# A CRITICAL EVALUATION OF CONTRAST SUSCEPTIBILITY AS A PREDICTOR OF DRIVING ACCIDENT INVOLVEMENT

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Contrast susceptibility is defined as the difference in visual acuity recorded for high and low contrast optotypes. Other researchers refer to this parameter as "normalised low contrast acuity".

Pilot surveys have revealed that contrast susceptibility deficits are more strongly related to driving accident involvement than are deficits in high contrast visual acuity. It has been hypothesised that driving situation avoidance is purely based upon high contrast visual acuity. Hence, the relationship between high contrast visual acuity and accidents is masked by situation avoidance whilst drivers with contrast susceptibility deficits remain prone to accidents in poor visibility conditions.

A national survey carried out to test this hypothesis provided no support for either the link between contrast susceptibility deficits and accident involvement or the proposed hypothesis. Further, systematically worse contrast susceptibility scores emerged from vision screeners compared to wall mounted test charts. This discrepancy was not due to variations in test luminance or instrument myopia. Instead, optical imperfections inherent in vision screeners were considered to be responsible.

Although contrast susceptibility is unlikely to provide a useful means of screening drivers' vision, previous research does provide support for its ability to detect visual deficits that may influence everyday tasks. In this respect, individual contrast susceptibility variations were found to reflect variations in the contrast sensitivity function – a parameter that provides a global estimate of human contrast sensitivity.

KEYWORDS: Normalised low contrast acuity, situation avoidance, contrast sensitivity, visibility, luminance.

*For my husband, Paul, and also for my parents*

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# CHAPTER 1: INTRODUCTION

## *1.1 Purpose*

Previous research carried out at Aston University has indicated that the contrast susceptibility (Csus) test may have potential as a means of screening drivers' vision. This thesis critically examines this assertion.

## *1.2 Chapter synopsis*

Chapter 2 reviews past research on the relationship between vision and driving performance. The barriers to finding a clear relationship are discussed. Contrast sensitivity tests are put into context as just one of many visual parameters that have been considered.

Chapter 3 provides a more in depth description of contrast sensitivity. The underlying theory is examined and the factors influencing contrast sensitivity are reviewed. Various laboratory and clinically based methods of measuring contrast sensitivity are compared.

Chapter 4 introduces the Csus test. Previous research carried out on this parameter is reviewed with particular emphasis on Aston University's preliminary research that links it with driving accidents. The objectives of the thesis are outlined.

Chapter 5 outlines the methodology of a large sample survey conducted, under the sponsorship of Vauxhall Motors Ltd., to achieve the objectives outlined in chapter 4. Emphasis is placed on the methodological developments of this survey, based on previous pilot surveys.

Chapter 6 compares the initial results of the large sample survey to preliminary findings of previous pilot surveys.

Chapter 7 explores factors that influence driving situation avoidance and the role situation avoidance plays in the relationship between vision, age, and road accidents.

Chapter 8 compares the agreement and repeatability of several different methods of measuring Csus. It also investigates whether the different methods are able to detect age related changes in Csus.

Chapter 9 examines the influence of test luminance on Csus scores.

Chapter 10 investigates the influence of instrument myopia on Csus scores derived from vision screeners as opposed to wall mounted charts.

Chapter 11 examines those elements of the contrast sensitivity function, a function that provides a description of spatial vision, that are effectively measured using the more clinically applicable contrast threshold and Csus scores.

# CHAPTER 2: CURRENT THOUGHTS ON DRIVING AND VISION

## *2.1 Introduction*

This chapter provides an overview of the research that has investigated the relationship between measures of vision and driving. It also identifies some of the difficulties associated with such research. The review presented is not intended to be an exhaustive account. The aim is to place contrast sensitivity in context relative to other visual measures and to demonstrate the potential of contrast sensitivity as a subject for further study.

## *2.2 Vision as a causative factor in road accidents*

It would be naïve to assert that vision is the only factor to influence driving performance. In fact, accidents are often deemed to be multifactorial (Ball and Owsley, 1991; Shinar and Schieber, 1991). Indeed, more than 1000 factors have been identified as contributory to accident causation (McKnight, 1972). Nevertheless, it is intuitive that vision has an essential part to play in the execution of the driving task. It has often been estimated that vision provides around 90% of the sensory input to driving (Hills, 1980; North, 1993). However, there is little quantitative evidence available to support this (Sivak, 1996). Vision is clearly essential: When vision was occluded, driving was found to be impossible after just a few seconds without further visual input (Senders *et al.*, 1967).

Vision has also been identified as one of the many causative factors in driving accidents (Sabey and Staughton, 1975; Staughton and Storie, 1977; Shinar *et al.*, 1978; Hills, 1980). "Improper look out" (Sabey and Staughton, 1975; Staughton and

Storie, 1977; Shinar *et al.*, 1978) was cited, along with distraction, as the most frequent source of perceptual driver error that result in accidents. These perceptual errors were considered to be the consequence of:

1. Impaired driver vision

2. Visual and perceptual limitations of the driver

3. Restriction of visibility due to car design

4. Restriction of visibility due to environmental factors e.g. occluding obstacles (Hills, 1980).

These studies provide further evidence that a link between vision and driving does exist. It must be observed, however, that perceptual errors may not occur solely due to impairments of vision or visibility, as an additional perceptual processing input on the part of the driver is required. Consequently, the influence of vision on accidents may be indirect, providing an initial sensory input where the output, in the form of accidents, may be modified by perceptual ability.

Irrespective of cause, driving accidents are expensive, both financially and in terms of human injury. Consequently, it is of interest to various authorities to reduce the number of driving accidents and their associated costs. The implication from the preceding argument is that good vision in drivers may help achieve the desired goal of reducing the incidence of driving accidents. This is probably the motivation for the existence of a minimum visual standard for driver licensure in many countries (Charman, 1985). It is almost certainly the guiding force behind vision research in this field.

Much of the literature available has considered whether a specific vision test, or battery of vision tests is able to accurately predict driving performance (Burg, 1967; Burg, 1968; Hills and Burg, 1977; Davison, 1985; Ball and Owsley, 1991; Owsley *et al.*, 1991; Ball *et al.*, 1993; Brabyn *et al.*, 1994; Owsley, 1994; Dunne *et al.*, In press). The aim has been to discover an effective method of driver screening that might help reduce the incidence of road traffic accidents. As might be expected, the driving performance indicator often used in such work has been accident involvement (Norman, 1960; Burg, 1967; Burg, 1968; Keeney, 1968; Gerstle, 1971; Council and Allen, 1974; Danielson, 1975; Hoftstetter, 1976; Barrett *et al.*, 1977; Hills and Burg, 1977; Shinar, 1977; Johnson and Keltner, 1983; Hebenstreit, 1984; Davison, 1985; Graca, 1986; Humphriss, 1987; Ball and Owsley, 1991; Owsley *et al.*, 1991; Ball *et al.*, 1993; Szlyk, Fishman *et al.*, 1993; Brabyn *et al.*, 1994; Gresset and Meyer, 1994; Marottoli *et al.*, 1994; Owsley, 1994; Dunne *et al.*, In press). However, other researchers have used assessments of closed road driving (Wood *et al.*, 1993; Wood and Troutbeck, 1994; Wood and Troutbeck, 1995; Higgins *et al.*, 1996), open road driving (Liesmaa, 1973; Stokx and Gaillard, 1986; Galski *et al.*, 1990; Korteling and Kaptein, 1996), and driving simulator performance (Hedin and Lovsund, 1987; Szlyk, Fishman *et al.*, 1993; Szlyk *et al.*, 1995; Rizzo and Dingus, 1996).

### *2.3 Vision assessment and driving performance*

Many different methods of vision assessment have been examined in relation to driving performance. Vision tests may be split into basic and higher order tests of visual function. To be classified as higher order, in accordance with the definition of Ball *et al.* (1993), a visual test needs to contain four characteristics.

1. A cluttered test environment

2. Simultaneous use of central and peripheral vision

3. Execution of a primary and a secondary task

4. Uncertainty about when an important visual event will occur

Tests that do not contain all four of these features are defined as basic tests. Such tests measure different aspects of a person's ability to see but may not measure how efficiently this ability is used in the execution of a task. Higher order tests require additional visual processing to enable their completion. Hence, such tests are considered to take into account the perceptual as well as the visual capability of the driver. It has already been indicated (Section 2.2) that perception as well as vision is used when driving.

Previous investigations have considered tests of static visual acuity, dynamic visual acuity, motion perception, visual fields, contrast sensitivity, glare, heterophoria, stereopsis, colour vision, functional field of view and visual search. Table 2.1 illustrates that only more complex tasks, such as are used in tests of functional field of view, perceptual style and reaction time, may be classified as higher order under the above definition.

| Visual test | Characteristic | | | |
|---|---|---|---|---|
| | *Clutter* | *Centre and periphery* | *Uncertainty* | *Primary and secondary tasks* |
| Static visual acuity | X | X | X | X |
| Dynamic visual acuity | X | X | X | X |
| Motion perception | X | X | ✓ | X |
| Visual field | X | X | ✓ | ✓ |
| Contrast sensitivity | X | X | X | X |
| Glare | X | X | X | X |
| Heterophoria | X | X | X | X |
| Stereopsis | ✓ | X | X | X |
| Colour vision | ✓ | X | X | X |
| Functional field of view | ✓ | ✓ | ✓ | ✓ |
| Perceptual style | ✓ | ✓ | ✓ | ✓ |
| Complex reaction time | ✓ | ✓ | ✓ | ✓ |

**Table 2.1** Characteristics of higher order tests of visual function contained in some visual tests used in driving research.

## *2.4 Basic tests of visual function*

### *2.4.1 Static visual acuity*

Static visual acuity typically involves reading high contrast optotypes under photopic illumination. It is the attribute most often used in driver screening for licensing purposes (Charman, 1985). A small but consistent relationship between visual acuity and accident involvement has typically been found (Burg, 1964; Burg, 1967; Burg, 1968; Clayton, 1976; Hoftstetter, 1976; Hills and Burg, 1977; Hebenstreit, 1984; Davison, 1985; Humphriss, 1987; Szlyk, 1997). A stronger relationship has been reported for older drivers (Davison, 1985). Some studies have shown that drivers with poor visual acuity are twice as likely to be involved in accidents (Hoftstetter, 1976; Hills and Burg, 1977). Other studies, however, have failed to demonstrate a relationship between visual acuity and driving performance (Galski *et al.*, 1990; Szlyk, Fishman *et al.*, 1993; Gresset and Meyer, 1994; Marottoli *et al.*, 1994; Szlyk *et al.*, 1995; Johansson *et al.*, 1996). These apparently contradictory findings could be explained by a number of factors:

1. There may be a restriction in the range of visual acuities represented in the sample. This would reduce the chance of demonstrating a relationship (Gresset and Meyer, 1994).

2. There may be under representation of accidents in subjects with poor acuity, as increased avoidance of challenging driving situations may act to reduce their accident involvement even if their driving performance is poor (Szlyk *et al.*, 1995).

3. Visual acuity may be inappropriately compared to aspects of driving performance that do not require good visual acuity. Good visual acuity is required for tasks that require good resolution (Rubin *et al.*, 1994) such as when reading road signs (Sheedy, 1980; Higgins *et al.*, 1996) or license plates (Sheedy, 1980). However, other driving tasks, such as manoeuvring and gap clearance, may be completed with relatively low levels of visual acuity (Higgins *et al.*, 1996). It has been agreed by many authors that visual acuity might not be able to predict performance in

more complex tasks such as driving (Ginsburg *et al*., 1982; Ginsburg and Easterly, 1983; Kruk and Regan, 1983; Owsley and Sloane, 1987; Shinar and Gilead, 1987; Bullimore *et al*., 1994).

### *2.4.2 Dynamic visual acuity*

Dynamic visual acuity is a measure of the ability of an observer to resolve details of a moving target. As targets in the driving environment are perceived in motion, dynamic visual acuity might be expected to correlate better with the driving task than static acuity. Studies have shown that dynamic visual acuity is more closely related to accident involvement (Burg, 1964; Burg, 1967; Burg, 1968; Hills and Burg, 1977; Shinar, 1977; Graca, 1986) and sign reading performance (Long and Kearns, 1996). In a battery of visual tests, dynamic visual acuity was found to have the strongest and most consistent relationship with accident involvement (Burg, 1967; Shinar, 1977). As found for static visual acuity, the relationship was stronger for older drivers (Hills and Burg, 1977). There has been a suggestion that dynamic visual acuity measured under night-time conditions could reveal further information about the visual difficulties of drivers in these conditions (Anderson and Holliday, 1995). It has been pointed out that there is no standard method of measuring dynamic visual acuity (Wood, 1997). This difficulty would need to be addressed if this method of visual assessment were to be included in a driver screening programme.

### *2.4.3 Motion perception*

The term motion perception refers to the ability to detect movement that produces either in and out or lateral displacement of a target relative to the observer. In driving, examples of such motion include pedestrians stepping off a pavement, another vehicle pulling out of a side road, or the sudden braking of the car in front. Thus, perception of motion is important in the detection of driving hazards. The motion detection threshold has been shown to exhibit a slight but statistically significant relationship with accidents (Henderson and Burg, 1974). The relationship was stronger for older drivers (Hills, 1975; Shinar, 1977).

### *2.4.4 Visual fields.*

Research that has investigated the relationship between visual field and driving performance has produced conflicting results. Some studies have found no consistent relationship between binocular visual field loss and driving performance (Burg, 1967; Burg, 1968; Council and Allen, 1974; Danielson, 1975; Hills and Burg, 1977; Shinar, 1977). Others have found a statistically significant relationship (Cashell, 1970; Johnson and Keltner, 1983; Hedin and Lovsund, 1987; Owsley *et al.*, 1991; Wood *et al.*, 1993; Szlyk, Brigell *et al.*, 1993; Brabyn *et al.*, 1994; Wood and Troutbeck, 1994; Wood and Troutbeck, 1995). The work of Johnson and Keltner (1983) appears to be one of the most influential in this area. Their investigation involved measuring a number of points in the visual field in both horizontal and vertical meridians. The results of the study revealed that the accident and conviction rates of drivers with binocular field loss were twice that of matched control subjects. The conclusions of later studies are in agreement with this finding (Hedin and Lovsund, 1987; Wood *et al.*, 1993; Szlyk, Brigell *et al.*, 1993; Wood and Troutbeck, 1994; Wood and Troutbeck, 1995). The reason for the variation in the conclusions drawn by different researchers has been attributed to a number of different reasons:

**1.** Simplistic screening devices used in earlier work that was often of non-standard design (Johnson and Keltner, 1983; North, 1985; Shinar and Schieber, 1991).

**2.** Some early studies measured as few as two points in the temporal field (Council and Allen, 1974), and often only measured visual field in the horizontal meridian (Johnson and Keltner, 1983; North, 1985).

**3.** Poor control of subject fixation (Johnson and Keltner, 1983; North, 1985).

Current opinion therefore, appears to be that binocular visual field loss does affect driving performance although a minimum field requirement for safe driving does not appear to have been established.

The case for monocular drivers seems to be more conclusive. The majority of studies do not find any significant difference in the driving performance of monocular and binocular drivers (Johnson and Keltner, 1983; Edwards and Schachat, 1991; McKnight *et al.*, 1991; Wood *et al.*, 1993; Gresset and Meyer, 1994; McCloskey *et al.*, 1994; Wood and Troutbeck, 1994; Wood and Troutbeck, 1995). These results contradict an earlier finding where, in a sample of 1153 drivers with known driving limitations, the incidence of monocular drivers was four times that of the normal population (Keeney, 1968). This study, however, has been criticised for not providing a definition for monocularity (North, 1985). It may be that amblyopes as well as true monocular subjects were included. This would artificially increase the number of monocular subjects included in the study. In turn, this could lead to the inflation of accident risk estimates for monocular drivers.

### *2.4.5 Contrast sensitivity*

The environment is made up of objects that have different levels of contrast relative to their background. Contrast sensitivity measures the ability of a human observer to detect such objects (Chapter 3). In this context, it is not surprising to find that contrast sensitivity has been found to predict performance in a number of complex "real world" tasks (Owsley *et al.*, 1981; Ginsburg *et al.*, 1982; Marron and Bailey, 1982; Ginsburg and Easterly, 1983; Owsley and Sloane, 1987; Shinar and Gilead, 1987; Bullimore *et al.*, 1994). However, once again, there are studies that provide evidence to the contrary (Kruk and Regan, 1983; O'Neal and Miller, 1987). This disparity has been explained by differences in methodology between studies (O'Neal and Miller, 1987). On one side, the strength of the relationship may have been exaggerated through positive interpretations of mixed results. On the other, detection of a link may have been confounded by variable testing conditions and inadequate measures of contrast sensitivity.

For the complex task of driving, it appears that the weight of evidence supports the existence of a relationship between contrast sensitivity and driving performance. Contrast sensitivity has been theoretically linked with driving for more than thirty years (Schmidt, 1961). More recently, contrast sensitivity has been significantly correlated with sign reading distance (Evans and Ginsburg, 1985; Owsley and Sloane, 1987), tasks that require distance judgements, and in night driving (Rubin *et al.*, 1994). It has also been linked with accident involvement (Ball *et al.*, 1993; Brabyn *et al.*, 1994; Dunne *et al.*, In press)

Several studies have demonstrated a correlation between the Pelli-Robson contrast threshold test (Section 3.7.4) and state recorded accident histories of older drivers (Brabyn *et al.*, 1994) or closed road driving performance (Wood *et al.*, 1993; Wood and Troutbeck, 1995).

In the context of other visual tests, contrast sensitivity appears to be a stronger predictor of performance than visual acuity (Ginsburg *et al.*, 1982; Ginsburg and Easterly, 1983; Evans and Ginsburg, 1985; Owsley and Sloane, 1987; Ball and Owsley, 1993; Bullimore *et al.*, 1994) (Section 2.4.1), glare, stereopsis and colour vision (Ball and Owsley, 1993). This association between contrast sensitivity and driving might also help explain the stronger relationship found between driving measures and visual acuity measured using low contrast targets (Brabyn *et al.*, 1994; Bullimore *et al.*, 1994) and in lower light levels (Shinar, 1977).

### *2.4.6 Night myopia*

The accommodative state of an eye tends towards an intermediate resting position under low luminance conditions resulting in a myopic shift in the refractive state of the eye (Leibowitz and Owens, 1975). This condition has been called night myopia. It might be expected that this phenomenon could occur under the low luminance conditions encountered in night driving. If so, it would result in blurred vision at night for affected drivers with a resultant increase in their risk of accident involvement. To overcome this problem, it has been suggested that those drivers affected should wear a more negative refractive correction at night (Owens and Leibowitz, 1976; Hope and Rubin, 1984).

The average light level found on the road has been shown to be around 1cdm$^{-2}$ for a wide range of British roads (Hargroves, 1981; Chauhan and Charman, 1993). It has been demonstrated by numerous authors that night myopia is not likely to be manifest under such conditions (Campbell, 1954; Richards, 1967; Leibowitz and Owens, 1975; Johnson, 1976; Epstein *et al.*, 1981; Chauhan and Charman, 1993; Charman, 1996; Arumi *et al.*, 1997). This is in agreement with clinical evidence that has indicated that the subjective response to negative additions is variable (Richards, 1967; Richards, 1978; Taylor, 1990; Fejer, 1995). From this evidence, it may be concluded that night myopia may only cause problems in a limited number of drivers.

### *2.4.7 Glare*

Glare has been cited as being a likely cause of night-time driving difficulties (Chauhan and Charman, 1993; Dunne *et al.*, 1993; Charman, 1996) especially for older drivers (Kosnik *et al.*, 1990; Ball and Owsley, 1991). Evidence to support this conviction however, is not strong. Glare has been found to differentiate accident free and accident involved older drivers in one study (Brabyn *et al.*, 1994). In other studies, glare has been found to have little relationship to driving (Burg, 1967; Shinar, 1977; Owsley *et al.*, 1991; Ball *et al.*, 1993; Rubin *et al.*, 1994). Furthermore, some research has revealed an inverse relationship where drivers with better glare recovery tended to have more accidents than those with glare problems (Gerstle, 1971).

These contradictory results may be the consequence of drivers avoiding challenging driving situations or ceasing to drive altogether resulting in the under representation of such drivers in the sample used (Gerstle, 1971; Rubin *et al.*, 1994). Alternatively, they may arise from the methodology used (Bichao *et al.*, 1995). It has been proposed that glare problems may be underestimated by standard glare tests (Bichao *et al.*, 1995). It has been indicated that detection of difficulty in glare situations may be better predicted if tests used low contrast targets (Hard *et al.*, 1990; Bullimore *et al.*, 1994) or transient glare sources (Bichao and Yager, 1994). Such testing conditions might be considered to be more like the night-time driving situation where hazards, such as pedestrians, are often of low contrast, and the headlight beams of passing cars provide an intermittent source of glare.

### *2.4.8 Heterophoria*

Heterophoria may be defined as the tendency for the two visual axes of the eyes not to be directed toward the point of fixation in the absence of an adequate stimulus to fusion (Millodot, 1986). Tests of heterophoria suspend binocular fusion either by temporary occlusion or by the presentation of different targets to each eye. As such, these test conditions are unlike those found in normal viewing circumstances. Consequently, it is not surprising that research on the subject of heterophoria has generally concluded that there is no relationship between heterophoria and accident involvement (Davis and Coiley, 1959; Cashell, 1966; Burg, 1967; Keeney, 1968; Clayton, 1976). Davison (1985) did find a statistically significant association with accident involvement for hyperphoria only. This weak association was largely confined to drivers over the age of 45 years.

### *2.4.9 Stereopsis*

Stereopsis tests provide an assessment of depth perception. Consequently, it might be thought that assessment of stereoacuity using these tests would be important in relation to driving, as depth judgements are needed in many driving situations.

However, stereoacuity measured with clinical stereopsis tests is assessed only at test distances that are much shorter than the viewing distances used when driving. In addition, monocular drivers who would by definition have no stereopsis have not been shown to be at increased risk of an accident (Section 2.4.4). Hence, the finding that there is little evidence available to support a link between stereoacuity and driving might not be unexpected. A number of authors have found no statistically significant association between stereoacuity and accident involvement (Burg, 1964; Cashell, 1966; Keeney, 1968; Clayton, 1976; Davison, 1978), self-reported difficulties of older drivers (Rubin *et al.*, 1994) or on road driving performance (Galski *et al.*, 1990). If coupled with slightly reduced visual acuity, however (6/15 Snellen acuity), older drivers with poor stereoacuity have been found to have about twice the accident risk of other drivers (Gresset and Meyer, 1994).

### *2.4.10 Colour vision*

Numerous studies of colour vision have failed to reveal a significant association between colour vision and accident involvement (Norman, 1960; Burg, 1964; Cashell, 1966; Keeney, 1968; Clayton, 1976; Davison, 1985; Owsley *et al.*, 1991; Ball *et al.*, 1993; Brabyn *et al.*, 1994). Verriest *et al.* (1980) however, deviate from this opinion. They found a significantly increased number of rear end collisions in protanopic drivers compared to deutanopes and colour normal drivers. This finding is consistent with earlier work that found colour defectives needed red lights, for example brake lights, to be four times more intense in order to perceive them than normal drivers (Coles and Brown, 1966).

## 2.5 *Higher order perceptual testing*

### 2.5.1 *Perceptual style*

Studies of perceptual style (the ability to extract information from a complex visual scene) have linked perceptual style performance to driving behaviour in driving simulations (Barrett *et al.*, 1969; Barrett *et al.*, 1977) and to accident involvement (Harano, 1970; Mihal and Barrett, 1976).

### 2.5.2 *Complex reaction time*

Tests of complex reaction time, such as braking in response to a hazard, also involve further processing. However, the results of driving studies in this area are variable. Some studies have linked complex reaction time to the driving situation (Mihal and Barrett, 1976; Korteling and Kaptein, 1996) while others have not (Stokx and Gaillard, 1986; Galski *et al.*, 1990).

### 2.5.3 *Functional field of view*

Functional field of view refers to the visual field area over which information can be acquired in a brief glance (Sanders, 1970). Functional field of view is a well established term in psychology literature. It should not be confused with the binocular functional field scoring system devised for use in perimetry (Estermann, 1982). Measurement of functional field typically requires the observer to focus attention on a central task while simultaneously detecting a peripheral target in a cluttered background environment. On the road, drivers are required to detect peripheral hazards, such as pedestrians, against the complex background of the driving environment whilst simultaneously attending to manoeuvring their own vehicle and considering the actions of the drivers of surrounding vehicles. The task imposed by the functional field of view test may, therefore, be considered to be comparable to the visual demand in driving. Comparison of functional visual field scores and driving performance have provided some evidence that this test is applicable to driving (Avolio *et al.*, 1985; Owsley *et al.*, 1991; Ball *et al.*, 1993; Wood *et al.*, 1993; Brabyn *et al.*, 1994; Owsley *et al.*, 1995; Wood and Troutbeck, 1995).

