher spatial frequencies which form the right side of the inverted-U in typical static CSFs. In addition, sensitivity scores were calculated by determining the lowest contrast grating that the participant reported as visible. Though blank “catch-trials” were employed to counter the possibility of correct-guessing, the authors admit that the counter-measure may have been only partially successful.

Most recently, Long and Zavod (2002) measured dynamic contrast sensitivity with letters of the alphabet of varying contrast at two sizes as targets, rather than gratings. They found that sensitivity decreased with increased velocity and with smaller targets. They also found an interaction between these two variables, with greater loss with increasing velocity for smaller targets. The use of these letter targets, however, only allowed for testing over a very limited range of spatial frequencies, which were difficult to pinpoint due to the use of complex spatial targets rather than gratings.

The present work attempted to address the recommendations of the Committee on Vision (1985) and provide a more detailed picture of an individual’s visual system and functioning than has yet been possible. To accomplish this, two tests that have shown much promise in the area of visual assessment, Dynamic Visual Acuity (DVA) and Contrast Sensitivity, were combined in the hopes of retaining the unique qualities of each while at the same time addressing their particular shortcomings. By measuring dynamic targets of varying contrast, it was hypothesized that the test may be a more powerful predictor of actual visual performance, such as that required for operation of an automobile, than either test employed individually. In addition, since normative data was established for two separate age populations, the information provided by the test may help us to learn more about specific changes that occur to the visual system during the aging process and help to determine the effects of aging on visual performance during everyday activities, such as operating an automobile.

Dynamic contrast sensitivity was measured for individuals of two age groups at 5 different spatial frequencies which span the typical human CSF. The targets were borrowed from the popular Vistech Vision Contrast Test (Vistech Consultants, Inc., Dayton, OH). This test uses grating targets of varying orientation to measure contrast sensitivity and plot a CSF. These targets were converted to slides which could project images of each grating onto a screen as part of an apparatus built to display moving targets. The targets were set in horizontal motion at 3 different angular velocities (30, 60, and 90 deg/sec), which cover the range of typical moving targets in everyday life. This allowed three separate "dynamic sensitivity functions" to be plotted for each individual. In addition, a contrast sensitivity function was also measured in the dynamic apparatus with the targets in a stationary position in order to create a baseline measure for the dynamic apparatus as well as compare sensitivity as measured in the apparatus with that of sensitivity as measured by the standard Vistech wall chart. The duration of target exposure remained constant across all trials in the dynamic apparatus at 500ms; a time period great enough to allow the initiation of both saccadic and smooth pursuit movements.

Since this effort was somewhat exploratory in nature, it was difficult to predict the exact pattern of results that would be revealed. However, some earlier related work as well as current accepted theories of visual processing provided the basis for specification of certain hypothetical outcomes.

Though traditional DVA literature has found decreases in acuity associated with increases in target velocity, it must be remembered that traditional DVA measurement has involved only targets in the high spatial frequency range. On the other hand, some early work on the effects of movement on contrast sensitivity at various spatial frequencies has found some diverging results. Of particular interest are studies by Owsley, et al. (1983) and Long & Homolka (1992), both of which found that sensitivity to targets of low spatial frequencies actually increased with low-velocity movement in adult participants. The authors attributed this phenomenon to the fact that low spatial frequencies are processed by the "transient" channels of the visual system, which also favor moderate motion. It could therefore be expected that in the younger adults in the present study, the lowest spatial frequency (1.5 c/deg) may reveal increased sensitivity over that with static targets when set in motion at the 30 and 60 deg/sec velocities. At the 90 deg/sec velocity, however, this effect would be expected to disappear due to tracking errors and slippage of the image on the retina. Indeed, Long & Homolka (1992) found that the positive effect of motion for low spatial frequencies was not apparent at velocities higher than 60 deg/sec. This is not to say though, that the positive effects of motion are completely negated at higher speeds. It could be predicted that motion at all velocities could have a positive effect on lower spatial frequency targets over their higher frequency counterparts. This would result in the loss of the typical inverted-U function representing the normal static CSF. Instead, it would be predicted that the lower spatial frequencies would show higher sensitivity than middle and high frequencies for the dynamic sensitivity functions. Since the higher spatial frequencies are processed by the "sustained" channels of the visual system, it would be predicted that they would be most negatively affected by motion, and that the pattern of higher sensitivity for middle-range frequencies over the highest frequencies found in the static CSF would be maintained. The resulting function, therefore, would be expected to roughly take the form of a straight line with a moderately negative slope. An interaction between spatial frequency and target velocity would be expected in the form of a more rapid decline in sensitivity with increasing spatial frequency as target velocity is increased.

The pattern of results revealed for the older participant group may vary somewhat from that of the younger group. As discussed earlier, Owsley, et al. (1983) found that sensitivity to low spatial frequencies remains relatively unchanged throughout adulthood. They also found that while moderate motion again provided an enhancement to sensitivity for these frequencies, this enhancement was of a much lesser degree than that displayed in younger observers. This could lead to the prediction that older observers will reveal lower sensitivity to the low spatial frequency targets than their younger counterparts, but that moderate motion may still provide an advantage in sensitivity over the higher spatial frequencies. For middle and high spatial frequencies, decreased contrast sensitivity associated with age and motion (see Higgins, et al., 1988; Owsley, et al., 1983), coupled with decreases in DVA associated with age (see Burg, 1966; Long & Crambert, 1990; Sharpe & Sylvester, 1978) should produce much steeper declines in dynamic sensitivity with increasing target velocity than found at lower spatial frequencies and the magnitude of these declines would be expected to be of a much greater order than that observed in the younger participant group (see Burg, 1966; Miller & Ludvigh, 1953).

METHOD

Participants

Two groups of 26 observers each were evaluated: a set of 18-22 year-old college students from the University of Central Florida (5 male, 20 female) and a set of "older" adults, aged 55-70 from the Orlando, Florida area (10 male, 15 female). The younger participants received course credit as reimbursement while the older participants received a cash payment of 10 dollars. All participants were pre-screened for known visual disabilities or pathologies. In addition, only participants with normal or corrected-to-normal (i.e., 20/40 or better) visual acuity were asked to participate in the study.

Apparatus and Stimuli

Static visual acuity for far viewing distance was assessed with a Titmus II Vision Tester to ensure at least 20/40 acuity. Standard static contrast sensitivity was assessed using the Vistech contrast sensitivity wall chart at the standard 10ft viewing distance.

The assessment of dynamic contrast sensitivity involved an apparatus similar to that employed by many DVA studies over the years (e.g., Long & Zavod, 2002; Long & Homolka, 1992; Ludvigh & Miller, 1958). A Kodak Ektagraph slide projector was used to project the targets onto a front-surface mirror mounted on a variable speed turntable. The mirror reflected the image of the target onto a 180-deg white hemicylindrical screen positioned 10ft from the observer. The voltage delivered to the motor (and the resulting motor speed and target velocity) was controlled by a mechanical potentiometer. Target duration was controlled through use of an Ilex electronic shutter positioned in front of the projector lens. An Ilex shutter timer controlled the position of the shutter and was set to open the aperture for a period of 500ms when triggered. A Radio Shack magnetic switch with one half mounted on the edge of the turntable platter and the other half mounted at a fixed position on the table base was used to trigger the shutter timer just as the target entered the screen area on the left-hand side. For the static trials, targets were manually positioned in the middle of the screen and the shutter timer was triggered manually by the experimenter.

The targets consisted of gratings printed on clear acetate borrowed from a portable version of the Vistech. Each grating was cut from the sheet and individually mounted in a 35mm glass slide. Since the background of each slide remained clear while the grating bars were darkened, the images created when projected onto the white screen took the form of white patches with darkened bars, similar to the Vistech wall chart. In order to achieve adequate luminance for the targets, the ambient lighting in the test room needed to be dimmed to a level representative of roughly mesopic viewing conditions. Grating targets of eight contrast steps were produced at each of 5 spatial frequencies: 1.5, 3, 6, 12, and 18 c/deg. Each grating was oriented vertically, tilted 15 deg to the left, or tilted 15 deg to the right. The lens and position of the projector were adjusted so that the diameter of the gratings matched that of the standard Vistech wall chart.

Observers were seated 10ft from the screen on a chair with the height adjusted so that their eyes were at target level. Fixed-head viewing was achieved using a standard head restraint with chin cup.