There has been considerable interest in a particular method of functional visual field measurement that has become commercially available. Its inventors (Sekuler and Ball, 1986) have called this the Useful Field Of View (UFOV) test. A significant relationship has been found between UFOV test results and prior accident involvement (Owsley *et al.*, 1991; Ball and Owsley, 1993), closed road driving performance (Wood *et al.*, 1993; Wood and Troutbeck, 1995), and the location of signs in cluttered environments (Ball *et al.*, 1990). It is also a useful predictor of prospective accident involvement (Owsley, 1994). Basic vision tests, as described in the preceding sections, have only been shown to influence act accident involvement indirectly through their contribution to the UFOV (Owsley *et al.*, 1991; Ball *et al.*, 1993) (Figure 2.1). The UFOV test accounted for 27% of accident variance (Ball and Owsley, 1991). Although this percentage was greater than the 5% of accident variance accounted for by basic visual tests (Ball and Owsley, 1991; Wood, 1997), it still leaves a large percentage of accident variance that was unaccounted for by UFOV. This finding is in agreement with the view of Avolio et al. (1985) who concluded that while attentional abilities are essential, on their own they are not sufficient when operating a motor vehicle.

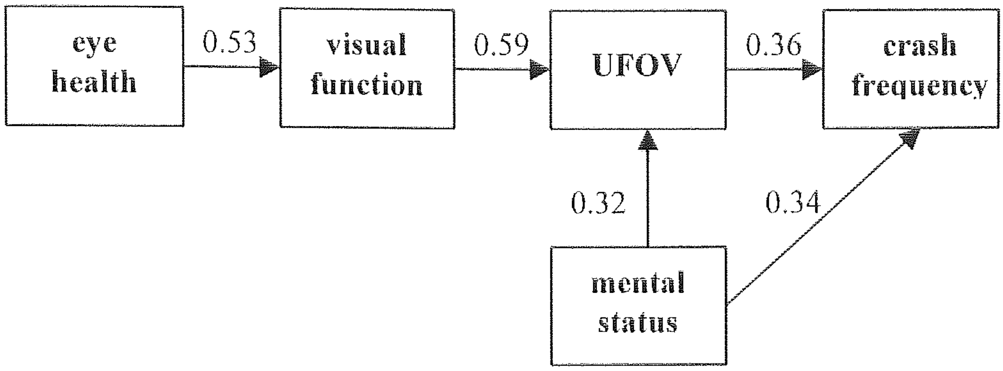


**Figure 2.1** Multiple regression analysis of the relationship between vision tests and accident involvement developed by Ball *et al.* (1993). Figures indicate correlation strength.

Interestingly, in some studies, basic tests of contrast sensitivity are more strongly related to driving performance (Wood *et al.*, 1993; Wood and Troutbeck, 1995) and accident involvement (Dunne *et al.*, In press) than the higher order UFOV test. However, for the study of Dunne *et al.* (*In press*), the difference in conclusions drawn may be attributed to the use of self-reported accidents and younger drivers. The study of Ball *et al.* (1993) found that UFOV was most effective in the discrimination of older drivers.

### *2.6 Factors that mask the relationship between vision and driving*

The vision tests reviewed in section 2.4 and 2.5 have revealed, at best, a statistically significant but weak relationship between vision and driving. Furthermore, some tests were not shown to be related to driving performance, while research on others has been inconclusive. If it is true that vision is essential to the driving task, as stated in section 2.2, then some explanation is needed for the tenuous relationships that have been demonstrated by researchers working in this field.

The relationship between vision and driving may be masked because of:

1. The inadequacy of dependent measures used to assess driving performance

2. The vision tests chosen for the visual assessment of drivers are unsuitable.

### *2.6.1 Measures of driving performance*

The limitations of the methods used to determine the level of a driver's performance are an important confounding factor when attempting to demonstrate the relationship between vision and driving. Measures of driving performance have included:

1. Accident involvement (prior and prospective)

2. Performance in driving simulators

3. Assessment of driving in closed and open road conditions.

#### *2.6.1.1 Accident involvement*

Accident involvement is a commonly used measure of driving performance. This approach is limited by a number of factors:

1. Accidents are rare events. The infrequency of accidents means that researchers have the statistical problem of attempting to predict a rare event. This may be partly due to the design of the road environment. Traffic systems have compensating features built in to reduce the consequences of driver error (Shinar *et al*., 1978; Shinar and Schieber, 1991).

2. Driver behaviour. Drivers may develop fast reaction times or emergency braking skills that help reduce the probability of an accident (Shinar *et al*., 1978; Shinar

and Schieber, 1991). They may also consciously avoid challenging driving situations. It has been postulated that the attenuated relationship between visual impairment and driving accidents may arise due to the reluctance of people with inadequate vision to drive (North, 1985; Owsley *et al.*, 1991; Shinar and Schieber, 1991; Owsley and Ball, 1993; Munton, 1995). It has been demonstrated that such self-regulation on the part of drivers does occur when they are aware of visual deficits (Gerstle, 1971; Steward *et al.*, 1983; Retchin *et al.*, 1988; Kosnik *et al.*, 1990; Ball and Owsley, 1991; Owsley *et al.*, 1991; Gresset and Meyer, 1994; Szlyk *et al.*, 1995). However, the relationship between self-regulation and accident involvement is complicated by the fact that some drivers may continue to drive as long as possible (Jette and Branch, 1992). Such drivers may be unaware of their limitations (Shinar, 1977) or continue to drive due to work commitments or to keep health related appointments (Rizzo and Dingus, 1996). The issue of driver situation avoidance is discussed in chapter 4.

3. Accidents are multifactorial. When accidents do occur it is rare that they are due to a single cause: they are more often multifactorial in nature (Ball and Owsley, 1991; Shinar and Schieber, 1991). 1300 different factors have been determined to contribute to the causation of accidents (McKnight, 1972) and vision is only one of these (Burg, 1967; Ball and Owsley, 1991).

4. Reliability of accident records. There are generally two sources of accident data used: (a) self-reported accident history and (b) official recorded accident history.

   (a) Self-reported data is probably the easiest to access. However this method has been found to be relatively unreliable compared to official records (Owsley *et al.*, 1991; Ball *et al.*, 1993). In general, the number of accidents reported is an underestimate of the true value (Ball *et al.*, 1993). This may be because some categories of driver deliberately under report. This has been found to be true in the case of young men (Ball and Owsley, 1991; Owsley *et al.*, 1991). It may also be true of older adults who rely on their car to maintain their independence and fear the consequences of admitting to multiple accidents (Ball and Owsley, 1991; Marottoli *et al.*, 1994). Alternatively, it may simply be that drivers are not able to accurately recall past events (Marottoli *et al.*, 1994).

(b) It has been thought that official records are more objective (Owsley *et al.*, 1991; Rizzo and Dingus, 1996). They may also include more information about the circumstances surrounding an accident (Owsley *et al.*, 1991; Rizzo and Dingus, 1996). This is important as some accident statistics may not have a visual cause and should be excluded from visual studies (Rizzo and Dingus, 1996; Wood, 1997). An important aspect of official records is that they are used by governmental agencies to determine policy and by insurance companies to predict accident risk and set premiums (Owsley *et al.*, 1991; Rizzo and Dingus, 1996). However, official data can be difficult to access (Ball and Owsley, 1991; Rizzo and Dingus, 1996). In addition, data could contain other errors, such as the omission of minor incidents that are not considered severe enough to be included, or that may not be reported by the driver (Ball and Owsley, 1991; Owsley *et al.*, 1991; Marottoli *et al.*, 1994; Rizzo and Dingus, 1996).

### *2.6.1.2 Road tests*

Road tests overcome some of the limitations of accident reports as a measure of driving performance (Liesmaa, 1973; Stokx and Gaillard, 1986; Galski *et al.*, 1990; Wood *et al.*, 1993; Wood and Troutbeck, 1994; Wood and Troutbeck, 1995; Higgins *et al.*, 1996; Korteling and Kaptein, 1996). Measurement of "open road" driving performance may be considered to be the gold standard as this assesses the real driving situation and is a direct test of driving performance (Ball and Owsley, 1991). However, the use of the "open road" gives little, or no, control over the events that may occur so inter-subject comparison of performance is difficult (Ball and Owsley, 1991; Rizzo and Dingus, 1996). It may also be hazardous to perform some driving assessments in the "open road" environment (Ball and Owsley, 1991; Rizzo and Dingus, 1996). More control over environmental conditions and events encountered may be achieved on "closed roads" or tracks. Nevertheless, this approach has the disadvantage that some of the more challenging road situations may not be easily reproduced (Ball and Owsley, 1991). In both types of road test, care needs to be taken to identify the correct variables to be observed in order to obtain meaningful results (Ball and Owsley, 1991). If the observations are to be made by trained observers the problems of inter-tester variation need to be considered (Ball and Owsley, 1991; Rizzo and Dingus, 1996).

### *2.6.1.3 Driving simulators*

The simulated driving environment allows test conditions to be fully controlled (Ball and Owsley, 1991). It is possible to replicate environmental conditions so that driver differences may be easily compared (Rizzo and Dingus, 1996) and training effects evaluated (Ball and Owsley, 1991). Driving simulators have none of the safety problems that may be associated with road testing and allow quantitative observations of performance that may be difficult to obtain with an instrumented car (Rizzo and Dingus, 1996). The biggest issue in driving simulation is its applicability to real life (Rizzo and Dingus, 1996). There is concern that driving simulations might not replicate the real driving task as they may not generate the perceived risks associated with driving on real road systems (Ball and Owsley, 1991; Wood, 1997). However, one study has reported that similar driving behavioural effects arose when driving simulator performance was compared to driving performance in an instrumented car on a closed road. If anything, the increased difficulty associated with controlling the driving simulator amplified some small behavioural effects that were not easily observed in instrumented car trials (Duncan, In press).

Although road tests and driving simulators have some advantages over accident history reports, it must be remembered that one of the main objectives of driving research is to achieve a reduction in accident incidence. Hence, these measures may still need to be validated against some measure of accidents involvement (Owsley *et al.*, 1991).

### *2.6.2 Limitations of vision assessment*

#### *2.6.2.1 Vision test relevance*

The relationship between vision and driving may be weakened or completely confounded if the vision test chosen measures inappropriate visual characteristics (Burg, 1967). Basic tests of visual function (Section 2.3) have been cited as being inappropriate to the driving task because they often minimise perceptual input (Ball and Owsley, 1991; Ball *et al.*, 1993; Owsley and Ball, 1993). This may be true if considering the whole of the driving task. However, it may be that a specific basic vision test may be applicable to a particular aspect of driving even though it may not have a significant influence on others. Thus, the preferred visual test may be chosen in order to complement the particular aspect of driving performance under investigation.

### *2.6.2.2 Variation in methodology*

The results of vision testing may still give rise to conflicting conclusions even if the attribute to be measured was determined to be appropriate. Variation in methodology has been stressed as a possible cause of inter-study differences (Johnson and Keltner, 1983; North, 1985; Shinar and Schieber, 1991). Studies that rely on screening devices, such as the Ergovision screener, may lack the sensitivity needed to detect a relationship between variables (Shinar and Schieber, 1991). Inadequate measurements (Johnson and Keltner, 1983) using unreliable testing methods (Burg, 1967; Johnson and Keltner, 1983) may also act to reduce the probability of a relationship being detected.

### *2.6.2.3 Limitations imposed by licensing laws*

In addition to these factors, the nature of licensing law itself may preclude the detection of relationships between vision and driving. The imposition of a minimum visual standard for drivers could restrict the range of visual impairment present in driver samples and thus dilute the strength of the visual attribute under study (Shinar and Schieber, 1991; Sheedy and Bailey, 1993).

## *2.7 Summary*

Though it seems logical that vision is an essential part of the driving, a number of factors (Section 2.6) confound demonstration of this supposition. Two types of visual test have been reviewed here: basic and higher order. Current opinion would appear to favour the use of higher order type tests as being most likely to predict driving performance.

Nevertheless, there is some evidence that supports the potential use of dynamic visual acuity or contrast sensitivity tests on drivers. The remainder of this thesis considers a particular test of contrast sensitivity and its relationship with driving performance

# CHAPTER 3: A REVIEW OF CONTRAST SENSITIVITY

## *3.1 Introduction*

This chapter provides a more detailed description of contrast sensitivity. The underlying theory is examined and the factors that influence contrast sensitivity are reviewed. Laboratory and clinically based tests are compared.

## *3.2 Why is contrast sensitivity important?*

Visual acuity measures the size of the smallest object resolvable by the human eye for visual targets of maximal contrast. The investigations of Campbell and Green (1965a), and Campbell and Robson (1968) demonstrated the usefulness of extending measurement of visual function beyond visual acuity to consider the visibility of objects of lower contrast. They showed that contrast could be used to quantify visual performance, and that simple targets could be used to make predictions about the nature of visual processing. Hence, contrast sensitivity may be considered to be a fundamental description of normal visual performance (Pelli *et al.*, 1988).

In the research environment, contrast sensitivity was initially devised to investigate the optical properties of the human eye (Schade, 1956; Campbell and Green, 1965a). Since then, this type of investigation of the visual system has been widely used to decipher the mechanisms that underpin human pattern discrimination or spatial vision.

From the clinical point of view, contrast sensitivity is important as it provides additional information above that given by traditional visual acuity testing. This assertion is supported by research that has shown that visual disturbances can occur which affect contrast sensitivity, while visual acuity remains virtually unaffected

(Regan *et al.*, 1977; Hess and Woo, 1978; Bodis-Wallner, 1980; Carney, 1982; Ginsburg, 1984; Regan, 1988; Leguire *et al.*, 1990; Regan, 1990). Consequently, contrast sensitivity assessment may reveal the otherwise undetected effects of disease (Bodis-Wallner and Diamond, 1976; Hess and Howell, 1977; Regan *et al.*, 1977; Arden and Jacobson, 1978; Hess and Woo, 1978; Bodis-Wallner, 1981; Ginsburg, 1984; Elliott and Whitaker, 1989). In addition, changes in contrast sensitivity have already been found to reflect performance in complex tasks such as face recognition (Owsley *et al.*, 1981), mobility (Marron and Bailey, 1982; Rubin *et al.*, 1994) and driving (Wood *et al.*, 1993; Brabyn *et al.*, 1994; Wood and Troutbeck, 1995). It has also been used to predict the daily vision problems of older adults (Owsley *et al.*, 1983) and cataract patients (Elliott, Hurst *et al.*, 1990). Hence, information derived from contrast sensitivity investigations could be used to predict how visual performance in every day tasks might be affected and used to advise patients.

Thus, the importance of contrast sensitivity measurement is twofold: It aids our understanding of the mechanisms underlying vision when used in laboratory experiments. In the clinic, changes in contrast sensitivity help clinicians predict how everyday task performance might be affected and enables monitoring of the effects of disease processes. As such, contrast sensitivity might be considered an important link between laboratory measurements and clinical findings (Figure 3.1).

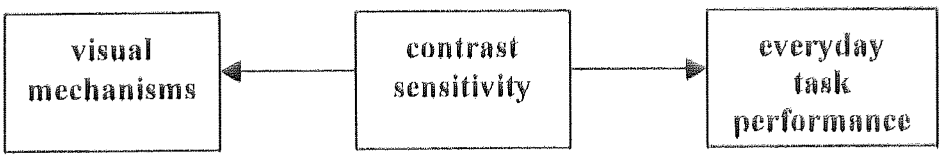


**Figure 3.1** The role of contrast sensitivity measurement as an important link between the mechanisms that underpin spatial vision and the effects changes in these mechanisms have on everyday task performance.

The aim of this review is to provide a general overview of contrast sensitivity. It will outline the methods of contrast sensitivity measurement used in laboratory and clinic. However, the scope of the literature in this field is far reaching. Hence, the discussion of how contrast sensitivity might be affected in particular circumstances has been limited to those relevant to issues that are raised later in the thesis.

### *3.3 Definitions of contrast and contrast sensitivity*

Contrast is a physical property of a visual stimulus. It is the magnitude of luminance variation in a stimulus relative to an average or background luminance (Shapley, 1991).

**Michelson contrast**, or contrast modulation (Equation 3.1), is used when calculating the luminance difference in a repetitive target pattern. For example, it may be used to calculate the contrast of the alternating light and dark bands in a grating target.

$$\text{Michelson Contrast} = (L_{max} - L_{min})/(L_{max} + L_{min}) \qquad \textbf{(3.1)}$$

(Where $L_{max}$ is maximum target luminance and $L_{min}$ is minimum target luminance)

**Weber contrast** (Equation 3.2) is more often used to express the luminance difference of aperiodic visual stimuli, such as the luminance difference of a letter relative to its background.

$$\text{Weber Contrast} = (L_t - L_b)/L_b \qquad \textbf{(3.2)}$$

(Where $L_t$ is target luminance and $L_b$ is the background luminance)

Both Michelson and Weber contrast ratios have scales from 0 to 1 where 0 is equal to no luminance modulation or zero contrast and 1 is equal to maximal luminance modulation or maximum contrast.

**Percentage contrast** may be obtained by the multiplication of either ratio by 100.

**Threshold contrast** refers to the contrast level at which a visual stimulus may just be perceived by an observer. Threshold is usually taken to be the point at which an observer correctly perceives a stimulus on a certain proportion of trials (e.g. 50% or 75%).

**Contrast sensitivity** is the reciprocal of contrast threshold.

### *3.4 The Contrast sensitivity function (CSF)*

Campbell and Green (1965a) first plotted the contrast sensitivity function (CSF) of the human visual system. The CSF (Figure 3.3) describes the contrast detection threshold of an observer for objects of different sizes.

Conventionally, the CSF has been determined in the laboratory with sinusoidal grating stimuli using methods pioneered by Schade (1956). Consequently, these methods are often considered to be the optimal method of CSF measurement. The luminance profile of sinusoidal gratings varies in a sinusoidal fashion creating a pattern of alternating light and dark bands. The amplitude of a sinewave indicates the grating contrast. Object size is represented by the spatial frequency of a grating. Spatial frequency is defined as the number of cycles per degree (cpd) of visual angle presented. One cycle is equal to the width of one dark plus one light bar (a complete sinewave) (Figure 3.2)

Sinewave gratings were originally generated using oscilloscopes (Schade, 1956; Campbell and Green, 1965a). Electronic generation of gratings using computer-controlled cathode ray tube (CRT) displays are now most frequently used.

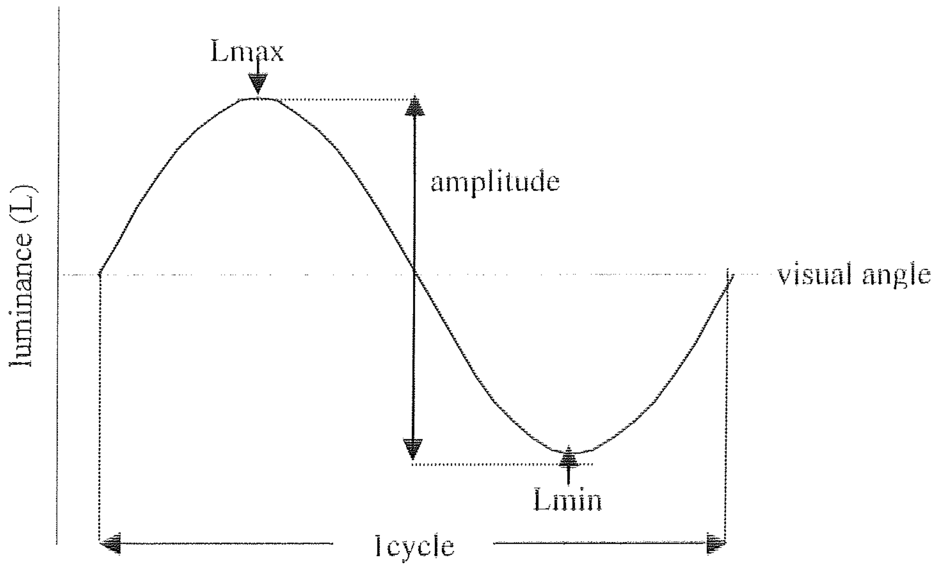


**Figure 3.2** Diagram of a sinewave. The amplitude of the wave is equal to the contrast of the grating. One complete sinewave is equal to one cycle. The spatial frequency of a sinewave grating is the number of cycles contained in one degree of visual angle.

The rationale underlying the use of sinewave gratings as visual stimuli stems from the work of Fourier (1822). He demonstrated that a waveform of any complexity could be broken down into a number of sinewave components of different amplitude, spatial frequency and phase (relative position). Therefore, if an observer's sensitivity to simple sinusoidal gratings of various frequencies were known, this information could be extrapolated to predict the detectability of more complex patterns (DeValois and DeValois, 1990). Furthermore, if simple sinewave gratings are used they cannot be broken down further. This is an advantage when they are used as visual targets as their sinusoidal shape is not distorted, even if the optical system is imperfect (Campbell and Green, 1965a).

### *3.4.1 The normal shape of the CSF*

The normal shape of the CSF, when measured in the laboratory under photopic luminance conditions using sinewave gratings, has been described as an inverted U (Sjostrand, 1979; DeValois and DeValois, 1990). The highest sensitivity is in the mid spatial frequency range with a sharp drop in sensitivity to high spatial frequencies and a gentler but still pronounced attenuation of low spatial frequency (Figure 3.3).

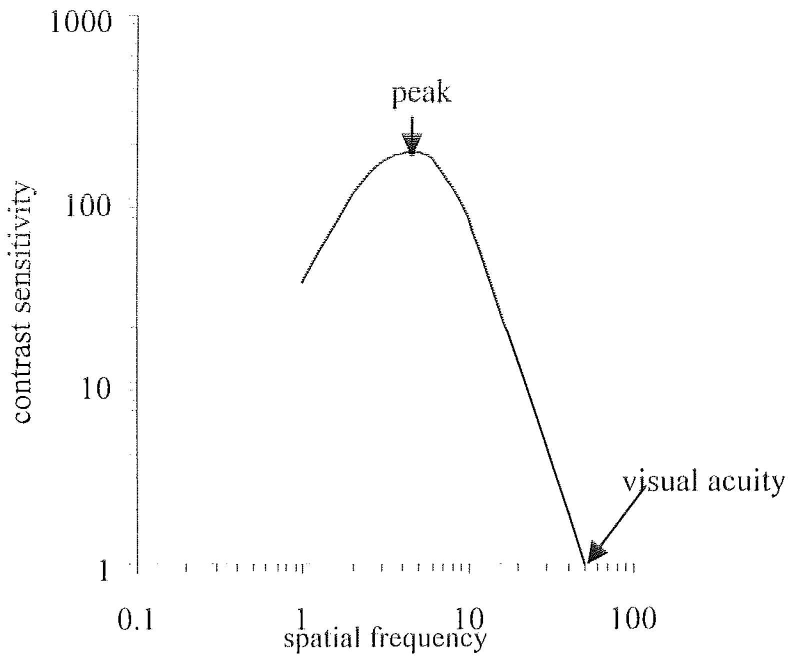


**Figure 3.3** The normal shape of the contrast sensitivity function measured under laboratory conditions with sinewave grating stimuli. Redrawn from R.L. DeValois *et al.*, 1974.

#### *3.4.1.1 Peak sensitivity*

Peak sensitivity is between 3-5cpd spatial frequency (Campbell and Green, 1965a; DeValois *et al.*, 1974; Derefeldt *et al.*, 1979; Sjostrand, 1979; Abrahamsson *et al.*, 1988; Lempert, 1990; Bailey, 1993).

#### *3.4.1.2 High spatial frequency decrease in sensitivity*

The high spatial frequency decline is approximately linear when plotted on logarithmic axes (Campbell and Green, 1965a; Rovamo *et al.*, 1993). The point on the CSF that equates to visual acuity is located where the function intersects the spatial frequency axis in the high spatial frequency region. The spatial frequency at this cut–off point is around 50-60cpd when measured under optimal conditions (Campbell and Green, 1965a; Campbell and Gubisch, 1966; Campbell and Robson, 1968; Anderson *et al.*, 1991). Because the slope of this descending limb of the CSF is steep large changes in contrast sensitivity result in only small changes in the acuity limit (Campbell and Green, 1965a).

The acuity limit is determined by the optical properties of the human eye (Campbell and Green, 1965a; Rovamo *et al.*, 1993). Evidence for this was obtained from experiments using laser interferometry. Using this technique, the neural resolution of the eye, by-passing the optics, was found to be slightly higher than that found when the optical system was included (Campbell and Green, 1965a). The neural resolution limit of the eye has been found to fit well with estimates of retinal receptor spacing at the fovea (Banks *et al.*, 1987; Williams and Coletta, 1987). The small difference between neural and overall CSF (Campbell and Green, 1965a) showed that the retina has receptor spacing that is good enough, but no better than, that needed to extract the spatial detail that is passed through the optical system.

#### *3.4.1.3 Low spatial frequency attenuation of sensitivity*

The attenuation of contrast sensitivity at low spatial frequencies is not readily explained by optical factors as these selectively affect only the high spatial frequencies (Campbell and Green, 1965a; Ohzu *et al.*, 1972). Schade, (1956) attributed the low spatial frequency fall off to neural inhibition in the retina. The decline in low frequency sensitivity has also been explained in terms of the existence of a luminance gradient perception threshold (Hoekstra *et al.*, 1974; Van den Brink and Bilsen, 1975). Below this threshold, the rate of change of contrast in a stimulus would be so small that it cannot be perceived. These ideas may be linked and explained by receptive field theory.

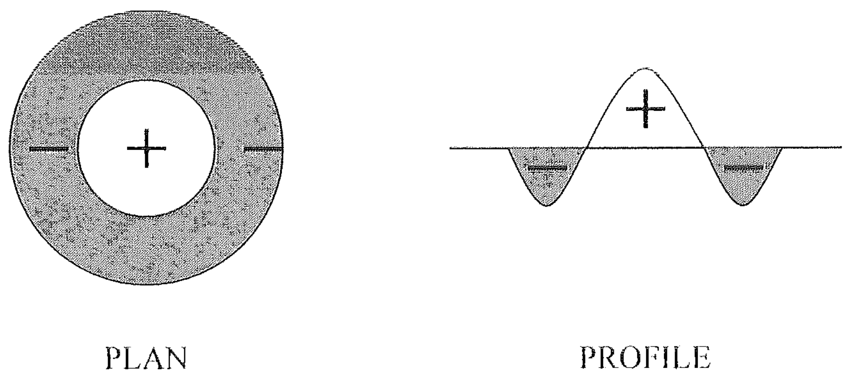


**Figure 3.4** Diagram of a receptive field. + indicates the positive response from the field centre. – indicates the inhibitory response of the field surround. If the same amount of light falls on each part of the receptive field, the two responses cancel out.

The receptive field of a sensory neurone receives input from many receptors (Hartline, 1940). Receptive fields are known to have a centre-surround antagonistic nature (Kuffler, 1953) (Figure 3.4). Consequently, if a similar amount of light falls on both centre and surround portions of a receptive field, the responses from each part cancel out resulting in a null overall response output from the neurone. At low spatial frequencies, the luminance gradient of a grating stimulus is very shallow (Van den Brink and Bilsen, 1975). Hence, over the area of an individual receptive field there is likely to be very little luminance difference between centre and surround portions. The resultant neural output would be approximately zero. Thus, the low spatial frequency fall off could occur as a consequence of the neural inhibition interaction between the centre and surround portions of retinal receptor fields (DeValois and DeValois, 1990).

#### *3.4.1.4 Multiple spatial filters*

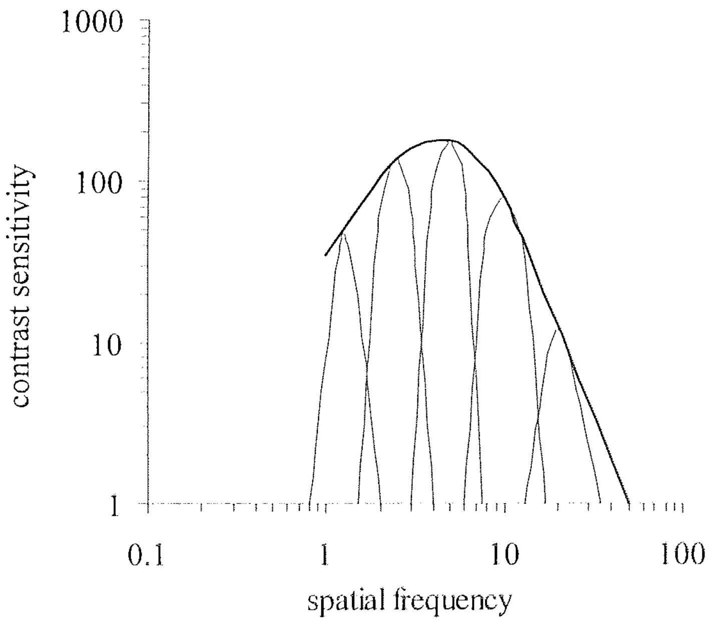


**Figure 3.5** The CSF for the whole visual system is the envelope of individual contrast response functions. Redrawn from (DeValois and DeValois, 1990).

It is currently thought that the CSF for the overall visual system is the envelope of individual contrast response functions for a number of overlapping, spatially tuned filters or channels (Figure 3.5). Each filter is subserved by receptive fields that are selectively responsive to a narrow range of spatial frequencies (Campbell and Green, 1965a; Campbell and Robson, 1968; Blakemore and Campbell, 1969; Graham and

Nachmias, 1971; Sullivan *et al.*, 1972; Green *et al.*, 1981; Livingstone and Hubel, 1987; Hess and Howell, 1988).

### *3.5 Factors that affect the CSF*

The normal shape of the CSF measured using sinewave gratings and described in section 3.4.1 may be altered under the influence of numerous different factors. Change in stimulus parameter, psychophysical method, defocus, luminance and aging can all influence the shape and position of the CSF. The CSF modifications that can occur as a result of these factors have been classified as five specific types (Hess and Howell, 1977; Regan *et al.*, 1977; Regan, 1988; Leguire, 1991) (Figure 3.6)

Figure 3.6a shows the CSF pattern that may be found when square waves are used as targets (Campbell and Robson, 1968; Jaschinski-Kruza and Cavonius, 1984; Leguire, 1991). (Section 3.4.2). Figure 3.6b illustrates contrast sensitivity loss affecting only medium and high spatial frequencies, as might be found with corneal oedema (Hess and Garner, 1977). Diffuse depression of contrast sensitivity throughout the spatial frequency range, as might be found in Optic neuritis (Nordmann *et al.*, 1987; Wright *et al.*, 1987) is shown in Figure 3.6c. Figure 3.6d demonstrates the effect of sensitivity loss at low and medium spatial frequencies only, sparing high spatial frequencies and thus also visual acuity. This pattern of loss is sometimes found with glaucoma (Hyvarinen *et al.*, 1983) or papilloedema (Buncic and Tytla, 1989). Notch loss (Figure 3.6e) affects only a specific range of spatial frequencies. This type of sensitivity loss might be found with astigmatic refractive errors (Apkarian *et al.*, 1987) and multiple sclerosis (Regan *et al.*, 1977). The shift of the whole function to the left, illustrated in 3.6f, may be found, for example, with amblyopia (Leguire *et al.*, 1990).

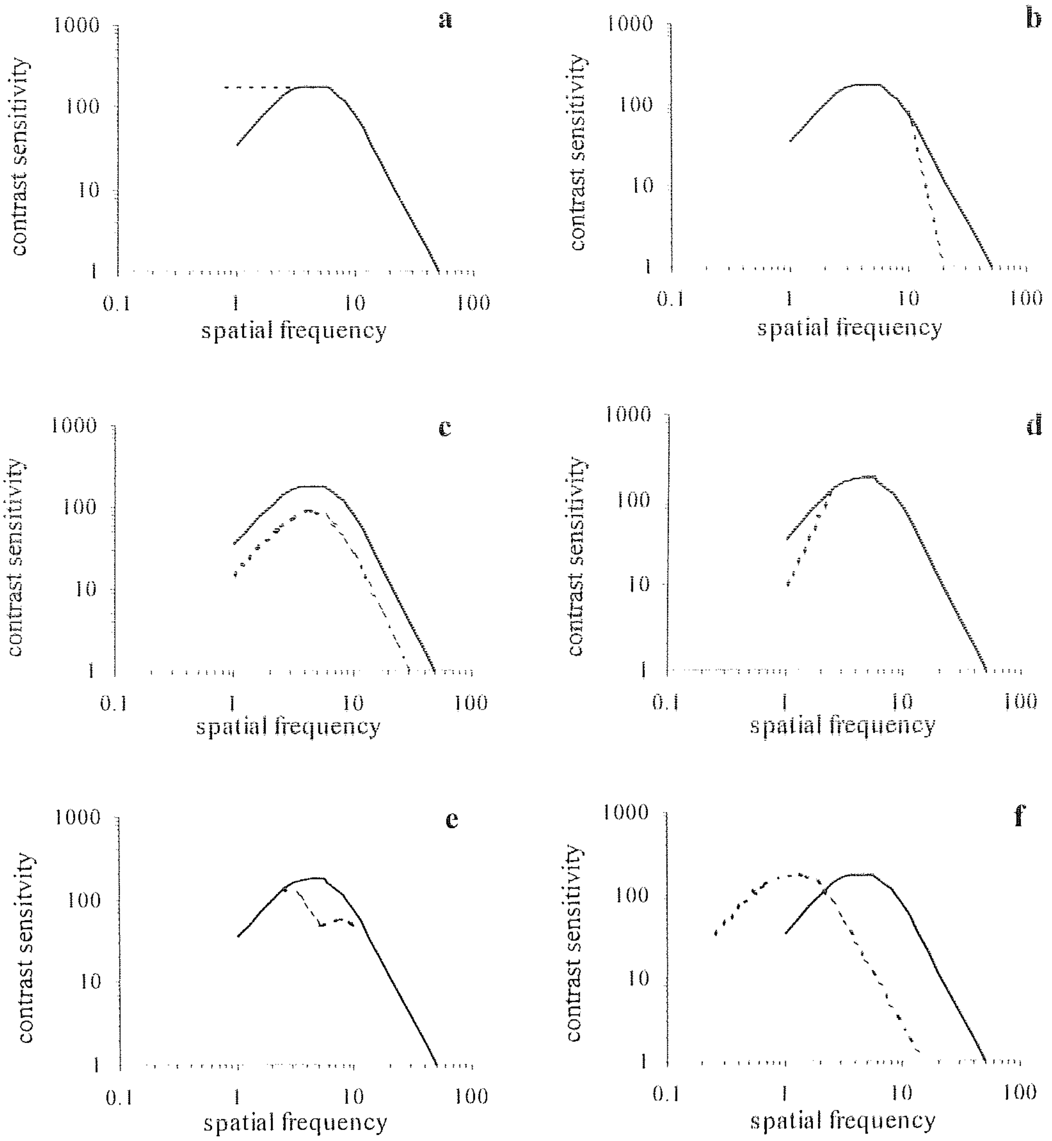


**Figure 3.6** Diagrammatic illustration of the types of change in CSF that may occur under the influence of different factors. Solid lines indicate the normal CSF shape. Dotted lines show the changes that may occur. a = shape of the CSF when measured using squarewave targets showing no low spatial frequency attenuation, b = sensitivity loss at high spatial frequencies, c = diffuse sensitivity loss at all spatial frequencies, d = sensitivity loss at low spatial frequencies, e = notch sensitivity loss, f = shift of the entire CSF towards low spatial frequencies. Redrawn after (Leguire, 1991).

### 3.5.1 *Binocular viewing*

Binocular summation is defined as an improvement of binocular performance over monocular performance (Pardhan, 1996). Such an improvement has been demonstrated for measurements of contrast sensitivity and thus results in higher contrast sensitivity values for binocular viewing than are found for monocular viewing (Campbell and Green, 1965b; Blake and Fox, 1973; Derefeldt *et al.*, 1979; Blake *et al.*, 1981). Thus, the effect of binocular summation might be described as an upward shift of the entire CSF. The magnitude of binocular summation is normally expressed as a ratio of binocular sensitivity to monocular sensitivity (Pardhan, 1996). When the monocular contrast sensitivity is equal in both eyes, the binocular summation ratio is approximately $\sqrt{2}$, equating to a 42% increase over monocular performance (Campbell and Green, 1965b; Blake *et al.*, 1981). Unequal contrast sensitivity between two eyes has been found to reduce the expected elevation in binocular performance (Pardhan, 1996). It has been suggested that this occurs because binocular cortical cells fire optimally when they receive equal inputs from the two eyes. Unequal monocular stimulation results in the suboptimal firing of these cells (Pardhan, 1996).

### 3.5.2 *Use of square wave gratings*

The square wave has been used as an alternative to simple sinewaves in gratings used to determine contrast sensitivity (Campbell and Robson, 1968; Woodhouse, 1975; Lundh *et al.*, 1983; Jaschinski-Kruza and Cavonius, 1984). The squarewave is a complex waveform that may be decomposed into component sinewaves in line with the theory of Fourier (Figure 3.7). It is a useful stimulus, as sharp edged objects are frequently encountered in our environment (Regan, 1991).

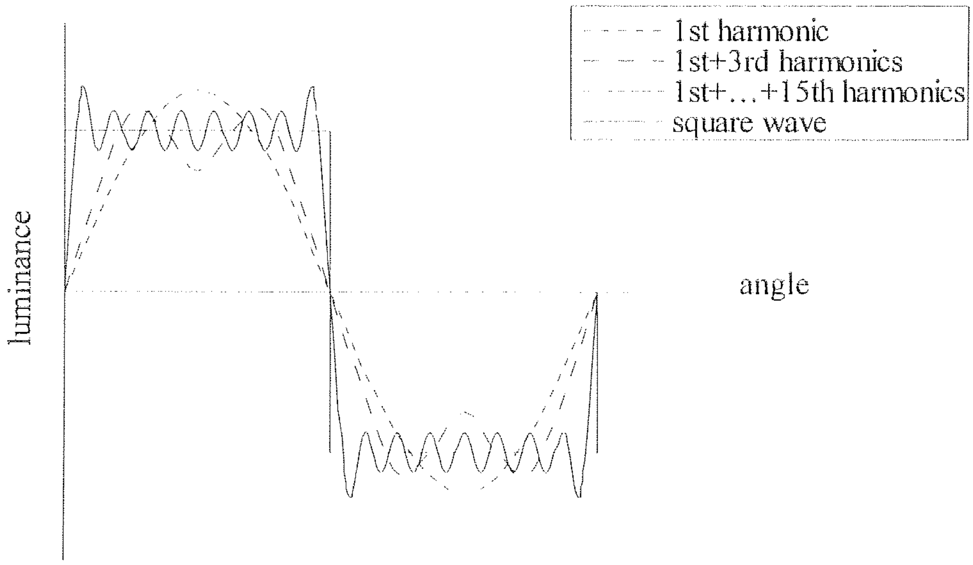


**Figure 3.7** Diagram of a square wave that shows some of its component sinewaves. A squarewave is made up of a fundamental or first harmonic (f) plus odd harmonics (3f, 5f,...15f). The fundamental is the lowest spatial frequency of the squarewave. Each harmonic has a spatial frequency that is an odd multiple of the fundamental. The harmonics are added in decreasing amplitude and may have a different phase (position) relative to the fundamental. Redrawn from (Woods and Wood, 1996)

CSFs plotted using square wave gratings do not have the typical low spatial frequency fall off that is present when sinewaves are used (Figure 3.6a) (Campbell and Robson, 1968; Jaschinski-Kruza and Cavonius, 1984; Leguire, 1991). This is because of the presence of sinewave components of a higher frequency than the fundamental (see Figure 3.7). It is these that become important in the detection of square waves with low fundamental frequencies (Campbell and Robson, 1968; Jaschinski-Kruza and Cavonius, 1984).

### *3.5.3 Changes in stimulus area*

It has been demonstrated that the CSF for sine waves is in part dependent on the number of cycles presented in the grating stimulus (Hoekstra *et al.*, 1974; Van den Brink and Bilsen, 1975; Rovamo *et al.*, 1993). The effect of an insufficient number of cycles predominantly affects the low spatial frequency part of the CSF and results in depressed sensitivity in this region (Hoekstra *et al.*, 1974; Van den Brink and Bilsen, 1975; Rovamo *et al.*, 1993) (Figure 3.6d). Contrast sensitivity increases with additional cycles up to a critical level above which the sensitivity remains constant (Hoekstra *et al.*, 1974; Van den Brink and Bilsen, 1975; Rovamo *et al.*, 1993). Maximising the number of cycles in a grating to overcome this problem has the effect of broadening the peak of the CSF. A low spatial frequency fall off does occur but it starts at a lower spatial frequency (<1cpd) (Hoekstra *et al.*, 1974).

### *3.5.4 Psychophysical method*

Psychophysics may be defined as a method of relating the internal psychological, and the external physical, world on the basis of experimental data (Treutwein, 1995). Psychophysical methods are procedures for collecting data in perceptual tasks (Woods and Thomson, 1993). They are designed to allow estimation of the stimulus magnitude at which a physical difference between two stimuli might just be distinguished by the human observer (i.e. a just noticeable difference) (Treutwein, 1995). In modern psychophysics, this threshold is defined as the magnitude of the stimulus difference that can be correctly discriminated for a fixed percentage of the number of stimulus presentations made (Treutwein, 1995). The percentage chosen is usually set at a level that is greater than the chance, or guess, level of correct responses for a particular design of psychometric method (Levitt, 1971; Gescheider, 1985; Wolfe, 1990).

#### *3.5.4.1 Psychophysical thresholds*

Classical threshold theory assumed that below threshold a stimulus was never detected. Above threshold, a stimulus was always detected resulting in a step response (Haber and Hershenson, 1973; Gescheider, 1985; Laming, 1991) (Figure 3.8a).

However, visual events take place against a background of noise due to the spontaneous discharge of cells (DeValois and DeValois, 1990). This leads to some instances where a real event may be masked by noise (a miss) and, others where random noise might be mistaken for the presence of a near threshold stimulus (false-alarm) (Wolfe, 1990). Consequently, attempts to measure the threshold at which a stimulus can be detected result in an ogive shaped distribution called the "probability of seeing" curve or psychometric function when stimulus intensity is plotted against the percentage of correct responses (Haber and Hershenson, 1973) (Figure 3.8b).

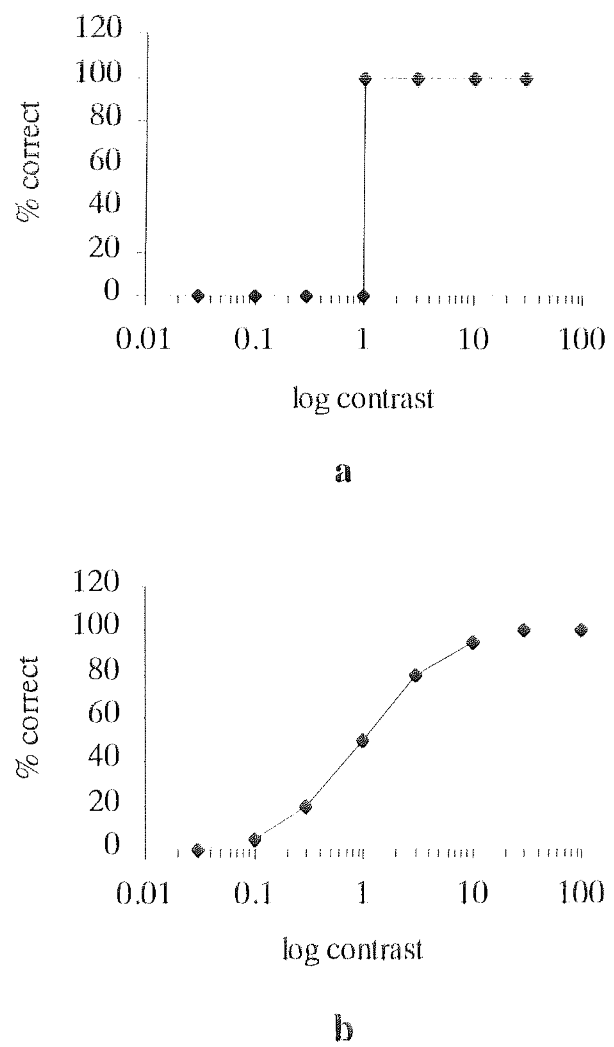


**Figure 3.8** Diagram of typical threshold functions. **a** is the step function of classical theory. **b** is the ogive function obtained empirically. Redrawn from Wolfe, 1990.

#### 3.5.4.2 *Decision criteria in psychophysics: yes/no and forced choice*

The decision criterion used in psychophysical threshold determination experiments may be based on either yes/no or forced choice decisions on the part of the observer.

In yes/no designs the observer replies "yes" or "no" when asked whether a stimulus is present or not. However, if this method is used the threshold found is subject to variation in the observer's decision making criterion. For instance, a cautious observer, not being entirely certain whether a stimulus is present may say "yes" less often (Haber and Hershenson, 1973). In addition, it has been demonstrated that just increasing the number of trials presented increases the number of times that an observer is likely to say "yes" (Gescheider, 1985). Consequently, thresholds determined using yes/no decisions are "criterion dependent" as the threshold is dependent on the decision making criterion adopted by the observer.

Forced choice or "criterion free" decision making overcomes the problems of response bias experienced in yes/no. The forced choice procedure involves the subject being forced to make a decision using predetermined responses even if unsure (Wolfe, 1990). For instance, a subject may be asked to decide whether a sinusoidal grating is present in the first or second presentation (two alternative forced choice, 2AFC). A "don't know" response would not be permitted (Wolfe, 1990). The decision making criterion is thus set by the examiner. Because there is no obvious benefit to the observer to choose one response rather than another, it is usually more natural for them to give a symmetrical response. Hence, the observers decision criterion is unlikely to be biased (Green and Swets, 1966).

Criterion free methods give more reliable estimates of threshold than criterion dependant methods (Vaegan and Halliday, 1982; Higgins *et al.*, 1984; Higgins *et al.*, 1988)

#### *3.5.4.3 Method of adjustment*

The method of adjustment may be used only if the stimulus value can be continuously varied. The observer adjusts the intensity of the stimulus from a point either well above (or well below) the threshold until the stimulus just becomes invisible (or visible). Repeated trials give an estimate of the average threshold value (Gescheider, 1985; Treutwein, 1995).

This method has the advantage that the observer has an active part in the process which may help to prevent boredom (Gescheider, 1985). However, this also makes it difficult to maintain constant conditions throughout threshold measurement as the criterion for detection used by subjects is prone to variability (Gescheider, 1985; Woods and Thomson, 1993). The decision criterion can even vary with the spatial frequency of the stimulus for the same observer (Woods, 1996). The method of adjustment is moreover prone to afterimage effects, as is the method of limits (Section 3.5.4.4). Of the two procedures, the method of limits has been shown to be more reliable than the method of adjustment (Vaegan and Halliday, 1982; Ginsburg and Cannon, 1983).

### *3.5.4.4 Method of limits*

In this method, the initial stimulus value is well above (or below) the expected threshold value. It is then varied by the experimenter in small ascending or descending steps. In a descending series, the stimulus is reduced in small steps until the stimulus is just not detected. At this reversal point the series is stopped. The stimulus intensity at each reversal is an estimation of threshold. The final threshold is the average of a number of reversals (Gescheider, 1985; Woods and Thomson, 1993).

This method of threshold determination may be severely affected by decision criterion changes on the part of the observer (Gescheider, 1985; Treutwein, 1995) resulting in large inter-subject differences (Vaegan and Halliday, 1982; Reeves *et al.*, 1988). It is susceptible to errors of expectation where there is a tendency for the observer to develop a habit of always giving the same response. Nevertheless, careful instruction and avoidance of overlong trials can be used to minimise this problem (Gescheider, 1985). In addition, in a descending series, afterimages of the higher stimulus strengths may persist when the actual stimulus present is sub-threshold. This gives artificially low threshold estimations. To avoid this, trials are often restricted to the ascending limit only (Kelly, 1972; Ginsburg and Cannon, 1983). The method of limits is thus less precise than the method of constant stimuli (Section 3.4.4.6). However, it is less time consuming (Gescheider, 1985; Woods and Thomson, 1993), and easily used even by inexperienced observers (Arden and Jacobson, 1978; Ginsburg and Cannon, 1983).

#### *3.5.4.5 The standard staircase*

The simple linear staircase method is a variation of method of limits (Gescheider, 1985). A sequence is presented in which stimulus intensity is progressively increased or decreased in value. When the observer's response changes the stimulus sequence is reversed and proceeds to alter the stimulus in the opposite direction (Gescheider, 1985; Wolfe, 1990). The threshold estimated is the average intensity found for a number of reversals. There are several variants of the standard staircase (e.g. Levitt, 1971). Each tends to asymptote at a particular threshold level.

#### *3.5.4.6 Method of constant stimuli*

For the method of constant stimuli, a fixed number of stimuli at predetermined intensity levels are repeatedly presented in a random order throughout the experiment (Gescheider, 1985; Treutwein, 1995). After a number of trials at each intensity the proportion of correct responses for every stimulus intensity tested is recorded and the threshold estimated.

The method of constant stimuli is the most repeatable of the classical methods of threshold determination (Blackwell, 1952; Woods and Thomson, 1993). However, it is also the most time consuming as a large number of responses are required to determine threshold (Woods and Thomson, 1993).

#### *3.5.4.7 Adaptive procedures*

These are designed to reduce the amount of time involved in psychophysical testing while still producing a reliable determination of threshold. They are based on modifications of the method of constant stimuli, the method of limits and staircase procedures (Treutwein, 1995). The intensity of the stimulus presented is adjusted on the basis of previous performance with the result that the stimulus presentations are centred on threshold (Shelton *et al.*, 1982; Treutwein, 1995). The time involved is reduced as unnecessary presentations away from the threshold value can be eliminated (Shelton *et al.*, 1982; Treutwein, 1995).

#### *3.5.4.8 Choice of psychophysical method*

The choice of psychometric method is an important variable in the determination of the contrast sensitivity function. It has, for instance, been highlighted as a possible reason for the conflicting results in investigations of the CSF in aging (Higgins *et al.*, 1988; Sloane *et al.*, 1988; Yager and Beard, 1994) (Section 3.4.5). In comparison experiments, the choice of psychophysical method has been shown to influence the CSF generated for both inexperienced (Vaegan and Halliday, 1982; Ginsburg and Cannon, 1983; Higgins *et al.*, 1984; Higgins *et al.*, 1988; Long and Tuck, 1988) and experienced observers (Kelly and Savoie, 1973).