Procedure

Each participant session began with an assessment of far static acuity to ensure that all participants had normal (20/40 or better) or corrected-to-normal vision. This was followed by administration of the standard Vistech static contrast sensitivity wall chart. It should be noted that the procedure for determining participants' contrast sensitivity thresholds was modified slightly to match that which was required by the dynamic apparatus. According to the original manufacturer's instructions, to measure sensitivity at each spatial frequency, participants are to examine the entire row of grating patches and report the orientation of the patch farthest to the right that they believe they can identify. Since the dynamic apparatus limited exposure to only a single target at a time, participants were asked to begin with the leftmost (highest contrast) target and identify the orientation of each successive target to the right. A participant's threshold for a particular spatial frequency was defined by the target farthest to the right for which the grating orientation was correctly identified.

When the dynamic trials began, each participant's sensitivity threshold was measured at all four target velocities of 0, 30, 60 and 90 deg/sec in a random order chosen prior to the session. Within each velocity trial bloc, sensitivity was measured at each of the 5 spatial frequencies of 1.5, 3, 6, 12, and 18c/deg, again in random order. Trial blocs began with the highest contrast target and were followed successively by targets of lower contrast until grating orientation could no longer be correctly identified. As specified above, sensitivity at a particular spatial frequency was defined by the target of least contrast for which grating orientation was correctly identified.

For each specific trial, the participant received an oral warning from the experimenter just before the target was to enter the screen. The target then entered the screen on the left-hand side and moved to the right. Once the target had passed, the participant was required to specify whether or not he/she perceived a target and if so, whether it was tilted to the left, tilted to the right, or vertical. If the participant reported seeing a target but was not sure of the orientation, he/she was asked to guess.

RESULTS

Contrast sensitivity scores were defined as the inverse of contrast proportion ((Target Luminance – Background Luminance) / Background Luminance) of the lowest contrast target correctly identified. Sensitivity scores associated with each target step for each spatial frequency are listed in Table 1. Upon an initial examination of the data collected, one participant from each age group was identified as an outlier and removed from all subsequent analyses. Mean contrast sensitivity scores for the remaining participants at each velocity and spatial frequency are listed separately for the younger and older participant groups in Tables 2 and 3, respectively. When statistically analyzing contrast sensitivity scores, it has been the traditional approach to first perform a log transform on the raw sensitivity scores due to the tendency for positive skewness. Accordingly, all raw sensitivity scores were subject to such a transform prior to formal statistical analysis.

Though it was predicted that participant sex would not be a factor in the study and no effort had been made to equate the number of male and female participants, it was decided to include the variable in an initial analysis to determine whether the data contained any evidence that could call the prediction into question. In an initial 4 (target velocity) X 5 (spatial frequency) X 2 (age) X 2 (sex) mixed-ANOVA performed on the log contrast scores with the dynamic apparatus, no significant main effect of participant sex was revealed and the variable did not significantly interact with any of the other variables. The sex variable was subsequently removed from the analysis and the log contrast scores with the dynamic apparatus were analyzed in a 4 (target velocity) X 5 (spatial frequency) X 2 (age) mixed-ANOVA with age as the only between-subjects variable. A significant triple interaction was found among the three variables, $F(12,576)=9.43$, $p<.001$. A significant interaction between spatial frequency and velocity was also found, $F(12,576)=12.00$, $p<.001$, as well as significant main effects of all three variables, $F(4,192)=178.57$, $p<.001$ for spatial frequency, $F(3,144)=308.08$, $p<.001$ for velocity, and $F(1,48)=41.62$, $p<.001$ for age. To probe for the underlying pattern of effects leading to the triple interaction, the simple interaction of age group and velocity was examined separately at each spatial frequency.

At a spatial frequency of 1.5 c/deg, a significant interaction of velocity and age group was found, $F(3,144)=17.35$, $p<.001$, as well as significant effects of both variables, $F(3,144)=138.72$, $p<.001$ for velocity and $F(1,48)=31.49$, $p<.001$ for age group (see Figure 1). The significant interaction was then further probed by examining the simple effects of velocity within each age group separately. Significant differences were found for both age groups, $F(3,72)=27.77$, $p<.001$ for the younger group and $F(3,72)=133.46$, $p<.001$ for the older group. Pairwise comparisons were employed at each age group to determine the specific pattern of effects associated with changes in target velocity (see Table 4). For the younger group, the 90 deg/sec condition was found to be associated with significantly lower contrast sensitivity than any of the other conditions, $p<.001$ in all cases. The only other significant difference found was that the 60 deg/sec condition was associated with lower sensitivity than the 30 deg/sec condition, $p=.049$. For the older group, the 90 deg/sec condition was also associated with lower sensitivity than any of the other conditions, $p<.001$ in all cases. In addition, the 60 deg/sec condition was associated with significantly lower sensitivity than the 30 deg/sec and 0 deg/sec conditions, $p=.033$ and $p=.022$, respectively.

At a spatial frequency of 3 c/deg, a significant interaction of velocity and age group was found, $F(3,144)=5.18$, $p=.002$, as well as significant effects of both variables, $F(3,144)=126.67$, $p<.001$ for velocity and $F(1,48)=27.88$, $p<.001$ for age group (see Figure 2). The significant interaction was then further probed by examining the simple effects of velocity within each age group separately. Significant differences were found for both age groups, $F(3,72)=45.57$, $p<.001$ for the younger group and $F(3,72)=83.85$, $p<.001$ for the older group. Pairwise comparisons were employed at each age group to determine the specific pattern of effects associated with changes in target velocity (see Table 5). For the younger group, the 90 deg/sec condition was found to be associated with significantly lower contrast sensitivity than any of the other conditions, $p<.001$ in all cases. For the older group, the 90 deg/sec condition was also associated with lower sensitivity than any of the other conditions, $p<.001$ in all cases. The 60 deg/sec condition was also found to be associated with significantly lower sensitivity than the 30 deg/sec and 0 deg/sec conditions, $p=.021$ and $p<.001$, respectively. Lastly, the 30 deg/sec condition was found to be associated with significantly lower sensitivity than the 0 deg/sec condition, $p<.001$.

At a spatial frequency of 6 c/deg, significant effects were found for both variables, $F(3,144)=144.55$, $p<.001$ for velocity and $F(1,48)=25.13$, $p<.001$ for age group. However, there was no significant interaction between the two variables (see Figure 3). The significant velocity effect was further probed through pairwise comparisons (see Table 6). These revealed that the 90 deg/sec condition was associated with significantly lower sensitivity than any of the other conditions, $p<.001$ in all cases. The 60 deg/sec condition was also found to be associated with significantly lower sensitivity than the 30 deg/sec or 0 deg/sec conditions, p=.007 and p<.001, respectively. Lastly, the 30 deg/sec condition was associated with significantly lower sensitivity than the 0 deg/sec condition, p<.001.

At a spatial frequency of 12 c/deg, a significant interaction of velocity and age group was found, $F(3,144)=3.62$, p=.015, as well as significant effects of both variables, $F(3,144)=115.88$, p<.001 for velocity and $F(1,48)=29.81$, p<.001 for age group (see Figure 4). The significant interaction was then further probed by examining the simple effects of velocity within each age group separately. Significant differences were found for both age groups, $F(3,72)=88.10$, p<.001 for the younger group and $F(3,72)=36.48$, p<.001 for the older group. Pairwise comparisons were employed at each age group to determine the specific pattern of effects associated with changes in target velocity (see Table 7). For the younger group, the 90 deg/sec condition was associated with significantly lower contrast sensitivity than any of the other conditions, p<.001 in all cases. The 60 deg/sec condition was also found to be associated with significantly lower sensitivity than the 30 deg/sec and 0 deg/sec conditions, p=.012 and p<.001, respectively. Lastly, the 30 deg/sec condition was found to be associated with significantly lower sensitivity than the 0 deg/sec condition, p<.001. For the older group, the 90 deg/sec condition was again associated with lower sensitivity than any of the other conditions, p<.001 in all cases. In addition, the 60 deg/sec and 30 deg/sec conditions were both associated with lower sensitivity than the 0 deg/sec condition, p=.001 and p=.004, respectively.

At a spatial frequency of 18 c/deg, a significant interaction of velocity and age group was found, $F(3,144)=8.83$, p<.001, as well as significant effects of both variables,

$\underline{F}(3,144)=93.69$, $\underline{p}<.001$ for velocity and $\underline{F}(1,48)=19.78$, $\underline{p}<.001$ for age group (see Figure 5). The significant interaction was then further probed by examining the simple effects of velocity within each age group separately. Significant differences were found for both age groups, $\underline{F}(3,72)=93.11$, $\underline{p}<.001$ for the younger group and $\underline{F}(3,72)=19.75$, $\underline{p}<.001$ for the older group. Pairwise comparisons were employed at each age group to determine the specific pattern of effects associated with changes in target velocity (see Table 8). For the younger group, the 90 deg/sec condition was associated with significantly lower contrast sensitivity than any of the other conditions, $\underline{p}<.001$ in all cases. The 60 deg/sec condition was also found to be associated with significantly lower sensitivity than the 30 deg/sec and 0 deg/sec conditions, $\underline{p}=.027$ and $\underline{p}<.001$, respectively. Lastly, the 30 deg/sec condition was found to be associated with significantly lower sensitivity than the 0 deg/sec condition, $\underline{p}<.001$. For the older group, the 90 deg/sec condition was again associated with lower sensitivity than any of the other conditions, $\underline{p}=.005$, $\underline{p}=.002$, and $\underline{p}<.001$ for the 60 deg/sec, 30 deg/sec, and 0 deg/sec conditions, respectively. The 60 deg/sec condition was also found to be associated with significantly lower sensitivity than the 30 deg/sec and 0 deg/sec conditions, $\underline{p}=.014$ and $\underline{p}<.001$, respectively. In addition, the 30 deg/sec condition was found to be associated with significantly lower sensitivity than the 0 deg/sec condition, $\underline{p}=.001$.

It was known that certain conditions required for measurement of contrast sensitivity with the dynamic apparatus (i.e., limited target duration, lower lighting conditions) could render it difficult to compare measurements with those made with the Vistech chart. In order to determine whether differences actually existed between contrast sensitivity as measured with the standard Vistech chart and measured with the dynamic apparatus, a separate 2 (age) X 5 (spatial frequency) X 2 (apparatus) mixed-ANOVA was performed which compared sensitivity scores measured with the Vistech chart to those measured with the dynamic apparatus at the 0 deg/sec (static) condition. Significant main effects were found for all three variables, $F(1,48)=19.76$, $p<.001$ for apparatus, $F(4,192)=202.57$, $p<.001$ for spatial frequency, and $F(1,48)=31.75$, $p<.001$ for age group. Significant interactions were also found between the spatial frequency and age group variables, $F(4,192)=13.46$, $p<.001$ and between the spatial frequency and apparatus variables, $F(4,192)=12.28$, $p<.001$. Since the focus of this particular analysis was on possible differences associated with test apparatus, the interaction between apparatus and spatial frequency was further probed by examining the simple effects of the test apparatus separately at each spatial frequency. At the first three spatial frequencies of 1.5, 3, and 6 c/deg, the dynamic test apparatus was associated with significantly lower sensitivity scores than was the Vistech test, $F(1,49)=34.18$, 26.68, and 16.58, respectively, $p<.01$ in all cases. However, for the two highest spatial frequencies of 12 and 18 c/deg, no significant differences between the two test conditions were revealed.

DISCUSSION

Overall, the pattern of results obtained in the study generally followed that predicted, albeit with some interesting and notable exceptions. The study was undertaken with the awareness that the apparatus used to measure dynamic contrast sensitivity could itself have an effect on measured sensitivity scores. To determine whether such an effect exists, all participants were measured for static contrast sensitivity using the standard Vistech chart with a slightly modified methodology to match that used in the dynamic apparatus. When these scores were compared with participants' sensitivity scores as measured in the dynamic apparatus in a static state (i.e., 0 deg/sec), a significant main effect was found in the form of overall decreased sensitivity when measured in the dynamic apparatus. This result was not completely unexpected, given two facts. First, contrast sensitivity with the Vistech chart was measured with unlimited target duration while the dynamic apparatus imposed a 500ms viewing duration on the observer. Second, sensitivity with the Vistech chart was measured under purely photopic conditions while the dynamic apparatus required mesopic conditions for measurement.

A significant interaction between the test conditions and spatial frequency was also found which would again not have been unexpected except for the specific nature of this interaction. Given that that the transient channels of the visual system (which are most sensitive to low spatial frequencies) "prefer" both high temporal frequency targets and lower light levels, it might have been predicted that at the lower spatial frequencies, measured sensitivity would have changed little if at all across the two tests or may have actually improved in the dynamic apparatus due to the introduction of temporal transients associated with the abrupt onset and offset of grating contrast (see Higgins, 1986;

Higgins, Caruso, Coletta, & DeMonasterio, 1983). Using the same logic, it would have been expected that at the high spatial frequencies, the dynamic apparatus would have been associated with reduced sensitivity scores. In fact, the opposite pattern was revealed. At the three lowest spatial frequencies, measured sensitivity was lower for the dynamic apparatus than for the Vistech chart. However, at the two highest spatial frequencies, this effect disappeared and no difference was apparent. One possible explanation for this counterintuitive pattern of results is that in the Vistech condition, free-head viewing allowed participants the opportunity to create their own motion relative to the targets. Though there was no direct evidence to support this theory and no other plausible can be offered at this time, it was nonetheless felt that the finding is of interest and should be examined further in future work in this area. It is also pointed out because it precludes a full comparison of the sensitivity measures obtained in the study with normative statistics established for the standard Vistech chart.

With three experimental variables of similar importance in the main analysis of dynamic contrast sensitivity, there were host of possible ways to examine the results. It was decided that the most intuitive method however, would be to focus on the effects of target velocity on contrast sensitivity at each of the five spatial frequencies separately, as well as any differential patterns observed among the two participant groups under each separate frequency condition. Past research has found that with targets of low spatial frequency, young adults experience no detrimental effects of moderate target motion (i.e., up to 60 deg/sec) and in fact, may display increased sensitivity over static targets, due to preference of the transient visual channels for this type of target. Indeed, the present study found that at the two lowest spatial frequencies (1.5 and 3 c/deg), sensitivity for the younger observers remained essentially unchanged for target velocities up to 60 deg/sec. The fact the a significant difference was found between the 30 deg/sec and 60 deg/sec conditions, but not between the 0 deg/sec and 60 deg/sec conditions at the lowest spatial frequency could suggest a possible benefit of low velocity targets over static targets at this spatial frequency, but the lack of a significant difference between the 0 deg/sec and 30 deg conditions leave the results unclear. While these finding are not fully congruent with those of earlier studies discussed, it should be noted that in both the Owsley, et al. (1983) and Long and Homolka (1992) studies, the spatial frequencies for which a sensitivity enhancement with motion was found were lower than the lowest spatial frequency (1.5 c/deg) employed in the present study, which may explain the discrepancy. In addition, the velocities for which an enhancement was found in the Owsley study were much lower than those employed in the present study. On the other hand, in congruence with the results of these previous studies, sensitivity dropped rather dramatically for the lower spatial frequencies when target velocity was increased to 90 deg/sec. Within the older participant group, it had been expected that the pattern of effects of target motion at this lower frequency range would be similar to that of the younger participants. At the very lowest spatial frequency (1.5 c/deg), the pattern of effects differed somewhat from that found in the younger group, with no apparent difference in sensitivity between the static condition and the 30 deg/second velocity condition, but a drop in sensitivity when velocity was increased to 60 deg/sec, indicating that the older group may have a lower "critical velocity" at which sensitivity begins to decrease. At 90 deg/sec, sensitivity for this group again drops dramatically, but at an even steeper rate than found in the younger group, an effect that appears to be the basis for the significant interaction found between the age group and velocity conditions at this spatial frequency. This pattern was expected due to known decreases in occulomotor functioning associated with advanced age resulting in decreased ability to acquire and pursue rapidly moving targets. At a spatial frequency of 3 c/deg, the pattern of velocity effects between the two groups continued to change, with the interaction between the age group and velocity variables appearing to occur at the very beginning of the velocity continuum, with decreased sensitivity in the older group for targets moving at even at lowest velocity (30 deg/sec). Interestingly, from this point on, the interaction seems to disappear and the pattern of decline in sensitivity essentially mirrors that of the younger group, with a slight decrease in sensitivity as velocity is increased from 30 to 60 deg/sec, followed by a dramatic decrease at 90 deg/sec.

At the middle spatial frequency of 6 c/deg, the patterns of sensitivity across the velocity continuum began to change both within and between the groups. For the first time, the younger age group was found to be subject to decrements in sensitivity even at the lowest velocity. The decrease in sensitivity also continued at approximately the same rate as velocity was increased from 30 to 60 deg/sec. Once again, this was followed by a steeper decline when velocity was increased to 90 deg/sec. What may be a more interesting finding was that at this spatial frequency, the interaction between the age group and target velocity variables seems to disappear altogether. Though the separation between the two age groups appears to be greater under the static (0 deg/sec) condition than it was at the lower spatial frequencies, the pattern of decline in sensitivity associated with increasing velocity mirrored that of the younger group along the entire continuum.

At a spatial frequency of 12 c/deg, sensitivity for the younger group again declined significantly between the static (0 deg/sec) targets and those moving at even the lowest velocity of 30 deg/sec. Sensitivity continued to decline as velocity was increased from 30 deg/sec to 60 deg/sec, though at what appears to be a slightly slower rate. At 90 deg/sec, sensitivity again dropped steeply. The pattern of results for the older participant group at this spatial frequency was very similar to that of the younger group except that no decline in sensitivity was found when velocity was increased from 30 deg/sec to 60 deg/sec, a result that appears to be the basis for the significant interaction of the velocity and age group variables at this spatial frequency.