The choice of method used depends on a number of factors. It may be important to adhere to a particular time limit, or to provide a high level of repeatability particularly in the clinical situation (Woods and Thomson, 1993). In research applications, it may be more important to produce experimental conditions that maximise the validity of the experiment when compared to a specified real-life situation (Woods and Thomson, 1993).

### 3.5.5 *The effect of aging on the CSF*

There has been some disagreement in the literature regarding the effect on the CSF of normal aging. The whole spectrum of possibilities has been covered. Some authors believe that no age related sensitivity loss occurs (Arden and Jacobson, 1978; Ginsburg, 1984; Gilmore *et al.*, 1991). Others have concluded that there is a diffuse loss at all spatial frequencies (Arden and Jacobson, 1978; Skalka, 1980; McGrath and Morrison, 1981; Vaegan and Halliday, 1982; Ross *et al.*, 1985; Sloane *et al.*, 1988) (Figure 3.6c). The theory that there is sensitivity loss only at medium and high spatial frequencies (Figure 3.6b) has also received considerable support (Arundale, 1978; Derefeldt *et al.*, 1979; Sokol *et al.*, 1980; Owsley *et al.*, 1983; Morrison and McGrath, 1985; Owsley *et al.*, 1985; Ross *et al.*, 1985; Wright and Drasdo, 1985; Elliott, 1987; Crassini *et al.*, 1988; Higgins *et al.*, 1988; Tulunay-Keesey *et al.*, 1988; Scialfa *et al.*, 1989; Elliott, Whitaker and McVeigh, 1990; Owsley and Burton, 1991; Steen *et al.*, 1994). However, one author found sensitivity loss at only low spatial frequencies (Sekuler *et al.*, 1980) (Figure 3.6d).

It has been determined that this variation in the pattern of sensitivity loss with age could be the result of the methods employed by investigators. It is unclear whether some studies screened for ocular pathology (e.g. Arden and Jacobson, 1978). Hence, it is uncertain whether the effects found were true aging or a consequence of pathology. In addition, some studies have not controlled for the effect of optical blur which is known to have an effect on sensitivity (e.g. Ginsburg *et al.*, 1984; Ginsburg, 1984) (Section 3.4.7). Furthermore, some have used small sample sizes (Sekuler *et al.*, 1980; Crassini *et al.*, 1988). It has been shown that there is a wide variation in the capability of the older adult (Sekuler *et al.*, 1980; Owsley *et al.*, 1983; Owsley and Burton, 1991). Thus, a small sample may not be representative of the older population and invalid inferences about this population may result (Owsley and Burton, 1991).

It had been thought that some sensitivity loss might be the consequence of more conservative decision making criteria being adopted by older adults (Owsley *et al.*, 1983). If so, some methods would be more influenced by this than others. It was found later that such conservatism of decision making did not result in sensitivity loss (Morrison and Reilly, 1986; Yager and Beard, 1994). However, the choice of psychophysical method used to determine the CSF of older adults can make a difference to the results (Higgins *et al.*, 1988; Sloane *et al.*, 1988; Yager and Beard, 1994). When a criterion dependent method such as the method of adjustment is employed, a diffuse loss of contrast sensitivity at all spatial frequencies has been shown with increasing age (Higgins *et al.*, 1988; Sloane *et al.*, 1988). Only high spatial frequencies are affected, though, when more reliable criterion free psychophysical methods are employed (Higgins *et al.*, 1988; Sloane *et al.*, 1988).

There are a number of possible mechanisms for the contrast sensitivity loss with age. Ocular factors that may contribute are miosis, increased lens absorption and increased intraocular light scatter. Miosis and lens absorption result in reduced retinal luminance. A decrease in retinal luminance has been shown to decrease contrast sensitivity (Van Nes and Bouman, 1967; DeValois *et al.*, 1974) (Section 3.4.6). Intraocular light scatter arises from inhomogeneity of the refractive index of the lens (Allen and Vos, 1967; Sigleman *et al.*, 1974). The effect of this factor would be to reduce contrast sensitivity at all spatial frequencies (Wolf and Gardner, 1965).

Retinal changes that may contribute to the loss of contrast sensitivity with age are loss of photoreceptors (Marshall, 1987; Curcio *et al.*, 1990) and loss of retinal ganglion cells (Gartner and Henkind, 1981; Curcio *et al.*, 1990; Curcio and Drucker, 1993). It may also be a consequence of cortical cell loss (Devaney and Johnson, 1980) although conclusive evidence of cortical cell loss was not found by Spear (1993).

A number of authors have reported that optical factors predominate in the decline of contrast sensitivity with age (Owsley *et al.*, 1983; Hemenger, 1984; Owsley *et al.*, 1985; Wright and Drasdo, 1985; Sloane *et al.*, 1988; Sturr *et al.*, 1988; Artal *et al.*, 1993).

However, there is strong evidence against the involvement of optical factors. Simulations of pupil miosis in young subjects, and artificial dilation of the pupils of older adults have demonstrated a minimal effect on contrast sensitivity (Higgins *et al.*, 1988; Sloane *et al.*, 1988; Elliott, Whitaker and McVeigh, 1990; Fiorentini *et al.*, 1996; Hennelly *et al.*, 1998). Indeed, it has been found that contrast sensitivity in older adults tends to be optimised when assessed using their natural pupils (Woodhouse, 1975; Sloane *et al.*, 1988). The contribution of lenticular absorption to age related contrast sensitivity reduction has also been found to be minimal (Owsley *et al.*, 1985; Higgins *et al.*, 1988; Elliott, Whitaker and McVeigh, 1990). A few authors have found that intraocular light scatter reduces contrast sensitivity (Hemenger, 1984; Sloane *et al.*, 1988).

However, many more have found that it is not a causative factor (Allen and Vos, 1967; Sigleman *et al.*, 1974; Owsley *et al.*, 1983; Morrison and McGrath, 1985; Elliott, 1987; Jay *et al.*, 1987). This would not be surprising if the true pattern of sensitivity loss with age is confined to the higher spatial frequencies as this factor affects all spatial frequencies (Wolf and Gardner, 1965).

One investigation of the contribution of neural factors concluded that there was no neural loss of contrast sensitivity with increasing age (Dressler and Rassow, 1981). However, more recent research appears to support a neural contribution (Morrison and McGrath, 1985; Owsley *et al.*, 1985; Elliott, 1987; Jay *et al.*, 1987; Higgins *et al.*, 1988; Sloane *et al.*, 1988b; Elliott, Whitaker and McVeigh, 1990; Whitaker and Elliott, 1992; Spear, 1993).

It may be, however, that neither optical nor neural factors alone explain the situation. It has been suggested that a combination of both might represent the true picture. Elliott (1987) has suggested that the depression of contrast sensitivity is predominantly a neural phenomenon. An additional optical component, mediated by reduced retinal luminance, contributes to the sensitivity loss only at higher spatial frequencies (>16cpd).

### *3.5.6 The effect of luminance on the CSF*

Decreasing luminance shifts peak CSF sensitivity toward lower spatial frequencies (Figure 3.6f) (Schade, 1956; Patel, 1966; Van Nes and Bouman, 1967; Daitch and Green, 1969; Kulikowski, 1971; Graham, 1972; Kelly, 1972; DeValois *et al.*, 1974; Rohaly and Buchsbaum, 1989). Moving from photopic to mesopic luminance may shift the peak from a spatial frequency of 6cpd to 2cpd (DeValois *et al.*, 1974). This shift in peak sensitivity results in a greater loss in contrast sensitivity for high spatial frequencies than for low spatial frequencies. At low scotopic luminance, the low spatial frequency attenuation seen under photopic conditions disappears (DeValois *et al.*, 1974).

The change in the CSF with decreasing luminance appears to be linked with the change from cone to rod function and the difference in their receptive field properties (DeValois and DeValois, 1990). At low light levels, signal strength is low. Consequently, in cones the signal is masked by random noise present in the visual system. However, rod receptive fields summate the responses from a wider area and can thus better distinguish the signal from noise. This summation also has the effect of reducing the spatial frequency to which the receptive field is optimally responsive. Hence, peak sensitivity is shifted toward lower spatial frequencies.

### *3.5.7 The effect of defocus on the CSF*

The effect on the CSF of optical defocus due to refractive error is similar to that of luminance. Defocus alters the retinal image by reducing contrast (Herse and Bedell, 1989). This contrast reduction has been found to be a constant fraction of the initial image contrast (Green and Campbell, 1965; Williams and Boothe, 1983; Kaye and Morrison, 1987). Hence, as the level of defocus increases, the entire CSF undergoes a parallel shift to the left toward lower spatial frequencies (Green and Campbell, 1965; Williams and Boothe, 1983; Kaye and Morrison, 1987; Rabin, 1994) (Figure 3.6f). Thus, refractive defocus results in a reduction in sensitivity to high spatial frequencies with relative sparing of low spatial frequency sensitivity (Campbell and Green, 1965a; Hess and Garner, 1977; Charman, 1979; Comerford, 1983; Regan and Neima, 1983;

Arden, 1988; Regan, 1988). Low spatial frequencies (1-2cpd) are relatively unaffected (Campbell and Green, 1965a).

The effect of optical defocus due to refractive blur described in the preceding section is different to defocusing effects induced by a diffusing filter (Herse and Bedell, 1989). Diffusive blur causes a general depression of contrast sensitivity affecting all spatial frequencies equally (Herse and Bedell, 1989; Irving and Woo, 1993) (Figure 3.6c).

Both refractive and diffusive defocus can, in some instances, result in a notch defect (Figure 3.6e) due to a narrow spatial frequency band of sensitivity loss (Apkarian *et al.*, 1987; Irving and Woo, 1993; Woods *et al.*, 1996; Strang *et al.*, 1997). In refractive defocus, notches can occur for both astigmatic (Apkarian *et al.*, 1987) and spherical refractive errors (Woods *et al.*, 1996; Strang *et al.*, 1997). The mechanism is monocular diplopia resulting from the interaction of the defocus with ocular aberrations of the eye. The "real" and "diplopic" images interfere giving partial cancellation of the target. Partial cancellation effectively reduces the target contrast to below threshold level (Apkarian *et al.*, 1987; Woods *et al.*, 1996). A similar interference effect occurs with diffusive filters as a result of the diffractive effect of the filter (Irving and Woo, 1993).

The pattern of sensitivity loss due to defocus is similar for grating and letter targets (Legge *et al.*, 1987). However, the magnitude of the sensitivity loss can be very different. For the same level of defocus, contrast sensitivity to letters is depressed relative to the contrast sensitivity for gratings (Legge *et al.*, 1987). Furthermore, the reduction of contrast sensitivity for letters seen with refractive defocus is rather greater than that found for defocus in diffusive conditions (Regan and Neima, 1983; Herse and Bedell, 1989).

### *3.6 Clinical contrast sensitivity testing*

#### *3.6.1 Clinical versus laboratory methods of contrast sensitivity testing*

The laboratory method of CSF determination using electronically generated sinewaves and formal psychophysical procedures has been discussed in the preceding sections. However, such methods have a number of disadvantages when applied to CSF determination in the clinical environment.

1. The equipment can be both bulky (Pelli *et al.*, 1988; Regan, 1988) and expensive (Regan and Neima, 1983; Arden, 1988; Greeves *et al.*, 1988; Pelli *et al.*, 1988; Regan, 1988; Rubin, 1988; Herse and Bedell, 1989).

2. Equipment often needs time consuming routine calibration and maintenance (Pelli *et al.*, 1988).

3. It can be difficult to standardise test conditions between clinics, as there is a wide variety of equipment in use. Hence, results may be difficult to compare (Beck *et al.*, 1993).

4. The duration of formal psychophysical testing, as described in section 3.5.4, is a considerable barrier to clinical use of such tests (Ginsburg, 1984; Greeves *et al.*, 1988; Rubin, 1988). It has been suggested that the full potential of clinical CSF measurement is unlikely to be realised unless it can be made as quick and simple

as the acuity test itself (Arden, 1988; Pelli *et al.*, 1988). It has also been pointed out that the advantages gained from the use of complex procedures can be offset by the long duration of such tests (Woods and Thomson, 1993)

The combination of the disadvantages of laboratory test methods with the potential usefulness of the CSF as a clinical tool has led to the development of a number of simple tests. These have been designed to make the clinical measurement of CSF rapid while attempting to retain its validity as a diagnostic procedure (Woods and Wood, 1996).

### *3.7 Clinical sinewave grating tests of contrast sensitivity*

Some clinical tests of contrast sensitivity use sinewave gratings similar to those used in laboratory testing (Arden and Jacobson, 1978; Ginsburg, 1984; Wilkins *et al.*, 1988). However, in clinical applications gratings are more usually photographed or printed rather than electronically generated.

#### *3.7.1 Arden plates*

The earliest commercially available contrast sensitivity test was the Arden grating test (Arden and Jacobson, 1978). This test measured contrast sensitivity using seven photographic plates of relatively low spatial frequencies (0.2 to 6.4cpd). Contrast was graduated from top to bottom of each plate. Each plate was gradually revealed manually to the observer by the examiner till the grating was just visible and the contrast recorded (Arden and Jacobson, 1978). However, this test which utilises the method of limits is no longer regarded as an efficient or reliable test of contrast sensitivity (Woods and Wood, 1996).

### *3.7.2 Cambridge gratings*

The Cambridge grating test (Wilkins *et al.*, 1988) consists of a spiral bound booklet that tests a single spatial frequency near the peak of the CSF (6 cpd). Plates are presented in pairs, one blank and one containing the grating. The observer states which of the two plates contains the stimulus (Wilkins *et al.*, 1988). This forced choice test has moderate reliability (Jones *et al.*, 1994) but is less common in clinical practice than other commercially available tests (Latham, 1998).

### *3.7.3 The Vistech chart.*

| **Row** | **Spatial frequency (cpd)** | **Column** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* |
| A | 1.5 | 0.48 | 0.84 | 1.08 | 1.30 | 1.54 | 1.84 | 2.08 | 2.23 |
| B | 3 | 0.60 | 0.95 | 1.18 | 1.38 | 1.64 | 1.92 | 2.23 | 2.34 |
| C | 6 | 0.70 | 1.04 | 1.32 | 1.65 | 1.84 | 2.10 | 2.26 | 2.41 |
| D | 12 | 0.70 | 0.90 | 1.18 | 1.50 | 1.74 | 1.94 | 2.10 | 2.23 |
| E | 18 | 0.60 | 0.84 | 1.00 | 1.18 | 1.41 | 1.60 | 1.81 | 1.95 |

**Table 3.1** Log contrast sensitivity values for each patch on the Vistech chart.

The Vistech chart (Ginsburg, 1984) is a clinical measure of contrast sensitivity that samples the CSF of the observer at five spatial frequencies. The chart consists of 5 rows (A to E) of nine discrete circular patches. Each patch contains a sinewave grating. The first patch on each row is a high contrast sample patch. Each row has a different spatial frequency and the contrast of each test patch reduces on moving from left to right across the chart (Table 3.1). The gratings are presented at three orientations: 15 degrees to the right, vertical, or 15 degrees to the left. The test is described by its inventor as being forced choice in style. However, it is not a true forced choice procedure because a "blank" response is allowed (Section 3.5.4.2). The contrast sensitivity value for each spatial frequency is the number of the last patch orientation correctly identified. This is plotted on the chart provided. When complete, a five point CSF is revealed (Figure 3.9).

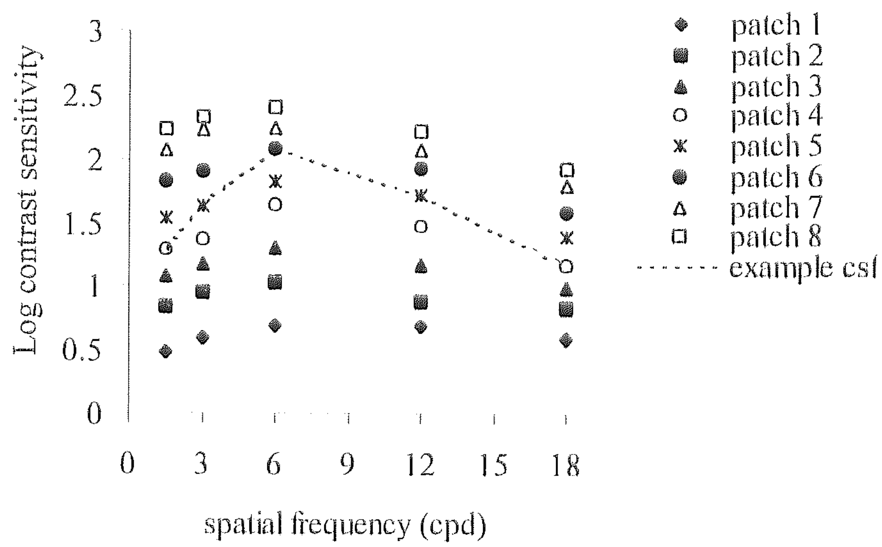


**Figure 3.9** The spatial frequency and contrast sensitivity of the Vistech chart patches. The dotted line illustrates an example of a CSF determined using the Vistech.

The Vistech chart has been shown to be reasonably sensitive to changes in contrast sensitivity (Reeves *et al.*, 1991). In addition, the highest spatial frequency result correlates well with visual acuity, as might be expected if the chart is an adequate measure of the CSF (Elliott and Whitaker, 1992). The pattern of age related sensitivity loss (Scialfa *et al.*, 1988; Scialfa *et al.*, 1991) and the reduction in sensitivity resulting from defocus (Bradley *et al.*, 1991) are also similar to that expected from laboratory CSF measurements. At low spatial frequencies, however, Vistech contrast sensitivity appears depressed (Ginsburg, 1984; Scialfa *et al.*, 1988). This has been attributed to the small number of cycles present in the grating patches at these spatial frequencies (Corwin and Richman, 1986; Greeves *et al.*, 1988; Scialfa *et al.*, 1988; Van Den Brom *et al.*, 1992) (Section 3.4.3).

Unfortunately, the Vistech has been criticised for poor reliability which limits its usefulness (Corwin and Richman, 1986; Long and Tuck, 1988; Rubin, 1988; Brown and Lovie-Kitchin, 1989; Kennedy and Dunlap, 1990; Bradley *et al.*, 1991; Reeves *et al.*, 1991; Scialfa *et al.*, 1991; Elliott and Whitaker, 1992; Elliott and Bullimore, 1993). This has been attributed to a number of causes:

1. Limited sampling. There is only one patch per spatial frequency and contrast combination which makes the test vulnerable to misreporting errors (Long and Tuck, 1988; Pelli *et al.*, 1988; Rubin, 1988; Reeves *et al.*, 1991; Scialfa *et al.*, 1991; Elliott and Bullimore, 1993). Such errors may be responsible for spurious notch loss commonly found with this chart (Rubin, 1988).

2. Large and variable steps in contrast between patches increases the magnitude of measurement errors (Reeves *et al.*, 1991; Scialfa *et al.*, 1991; Bailey, 1993)

3. Poor psychophysical methodology as blank responses are allowed (Elliott and Bullimore, 1993)

4. The number of cycles in low spatial frequency patches is below critical level (Corwin and Richman, 1986; Greeves *et al.*, 1988; Scialfa *et al.*, 1988; Van Den Brom *et al.*, 1992). Reliability has been shown to increase with increasing spatial frequency (Corwin and Richman, 1986; Long and Tuck, 1988; Scialfa *et al.*, 1991)

5. Use of truncated round patches. Experiments using round masks have demonstrated that this depresses contrast sensitivity compared to a larger field (Corwin and Richman, 1986).

A number of recommendations have been made to improve the reliability of the Vistech charts. Repeat administration, together with the use of the average contrast sensitivity value for each patch, has been shown to improve reliability (Rubin, 1988; Scialfa *et al.*, 1988; Kennedy and Dunlap, 1990; Scialfa *et al.*, 1991). Adoption of a different scoring method has also been suggested. It has been found that as long as a wrong response is followed by two correct answers it can be discounted (Rubin, 1988). This improves the reliability of the Vistech as it helps reduce the effect of misreporting errors (Rubin, 1988). Other authors, however, suggest that major design changes, such as the inclusion of more contrast steps and higher contrast gratings for high spatial frequencies, are needed to allow a better contrast sensitivity evaluation across all age groups (Scialfa *et al.*, 1988).

### *3.7.4 The functional acuity contrast test (FACT)*

The functional acuity contrast test (FACT) is a revised version of the Vistech chart designed to improve the earlier test (Ginsburg, 1993). It has a similar arrangement and number of patches as the Vistech (Section 3.7.3). The spatial frequencies represented and scoring method are also the same. The high contrast sample patch has been eliminated so there are nine test patches. The contrast steps used are smaller (average step size is 0.15 log units) and more uniform (Table 3.2). This acts to decrease the magnitude of measurement errors. Furthermore, the gratings themselves are no longer definite round patches bordered by a black line. They now merge into an average grey background that has a luminance equivalent to the mean luminance of the grating. This eliminates ghost images and keeps mean retinal luminance constant. The forced choice procedure has also been improved with the elimination of the blank response option. However, results obtained from this chart are still likely to be affected by the limited sampling, low cycle number and large step sizes it shares with the earlier Vistech version. The suggestions mentioned earlier, with respect to improving the reliability of the Vistech chart through repeated measures and improved scoring, also apply to the FACT.

| Row | Spatial Frequency (cpd) | Column | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* |
| A | 1.5 | 0.84 | 0.95 | 1.11 | 1.25 | 1.40 | 1.56 | 1.70 | 1.85 | 2.00 |
| B | 3 | 1.00 | 1.18 | 1.30 | 1.46 | 1.60 | 1.75 | 1.90 | 2.05 | 2.20 |
| C | 6 | 1.08 | 1.20 | 1.36 | 1.52 | 1.65 | 1.81 | 1.95 | 2.11 | 2.25 |
| D | 12 | 0.90 | 1.04 | 1.18 | 1.34 | 1.48 | 1.63 | 1.78 | 1.93 | 2.07 |
| E | 18 | 0.60 | 0.78 | 0.90 | 1.08 | 1.23 | 1.36 | 1.52 | 1.66 | 1.81 |

**Table 3.2** Log contrast sensitivity values for each patch on the FACT chart.

### *3.8 Clinical contrast sensitivity tests that use letters*

#### *3.8.1 Letters in contrast sensitivity tests*

Letters are a popular choice for use in clinical contrast sensitivity tests as patients and practitioners are already familiar with traditional acuity tests that predominantly use letters as targets (Pelli *et al.*, 1988; Elliott, Sanderson *et al.*, 1990). Consequently, they find tasks involving letters easier to understand.

#### *3.8.2 Letter construction is spatially complex*

The construction of letters in spatial terms is based on the square wave (Regan, 1991) (Section 3.5.2). Hence, letters might be considered as composed from a number of square waves of different orientations. Each section would contain a range of spatial frequencies based on the fundamental spatial frequency of the stroke width of the letter part (Leguire, 1991; Regan, 1991).

However, there is an additional factor involved in the detection of letters. This relates to differences in letter legibility. Letters of different legibility contain different amounts of information in terms of the minimum spatial frequency needed to identify the letter (Regan *et al.*, 1981). Low difficulty letters can be distinguished from their general shape (global information). High difficulty letters require analysis of the higher spatial frequencies contained in the letter detail (local information) (Bouma, 1971; Lupker, 1979; Elliott, Whitaker and Bonette, 1990). Hence, in letter discrimination it is more difficult to determine the spatial frequencies being measured than for sinewave targets. It is advisable to consider letters as consisting of a broad band of spatial frequencies (Elliott, Sanderson *et al.*, 1990).

### *3.8.3 The validity of using letters in contrast sensitivity tests*

The validity of using letters rather than sinewaves in the measurement of contrast sensitivity has been questioned on a number of points (Leguire, 1991).

1. Letters consist of mixed spatial frequencies (Section 3.8.2). Hence, they cannot be said to be measuring contrast sensitivity at any particular spatial frequency (Leguire, 1991). They also combine different orientations.

2. Low contrast letter charts in which letters reduce in contrast down the chart have a variable mean luminance. In laboratory measures, mean luminance is usually kept constant (Leguire, 1991).

3. Letter recognition may be viewed as specifying the smallest resolvable character size for given values of contrast (Legge *et al.*, 1987). It is argued that letter tests may actually be measuring resolution at suprathreshold levels of contrast rather than contrast threshold (Leguire, 1991).

However, there is also evidence to support the point of view that letters can be valid targets for use in contrast sensitivity tests. Contrast sensitivity functions plotted using letter targets have been found to be qualitatively similar to CSFs measured using sinusoidal gratings (Legge *et al.*, 1987). In addition, the quantitative reduction in contrast sensitivity found using letters relative to sinewave gratings may be accounted for by the difference between detection and identification (Legge *et al.*, 1987). Even when using sinewave gratings it has been found that the contrast needed to identify a target is greater than that needed just to detect it (Owsley and Sloane, 1987). Hence, sensitivity for identification is depressed. Furthermore, the shape of the letter CSF and the effects of optical defocus are similar to those found for more simple square waves (Greeves *et al.*, 1988) (Section 3.4.2; Section 3.4.7). Thus, the difference in CSF for letters and sinewaves may be no different to the variation in CSF for sinewaves found when different laboratory conditions are used.

Considering the issue of mean luminance variation, it has been found that the magnitude of mean luminance variation in low contrast letter charts (such as the Pelli-Robson contrast threshold chart (Pelli *et al.*, 1988) has a negligible effect on contrast sensitivity (Zhang *et al.*, 1989).

An advantage of letter usage is that the task of letter identification involves a multiple forced choice technique. Forced choice is a good psychophysical method which limits criterion effects (Vaegan and Halliday, 1982; Higgins *et al.*, 1988; Elliott, Sanderson *et al.*, 1990) (Section 3.4.4.2).

Above all, the main reason for using letters in contrast tests is that they have shown to be clinically useful in the detection of visual deficits that would not be picked up if visual acuity alone was measured (Regan *et al.*, 1977; Regan, 1988).

### *3.8.4 The Pelli-Robson contrast threshold chart*

The Pelli-Robson chart (Pelli *et al.*, 1988) is a commercially available low contrast letter chart. It consists of 16 letter triplets arranged in eight rows. All letters are the same height. Percentage contrast ranges from approximately 100% to 0.9%. Contrast sensitivity decreases in 0.15 log unit steps between successive triplets. As a letter identification task it uses a true forced choice procedure. The manufacturers recommend that the end point of the test be recorded as the sensitivity of the last triplet in which two out of three letters are correctly identified.

The original version of the test was carried out at 3m and as such provided a measure of contrast sensitivity close to the peak of the CSF (around 3cpd) (Pelli *et al.*, 1988). In the commercially produced test, however, this distance was reduced to 1m. Thus, the spatial frequency of the letter detail is closer to 1cpd although higher harmonics at 3cpd and 5cpd are present (Pelli *et al.*, 1988; Woods and Wood, 1996). It has been argued that it is not possible to use letters to test low spatial frequencies as, like square waves, the higher harmonics of the letter are responsible for detection (Greeves *et al.*, 1988). However, it has been demonstrated that the contrast threshold measured using the Pelli-Robson chart is correlated with the fundamental spatial frequency component of the letters rather than these higher harmonics (Woods, 1993). Hence, the Pelli-Robson chart is more properly provides a test of low to intermediate spatial frequencies (Pelli *et al.*, 1988).

When measured at 3m, Pelli-Robson scores have been shown to correlate well with the peak of the CSF (Pelli *et al.*, 1988; Rubin, 1988). The chart is relatively unaffected by all types of ocular defocus (Zhang *et al.*, 1989; Bradley *et al.*, 1991), and luminance (Zhang *et al.*, 1989). This is expected, as the low spatial frequencies of laboratory generated CSF would be similarly unaffected (Campbell and Green, 1965a). These are useful test properties given that the test conditions may vary widely between clinics (Pelli and Robson, 1991). However, the Pelli-Robson chart is still sufficiently sensitive to be able to detect age related changes (Zhang *et al.*, 1989).

The reliability of the Pelli-Robson chart using the original two out of three scoring criterion (Pelli *et al.*, 1988) has been shown to be high (Rubin, 1988; Elliott, Sanderson *et al.*, 1990). However, a number of further changes have been made. The adoption of "letter by letter" scoring (each letter worth 0.05 log units) has been found to improve reliability (Elliott *et al.*, 1991). In addition, it has been found that differences in letter legibility exist for letters of near threshold contrast (Elliott, Whitaker and Bonette, 1990; Illueca *et al.*, 1995). Nevertheless, differences in legibility may be balanced if Cs, when miscalled as Os are included as correct responses (Elliott, Whitaker and Bonette, 1990).

For optimum repeatability, it is important that the test should be carried out in an unhurried manner (Whitaker and Elliott, 1992). Subjects sometimes need as long as 25-30 seconds to resolve letters that are close to threshold levels of contrast (Tunnacliffe, 1989).

Compared to the Vistech and FACT charts, the measurement of only one spatial frequency by the Pelli-Robson chart may appear inadequate. However, it has been shown that CSF can adequately be predicted from a measure of visual acuity plus one other contrast measurement at a low spatial frequency, such as that made using the Pelli-Robson (Kennedy and Dunlap, 1990; Elliott and Whitaker, 1992; Cornelissen *et al.*, 1995). Indeed, it has been indicated that the high inter-correlation between the adjacent spatial frequencies of the Vistech and FACT suggests that there is a high level of redundant information contained in this test (Brown and Lovie-Kitchin, 1989; Kennedy and Dunlap, 1990; Elliott and Whitaker, 1992).

### *3.9 Summary*

The contrast sensitivity function could be viewed as the link between the mechanisms that underpin human spatial vision and the effects that changes in these mechanisms have on visual performance during everyday tasks. It is believed that contrast sensitivity provides more information about visual deficits than is provided by measurement of visual acuity (Regan *et al.*, 1977; Hess and Woo, 1978; Bodis-Wallner, 1980; Carney, 1982; Ginsburg, 1984; Regan, 1988; Leguire *et al.*, 1990; Regan, 1990). Because of this, measurement of contrast sensitivity has been introduced to the clinical environment. This has led to the design of new tests intended for clinical use, driven by the need for inexpensive, quick, and reliable contrast sensitivity assessment (Rubin, 1988). There are advantages and disadvantages associated with the use of clinical charts. Whichever type is used, it is important to note that the effectiveness of any clinical chart stands or falls on its ability to predict performance in real life tasks.

# CHAPTER 4: INTRODUCING CONTRAST SUSCEPTIBILITY

## *4.1 Introduction*

This chapter introduces Csus as a clinically applicable measure of contrast sensitivity. Its relationship to the CSF is examined. Aspects such as normal Csus values, age variations and the relationship between Csus and ocular pathology are discussed. Previous Aston University research linking Csus deficits to accident involvement is briefly reviewed followed by an outline of the thesis objectives.

## *4.2 What is contrast susceptibility?*

Contrast susceptibility (Csus) is defined as the difference between high contrast visual acuity and low contrast visual acuity and is calculated using equation 4.1. When measuring visual acuity "by the line", Csus is recorded as the number of lines dropped. More recently, LogMAR charts (Bailey and Lovie, 1976) facilitate measurement of visual acuity "by the letter". When using these charts, Csus is recorded as a difference in LogMAR acuity score.

Contrast Susceptibility = Low Contrast Acuity – High Contrast Acuity **(4.1)**

Researchers at Aston University have adopted the term Csus. However, the measurement of Csus is not new. Previous researchers have referred to the same measurement as normalised low contrast acuity (Regan *et al.*, 1977; Regan, 1988; Regan, 1990).

### *4.3 Contrast susceptibility and the contrast sensitivity function.*

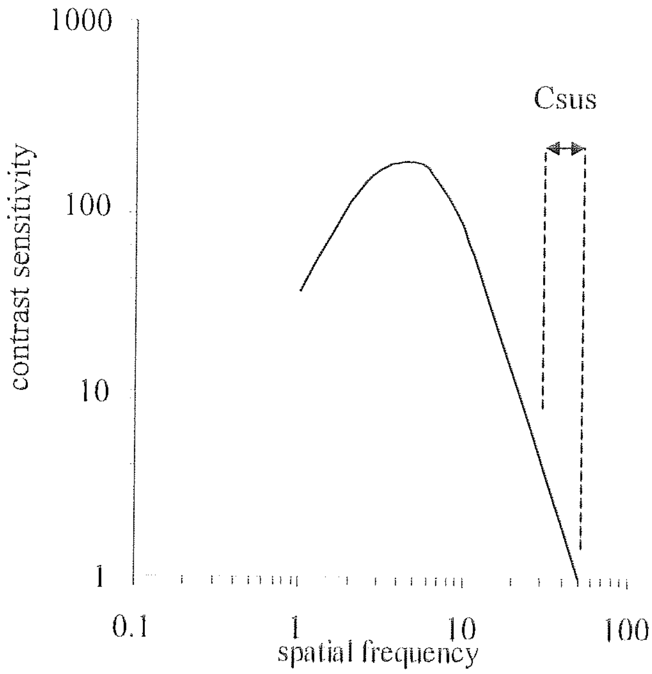


**Figure 4.1** Graphical representation of the relationship between the contrast sensitivity function (CSF) and contrast susceptibility (Csus). Redrawn from R. L. DeValois *et al.* (1974).

The contrast sensitivity function (CSF) has been described in chapter 3. Contrast susceptibility provides an estimate of the slope of the right hand descending limb of the contrast sensitivity function (CSF). (Regan, 1988; Woods and Wood, 1996; Figure 4.1). Changes in either high or low contrast acuity would alter the position or angle of this slope. In principle, therefore, Csus measured using letter acuity may be considered to be an indicator of changes in the contrast sensitivity function at medium and high spatial frequencies (Woods and Wood, 1996).

### *4.4 Normal value of contrast susceptibility*

The typical value of Csus found in normal observers is just over two lines of visual acuity or 0.2 LogMAR (Brown and Lovie-Kitchin, 1989; Bailey, 1993; Elliott and Bullimore, 1993).

### *4.5 Contrast susceptibility and aging*

Investigation of the magnitude of Csus with increasing age has indicated that it remains approximately constant (Brown and Lovie-Kitchin, 1989; Regan, 1990; Elliott and Bullimore, 1993). This is perhaps not surprising, as the change in the contrast sensitivity function with age has been described as a shift to the left (Section 3.4.5). This would imply that the actual shape of the CSF including the descending slope is generally unchanged giving rise to a constant value of Csus.

### *4.6 Contrast susceptibility and ophthalmological disorders*

The measurement of Csus has been shown to be useful in the detection of various ophthalmological and neurological disorders including multiple sclerosis, Parkinson's disease and amblyopia (Regan *et al.*, 1977; Regan, 1988; Regan, 1990). Contrast susceptibility was also shown to have the highest level of sensitivity and specificity in the differentiation of glaucoma compared to other measures of contrast sensitivity. Nevertheless, the relatively low absolute level of sensitivity and specificity indicated that Csus was not of practical use in glaucoma screening as a significant proportion of cases would remain undetected (Wood and Lovie-Kitchin, 1992).

### *4.7 Contrast susceptibility and previous driving research*

Research relating contrast sensitivity to driving performance has been reviewed in section 2.4.5. Much of this research has used the Pelli-Robson letter chart to measure contrast threshold (Ball *et al.*, 1993; Wood *et al.*, 1993; Brabyn *et al.*, 1994; Wood and Troutbeck, 1995) or charts that present grating stimuli (Ginsburg *et al.*, 1982; Ginsburg and Easterly, 1983; Kruk and Regan, 1983; Evans and Ginsburg, 1985; O'Neal and Miller, 1987). Contrast susceptibility has not been used in driving research, although the potential benefit of using low contrast charts for driver assessment, particularly in low visibility conditions, has been acknowledged (Regan, 1990).

### *4.8 Contrast susceptibility driving research conducted at Aston University*

#### *4.8.1 1994 Survey: Contrast susceptibility measured using the Ergovision screener*

Research carried out at Aston University in 1994 pointed to a possible link between Csus, measured binocularly, and self-reported accidents (Dunne *et al.*, In press). This survey had been designed to investigate the practical aspect of driver vision screening and to reinvestigate the role of eyesight as a causative factor in road accidents. More details of the 1994 survey are provided in chapter 5.

Funding for this research was obtained from a consortium of health and local authorities based in Warwickshire and North Wales working in conjunction with the Guild of Experienced Motorists (GEM).

A range of visual tests and a questionnaire were administered to 284 drivers. The majority of the tests (9 out of 11) were conducted using an Ergovision vision screener manufactured by Essilor, France. Visual attention was measured using the UFOV visual attention analyser manufactured by Visual Resources Inc., USA. A number plate test was also carried out in accordance with UK driver licensing requirements.

Of the 11 tests listed in figure 4.2, Csus was found to be the strongest predictor of self-reported accident history in both younger (aged $\leq$ 40 years) and older drivers (aged > 40 years). It had sensitivity of 29% and had a specificity of 96%. Furthermore, drivers who had below average Csus scores (i.e. those that exhibited a drop of $\geq$4 lines of acuity) were twice as likely to have had accidents than drivers with better Csus scores. This relationship was statistically significant to at least the 95% level (Dunne *et al.*, In press). Figure 4.2 shows that high contrast visual acuity did not exhibit a statistically significant association with accidents.

**Association with accident involvement**

| **Under 40 years** | | **Greater than 40 years** |
|---|---|---|
| **Contrast Susceptibility** | ↓ decreasing strength of association with accident involvement | **Contrast Susceptibility** |
| Dynamic Visual Acuity | | Night Vision |
| Heterophoria | | Stereopsis |
| Stereopsis | | Useful Field of View |
| Visual Acuity | | Heterophoria |
| Night Vision | | Number Plate |
| Useful Field of View | | Colour Vision |
| Number Plate | | *Visual Acuity* |
| *Visual Fields* | | *Dazzle* |
| *Dazzle* | | *Visual Fields* |
| *Colour Vision* | | *Dynamic Visual Acuity* |

**Figure 4.2** The association between different visual tests and self-report accident involvement reproduced from (Dunne *et al.*, In press). Contrast susceptibility is the strongest indicator of self-report accident history. All visual tests except UFOV and the number plate test were carried out on the Ergovision screener. A fuller description of methods is contained in (Dunne *et al.*, In press). Bold type indicates a statistically significant relationship to the 95% level. Italics indicate paradoxical relationships where higher levels of vision were accompanied by increased self-report accidents.

The use of Csus as a measure of visual performance in drivers emerged after experimentation with the results of the Ergovision "variable contrast" test. Derivation of the original Csus score, using the Ergovision screener, was complicated and an explanation follows.

The Ergovision screener only permitted measurement of high and low contrast visual acuity at an intermediate testing distance of 66cm. Binocular visual acuity was measured during the "Mesopic Visual Acuity" test provided by the Ergovision screener. The alphanumeric symbols used, their Snellen fractions, and equivalent LogMAR scores are shown in Table 4.1.

| Test letters | Test numbers | Snellen fraction | LogMAR |
|---|---|---|---|
| XHPU | 9037 | 6/5 | -0.08 |
| RTZD | 3264 | 6/6 | 0.00 |
| XOFN | 2790 | 6/7.5 | +0.10 |
| ONZH | 4032 | 6/10 | +0.22 |
| TKUD | 7092 | 6/15 | +0.40 |
| UXH | 674 | 6/30 | +0.70 |

**Table 4.1** Alphanumeric symbols used for testing high contrast visual acuity.

Visual acuity was scored "by-the-line". The recorded visual acuity equated to the lowest line in which 3 out of 4 letters or numbers were read correctly.

Low contrast photopic binocular visual acuity was measured during the "Variable Contrast" test provided by the Ergovision screener. The alphanumeric symbols used, their Snellen fractions, and equivalent LogMAR scores are shown in Table 4.2.

| Test letters and numbers | Snellen fraction | LogMAR |
|---|---|---|
| TH73 | 6/15 | +0.40 |
| HN49 | 6/10 | +0.22 |
| UT27 | 6/7.5 | +0.10 |

**Table 4.2** Alphanumeric symbols used for testing low contrast visual acuity.

| Snellen fraction recorded | Acceptance criteria |
|---|---|
| 6/5 | All 4 symbols read on 6/7.5 line |
| 6/7.5 | 3 out of 4 symbols read on 6/7.5 line |
| 6/10 | 3 out of 4 symbols read on 6/10 line |
| 6/15 | 3 out of 4 symbols read on 6/15 line |
| 6/30 | Less than 3 symbols read on 6/15 line |

**Table 4.3** Conversion of low contrast visual acuity scores to a 5 line scale.

| | | Low contrast visual acuity score | | | | |
|---|---|---|---|---|---|---|
| | | 6/5 | 6/7.5 | 6/10 | 6/15 | 6/30 |
| **High contrast visual acuity score** | 6/5 | NONE* | TWO | THREE | FOUR | > FOUR |
| | 6/6 | | ONE | TWO | THREE | FOUR* |
| | 6/7.5 | | NONE | ONE | TWO | THREE* |
| | 6/10 | | | NONE | ONE | TWO* |
| | 6/15 | | | | NONE | ONE* |
| | 6/30 | | | | | NONE* |

**Table 4.4** Derivation of the Csus score (number of lines dropped).

An obvious problem was that the Csus score was derived from six lines of high contrast visual acuity (Table 4.1) compared to three lines of low contrast visual acuity (Table 4.2). To overcome this, a consistent means of converting low contrast visual acuity scores to a 5-level score was derived (Table 4.3). Table 4.4 illustrates how the final Csus score emerged.

### *4.8.2 1995 survey: Contrast susceptibility measured using ADCT*

The ADCT (Aston Drivers Contrast Test) was developed to overcome the problems experienced when measuring Csus using the Ergovision. The ADCT consisted of an adapted slide viewer. Back illuminated test charts were presented at optical infinity. Adoption of high and low contrast LogMAR test charts (Bailey and Lovie, 1976) allowed acuity to be scored "by the letter". Use of Landolt Cs simplified chart construction. Csus was simply recorded as the difference between high and low contrast LogMAR visual acuity scores.

Research carried out in 1995 on 229 drivers made use of the ADCT to continue the investigation of Csus and its association with accidents. This research was supported by Warwickshire county council road safety unit and North Wales's county council road safety units (Gwynedd and Clwyd) in conjunction with the Gwynedd police force. More details of the 1995 survey are provided in chapter 5.

The findings of this survey supported those of the 1994 survey. The trend for drivers with Csus scores of $\geq$4 lines to have twice the accident compared to drivers with better Csus scores remained. This relationship failed to achieve statistical significance at the 95% level. The reason for this might have been that there was a lower proportion of accident involved drivers present in the 1995 survey (16%) compared to the 1994 survey (24%). A much weaker association between high contrast visual acuity and accidents was again noted, supporting the findings of the 1994 survey.

### *4.8.3 Thesis objectives*

The promising results found in the surveys conducted in 1994 and 1995 prompted further investigation of the Csus test. The investigations planned are outlined below and define the main objectives of the experimental work described in the remaining chapters of this thesis.

1. A large sample survey should be conducted in order to establish normal values of Csus and verify its variation with age and its relationship with driving accident involvement.

2. This large sample survey should attempt to ascertain why Csus is more strongly associated with accidents than high contrast visual acuity. A tentative hypothesis

now follows. Drivers with visual deficits may reduce accident risk by avoiding certain driving situations. Drivers may judge their visual ability on high contrast targets (e.g. traffic signs) rather than low contrast targets (e.g. pedestrians and cyclists). Deficits in high contrast visual acuity would thus lead to increased situation avoidance. Hence, little relationship would exist between high contrast visual acuity and road accidents. It follows that drivers with only a small reduction in visual acuity for low contrast targets (i.e. low Csus score) would have a fairly realistic perception of their visual abilities and could accurately apply situation avoidance when needed. On the other hand, drivers with a large reduction of vision for low contrast objects (i.e. high Csus score) would tend to overestimate their visual abilities, would fail to practise situation avoidance when needed and would thus be prone to accidents. Hence, the finding that Csus deficits are linked to accidents. As this hypothesis places heavy emphasis on situation avoidance, the survey should include a questionnaire that examines this factor in greater detail.

3. Comparisons should be made of the repeatability and agreement between various methods of measuring Csus.

4. A study should be carried out to investigate the influence of instrument myopia on measurements of Csus made with vision screeners. Instrument myopia could lead to systematic differences between Csus values measured with vision screeners and wall mounted test charts in younger (pre-presbyopic) drivers. This could seriously limit the utility of vision screeners for the task of assessing drivers' vision.

5. It is possible that the link between Csus and driving is mediated through a possible association between Csus and the integrated area under the contrast sensitivity function (ICS) (Van Meeteren and Vos, 1972). Research has shown that ICS predicts search task performance (Cornelissen *et al.*, 1995). Hence, the link between Csus and ICS should be established.

### *4.9 Summary*

Previous research conducted at Aston University has prompted further questions relating to Csus as a potentially better predictor of driving accident risk than conventional measures of high contrast visual acuity. Experiments designed to answer these questions form the basis of the objectives of this thesis.

# CHAPTER 5: METHODOLOGY OF THE 1996 SURVEY

## *5.1 Introduction*

This chapter outlines the methodology used in the large sample survey carried out in 1996, under the sponsorship of Vauxhall Motors Ltd. It was conducted to achieve the objectives set down in section 4.8.3. Throughout the chapter, reference is made to the methodological developments of this survey based on the pilot surveys of 1994 and 1995.

## *5.2 Sample size and composition*

| Attribute | 1994 Survey | 1995 Survey | 1996 Survey |
|---|---|---|---|
| Sample size | 284 drivers | 229 drivers | 7254 drivers |
| Gender | 57% male | 53% male | 76% male |

**Table 5.1** Comparison of sample size and gender proportions of the three surveys.

Table 5.1 compares the sample size and proportion of males participating in each of the three surveys. A substantially greater proportion of males took part in the 1996 survey. This may have occurred as a result of differences in the type of testing venues used (Section 5.3).

## *5.3 Location of testing sites*

Five teams of trained promotion representatives administered the questionnaire and Csus test at a number of locations around the UK (see Table 5.2 and Figure 5.1 for locations). Forty-four locations were visited. Thirty-two of these were motorway service areas owned by Granada Group plc. The remaining locations comprised local festivals, supermarkets and open days. The time spent at each location was four days.

All sites were visited over a period of six weeks during July and August 1996. This period was chosen to coincide with the increase in traffic flow associated with the holiday season.

| Team number | Location type | Locations visited |
|---|---|---|
| 1 | Motorway services | Tamworth, Nottingham, Worksop, Pontefract, Wakefield, Manchester, Scotch Corner, Washington |
| 2 | Motorway services | Frankley, Stafford, Monmouth, Swansea, Cardiff, Warminster, Exeter, Plymouth, |
| 3 | Motorway services | Hilton Park, Knutsford, Bangor, Lancaster, Burton, Carlisle, Stirling, Kinross |
| 4 | Motorway services | Luton, Oxford, Chippenham, Newbury, Reading, Heathrow, Gillingham, Dartford Crossing |
| 5 | Festivals | Royal Show (Stoneleigh), Great Yorkshire (Harrogate), East of England (Peterborough), New Forest and Hants., Town and Country (Stoneleigh) |
| | Supermarkets | Witham, Halstead, Braintree. |
| | Open Days | Berkshire Emergency Services Tournament (Reading), Royal Welsh (Builth Wells), 999 Open Day (Bodelwyddan), West Mercia Police. |

**Table 5.2** Locations visited by each testing team during the 1996 survey.


**Figure 5.1** Map of the locations visited in the 1996 survey. Each symbol type refers to an individual team.

Table 5.3 compares the number and type of locations visited during the surveys of 1994, 1995 and 1996. The 1996 survey was mainly conducted at motorway service areas whilst the surveys of 1994 and 1995 primarily covered festivals and shopping centres. The emphasis on motorway testing sites may have increased the proportion of male volunteers participating in the 1996 survey (Table 5.1).

| Attribute | 1994 Survey | 1995 Survey | 1996 Survey |
|---|---|---|---|
| Number of locations | 29 | 3 | 44 |
| Location type | Festivals<br>Shopping centres | Festivals<br>Shopping centres | Motorway service areas<br>Festivals<br>Supermarkets |

**Table 5.3** Summary of the number and type of locations visited in each survey.

### *5.4 Contrast susceptibility measurement: The Titmus vision screener*

Eleven Titmus vision screeners, supplied by Bollé (UK) Ltd. were used to measure binocular Csus. These were chosen, as they were robust portable machines. The design of the Csus test conducted using the Titmus screener was similar to that of the ADCT.

For the purpose of Csus measurement with the Titmus screener, two new slides were designed. Both slides consisted of LogMAR type charts advocated by Bailey and Lovie (1976), as previously used in the ADCT. One slide had high contrast Landolt C symbols, the other had low contrast Landolt C symbols. The symbol sizes used were +0.8 to –0.3 LogMAR (equivalent to 6/38 to 6/3 Snellen) in 0.1 log unit steps. This extended range overcame frequent truncation problems experienced with the ADCT during the 1995 survey. The mean background luminance and contrast of each chart is summarised in table 5.4. Procedures used to determine these values are outlined in appendix C.

Acuity was measured "by the letter". Each symbol added a value of 0.02 log units to the acuity score, in accordance with equation 5.1. The best measurable acuity score was –0.3LogMAR (6/3 Snellen).

$$\text{LogMAR acuity} = (\text{number of incorrect responses} \times 0.02) - 0.3 \qquad \textbf{(5.1)}$$

The high contrast chart was always read first followed by the low contrast chart. Contrast susceptibility was calculated from high and low contrast acuity scores using equation 4.1

| Attribute | 1994 Survey | 1995 Survey | 1996 Survey |
|---|---|---|---|
| Vision screener | Ergovision | ADCT | Titmus |
| Background luminance (mean ± SD, $cdm^{-2}$) | 65 ± 10* | 52 ± 9* | 14 ± 6** |
| Symbols | Alphanumerics (Snellen 6/30 to 6/5) | Landolt C (LogMAR +0.7 to-0.1) | Landolt C (LogMAR +0.8 to-0.3) |
| % Contrast of high contrast symbols (mean ± SD, Weber) | ≈100 | 99 ± 0 | 99 ± 0** |
| % Contrast of low contrast symbols (mean ± SD, Weber) | ≈12 | 9 ± 3 | 9 ± 3** |
| Testing distance | 66cm | Infinity | Infinity |

**Table 5.4** Summary of the characteristics of the three Csus testing methods. *Values obtained from measurements described in appendix B. ** Average for the 11 Titmus screeners evaluated in appendix C.