At the highest spatial frequency of 18 c/deg, a significant interaction between velocity and age group was again found, but the apparent nature of this interaction is notable. It appears that the older participant group experienced a drop in sensitivity of a similar magnitude to the younger group when moving from the static to 30 deg/sec velocity and again as velocity was increased to 60 deg/sec. However, at the 90 deg/sec velocity, the older group seemed to experience a less steep decline in sensitivity than that of the younger group, with the effect of a decrease in the disparity of sensitivity among the two groups. This finding is of particular interest because this pattern was opposite to that which was hypothesized a priori. It was initially thought that at the higher spatial frequencies (and especially under conditions of high velocity), the combination of age effects on the amount of light allowed to pass through the eye and occulomotor tracking ability would manifest itself in a more rapid decline in sensitivity for the older participants than their younger counterparts. One possible explanation for this unexpected finding is that a "cellar" effect limited the amount of decline for the older group that the test was sensitive enough to measure. This theory is further bolstered by the fact that for every spatial frequency grating set on the Vistech chart, the initial (highest contrast) grating patch is always of a vertical orientation. Given the necessary modifications to the experimental procedure discussed earlier (i.e., the highest contrast patch was always presented first) it is quite plausible that this fact was quickly learned by participants, rendering the first trial within each bloc essentially a "gimme". With this in mind, it can be argued that the actual "falling off" point of contrast sensitivity may have been located on the log sensitivity scale somewhere between .48 and .7, depending on the particular spatial frequency, rather than at the true "zero" point. An examination of the plotted sensitivities reveals that if this is true, then indeed, scores at the highest velocity appear to closely approach the "cellar", especially within the older participant group.

Though it was felt most important to examine and statistically analyze the effects of age and velocity at each spatial frequency separately, the importance of examining participants' contrast sensitivity as an overall function cannot be overlooked. One of the goals of this study was to create a series of "Dynamic Sensitivity Functions" in order to examine changes that occur across the human "window of visibility" under conditions of target motion. Separate contrast sensitivity functions are plotted for each velocity condition for the younger and older participants in Figures 6 and 7, respectively. For the younger group, it can be seen that the addition of moderate (i.e., up to 60 deg/sec) target motion had little effect on the first two points of the function. It is only at the middle frequency (6 c/deg) that the shape of the function begins to change under those same velocity conditions. Significant decreases in sensitivity as velocity is increased incrementally from 0 to 30 and 30 to 60 deg/sec caused both dynamic functions to separate from the static function and begin their descent at an earlier point, causing what appears to be a shift in peak sensitivity from 6 c/deg under the static condition to 3 c/deg under the two moderate motion conditions. At the 12 c/deg point, the drop in sensitivity associated with moderate motion appears to be of a more dramatic nature than that found at 6 c/deg, causing both dynamic functions to separate farther from the static function. Interestingly, the separation between the functions at the two velocity conditions does not appear to increase over that found at the previous spatial frequency.

At highest end of the function, sensitivity appears to decline more sharply than found between the previous two points, but once again, the separation between the functions appears to remain unchanged. The separation of the moderate velocity functions from the static function at the middle and high spatial frequencies appears to change the overall shape of these functions from the standard “inverted-U”, to a curve that reflects a slightly positive skew.

At the highest velocity condition of 90 deg/sec, the shape of the resulting sensitivity function undergoes a much more dramatic transformation. Large decreases in sensitivity across the entire frequency spectrum coupled with what appears to be an increasingly detrimental effect with higher spatial frequency, cause not only a downward shift of the entire function on the sensitivity scale, but an apparent “flattening” of the curve at the low and middle spatial frequency points.

The effects of moderate motion on the sensitivity function differed somewhat for the older participants. First, a visible inspection of the functions reveals that the initial separation of the dynamic curves from the static one occurs earlier along the continuum than it did for the younger participants. At 30 deg/sec, the functions first begin to separate at 3 c/deg and at 60 deg/sec, the functions separate right from the outset, at 1.5 c/deg. At the middle point of the functions, the separation between the static and 30 deg/sec functions appears to remain unchanged, while the 60 deg/sec function seems to experience a decrease in its negative slope, bringing it closer to the 30 deg/sec function. From this point on, all three functions appear to represent a linear decline and the separation among them remains relatively unchanged.

The 90 deg/sec condition was once again associated with not only a dramatic downward separation from the other functions, but also changes in shape of the form of an overall flattening of the curve. As has been previously pointed out, since this function is located so close to the lowest point on the sensitivity scale, a possible cellar effect may have something to do with the resulting shape of the function.

Since none of the sensitivity functions for either age group actually reached the zero point of the sensitivity scale, there can be no solid inferences made about the effect of target motion on the breadth of the overall human window of visibility. However, if we extrapolate from the available data, it appears that for all participants, the addition of motion could result in a lower absolute cutoff point at the high frequency end of the sensitivity function, resulting in an overall constriction of the visible spatial frequency spectrum.

The ramifications of the present work are several. At a basic level, this was the first effort to examine contrast sensitivity over a range adequate to plot a full CSF under a range of motion conditions that represent targets that may be encountered in everyday life activities. While it is known that both the contrast sensitivity and dynamic visual acuity measures provide more information about overall visual functioning than standard measures of static acuity, the melding of the two measures appears to provide an even more robust picture of the performance of the human visual system. While contrast sensitivity allows the measurement of specific spatially tuned visual channels, the addition of target motion provides new information about the temporal tuning characteristics of these channels and also provides a better analog for actual targets encountered in everyday life. Conversely, the use of spatial frequency gratings as targets in measurements of dynamic vision allows for pinpointing of the effects of motion on more than one specific visual channel and once again, provides a more realistic target than those of perfect contrast, as traditionally employed. Indeed, the present work revealed that not only does the addition of target motion change the shape of the contrast sensitivity function, but the particular ways in which it changes depend not only on the actual speed of the target, but also the age of the participant.

The results of this effort may have far-reaching implications in the applied realm as well. While is has already been found that the standard DVA and contrast sensitivity measures are better predictors of performance in many real-life activities that rely on visual ability, it may be that the dynamic contrast sensitivity provides an even more complete assessment of visual performance. For example, DVA seems to be a better predictor than SVA of performance in real-life activities because it measures the ability to resolve targets in motion, similar to that experienced during common tasks such as driving. Contrast sensitivity measurement seems to hold an advantage over SVA because it employs targets of less than perfect contrast which again are viewed as a better analog to actual targets of compromised contrast encountered while driving. In addition, it examines the differential ability to resolve targets of specific spatial frequency (i.e., size).

It would stand to reason then that since the targets employed in the present study shared the advantageous characteristics of both measures, they may provide an even more accurate proxy for real-life targets, leading to the reasonable assumption that they would have greater predictive capability. If it can be shown that the measure is indeed a strong predictor of actual driving performance, it may provide another possible alternative to the standard SVA measure that is still used almost exclusively to determine whether an individual is fit to operate an automobile on public roadways. This is especially relevant as we currently experience increases in life expectancy, resulting in larger numbers of elderly drivers on the roadways and the propensity for individuals to continue to operate automobiles through later stages of life. Consider that the highest velocity employed in the present study (90 deg/sec) would correspond to a driving situation in which an individual views an object at a distance of 30 ft while traveling at a speed of only 36 mph (Long & Homolka, 1993). Though all of the older participants in the study would most likely pass the legal SVA requirements to obtain and/or maintain a driver's license, the fact that contrast sensitivity at this velocity fell to extremely low levels across the entire spatial frequency spectrum may indicate that the current methods and standards are insufficient to screen out drivers who could represent a hazard to themselves and others. The possible benefit in driver screening is not limited to the elderly. Even the younger participants in the study displayed what could be considered dangerously low levels of sensitivity under conditions of "high" target velocity, especially for targets of higher spatial frequency.

The preceding point highlights another possible track of applied work that could reap the benefits of a dynamic contrast sensitivity measure. The information provided by the measure could also be important in the area of the design of driving environments. Knowledge of driver contrast sensitivity for targets of specific spatial frequencies and under specific velocity conditions may be utilized to not only determine the optimum size and placement of road or highway markers and signs, but to tailor this knowledge depending on specific driving conditions, such as expected vehicle speed or environmental conditions such as fog. Conversely, knowledge of driver dynamic contrast sensitivity combined with knowledge of the size and distance of targets that must be resolved on a given roadway and expected environmental conditions could aid in the setting and verification of safe vehicle speed limits.

Lastly, it is possible that the dynamic contrast sensitivity measure could provide an even better tool for the diagnosis of certain pathological disorders than the standard contrast sensitivity measure. As discussed above, the literature is replete with examples of specific patterns of contrast sensitivity found to be associated with various conditions. In these cases, the contrast sensitivity function as a whole often represents an "emergent feature" (Pomerantz, 1981; cited in Sander & McCormick, 1993), which under normal conditions, would take the shape of an inverted-U. Changes to this feature such as notches or overall shape shifts are used to identify specific pathologies. Since the current study found that the same sets of "normal" observers displayed sensitivity functions of distinctly different shape under various conditions of target motion, it is possible that the various functions could be merged to create a 3-dimensional "contrast sensitivity surface", an idea first put forth by Long and Zavod (2002). It could be the case that certain conditions manifest themselves in a differential manner across static and dynamic sensitivity functions, thereby altering the overall shape of the surface. If this is the case, adding the third dimension to the feature could allow for even more accurate pinpointing of certain conditions as well as the diagnosis of other conditions that may have no visible effect on the static sensitivity function.

APPENDIX A: TABLES AND FIGURES

Table 1: Target Contrast Sensitivity Values

			Target Step							
			1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Spatial Frequency (c/deg)	**1.5**	Raw	3	7	12	20	35	70	120	170
		Log	.48	.85	1.08	1.30	1.54	1.85	2.08	2.23
	3	Raw	4	9	15	24	44	85	170	220
		Log	.60	.95	1.18	1.38	1.64	1.93	2.23	2.34
	6	Raw	5	11	21	45	70	125	185	260
		Log	.70	1.04	1.32	1.65	1.85	2.10	2.27	2.42
	12	Raw	5	8	15	32	55	88	125	170
		Log	.70	.90	1.18	1.51	1.74	1.94	2.10	2.23
	18	Raw	4	7	10	15	26	40	65	90
		Log	.60	.85	1.00	1.18	1.42	1.60	1.81	1.95

Table 2: Mean Raw Contrast Sensitivity – Younger Participants

			Spatial Frequency (c/deg)				
			1.5	**3**	**6**	**12**	**18**
Velocity (deg/sec)	**0**	M	40.80	89.00	104.40	81.96	26.24
		SD	21.15	41.17	48.87	33.16	11.62
	30	M	42.00	89.96	82.28	48.72	13.60
		SD	20.31	46.28	41.94	28.46	8.12
	60	M	35.20	78.40	61.00	34.04	10.80
		SD	8.35	47.66	34.46	19.15	6.78
	90	M	19.44	25.72	24.52	12.16	5.20
		SD	11.30	18.61	19.53	11.76	2.29

Table 3: Mean Raw Contrast Sensitivity – Older Participants

			Spatial Frequency (c/deg)				
			1.5	**3**	**6**	**12**	**18**
Velocity (deg/sec)	**0**	M	32.60	79.64	60.32	32.40	12.12
		SD	15.82	61.03	38.25	27.03	10.20
	30	M	31.16	54.48	43.56	22.60	8.88
		SD	14.35	43.23	35.35	24.17	9.88
	60	M	25.80	36.36	42.00	20.20	6.32
		SD	10.44	19.59	46.24	18.00	4.70
	90	M	5.76	8.52	8.20	5.48	4.08
		SD	4.50	9.02	8.52	1.12	1.19

Table 4: Velocity Pairwise Comparisons – 1.5 cycles/degree

Velocity (deg/sec)			30	60	90
0	Younger	Mean Difference	-.019	.037	.370*
		p Value	.551	.306	.000
	Older	Mean Difference	.020	.109*	.804*
		p Value	.473	.022	.000
30	Younger	Mean Difference		.056*	.389*
		p Value		.049	.000
	Older	Mean Difference		.089*	.783*
		p Value		.033	.000
60	Younger	Mean Difference			.333*
		p Value			.000
	Older	Mean Difference			.694*
		p Value			.000

* The mean difference is significant at the .05 level

Table 5: Velocity Pairwise Comparisons – 3 cycles/degree

Velocity (deg/sec)			30	60	90
0	Younger	Mean Difference	.010	.089	.626*
		p Value	.815	.126	.000
	Older	Mean Difference	.161*	.297*	.983*
		p Value	.000	.000	.000
30	Younger	Mean Difference		.079	.616*
		p Value		.224	.000
	Older	Mean Difference		.136*	.822*
		p Value		.021	.000
60	Younger	Mean Difference			.537*
		p Value			.000
	Older	Mean Difference			.686*
		p Value			.000

* The mean difference is significant at the .05 level

Table 6: Velocity Pairwise Comparisons – 6 cycles/degree

Velocity (deg/sec)		30	60	90
0	Mean Difference	.138*	.239*	.797*
	p Value	.000	.000	.000
30	Mean Difference		.101*	.659*
	p Value		.007	.000
60	Mean Difference			.558*
	p Value			.000

* The mean difference is significant at the .05 level

Table 7: Velocity Pairwise Comparisons – 12 cycles/degree

Velocity (deg/sec)			30	60	90
0	Younger	Mean Difference	.261*	.399*	.903*
		p Value	.000	.000	.000
	Older	Mean Difference	.169*	.224*	.635*
		p Value	.004	.001	.000
30	Younger	Mean Difference		.138*	.642*
		p Value		.012	.000
	Older	Mean Difference		.055	.466*
		p Value		.321	.000
60	Younger	Mean Difference			.504*
		p Value			.000
	Older	Mean Difference			.411*
		p Value			.000

* The mean difference is significant at the .05 level

Table 8: Velocity Pairwise Comparisons – 18 cycles/degree

Velocity (deg/sec)			30	60	90
0	Younger	Mean Difference	.301*	.415*	.690*
		p Value	.000	.000	.000
	Older	Mean Difference	.151*	.224*	.364*
		p Value	.001	.000	.000
30	Younger	Mean Difference		.114*	.390*
		p Value		.027	.000
	Older	Mean Difference		.072*	.213*
		p Value		.014	.002
60	Younger	Mean Difference			.275*
		p Value			.000
	Older	Mean Difference			.141*
		p Value			.005