### *5.5 Accident history questionnaire*

The 1994, 1995 and 1996 questionnaires were used to establish age gender, and self-reported accident history. The questions on accident history became more focused in each successive survey.

---

We would now like you to tell us about all kinds of road accidents you have been involved in, either as a pedestrian, a cyclist, a motorcyclist or as a driver, within the last five years. By 'accident' we mean any incident which involved injury to another person or yourself, damage to property, damage to another vehicle, or damage to the vehicle that you were driving.

What were you at the accident? Pedestrian/Cyclist/Motorcyclist/Driver

---

**Figure 5.2** The accident history portion of the 1994 questionnaire.

The accident history portion of the 1994 questionnaire is detailed in figure 5.2. The question was initially aimed at all road user types. Subsequent data analysis, however, revealed that the sample of non-car drivers participating in the survey was too small to be statistically analysed (Dunne *et al.*, In press).

The 1994 questionnaire underwent a number of modifications while the survey was still in progress. Initial fears that drivers would not be willing to specify whether they were "at fault" were proved groundless. Hence, an indication of driver responsibility in reported accidents was added to the questionnaire. Furthermore, a question was included to help determine whether "visual difficulties" had been a causative factor in the road accident. Researchers conducting the 1994 survey were encouraged to target a high proportion of accident involved drivers. Ball *et al.* (1993) had recommended that driving surveys should contain a high percentage of accident involved drivers to facilitate the statistical analysis of the relationship between vision and driving performance.

We would now like you to tell us about the road accidents you have been involved in **AS A DRIVER** for which you were deemed to be **FULLY OR PARTIALLY AT FAULT** within the last five years. By 'accident' we mean any incident which involved injury to another person or yourself, damage to property, damage to another vehicle, or damage to the vehicle that you were driving.

How many accidents of this kind have you had in the last five years?
Which of the following factors contributed to the accident?
*CIRCLE MORE THAN ONE IF NECESSARY*
*1 = poor judgement*
*2 = over speeding*
*3 = alcohol*
*4 = tiredness*
*5 = poor vision/visibility*
*6 = inattention/distraction*

Please provide a brief description of each accident

**Figure 5.3** The accident history portion of the 1995 questionnaire.

Figure 5.3 shows the question on accident history used in the 1995 pilot survey. For this questionnaire, accidents were now specifically targeted in which the driver was considered to be fully or partially at fault. A list was also introduced so that drivers could indicate factors that had contributed to their accidents. This list accounted for the fact that many accidents have multifactorial causes (Ball and Owsley, 1991; Shinar and Schieber, 1991). As for the 1994 survey, researchers were asked to include a high proportion of accident involved drivers.

The 1996 questionnaire was further developed (Figure 5.4). Even more emphasis was placed on accidents involving an element of visual difficulty and for which the driver was considered to be at least partially at fault. Unlike previous surveys, there was no attempt to raise the proportion of drivers involved in accidents, as the sponsors of this research were reluctant to turn any driver away.

**1.** If you have had an accident within the last 5 years, for which you were deemed to be at least partly at fault, did any of your accidents involve you not seeing the hazard in time whilst driving under the following conditions?

(a) Good visibility during daylight hours y/n
(b) Poor visibility during daylight hours (i.e. dull or foggy) y/n
(c) Good visibility during hours of darkness (i.e. well lit roads) y/n
(d) Poor visibility during hours of darkness (i.e. poor road lighting, dull or foggy) y/n

**2.** How often have you slowed down or avoided driving because you feel uneasy about your vision under the following conditions?
(a) Good visibility during daylight hours
(b) Poor visibility during daylight hours (i.e. dull or foggy)
(c) Good visibility during hours of darkness (i.e. well lit roads)
(d) Poor visibility during hours of darkness (i.e. poor road lighting, dull or foggy)

**Figure 5.4** The accident history and driving situation avoidance section of the 1996 questionnaire. Question 2 was answered using a four-point scale. The responses requested were "never", "rarely", "occasionally" and "often".

A major addition to the 1996 questionnaire was the question relating to driver situation avoidance. This question was devised in an attempt to verify the hypothesis that Csus was a stronger accident predictor because low contrast visual acuity was not taken into account when avoiding certain driving situations (Section 4.8.3). It was also of interest to determine whether situation avoidance was a contributory factor to the weak relationship found between measures of vision and driving performance, as had been suggested by others (North, 1985; Owsley *et al.*, 1991; Shinar and Schieber, 1991; Owsley and Ball, 1993; Munton, 1995).

### *5.6 Summary of 1996 survey methodology*

In summary, it can be seen that the 1996 survey consisted of parts: a test of Csus using modified Titmus vision screeners and a questionnaire that probed for self-reported accident involvement in addition to addressing the important issue of driving situation avoidance. The methods used in both parts of this survey were developed from the earlier pilot surveys of 1994 and 1995.

# CHAPTER 6: RESULTS OF THE 1996 SURVEY: COMPARISON WITH 1994 AND 1995 SURVEYS

### *6.1 Introduction*

In this chapter, the findings of the 1996 survey are compared to those of the 1994 and 1995 surveys.

### *6.2 Mean value of contrast susceptibility*

The mean Csus value found for each survey is compared in table 6.1. The Csus results of the 1995 and 1996 surveys were converted from LogMAR scores to the number of lines dropped to enable comparison with the 1994 survey. This conversion gave rise to a five point scale that was approximately the same for all three surveys. Very similar the modal values of Csus emerged for all three surveys (Table 6.1).

| **Survey** | **Modal Csus values** | |
|---|---|---|
| | ***LogMAR*** | ***Number of lines dropped*** |
| 1994 | - | 3 |
| 1995 | 0.260 | 3 |
| 1996 | 0.300 | 3 |

**Table 6.1** Modal values of Csus obtained for each survey.

### *6.3 The relationship between contrast susceptibility and age*

The results in table 6.2 show that there was no statistically significant relationship between Csus and age in any of the three surveys.

| Survey | Mean Csus ± standard deviation (No. of lines) | | Regression | | | |
|---|---|---|---|---|---|---|
| | *≤ 40 years* | *> 40 years* | *Equation* | *df* | *F* | *P* |
| 1994 | 2.8 ± 1.2 | 2.8 ± 1.2 | – | – | – | – |
| 1995 | 3.3 ± 1.5 | 2.9 ± 1.1 | (0.000 x age)+0.29 | 335 | 0.218 | 0.6412 |
| 1996 | 3.3 ± 0.9 | 3.3 ± 1.0 | (0.000 x age)+0.33 | 7252 | 1.486 | 0.2229 |

**Table 6.2** The relationship between Csus and age. The format of the 1994 data did not permit regression analysis.

The fact that Csus did not change with age could be explained in terms of the relationship between Csus and the CSF. It has already been stated that Csus represents the slope of the right hand descending limb of the CSF (Section 4.3). This slope remains unchanged as age increases (Section 3.5.5). Consequently, a significant deterioration in Csus with advancing age would not be expected.

### *6.4 Derivation of Csus pass/fail criteria using measures of sensitivity and specificity*

In the 1994 survey, measures of sensitivity, specificity and the positive likelihood ratio, were used to evaluate the discriminative ability of different Csus pass fail criteria in each of two age groups; ≤ 40 years and > 40 years.

The sensitivity of a test relates to its ability to correctly identify accident involved drivers (Katz, 1997) and is calculated using equation 6.1.

$$\text{Sensitivity (\%)} = [a \div (a + c)] \times 100 \qquad \textbf{(6.1)}$$

where a is the number of accident involved drivers who failed the test and c is the number of accident involved drivers who passed the test.

The specificity of a test related to its ability to correctly identify accident free drivers (Katz, 1997). It is calculated using equation 6.2.

Specificity (%) = [d ÷ (b + d)] x 100 **(6.2)**

where b is the number of accident free drivers who failed the test and d is the number of accident free drivers who passed the test.

The positive likelihood ratio is the ratio of the sensitivity of a test to the false-positive error rate of the test (Katz, 1997). Hence, the larger the value of the positive likelihood ratio, the better the test is at correctly discriminating accident involved drivers. This ratio is calculated using equation 6.3

Positive likelihood ratio = [a ÷ (a + c)] ÷[b ÷ (b + d)] **(6.3)**

| **Csus fail criteria *(lines dropped)*** | **Survey** | **Sensitivity (%)** | | **Specificity (%)** | | **Positive likelihood ratio** | |
|---|---|---|---|---|---|---|---|
| | | *≤40* | *> 40* | *≤40* | *> 40* | *≤40* | *> 40* |
| ≥ 2 lines | 1994 | 100.0 | 96.4 | 16.9 | 13.6 | 1.2 | 1.1 |
| | 1995 | 85.7 | 93.3 | 10.0 | 17.3 | 0.9 | 1.1 |
| | 1996 | 94.6 | 91.2 | 6.5 | 6.1 | 1.0 | 1.0 |
| ≥ 3 lines | 1994 | 92.3 | 78.6 | 31.2 | 36.4 | 1.3 | 1.2 |
| | 1995 | 47.6 | 66.7 | 43.3 | 53.4 | 0.8 | 1.4 |
| | 1996 | 68.8 | 68.1 | 32.0 | 29.3 | 1.0 | 1.0 |
| ≥ 4 lines | 1994 | 38.5 | 42.9 | 87.0 | 77.1 | 3.0 | 1.9 |
| | 1995 | 42.9 | 33.3 | 73.3 | 82.0 | 1.6 | 1.8 |
| | 1996 | 19.9 | 14.7 | 80.1 | 76.6 | 1.0 | 0.6 |
| > 4 lines | 1994 | 7.7 | 21.4 | 100.0 | 95.7 | ∞ | 5.0 |
| | 1995 | 9.5 | 0.0 | 81.7 | 97.0 | 0.5 | 0.0 |
| | 1996 | 4.9 | 2.5 | 94.9 | 94.4 | 1.0 | 0.5 |

**Table 6.3** Sensitivity, specificity and positive likelihood ratios at each Csus cut off level for all three surveys. Drivers aged ≤ 40 and > 40 were analysed separately.

From table 6.3, it is seen that there is a general tendency for sensitivity to decline and specificity to increase as the fail borderline is raised. The remarkable positive likelihood ratios found during the 1994 survey are not replicated in the surveys of

1995 and 1996. This would imply that the outcome of the 1994 survey could be a small sample artefact. However, the role played by individual research teams, operating in different regions, should be closely looked at with regard to their influence on results.

### *6.5 Comparison of percentage accident frequencies derived from surveys 1994-96*

Table 6.4 compares the percentage accident frequencies found for each Csus pass/fail criterion for all three surveys. The systematic increase in accident frequency that emerged in the 1994 survey was present to a lesser extent in the 1995 survey and was not apparent at all in the 1996 survey.

| Csus score | Survey | Age <40 years | | Age 40+ years | |
|---|---|---|---|---|---|
| | | *%* | *Count (accidents/total drivers)* | *%* | *Count (accidents/total drivers)* |
| ≤ 1 line dropped | 1994 | 0 | 0 / 13 | 5 | 1 / 20 |
| | 1995 | 33 | 3 / 9 | 4.2 | 1 / 24 |
| | 1996 | 10 | 21 / 215 | 7.4 | 18 / 243 |
| 2 lines dropped | 1994 | 21 | 3 / 14 | 14 | 5 / 37 |
| | 1995 | 29 | 8 / 28 | 8 | 4 / 52 |
| | 1996 | 12 | 101 / 864 | 5 | 47 / 894 |
| 3 lines dropped | 1994 | 33 | 21 / 64 | 15 | 10 / 67 |
| | 1995 | 5 | 1 / 19 | 12 | 4 / 43 |
| | 1996 | 12 | 59 / 502 | 6 | 109 /1842 |
| 4 lines dropped | 1994 | 55 | 12 / 22 | 19 | 6 / 32 |
| | 1995 | 58 | 7 / 12 | 20 | 5 / 25 |
| | 1996 | 12 | 59 / 502 | 4 | 25 / 679 |
| >4 lines dropped | 1994 | 100 | 3 / 3 | 50 | 6 / 12 |
| | 1995 | 15 | 2 / 13 | 0 | 0 / 4 |
| | 1996 | 11 | 19 / 173 | 2 | 5 / 210 |

**Table 6.4** Comparison of the percentage accident frequencies found for each Csus pass/fail criterion based upon the results of the 1994, 1995 and 1996 surveys.

### *6.6 The association between accident involvement and Csus*

The association between Csus and accident involvement was tested by comparing the accident frequency of drivers with Csus scores of ≤ 3 lines dropped against those with a Csus scores of ≥ 4 lines dropped (Table 6.5). This approach followed the observation that the modal Csus score for each survey was equal to a drop of 3 lines (Table 6.1).

| Survey | Age (years) | CSUS score | | Chi-square ($X^2$, *df*, *P*) |
|---|---|---|---|---|
| | | *≤ 3 lines dropped* | *≥ 4 lines dropped* | |
| 1994 | <40 | 26% (24/ 91) | 60% (15/ 25) | 8.487, 1, >99% |
| | 40+ | 13% (16/ 124) | 27% (12/ 44) | 3.849, 1, >95% |
| 1995 | <40 | 21% (12/ 56) | 36% (9/ 25) | 1.228, 1, NS |
| | 40+ | 8% (10/ 119) | 17% (5/ 29) | 1.147, 1, NS |
| 1996 | <40 | 12% (313/ 2711) | 12% (78/ 675) | 0.004, 1, NS |
| | 40+ | 6% (174/ 2979) | 3% (30/ 889) | 7.850, 1, >99% |

**Table 6.5** The percentage accident frequency for drivers with high and low Csus scores, based on the results of the surveys of 1994, 1995 and 1996. Figures in brackets relate to the number of accident involved drivers against the total number of drivers falling in each subsample. The Chi-square test with Yates' continuity correction was used to test the association between Csus and accident involvement.

The association between Csus score and accident frequency was tested for statistical significance using Chi-square with Yates' continuity correction (Table 6.5). The 1994 survey revealed that drivers with low Csus scores had approximately twice the accident involvement compared to those drivers with high Csus scores. This association was statistically significant. Approximately the same increase in accident involvement with reduced performance on the Csus test was observed in the 1995 survey. The relationship was not statistically significant. For the 1996 survey, no increase in accident rate occurred for drivers with poor Csus scores.

### *6.6.1 Reasons for discrepancies between the 1994, 1995 and 1996 driving surveys*

The promising results of the 1994 and 1995 surveys may have been a consequence of small sample bias. However, there were factors other than sample size that may have contributed to the discrepancies observed. Examination of table 6.6 shows inter-study variations in age, testing team, gender proportion and accident frequency.

| Survey | Region Team | Gender (male) | Age (<40) | Accident frequency | | Chi-square, ($X^2$, *df*, *P*) |
|---|---|---|---|---|---|---|
| | | | | *Csus* $\leq 3$ *lines dropped* | *Csus* $\geq 4$ *lines dropped* | |
| 1994 | England | 47% | 40% | 19% (12, 62) | 52% (25, 48) | 11.558, 1, >99.9% |
| | Wales | 64% | 41% | 18% (28, 153) | 10% (2, 21) | 0.477, 1, NS |
| 1995 | England | 47% | 57% | 31% (10, 32) | 53% (8, 15) | 1.277, 1, NS |
| | Wales | 60% | 30% | 8% (12, 143) | 15% (6, 39) | 0.988, 1, NS |
| 1996 | M'way 1 | 82% | 45% | 11% (108, 993) | 10% (25, 278) | 0.634, 1, NS |
| | M'way 2 | 80% | 50% | 10% (74, 729) | 6% (14, 224) | 2.660, 1, NS |
| | M'way 3 | 76% | 46% | 3% (35, 1147) | 2% (7, 341) | 0.626, 1, NS |
| | M'way 4 | 80% | 49% | 12% (157, 1331) | 9% (34, 362) | 1.410, 1, NS |
| | Festivals | 64% | 44% | 8% (113, 1490) | 7% (28, 419) | 0.268, 1, NS |

**Table 6.6** Inter-study variation in gender, age, testing team and accident frequency. The figures in brackets relate to the number of accident involved drivers against the total number of drivers in each subsample. The chi-square test with Yates' continuity correction was used to test the association between Csus and accident involvement.

Table 6.6 shows that there was considerable variation in the strength of the association between Csus and accident involvement even within individual surveys. For instance, there were discrepancies between test locations within the 1994 survey. In this survey, the research team operating in England found an almost threefold increase in accident frequency for those drivers with poor Csus scores. On the other hand, the team operating in Wales found that lower accident involvement in drivers with poor Csus scores. This may have occurred as a consequence of inter-team differences in interview technique. Interestingly, more males took part in the Welsh part of the survey and a lower accident frequency was recorded. This is in agreement with other studies that found that male drivers are more likely to under report accident involvement (Ball and Owsley, 1991; Owsley *et al.*, 1991).

The tests carried out in both England and Wales in 1995 revealed a twofold increase in accident frequency for drivers with below average Csus scores, despite a similar tendency for there to be more male drivers in the Welsh part of the study. This suggests that it was not likely to be regional differences in the proportion of males taking part in the survey that caused the regional discrepancies in the 1994 survey. It was more likely to have been differences in the interviewing technique of the two teams. However, the trend for the subsample with the highest proportion of male drivers to have the lowest reported accident involvement still arose.

The 1996 survey, conducted mainly at motorway testing locations, had a consistently high proportion of males across all of the testing locations and a low accident frequency. No statistically significant associations between Csus and accident frequency were found at any of the testing locations. As previously mentioned, (Section 5.5) the 1996 survey also differed from the surveys of 1994 and 1995 in that no attempt was made to increase the proportion of accident involved drivers.

### *6.7 Conclusion*

In conclusion, the larger survey of 1996 did not support earlier findings that indicated that Csus was predictive of accident involvement. However, a number of inter-study differences may have contributed to this finding.

# CHAPTER 7: SITUATION AVOIDANCE

## *7.1 Introduction*

Driver situation avoidance was defined in section 5.1 as occurring when a driver slows down or completely avoids some driving situations because it is felt that they are hazardous. It has often been thought that driver situation avoidance might confound the relationship between vision and driving accidents (Section 2.6.1.1). The hypothesis arising from the results of the 1994 survey, outlined in section 4.8.3, indicated that high contrast visual acuity may influence the level of situation avoidance practised by drivers. This hypothesis was tested during the 1996 survey (Chapter 5). Further evidence was gathered from a survey carried out in the West Midlands (Section 7.2). In this chapter, evidence from both surveys is examined in order to explore the factors that influence situation avoidance and the role situation avoidance plays in the relationship between vision, age and road accidents.

## *7.2 The West Midlands survey*

### *7.2.1 Aim*

This survey formed part of a road safety initiative co-ordinated by the West Midlands Police. The survey was designed to determine how drivers might gauge their vision prior to making the decision to avoid a given driving situation.

### 7.2.2 *Method*

The survey was conducted on drivers having routine eye examinations at one of 56 optometric practices in the West Midlands area. It consisted of a questionnaire. The eye examination fee was reduced for drivers that agreed to take part in the survey. The questionnaire was designed to gather information about the age, gender and best corrected acuity of each driver. The optometrist noted the presence of any ocular disorder. Two questions on the subject of driver situation avoidance were also asked. The first question, relating to the level of avoidance practised by drivers in different visibility conditions, was identical to that used in the 1996 survey (Figure 5.4). A second question (Figure 7.1) was designed to establish the visual cues used by drivers to decide whether they should slow down or avoid driving.

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" If you do slow down or avoid driving because of your vision, what prompted you to be concerned about your vision? (Tick any of the following responses that apply)

(a) You have difficulty reading road signs

(b) Passengers in your car have been able to read road signs before you could

(c) You have difficulty seeing pedestrians, cyclists and other vehicles

(d) You have tested yourself using the number plate test

(e) You are acting on the advice that your optician/doctor has given you about your vision

(f) Other (please specify)

---

**Figure 7.1** Question relating to the visual cues that may prompt drivers to avoid some driving situations.

### 7.2.3 *Results of the West Midlands survey*

Responses were obtained from 690 drivers, 49% of which were male. The mean age of the respondents was 45 years ± 15 years standard deviation. The proportion of drivers reporting that they practised situation avoidance under various levels of visibility is given in table 7.1. The table shows that the frequency of situation avoidance increased with reduced visibility.

| Visibility condition | % of drivers avoiding some driving situations |
|---|---|
| Daytime / good visibility | 28.8 |
| Daytime / poor visibility | 60.3 |
| Night-time / good visibility | 57.2 |
| Night-time / poor visibility | 79.3 |

**Table 7.1** West Midlands survey: Percentage of drivers practising situation avoidance under various visibility conditions.

| Visual cue | % of drivers practising situation avoidance as a result of each cue |
|---|---|
| None | 38 |
| Number plate | 16 |
| Road signs | 14 |
| Passenger | 13 |
| Optician/GP | 9 |
| Pedestrian/cyclist | 8 |
| Other | 8 |

**Table 7.2** Percentage of drivers using various visual cues as the basis for driving situation avoidance. Visual cues are ranked in descending order. "None" means that no visual cue was selected by the driver as the basis for situation avoidance. "Other" refers to visual cues not included on the list given in the questionnaire.

Table 7.2 shows the percentage of drivers that reported using various visual cues as the basis for driving situation avoidance. A large proportion of drivers were unsure what prompted situation avoidance (38%). Of the remainder, most drivers reported basing situation avoidance on the appearance of road signs or number plates. Fewer drivers based situation avoidance on the appearance of pedestrians and cyclists.

### *7.3 The 1996 survey*

#### *7.3.1 The effect of visibility on situation avoidance*

| Visibility condition | % of drivers avoiding some driving situations |
|---|---|
| Daytime / good visibility | 9.5 |
| Daytime / poor visibility | 54.3 |
| Night-time / good visibility | 28.9 |
| Night-time / poor visibility | 62.2 |

**Table 7.3** 1996 survey: Percentage of drivers practising situation avoidance under various visibility conditions.

Table 7.3 shows that the pattern of situation avoidance with changing visibility was similar in the 1996 survey to that found in the West Midlands survey (Table 7.1). However, a lower proportion of drivers practised situation avoidance in the 1996 survey compared to the West Midlands survey. This difference may have arisen because more males took part in the 1996 survey. Males are less likely to practise situation avoidance. Evidence for this emerged from the finding that only 64% of male drivers (3529 out of 5480 drivers) practised situation avoidance compared to 72% of female drivers (1276 out of 1774 drivers). This difference was highly statistically significant (df = 1, $X^2$ = 33.98, P <0.0001). A similar, but statistically non-significant (df = 1, $X^2$ = 3.49, P = 0.0615), trend was also found in the West Midlands survey in which 82% of females (289 out of 352 drivers) practised situation avoidance compared to only 66% of males (258 out of 388 drivers).

#### *7.3.2 The effect of situation avoidance on the relationship between vision, age and road accidents*

Further analysis of the 1996 survey results was undertaken to try to separate the influences of vision and age upon situation avoidance. A problem encountered in trying to perform this analysis was that all the variables were highly correlated with each other (Table 7.4). This made the isolation of individual effects difficult. To overcome this problem, a Structural Equation Model (SEM) was constructed using LISREL 8.12a statistical software (Jöreskog and Sörbom, 1993) and expert statistical help.

| | High contrast acuity | Low contrast acuity | Csus | Age | Accidents | Situation Avoidance |
|---|---|---|---|---|---|---|
| High contrast acuity | **1.00** | **0.616** | **-0.160** | **0.243** | **-0.063** | **0.064** |
| Low contrast acuity | | **1.00** | **0.282** | **0.240** | **-0.063** | **0.063** |
| Csus | | | **1.00** | 0.015 | -0.011 | -0.009 |
| Age | | | | **1.00** | **-0.106** | **0.045** |
| Accidents | | | | | **1.00** | 0.003 |
| Avoidance | | | | | | **1.00** |

**Table 7.4** Kendall rank correlation coefficients between the variables measured in the 1996 survey. Figures in bold were statistically significant to at least the 99% level

Structural equation models allow examination of linear relationships between variables. This technique is used to examine complex relationships between multiple variables completely and simultaneously.

The SEM technique was not applied to the earlier data of 1994 and 1995 as it has been found to be unreliable when used on sample sizes of less than 2500 subjects (Hu *et al.*, 1992).

A two group SEM was applied to the 1996 data. The two groups comprised of drivers that did or did not practise situation avoidance. Here, the SEM tests the null hypothesis that the data from each group is from the same population.

The output of the SEM takes the form of a path diagram of the relationships between variables (Figure 7.2). In the diagram, rectangles indicate measured variables. The arrow heads point toward the dependent variable. Figures indicate the strength of the correlation between pairs of variables, where the correlation is statistically significant to at least the 95% level. The circles with "E" in the centre indicate the residual variance not accounted for by the model.

The initial model estimate (Figure 7.2) was the best fitting model that could be obtained from the data ($X^2 = 0.00$, df = 2, P = 1.00).

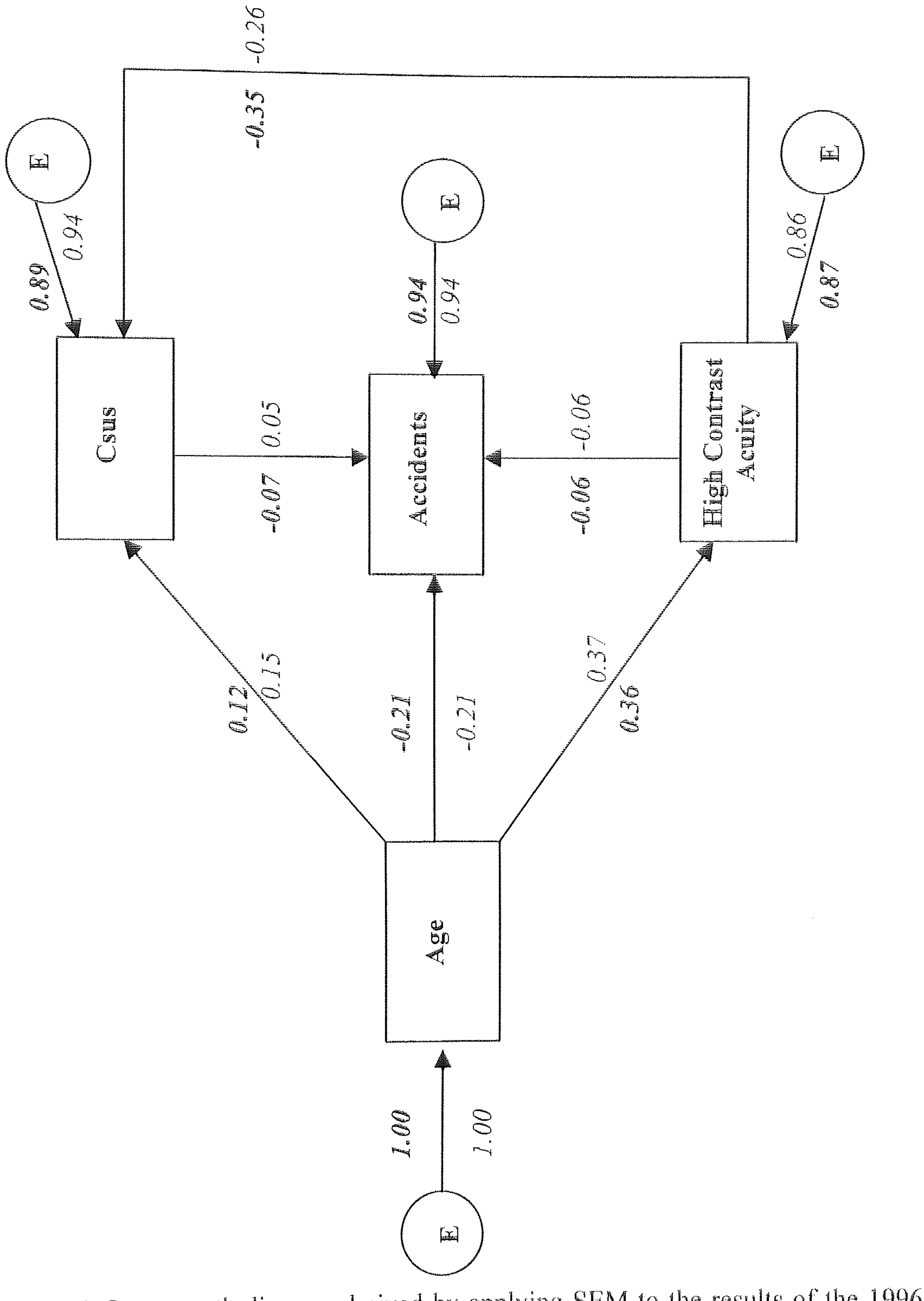


**Figure 7.2** Output path diagram derived by applying SEM to the results of the 1996 survey. Rectangles represent measured variables and circles represent latent or non measured variables. E = residual variance associated with a particular variable. Arrows point toward the dependent variable in each relationship. Figures denote correlation coefficients. All relationships shown were significant to at least the 95% level. In the two group analysis carried out; one group included those drivers that did practise situation avoidance (figures shown in bold text), the other included drivers that did not practice situation avoidance (figures shown in plain text).

*7.4 Discussion*

One of the main objectives of this thesis (Section 4.8.3) was to determine why the association between Csus and accidents is stronger than that between visual acuity and accidents.

A tentative hypothesis was proposed in which it was suggested that deficits in high contrast acuity would lead to situation avoidance so that little relationship would exist between high contrast visual acuity and accidents.

If this hypothesis were true, the SEM analysis should have revealed a relationship between visual acuity and accidents for drivers that did not practise situation avoidance whilst no relationship should have arisen for drivers that did practice situation avoidance. However, the SEM analysis (Figure 7.2) revealed a paradoxical relationship in which declining high contrast visual acuity accompanied a reduction in accident frequency. This relationship arose, regardless, whether situation avoidance was practised or not. The SEM analysis did not tend to support the proposed hypothesis.

It was also hypothesised (Section 4.8.3) that situation avoidance was not based upon low contrast objects. This would mean that drivers with Csus deficits would be more prone to accidents through failure to practice situation avoidance in poor visibility conditions. If this were the case, the SEM analysis should have revealed a relationship between Csus and accidents regardless of whether drivers practice situation avoidance or not. This was not the case. Figure 7.2 shows that a paradoxical relationship emerged for drivers that practised situation avoidance. Here, declining Csus was accompanied by a fall in accidents. Conversely, drivers that did not practice situation avoidance exhibited a positive relationship in which declining Csus lead to an increase in accident frequency. This finding might indicate that situation is based upon low contrast targets. Hence, the original hypothesis is again rejected.

The West Midlands survey revealed that road signs and number plates were most likely to be used to gauge vision and hence situation avoidance. These targets are likely to be seen in low contrast under the poor visibility conditions that prompt situation avoidance (Table 7.1 and 7.3). If this is the case, it then seems plausible that Csus deficits could prompt situation avoidance.

When considering the conclusions drawn from the evidence presented in this chapter two important points must be borne in mind. The first point is that both situation avoidance and accident involvement were self-reported. Disadvantages of self-reported accident histories were outlined in section 2.6.1.1. It is likely that some of the objections raised could also apply to situation avoidance. The second point is that the coefficients shown in the SEM path diagram (Figure 7.2), albeit statistically significant to the 95% level, are only very weak according to a statistical classification outlined by Cohen (1988).

The final question to be addressed relates to whether Csus measurements have any role to play in driver vision screening. The evidence presented here led to the conclusion that there is no support for a clear link between Csus and driving accidents. It is also found that there is only a slight tendency for drivers that do not practice situation avoidance to be more prone to accident involvement if they have Csus deficits. Therefore, it is unlikely that Csus testing would be of practical value in driver vision screening.

### *7.5 Conclusion*

Situation avoidance increases with reduced visibility. Objects such as road signs and number plates are more likely to be used to gauge vision in poor visibility conditions than pedestrians and cyclists.

Situation avoidance exerts little influence on the relationship between age, vision and road accidents. However, drivers that do not practice situation avoidance are slightly more prone to accidents if they also have Csus deficits.

# CHAPTER 8: COMPARISON OF REPEATABILITY AND AGREEMENT BETWEEN VARIOUS CONTRAST SUSCEPTIBILITY MEASUREMENT METHODS

## *8.1 Introduction*

Previous researchers have used the Bailey-Lovie chart to measure Csus (Brown and Lovie-Kitchin, 1990; Bailey, 1993; Section 4.4). The driving surveys of 1994, 1995 and 1996 used three different instruments to measure Csus: the Ergovision, ADCT and Titmus vision screeners respectively (Section 5.4).

Studies with the Bailey-Lovie chart have revealed that Csus has a normal value of about two lines LogMAR acuity (0.2 LogMAR) (Section 4.4). The driving surveys yielded a mean Csus value of three lines (Table 6.1).

The aim of the study described in this section was to compare the Csus scores derived from each method in order to determine whether the aforementioned differences in typical Csus scores arose from methodological differences or sampling errors. In addition, an attempt is made to establish whether each measurement method can detect age related changes to Csus scores.

The repeatability of each instrument was also assessed, as a clinically significant change in Csus is one that is greater than the limit of repeatability of the test method used.

## 8.2 Method

### 8.2.1 Subject selection

Fifty subjects took part in the experiment. All were free from ocular abnormality. Twenty five subjects were classified as young (mean age = 23.0 years ± 3.9 years standard deviation). The remaining 25 were classified as old (mean age = 72.2 years ± 5.7 years standard deviation). Each age group comprised 14 males and 11 females. The inclusion of two age groups allowed investigation of whether each measurement method could detect age related changes in Csus scores.

### 8.2.2 Vision screeners

The attributes of the Ergovision, ADCT and Titmus screeners have been summarised earlier in table 5.4. The internal luminance of each instrument was monitored throughout the experiment. The luminances found are given in table B.1 of appendix B.

Contrast susceptibility was scored "by the line" when using the Ergovision screener (Section 4.7.1) while both the ADCT and Titmus vision screeners yielded a "by the letter" Csus score (Section 4.8.2).

### 8.2.3 The Bailey-Lovie chart

A standard Bailey-Lovie chart (Bailey and Lovie, 1976) was externally illuminated using the lighting system described in appendix A. The mean luminance level at which Csus measurements were taken is given in table A.3.1 of appendix A. Contrast susceptibility was scored "by the letter" when using this chart.

### *8.2.4 Test procedure*

Measurements of Csus were made on two occasions separated by 1 week. At each session, Csus was measured once with each of the three vision screeners and once with the Bailey-Lovie chart. The high contrast portion of each test was always read first, followed by the low contrast portion. The order in which the instruments were used was balanced to minimise the influence of learning effects.

## *8.3 Results and discussion*

To allow comparison between the results of the Ergovision and the other measurement methods, the results of the ADCT, Titmus and Bailey-Lovie were converted from LogMAR to the number of lines dropped (Section 6.2).

### *8.3.1 Repeatability of contrast susceptibility measurement*

The repeatability of all measurement methods was assessed using the coefficient of repeatability (COR, Bland and Altman, 1986). The COR for all three vision screeners was approximately 2 lines (Table 8.1). The best repeatability arose from the Bailey-Lovie chart which had a COR of 1.4 lines (Table 8.1).

| **Instrument** | **Coefficient of repeatability (COR)** | |
|---|---|---|
| | ***LogMAR*** | ***Lines*** |
| Ergovision | - | 2.1 |
| ADCT | 0.24 | 2.4 |
| Titmus | 0.20 | 2.0 |
| Bailey-Lovie | 0.14 | 1.4 |

**Table 8.1** Repeatability of various methods of measuring Csus.

### *8.3.2 Typical contrast susceptibility scores derived from each method*

| **Subject group** | **Mean Csus ± standard deviation (lines)** | | | |
|---|---|---|---|---|
| | *Ergovision* | *ADCT* | *Titmus* | *Bailey-Lovie* |
| Young | 2.5 ± 0.8 | 2.7 ± 1.0 | 2.8 ± 0.8 | 1.3 ± 0.5 |
| Old | 3.0 ± 1.1 | 3.4 ± 0.8 | 3.1 ± 0.9 | 2.0 ± 0.8 |
| All | 2.8 ± 1.0 | 3.0 ± 1.0 | 3.0 ± 0.8 | 1.7 ± 0.8 |

**Table 8.2** Mean Csus scores for various methods of determining Csus.

Table 8.2 shows the mean Csus scores derived from each measurement method. Statistical analysis of age effects and inter-Csus variability is covered in sections 8.3.3 and 8.3.4 respectively.

### *8.3.3 Effect of age*

All methods of measuring Csus revealed deterioration with age (Table 8.2). This age effect was statistically significant ($F_{1,48}$ = 15.350, P = 0.0003).

| **Age interaction (young * old for each method)** | **Difference** | **Critical difference** | **Significant (95% level)** |
|---|---|---|---|
| Ergovision | 0.56 | ± 0.65 | NS |
| ADCT | 0.74 | ± 0.65 | S |
| Titmus | 0.24 | ± 0.65 | NS |
| Bailey-Lovie | 0.80 | ± 0.65 | S |

**Table 8.3** Post hoc tests of least significant difference between age groups for individual measurement methods (S = statistically significant, NS = not statistically significant).

It is uncertain why different measurement methods were differentially affected by age (Table 8.3). It might have been expected, for instance, that the ADCT and Titmus scores would have been similarly affected by age as their design was essentially the same (Table 5.4). However, the age effects in these methods were rather different (Table 8.3).

Furthermore, a significant difference between age groups might have been expected for the Ergovision. The Ergovision uses an intermediate testing distance (66cm).

It was thought that this could have created difficulties for older subjects, as they would be reliant on their level of reading addition for target clarity. However, this appears not to have had a statistically significant effect on the results obtained with this instrument (Table 8.3).

However, even where a statistically significant age effect was found for individual measurement methods the increase in Csus due to age was always less than one line of acuity (Table 8.2). This increase was less than the measurement error revealed by the COR for any of the measurement methods (Table 8.1). Therefore, the increase in Csus due to age is likely to be clinically undetectable.

### *8.3.4 Effect of measurement method*

Table 8.2 and figure 8.1 show that the Csus values obtained using the three vision screeners were very similar, while the Bailey-Lovie Csus score was lower. This result suggested that differences found between Csus scores reported here and those reported by previous workers (Section 8.1) occurred due to measurement method rather than as a consequence of sample differences. That is, previous researchers used test charts rather than vision screeners.

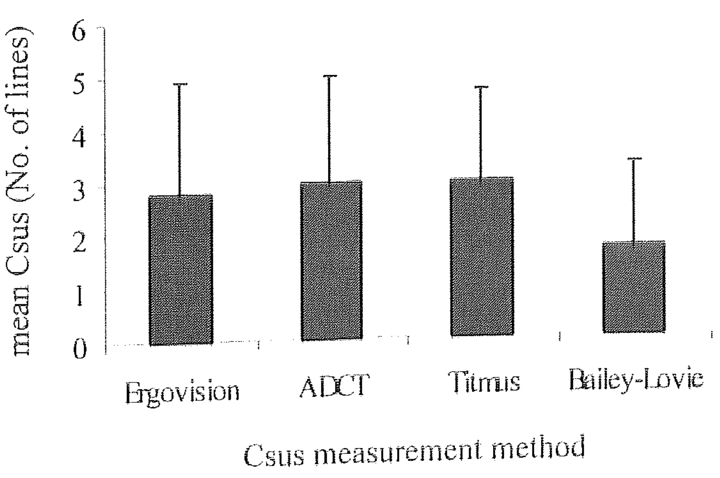


**Figure 8.1** Mean Csus values for each measurement method. All subjects were included. Error bars indicate 95% confidence interval.

The variation in Csus due to measurement method was statistically significant ($F_{3,144}$ = 31.119, P <0.0001). Post hoc tests of least significant difference (Freese, 1984) (Table 8.4) showed that Csus measured with the Bailey-Lovie chart was significantly lower than that measured using any of the vision screeners. The Csus vision screener measurements were not significantly different from each other. This pattern of results was consistent even when young and old groups were analysed separately (Table 8.5).

| Measurement method interaction | Difference | Critical difference | Significant (95% level) |
|---|---|---|---|
| Bailey-Lovie * ADCT | 1.38 | ± 0.32 | S |
| Bailey-Lovie * Titmus | 1.30 | ± 0.32 | S |
| Bailey-Lovie * Ergovision | 1.10 | ± 0.32 | S |
| ADCT * Titmus | 0.08 | ± 0.32 | NS |
| ADCT * Ergovision | 0.28 | ± 0.32 | NS |
| Titmus * Ergovision | 0.20 | ± 0.32 | NS |

**Table 8.4** Post hoc tests of least significant difference between measurement methods for the whole subject group (S = statistically significant, NS = not statistically significant).

| Age Group | Measurement method interaction | Difference | Critical difference | Significant (95% level) |
|---|---|---|---|---|
| Young | Bailey-Lovie * ADCT | 1.40 | ± 0.45 | S |
| | Bailey-Lovie * Titmus | 1.56 | ± 0.45 | S |
| | Bailey-Lovie * Ergovision | 1.20 | ± 0.45 | S |
| | ADCT * Titmus | 0.16 | ± 0.45 | NS |
| | ADCT * Ergovision | 0.20 | ± 0.45 | NS |
| | Titmus * Ergovision | 0.36 | ± 0.45 | NS |
| Old | Bailey-Lovie * ADCT | 1.33 | ± 0.45 | S |
| | Bailey-Lovie * Titmus | 1.00 | ± 0.45 | S |
| | Bailey-Lovie * Ergovision | 0.96 | ± 0.45 | S |
| | ADCT * Titmus | 0.33 | ± 0.45 | NS |
| | ADCT * Ergovision | 0.37 | ± 0.45 | NS |
| | Titmus * Ergovision | 0.04 | ± 0.45 | NS |

**Table 8.5** Post hoc tests of least significant difference between measurement methods for old and young subject groups (S = statistically significant, NS = not statistically significant).

It was seen from table 8.4 that the difference between the Bailey-Lovie Csus score and the Csus scores of the vision screeners was just over one line. This is in agreement with the previous finding of a one line difference between chart and vision screener measurements of Csus (Section 8.1). The magnitude of this difference is approximately the same as the COR of the Bailey-Lovie chart. Hence, the difference found between chart and vision screener Csus scores is on the borderline of being clinically detectable.

### *8.4 Conclusion*

This investigation has revealed that differences between normal values of Csus found by other researchers and the values found during the driving surveys of 1994 to 1996 (Section 8.1) were most likely caused by the method of measurement employed i.e. whether a chart or a vision screener was employed. It was unlikely to be a consequence of sampling differences between studies.

Why wall charts and vision screeners should yield different Csus results is unknown. It may feasibly be a consequence of known luminance differences between methods, or a manifestation of instrument myopia. In view of the potential clinical implications that these differences might have if use of these tests became widespread, these factors are examined in chapters 9 and 10.

All measurement methods also revealed age related deterioration in Csus score. This would tend to contradict the statement that Csus represents the slope of the descending limb of the CSF (Section 4.3) as this slope does not vary with age (Section 3.5.5). Hence, Csus may not be exactly linked to the slope of the CSF. This question is further investigated in chapter 11.

# CHAPTER 9: THE EFFECT OF LUMINANCE ON CONTRAST SUSCEPTIBILITY

## *9.1 Introduction*

Chapter 8 described how vision screeners yielded systematically worse Csus scores compared to wall charts. One reason for this could be that wall charts tend to be better illuminated than vision screeners are. This chapter presents the findings of an experiment conducted to investigate the influence of test luminance on Csus scores.

## *9.2 Method*

Contrast susceptibility was measured at three luminance levels using neutral density filters in conjunction with the Bailey-Lovie chart. The Bailey-Lovie chart was more easily used with neutral density filters than the other vision screening instruments.

### *9.2.1 Subject selection*

Eight subjects took part in the experiment: 4 young subjects (mean age 25 years ± 0.8 years standard deviation) and 4 old subjects (mean age 61.5 years ± 6.4 years standard deviation). Subjects were optimally corrected for the 3m testing distance.

### *9.2.2 Luminance level*

The maximum luminance of the Bailey-Lovie chart with the lighting system was $89cdm^{-2}$ ± $2cdm^{-2}$ standard deviation (Table A.3.1 of appendix A). This was used as the highest luminance level. The other two levels were set at 0.3 log units ($45cdm^{-2}$ ± $2cdm^{-2}$ standard deviation) and 0.9 log units ($11cdm^{-2}$ ± $2cdm^{-2}$ standard deviation) below. This covered the entire range of luminances under which Csus had been previously measured (see table A.3.1 of appendix A and table B.1 of appendix B). The reduction in luminance was achieved using neutral density filters worn as goggles by the subjects.

### *9.2.3 Test procedure*

Subjects were allowed 6 minutes adaptation time before measurements were taken at each luminance level. Pilot studies had confirmed that this interval was adequate for adaptation to each light level. It also matched the adaptation time adopted by Rabin (1994). The high contrast Bailey-Lovie chart was always read first followed by the low contrast chart. Contrast susceptibility was scored "by the letter" (Section 4.7.2). This measurement procedure was repeated for all three luminance levels. The order in which the different luminances were presented was randomised between subjects to control for learning effects.

## *9.3 Results*

### *9.3.1 Mean contrast susceptibility values for each luminance level and age group*

| **Subject group** | **Mean Csus for each luminance level ± standard deviation (LogMAR)** | | | **Change in Csus (Low – High) (LogMAR)** |
|---|---|---|---|---|
| | ***High*** | ***Medium*** | ***Low*** | |
| Young | 0.19 ± 0.03 | 0.18 ± 0.03 | 0.22 ± 0.02 | 0.03 (1 letter) |
| Old | 0.13 ± 0.07 | 0.15 ± 0.08 | 0.19 ± 0.06 | 0.06 (3 letters) |
| All subjects | 0.16 ± 0.06 | 0.16 ± 0.06 | 0.21 ± 0.02 | 0.05 (2 letters) |

**Table 9.1** Mean Csus values found at each luminance level for each subject group. High = 89cdm$^{-2}$, medium = 45cdm$^{-2}$, and low = 11cdm$^{-2}$.

The Csus value found at each luminance level for each age group is given in table 9.1. The increase in Csus between the highest and lowest luminance levels was between 0.03 LogMAR and 0.06 LogMAR, depending on age. This represented a change in Csus of 1-3 letters.

### *9.3.2 Effect of luminance*

The data was analysed using two-way analysis of variance. Luminance had a statistically significant effect on Csus ($F_{2,12}$ = 4.020, P = 0.0461). Post hoc tests of least significant difference (Freese, 1984) revealed that deterioration in Csus between the high and medium luminance levels did not achieve statistical significance at the 95% level (Table 9.2). However, the change in luminance was statistically significant between high and low, and between medium and low luminance levels (Table 9.2).

| Luminance change | Change in Csus (Whole subject group) (LogMAR) |
|---|---|
| High to medium | 0.005 |
| High to low | 0.048* |
| Medium to low | 0.042* |

**Table 9.2** Mean change in Csus between luminance levels. The asterisk indicates that the change was statistically significant at the 95% level. Least significant difference in this case is 0.039 LogMAR. The change in Csus must be greater than this critical value to achieve statistical significance at the 95% level.

### *9.3.3 Effect of age*

There was no statistically significant difference in the magnitude of Csus between age groups ($F_{1,6}$ = 1.913, P = 0.2159). There was a tendency for young subjects to have poorer Csus scores compared to the old subjects. This is opposite to the findings of chapter 8 (Table 8.2). This may have occurred due to small sample variation.

The interaction between age and luminance was not significant ($F_{2,12}$ = 0.602, P = 0.5632). This indicated that the effect of luminance on Csus was similar for both age groups.

### *9.3.4 The nature of contrast susceptibility deterioration with decreasing luminance*

The deterioration of Csus with decreasing luminance could have manifested itself in two ways:

1. High contrast visual acuity may remain constant, while low contrast acuity is reduced
2. High contrast acuity may be reduced but by less than the reduction in low contrast acuity.

To determine which of the above was taking place, the change in mean high and low contrast acuity for each luminance level was examined separately. As age did not influence Csus scores, the mean high and low contrast acuity levels for the whole subject group are shown for each luminance level (Table 9.3). It is seen in figure 9.1 that the increase in Csus occurred due to a greater reduction in low contrast acuity compared to high contrast acuity as luminance was reduced.

| | **Mean acuity for each luminance level ± standard deviation (LogMAR)** | | | **Change in acuity (low – high luminance) (LogMAR)** |
|---|---|---|---|---|
| | ***High*** | ***Medium*** | ***Low*** | |
| High contrast acuity | -0.06 ± 0.12 | -0.02 ± 0.12 | 0.04 ± 0.12 | 0.10<br>(5 letters) |
| Low contrast acuity | 0.10 ± 0.09 | 0.14 ± 0.11 | 0.25 ± 0.10 | 0.15<br>(7 letters) |

**Table 9.3** Mean high and low contrast acuity at each luminance level. The means were calculated for all 8 subjects, as there was no significant age effect.