* The mean difference is significant at the .05 level

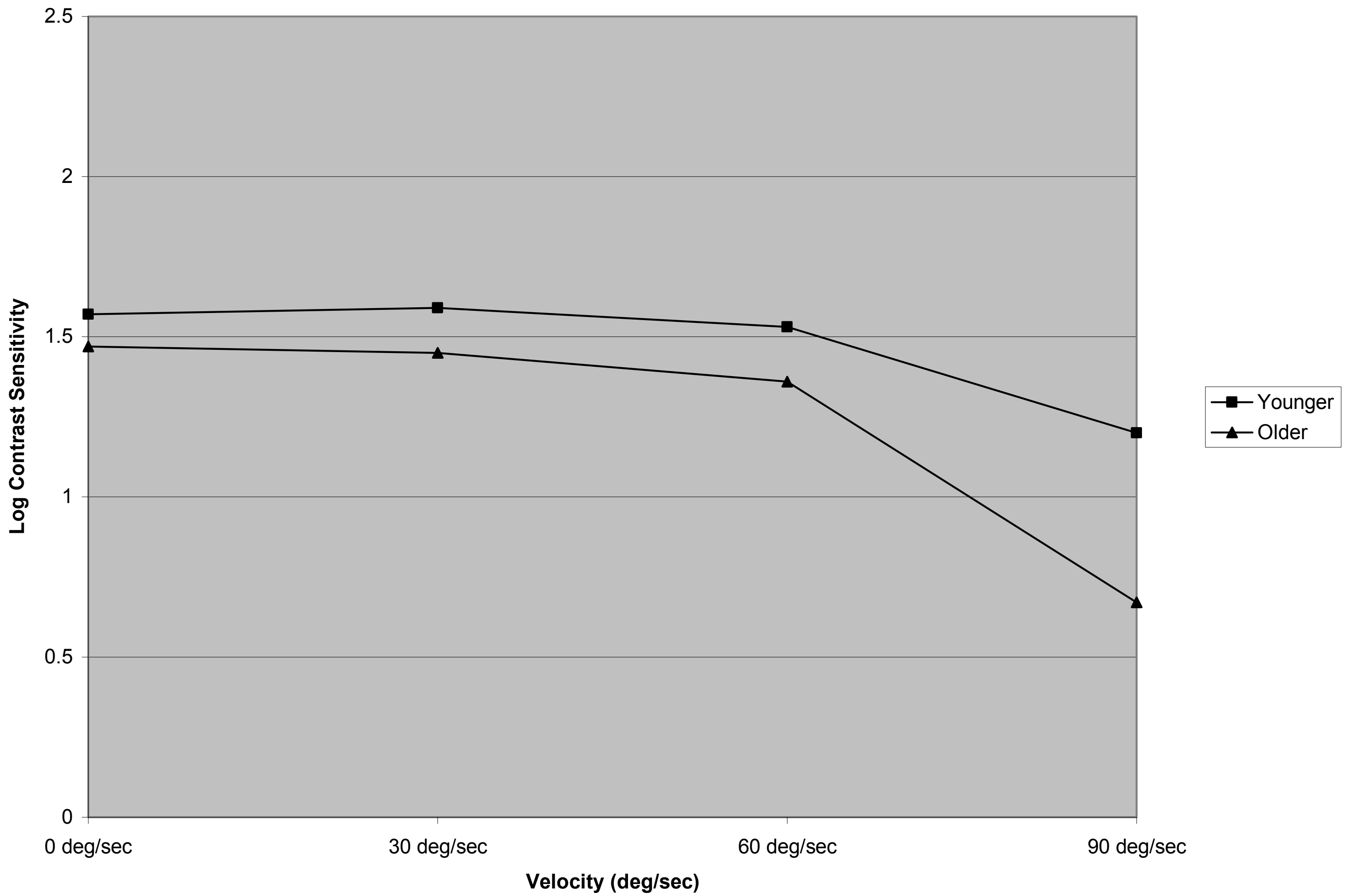

Figure 1: 1.5 cycles/degree

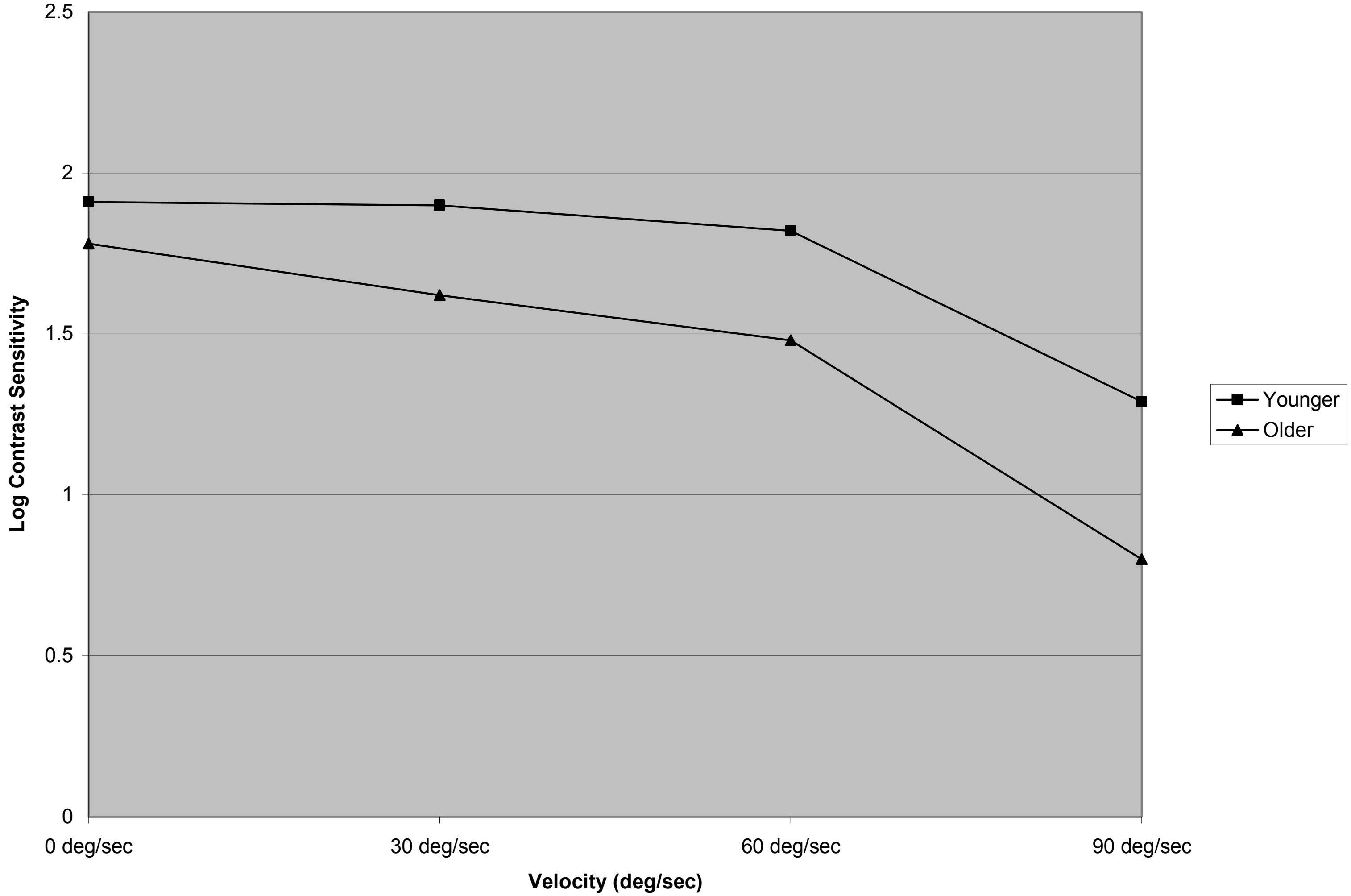

Figure 2: 3 cycles/degree

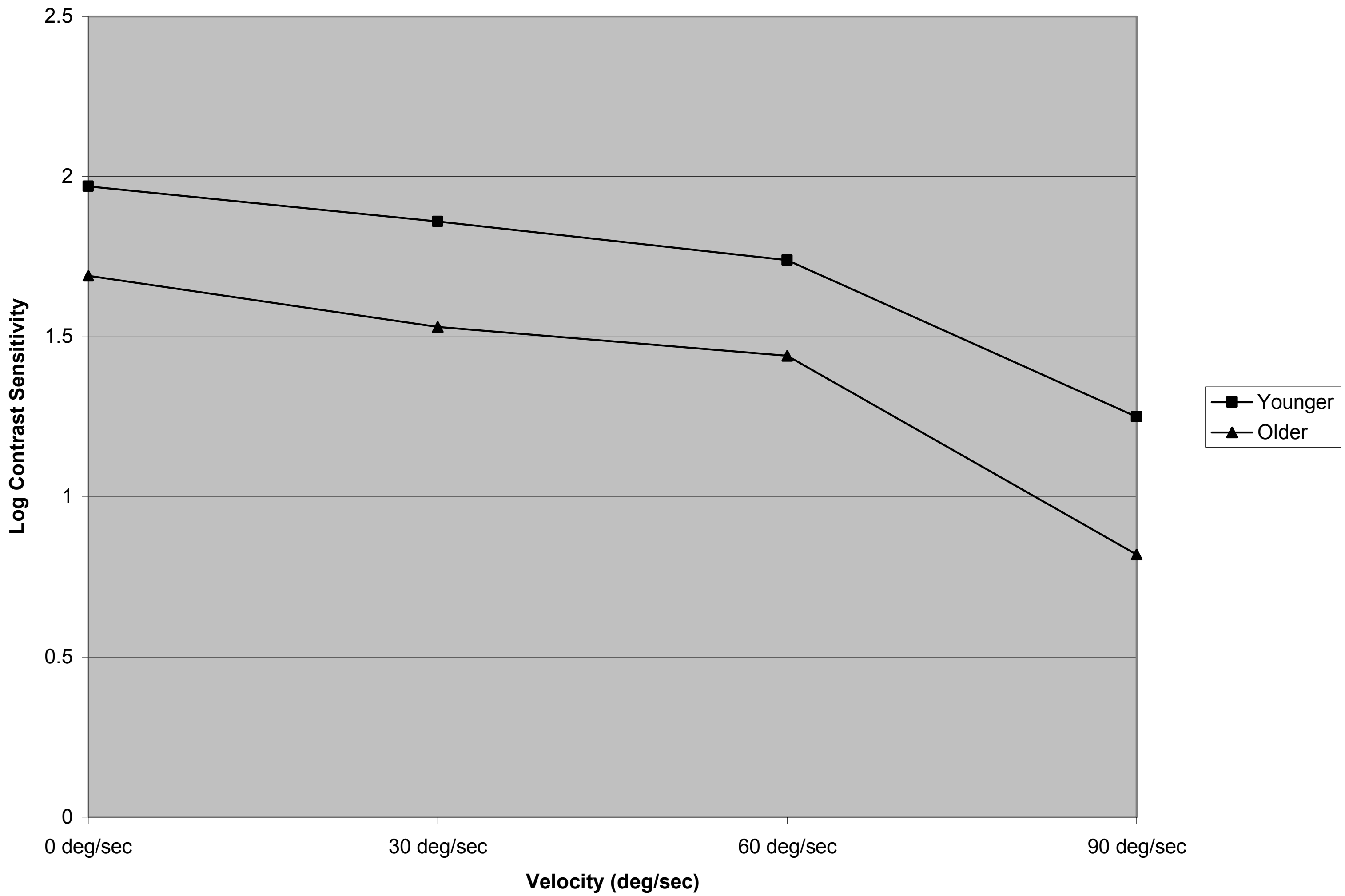

Figure 3: 6 cycles/degree

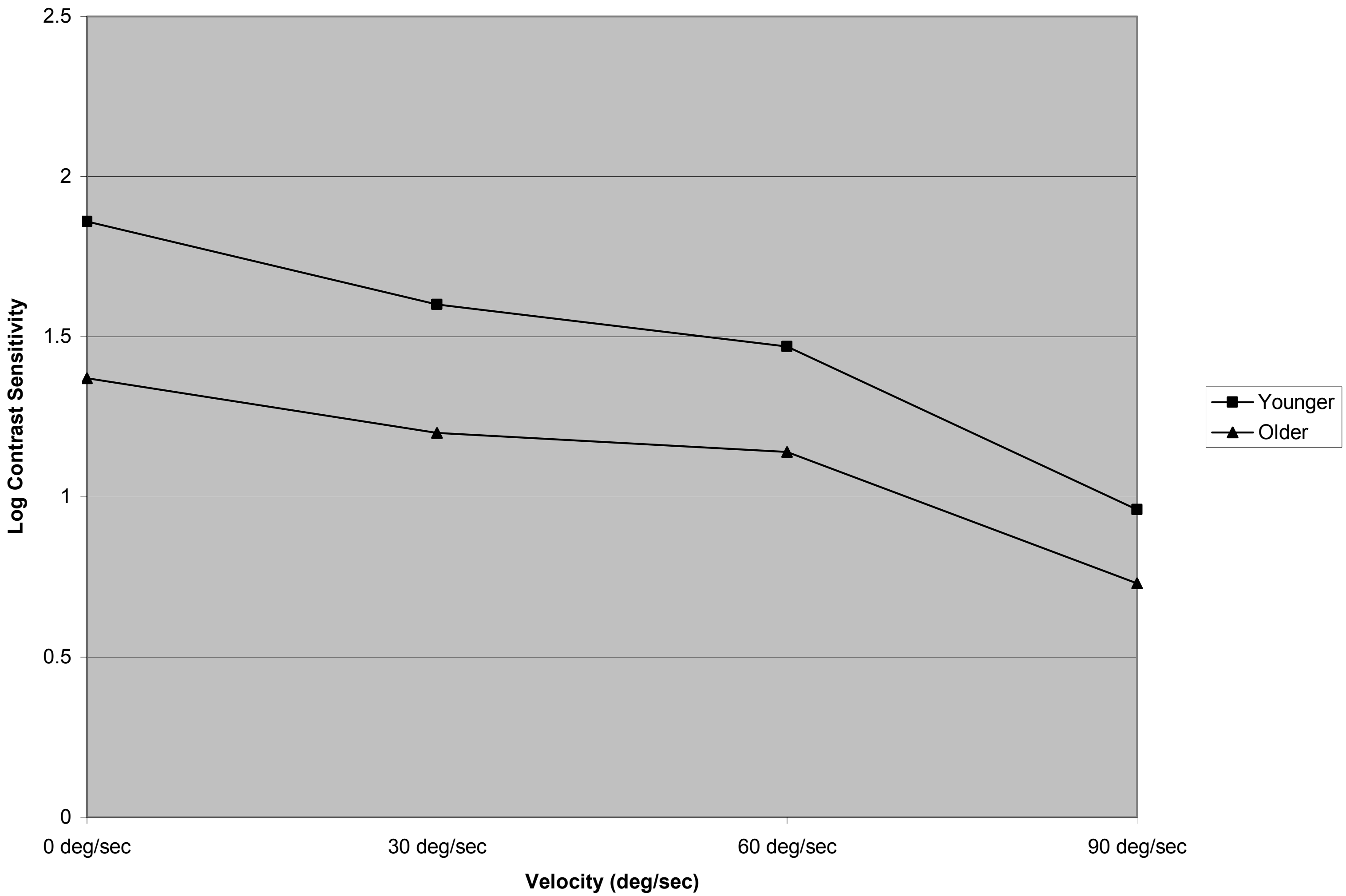

Figure 4: 12 cycles/degree

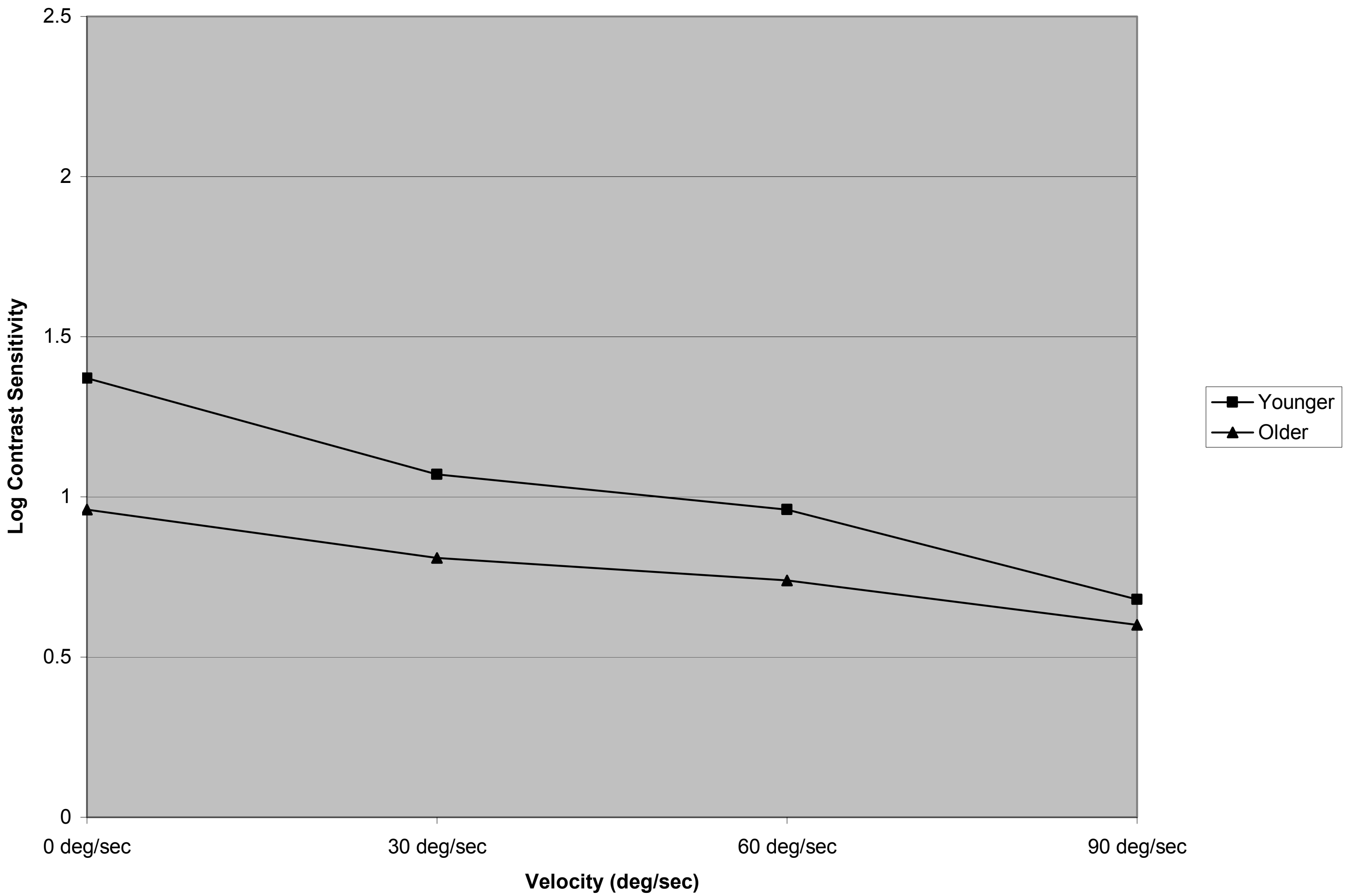

Figure 5: 18 cycles/degree

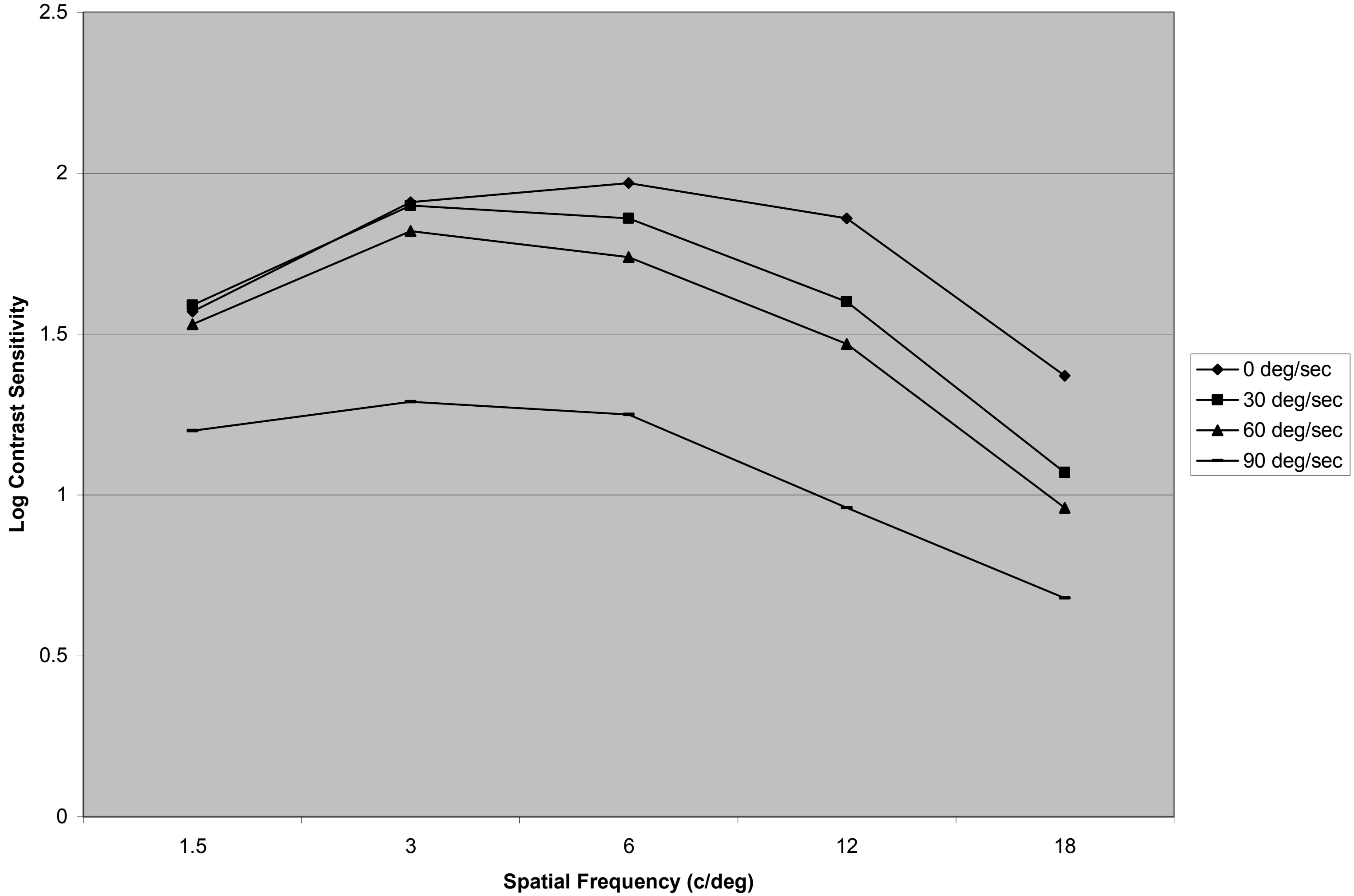

Figure 6: Dynamic Sensitivity Functions – Younger Participants

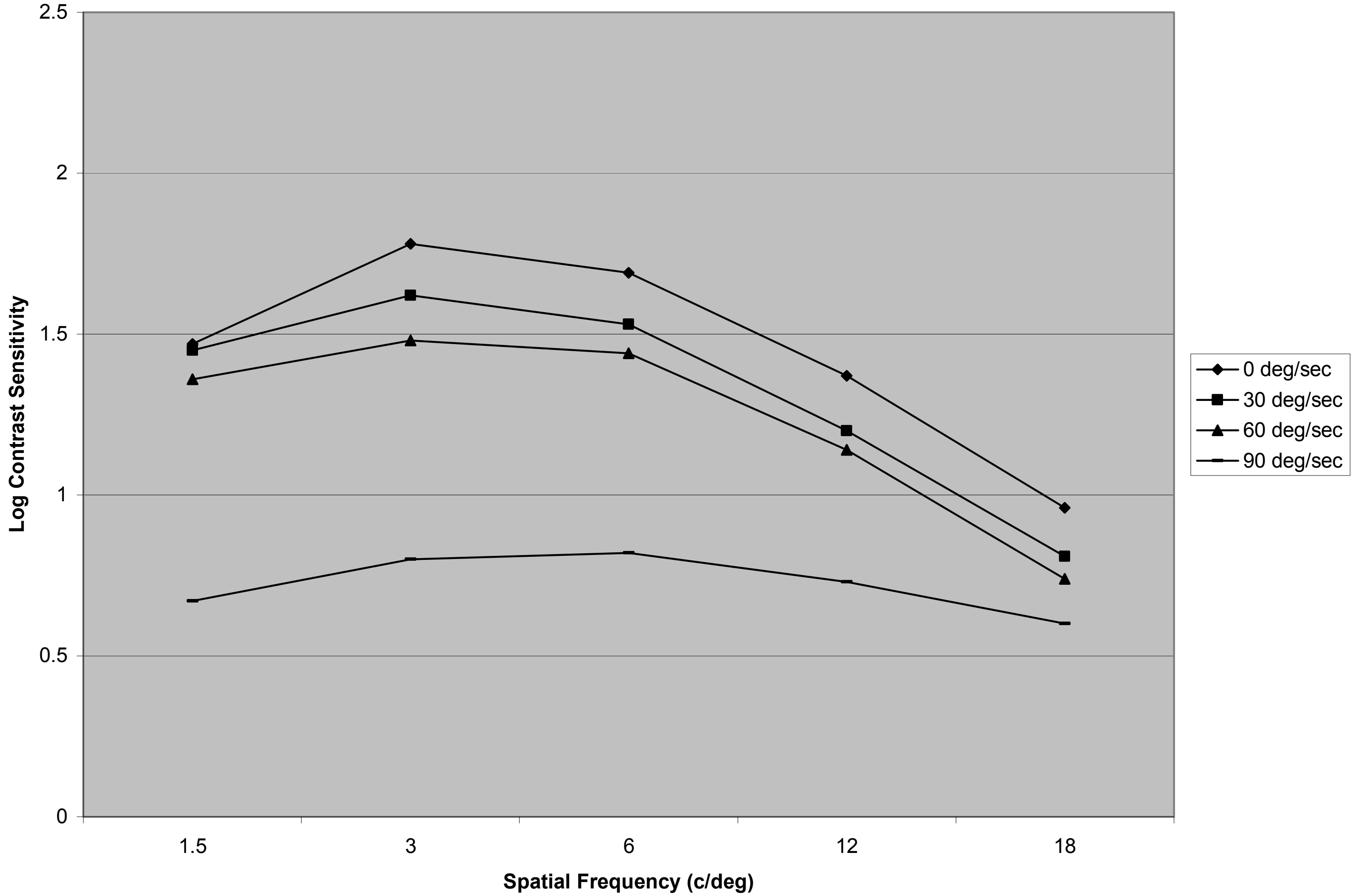

Figure 7: Dynamic Sensitivity Functions – Older Participants

APPENDIX B: IRB HUMAN SUBJECTS PERMISSION LETTER

University of
Central
Florida

Office of Research

November 6, 2003

Merill Zayod
32 Fawn Lane
Chadds Ford, PA 19317

Dear Mr. Zayod:

With reference to your protocol entitled, "The Effects of Stimulus Motion on Contrast Sensitivity: Dynamic Sensitivity Functions," I am enclosing for your records the approved, executed document of the UCFIRB Form you had submitted to our office.

Please be advised that this approval is given for one year. Should there be any addendums or administrative changes to the already approved protocol, they must also be submitted to the Board. Changes should not be initiated until written IRB approval is received. Adverse events should be reported to the IRB as they occur. Further, should there be a need to extend this protocol, a renewal form must be submitted for approval at least one month prior to the anniversary date of the most recent approval and is the responsibility of the investigator (UCF).

Should you have any questions, please do not hesitate to call me at 823-2901.

Please accept our best wishes for the success of your endeavors.

Cordially,

Chris Grayson
Institutional Review Board (IRB)

Copies: Lorenzo Torrez
Edward Rinalducci, Ph.D.
IRB File

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