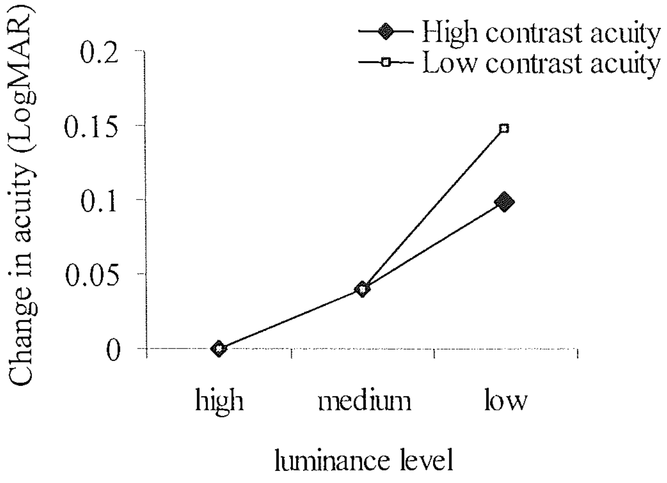


**Figure 9.1** The relative change in high and low contrast acuity with decreasing luminance. The data has been adjusted so that the baseline acuity in the high luminance condition is zero for both high and low contrast targets.

### *9.4 Discussion*

#### *9.4.1 Change in high contrast acuity with decreasing luminance*

The reduction in high contrast acuity between the highest and lowest luminance levels was around 5 letters (1 line on the Bailey-Lovie chart) (Table 9.3). This is in agreement with the reduction in high contrast acuity determined by a number of other researchers for a similar drop in luminance (Sheedy *et al.*, 1984; Taub and Sturr, 1991; Rabin, 1994; Arumi *et al.*, 1997). It is, however, greater than the 1 letter drop in acuity determined by Adams et al. (1988). This might have occurred because the study of Adams et al. (1988) used Landolt C targets to measure visual acuity. It has been demonstrated that the drop in acuity for Landolt C targets is less than for letters over a given luminance range (Sheedy *et al.*, 1984).

### *9.4.2 Change in low contrast acuity with decreasing luminance*

Similarly, the 7 letter reduction in low contrast acuity found between the highest and lowest luminance levels (Table 9.3) was similar to the results of Taub and Sturr (1991) who reported a 6 letter reduction in low contrast acuity for the same drop in luminance.

Studies that have examined the effect of decreasing luminance on both high and low contrast letter targets have demonstrated a slightly greater reduction in low contrast acuity compared to high contrast acuity (Adams *et al.*, 1988; Taub and Sturr, 1991; Johnson and Casson, 1995). These findings are to be expected as it has been demonstrated that the effects of reducing luminance and stimulus contrast are additive (Johnson and Casson, 1995).

### *9.4.3 Contrast susceptibility and decreasing luminance*

The difference in the magnitude of the reduction of low contrast acuity relative to that of high contrast acuity has been shown to be of the order of 1-2 letters (Adams *et al.*, 1988; Taub and Sturr, 1991). Again, this concurs with the findings of the present study (Table 9.1).

### *9.4.4 Effect of age*

The finding that age has no effect on Csus (Section 9.3.3) conflicts with previous research (Adams *et al.*, 1988; Taub and Sturr, 1991). However, this might have occurred as the present study included measurements on a smaller number of subjects.

Small subject numbers have been implicated as a cause of variation in the conclusions drawn by different age studies (Owsley and Burton, 1991).

Alternatively, it might be a consequence of the larger luminance ranges used by other studies (Adams *et al.*, 1988; Taub and Sturr, 1991). The study of Adams et al (1988) measured the age effect for luminances between 540cdm$^{-2}$ to 5.4cdm$^{-2}$. They found an age interaction only for a combination of the lowest contrast stimulus and lowest luminance. The lowest luminance used in the study of Taub and Sturr (1991) was 0.85cdm$^{-2}$. This was considerably lower than the minimum luminance used here. On careful examination of their data, it would appear that, over the luminance range matching that of this study their data shows no obvious age effect. Hence, it would not be unreasonable to attribute the differences in results to the differences in the luminance range over which the age effect was analysed.

### *9.4.5 The cause of contrast susceptibility deterioration with reduced luminance*

The cause of the deterioration in Csus with decreasing luminance has been attributed to neural factors (Arumi *et al.*, 1997). This explanation is feasible if the increase in rod function, and associated increase in receptive field size, is taken into account when considering how vision is processed at lower light levels (Section 3.5.6).

Alternatively, it might be thought that the reduction in acuity with reduced luminance could be attributed to night myopia. Night myopia may be defined as the myopic shift in the refraction of the eye as luminance is decreased (Charman, 1996). This would result in a reduction of acuity due to increased blur. It has been found that night myopia is caused by the loss of target contrast rather than a simple reduction of luminance (Raymond *et al.*, 1984). Consequently, it would be expected that night myopia would make low contrast letters more difficult to see than high contrast letters, due to the combined effects of low luminance and low stimulus contrast. However, it is unlikely that night myopia is a contributory factor in the reduction of acuity over the luminance range measured in this study (Johnson, 1976; Rabin, 1994; Arumi *et al.*, 1997). Significant myopic shifts in refraction do not occur until the luminance level drops to a much lower level than that used in the present study; around 0.03cdm$^{-2}$ (Arumi *et al.*, 1997).

The increase in Csus found with reduced luminance is also unlikely to be an artefact of uncorrected refractive error. It has been demonstrated that the effect of blur on high and low contrast targets is the same at all luminance levels (Johnson and Casson, 1995). Thus, such an effect could not account for the greater reduction in low contrast acuity relative to high contrast acuity.

In addition, pupil dilation may be eliminated as a contributory cause of the increase in Csus with decreased luminance. It has been shown that pupil mydriasis does not adversely affect acuity (Rabin, 1994) or contrast sensitivity (Sloane *et al.*, 1988) in reduced luminance conditions. Furthermore, if pupil size were a factor, one would have expected a significant age versus luminance interaction due to senile miosis in the older group. This was not found (Section 9.3.3).

### *9.4.6 Clinical significance of the deterioration of contrast susceptibility with reduced luminance*

Although the 1-2 letter deterioration in Csus with reduced luminance was found to be statistically significant (Section 9.3.2), it is unlikely to be clinically detectable in individual subjects. This is because a 1-2 letter change is less than the clinical reliability of acuity measurements made using the Bailey-Lovie chart (Lovie-Kitchin, 1988; Arditi and Cagenello, 1993; Bailey, 1993; Brown and Lovie-Kitchin, 1993; Reeves *et al.*, 1993; Table 8.1). These authors show that the test-retest reliability of the Bailey-Lovie chart is between 1 and 2 lines (5-10 letters). Furthermore, similar levels of repeatability arise for acuity measurements made using high and low contrast letters (Greeves *et al.*, 1988; Reeves *et al.*, 1993).

Contrast susceptibility measurements made using the Bailey-Lovie chart were also found to be more repeatable than other vision screening instruments (Table 9.1). Hence, the deterioration of Csus with reduced luminance is even less likely to be detected when using vision screeners.

That Csus does not deteriorate markedly with reduced luminance supports the assertion that Csus represents the slope of the descending limb of the CSF (Regan, 1988; Woods and Wood, 1996). Reduced luminance is known to shift the CSF towards lower spatial frequencies without altering the slope of the descending limb (DeValois *et al.*, 1974).

### *9.5 Conclusion*

Reduced luminance gives rise to practically undetectable deterioration in Csus score over the luminance ranges adopted when using the wall mounted charts and vision screeners in this study. Therefore, the systematic discrepancy between Csus measured using wall charts and vision screeners (Chapter 8) is unlikely to have arisen due to luminance differences.

# CHAPTER 10: THE EFFECT OF INSTRUMENT MYOPIA ON CONTRAST SUSCEPTIBILITY

## *10.1 Introduction*

Research described in chapter 9 has confirmed that systematic differences in Csus scores derived from vision screeners compared to wall mounted charts (Chapter 8) cannot be attributed to test luminance. In view of this, this chapter presents the findings of an experiment conducted to determine whether instrument myopia might be responsible.

## *10.2 Instrument myopia*

The term instrument myopia refers to the persistent state of over accommodation that occurs during observation of a target through an optical system (Baker and Roy, 1966; Schober *et al*., 1970; Hennessy, 1975; Richards, 1976; Miller *et al*., 1984; Wesner and Miller, 1986).

The mechanism of instrument myopia is thought to be related to the resting focus of the eye (Toates, 1970; Toates, 1972; Hennessy, 1975; Leibowitz, 1976; Richards, 1976; Leibowitz and Owens, 1978). It occurs as a consequence of the tendency for accommodation to return to its resting level when the stimulus to accommodation is degraded (Hennessy, 1975; Leibowitz and Owens, 1975; Lovasik *et al*., 1987; Rosenfield *et al*., 1993). This resting level does not leave the eye focused at infinity but at a closer distance leaving the eye in a myopic refractive state. Instrument myopia is considered to be one of the group of anomalous myopias that includes night myopia and empty field myopia (Hennessy, 1975; Leibowitz and Owens, 1975).

The stimulus for accurate accommodation may be degraded as a consequence of reduced luminance or stimulus contrast (Heath, 1956; Schober *et al.*, 1970). Alternatively, increased depth of focus due to small pupils, or due to small exit pupils in the optical systems employed may also result in reduced accommodative stimulation (Ward and Charman, 1985). Thus, any of these factors may contribute to instrument myopia. The influence of proximal accommodation on instrument myopia is unclear. Some authors report no proximal accommodation effect (Schober *et al.*, 1970; Hennessy, 1975; Hennessy *et al.*, 1976) while others have demonstrated that proximal effects do influence instrument myopia (Fitch, 1971; Ditchburn, 1980).

When measuring Csus with a vision screener, instrument myopia might be expected to result in an increase in the magnitude of Csus. Compared to high contrast letters, low contrast letters would be a weaker stimulus to accurate accommodation. Thus, when viewing low contrast letters, accommodation may tend to move further towards its resting focus. This would mean that low contrast letters would become more difficult to view and low contrast acuity would be reduced. As high contrast acuity would be less affected, Csus would increase. This effect would be most pronounced in pre-presbyopic subjects as accommodative facility declines with age (Richards, 1976; Wesner and Miller, 1986).

## 10.3 Method

### 10.3.1 Subject selection

Thirty six subjects took part in the experiment. Eighteen subjects were classified as pre-presbyopes (mean age = 22.4 years ± 3.7 years standard deviation). The remaining 18 subjects were classified as presbyopes (mean age = 72.1 years ± 4.8 years standard deviation).

It has been demonstrated that up to around the age of 55 years subjects may have some residual accommodative facility (Charman, 1989). In addition, at this age it would be difficult to separate depth-of focus effects from true accommodative amplitude (Charman, 1989). Hence, RAF rule measurements could not be relied upon to give an accurate measurement of accommodative amplitude in presbyopic subjects. Therefore, a minimum age of 60 years was imposed to ensure that subjects classified as presbyopes had no accommodation.

All the subjects were free of ocular abnormality. Where appropriate, subjects wore their habitual distance correction.

### 10.3.2 Titmus vision screener

The attributes of the Titmus vision screener and the Csus measurement procedure have been described in section 5.4.

### 10.3.3 Wall mounted chart

The wall mounted charts were similar in design to the slides incorporated in the Titmus screener. They were in the LogMAR style and used Landolt C targets (range =

+0.5 LogMAR to –0.3 LogMAR). The symbol contrasts (Weber) on the high and low contrast charts was 99% ± 0% standard deviation and 9% ± 3% standard deviation respectively.

The charts were binocularly viewed from a distance of 3m. This was the longest practical viewing distance given the size of the Landolt Cs available on the charts. However, this testing distance was sufficient to avoid any potential influence of proximal accommodation (Rosenfield *et al.*, 1991). The charts were illuminated using the lighting system described in appendix A.

### *10.3.4 Testing procedure*

Csus was measured once using the Titmus vision screener and once using the wall mounted charts. The high contrast portion of each test was always read first. Contrast susceptibility was scored "by the letter" (Section 5.4). The order of presentation of vision screener and wall chart tests was balanced to control for learning effects.

## *10.4 Results and discussion*

| **Age group** | **Mean Csus ± standard deviation (LogMAR)** | |
|---|---|---|
| | ***Vision screener*** | ***Chart*** |
| Pre-presbyopic | 0.28 ± 0.12 | 0.11 ± 0.05 |
| Presbyopic | 0.33 ± 0.08 | 0.15 ± 0.05 |

**Table 10.1** Mean Csus values obtained with a wall chart and a vision screener.

Table 10.1 shows that the Titmus vision screener yielded a higher Csus score compared to the wall chart (Table 10.1). The discrepancy between Csus scores was statistically significant ($F_{1,33} = 93.347$, $P < 0.0001$).

If instrument myopia were responsible for the observed discrepancy in Csus scores, it would be expected that this discrepancy should be present in pre-presbyopes but almost non-existent in presbyopes. Table 10.1 shows that this was not the case. In fact, the magnitude of the discrepancy was found to be almost equal in both subject groups ($F_{1,33} = 0.109$, $P = 0.7435$)

The absence of clinically observable effects of instrument myopia might not be entirely unexpected under the experimental conditions used. It has been demonstrated that binocular viewing reduces instrument myopia (Schober *et al.*, 1970; Miller, 1980; Richards *et al.*, 1981; McBrien and Millodot, 1985; Wesner and Miller, 1986; Leibowitz *et al.*, 1988). Also, considerable reduction of image contrast is required before the accommodative response is affected (Bour, 1981; Cuiffreda, 1991). In this case, the reduction in contrast between the high and low contrast acuity symbols might not have been sufficient to affect accommodation.

### *10.5 Conclusions*

In conclusion, the difference in Csus scores determined using vision screeners and wall charts could not be attributed to the effects of instrument myopia. Chapter 9 has already confirmed that differences in chart luminance are also not responsible.

This being the case, one can only speculate that the difference may have been due to reduced image quality of the vision screener slides due either to imperfections in the optical system through which they were observed or imperfections in the photographic procedures used to manufacture these slides.

# CHAPTER 11: THE RELATIONSHIP BETWEEN CONTRAST SUSCEPTIBILITY AND THE CONTRAST SENSITIVITY FUNCTION

## *11.1 Introduction*

In Chapter 3 the CSF was described as the link between mechanisms that underpin spatial vision and the effects that changes in these mechanisms have on visual performance in everyday tasks. Although a comprehensive evaluation of the CSF may call upon sophisticated computerised methods, it was also acknowledged that the CSF contains extraneous information. Hence, more clinically applicable tests such as contrast threshold, measured using the Pelli-Robson chart, yield useful information about the ability of people with visual deficits to cope with everyday situations. Discussions in chapter 4 indicate that Csus may have a similar ability. This chapter investigates this issue through exploration of those elements of the CSF that correlate with contrast threshold and Csus scores.

Further, if it is true that Csus is equal to the slope of the descending limb of the CSF then it follows that Csus should also be related to the integrated area under the contrast sensitivity function (ICS; Van Meeteren and Vos, 1972). The ICS has been shown to predict real life search behaviour (Cornelissen *et al.*, 1995). Hence, a link between Csus and ICS may explain how Csus may be related to "real world" activities such as driving. This chapter, therefore, also examines the link between Csus and ICS.

### *11.2 Method*

There were two plausible experimental approaches. The first of these involved the administration of the Csus test via a computer using formal psychophysical procedures. This would allow comparison of the Csus score with computer generated CSFs. The second approach was to compare the current clinically applicable Csus test with a clinical method of approximating the CSF. Although the first of these options was preferred, development of the required software was not feasible within the time limits of this research project.

#### *11.2.1 Subject selection*

Twenty five young observers (mean age = 23.0 years ± 3.9 years standard deviation) and 25 old observers (mean age = 72.2 years ± 5.7 years standard deviation) took part in this experiment. All subjects were free of ocular abnormality and were corrected for the testing distance used. For the purposes of this chapter, the results of both age groups were pooled.

#### *11.2.2 Testing procedure*

All the charts used in this experiment were illuminated using the lighting system described in appendix A (Section A.2.2). The importance of comparing tests under similar luminance conditions has been previously discussed (Chapter 9).

Csus was measured with a Bailey-Lovie chart (Bailey and Lovie, 1976) using the procedure outlined in section 4.7.2.

The functional acuity contrast test (FACT, see section 3.7.4) was used to define a five point CSF (Figure 3.9). Subjects stood 3m from the chart. They were asked to identify the orientation of the stripes in each sample patch using the responses "left", "right" or "up". "Blank" or "don't know" responses were not allowed in accordance with forced choice procedure (Section 3.5.4.2). Subjects started on the top row and worked left to right naming the stripe orientation of each patch. This was repeated for each of the four remaining rows. The number of the last patch named correctly on each row was recorded. When uncertain, subjects were encouraged to guess.

The slope of the right hand descending limb of the CSF was derived from FACT measurements described above as this attribute of the CSF is considered to be estimated by Csus measurements (Section 4.3). From figure 3.9 (p75) it may be seen that there were three possible ways of assessing the slope of the CSF using FACT scores.

Slope could be calculated using the difference in scores between points C and D, points C and E, or points D and E. Being uncertain of which of these provided the best estimate, all three were calculated.

An ICS score was also derived from the FACT chart measurements. Integrated contrast sensitivity is a measure of the integrated area under the CSF (Van Meeteren and Vos, 1972). Cornelissen *et al.* (1995) have reported that ICS is a useful predictor of search task performance. Therefore, it could be that Csus exerts its influence upon complex task performance by way of its relationship with ICS. The simplest way of deriving ICS from FACT chart measurements was to sum the scores for rows A to E.

The Pelli-Robson chart (Section 3.8.4) was used to measure contrast threshold as it has often been found to be a useful measure of visual performance in various driving studies (Ball *et al.*, 1993; Wood *et al.*, 1993; Brabyn *et al.*, 1994; Wood and Troutbeck, 1995). This measure of contrast threshold has been described as a test of low to medium spatial frequencies (Section 3.8.4) and, together with a measure of visual acuity, is able to predict search task performance as well as the ICS (Cornelissen *et al.*, 1995).

The Pelli-Robson chart was positioned 1m from the subject. The height of the chart was set so that the eyes of the subject were approximately aligned with the centre of the chart, as recommended by the manufacturer. Subjects were asked to start at the top left of the chart and identify as many letters as possible. Each row was read from left to right. As lower contrast letters were encountered, subjects were encouraged to guess. Subjects were also advised that they could move their head from side to side in order to try to detect extra letters as directed in the manufacturer's instructions. Ample time was allowed for letter detection (Tunnacliffe, 1989; Whitaker and Elliott, 1992).

The order in which Csus, FACT and Pelli-Robson measurements were made was balanced to compensate for learning effects. All three measurements were made on two separate occasions separated by a time interval of 1 week. This allowed test-retest reliability of the measurements to be assessed.

Although the repeatability of each of these tests has been previously reported (Corwin and Richman, 1986; Long and Tuck, 1988; Lovie-Kitchin, 1988; Elliott, Sanderson *et al.*, 1990; Scialfa *et al.*, 1991; Arditi and Cagenello, 1993; Bailey, 1993; Beck *et al.*, 1993; Elliott and Bullimore, 1993; Reeves *et al.*, 1993; Pardhan, 1995; Simpson and Regan, 1995), the importance of comparing test reliability under the same experimental conditions has been stressed (Arditi and Cagenello, 1993; Pardhan, 1995).

### *11.3 Results and discussion*

#### *11.3.1 Repeatability*

The repeatability of all tests was assessed using coefficients of repeatability (COR; Bland and Altman, 1986).

| Chart | COR (measured unit) |
|---|---|
| Pelli-Robson | 1 letter triplet |
| Bailey-Lovie (Csus) | 1.4 lines (7 letters) |
| FACT (A) | 2 patches |
| FACT (B) | 2 patches |
| FACT (C) | 2 patches |
| FACT (D) | 2 patches |
| FACT (E) | 4 patches |
| FACT (ICS) | 6 patches |
| FACT (slope C-D) | 3 patches |
| FACT (slope C-E) | 3 patches |
| FACT (slope D-E) | 4 patches |

**Table 11.1** Coefficients of repeatability for scores derived from the Bailey-Lovie, FACT and Pelli-Robson charts.

Table 11.1 shows that a clinically significant change for each chart used is approximately 2 measurement units. This equates to 2 letter triplets on the Pelli-Robson chart, 2 lines of the Bailey-Lovie chart or 2 patches on the FACT chart. This is in agreement with the findings of other authors (Reeves *et al.*, 1993).

The reliability of the FACT chart has previously been shown to be spatial frequency dependent (Corwin and Richman, 1986; Long and Tuck, 1988; Scialfa *et al.*, 1991). That is, reliability increased with increasing spatial frequency (Long and Tuck, 1988; Scialfa *et al.*, 1991). However, the results of the present study do not agree with previous reports. The repeatability for individual rows on the FACT given in table 11.1 is similar and actually becomes worse rather than better at the highest spatial frequency (row E). This might be partly attributed to a ceiling effect found at low spatial frequencies as the majority of subjects correctly identified all the patches in the first two rows. Thus, the range of measurements for these rows was restricted and could have resulted in an artificially high level of repeatability for these points. Furthermore, the reduction in repeatability at the highest spatial frequency may have been caused by unwillingness on the part of subjects to guess grating orientation.

The repeatability of Pelli-Robson scores was in general agreement with that of other authors (Elliott, Sanderson *et al.*, 1990; Beck *et al.*, 1993; Elliott and Bullimore, 1993; Reeves *et al.*, 1993; Pardhan, 1995; Simpson and Regan, 1995). Similarly, the repeatability of the Bailey-Lovie chart was also in agreement with that of other authors (Lovie-Kitchin, 1988; Bailey, 1993; Reeves *et al.*, 1993)

### *11.3.2 Mean Bailey-Lovie, Pelli-Robson and FACT scores*

Table 11.2 shows the mean scores obtained from the FACT, Bailey-Lovie and Pelli-Robson charts. The Log contrast sensitivity values for the FACT were derived from table 3.2 (p78) in which each patch number has a corresponding contrast sensitivity value. This table is supplied with the instructions for the FACT chart (Ginsburg, 1993).

| Chart | Mean score ± standard deviation |
|---|---|
| Bailey-Lovie Csus *(LogMAR)* | 0.17 ± 0.1 |
| Pelli-Robson *(Log contrast sensitivity)* | 1.89 ± 0.1 |
| FACT point A *(Log contrast sensitivity)* | 1.96 ± 1.0 |
| FACT point B *(Log contrast sensitivity)* | 2.15 ± 1.3 |
| FACT point C *(Log contrast sensitivity)* | 2.21 ± 1.4 |
| FACT point D *(Log contrast sensitivity)* | 1.94 ± 1.5 |
| FACT point E *(Log contrast sensitivity)* | 1.60 ± 1.3 |
| FACT slope C-D *(Log contrast sensitivity)* | 1.87 ± 1.4 |
| FACT slope C-E *(Log contrast sensitivity)* | 2.09 ± 1.3 |
| FACT slope D-E *(Log contrast sensitivity)* | 1.68 ± 1.3 |
| FACT ICS *(Log contrast sensitivity)* | 2.72 ± 1.9 |

**Table 11.2** Mean scores for the FACT, Bailey-Lovie and Pelli-Robson charts.

### *11.3.3 Comparison between contrast susceptibility and the CSF*

Table 11.3 shows that Csus exhibited a strong correlation with the slope of the CSF defined as the algebraic difference between FACT chart scores obtained for rows C and E. However, a stronger correlation emerged between Csus and the ICS.

| Measure | Correlation with Csus | |
|---|---|---|
| | *r* | *P* |
| FACT A | -0.33 | 0.0194 |
| FACT B | -0.02 | 0.8781 |
| FACT C | -0.34 | 0.0140 |
| FACT D | -0.34 | 0.0148 |
| FACT E | -0.40 | 0.0038 |
| C-D | 0.27 | 0.0582 |
| C-E | 0.37 | 0.0079 |
| D-E | 0.21 | 0.1483 |
| ICS | 0.49 | 0.0023 |

**Table 11.3** The correlation of Csus with measures derived from FACT scores.

### *11.3.4 Comparison between contrast threshold and CSF*

As with Csus, contrast threshold was more closely related to ICS than any other parameter measured using the FACT chart (Table 11.4). Pelli-Robson chart letters have a fundamental spatial frequency of approximately 1cpd (Section 3.8.4). It may therefore be expected that contrast threshold scores would exhibit a higher correlation with FACT chart scores from row A (1.5cpd, Table 3.2) compared to other rows. However, the reverse was actually found (Table 11.4). This might have occurred because of a ceiling effect that caused truncation of the data at lower spatial frequencies. Hence, the variation in contrast threshold scores was not reflected by similar variation in FACT scores derived from row A. This, in turn, would attenuate any potential relationship between these two tests.

The above explanation might also help explain why contrast threshold was better correlated with the higher spatial frequency gratings of the FACT chart. Here, lack of a ceiling effect gave rise to greater variation in FACT scores for higher spatial frequency gratings thereby enhancing their correlation with contrast threshold scores.

| **Measure** | **Correlation with Pelli-Robson** | |
|---|---|---|
| | ***r*** | ***P*** |
| Csus | -0.55 | <0.0001 |
| FACT A | 0.07 | 0.6213 |
| FACT B | 0.15 | 0.2983 |
| FACT C | 0.60 | <0.0001 |
| FACT D | 0.57 | <0.0001 |
| FACT E | 0.65 | <0.0001 |
| Slope (C-D) | -0.44 | 0.0011 |
| Slope (C-E) | -0.59 | <0.0001 |
| Slope (D-E) | -0.33 | 0.0198 |
| ICS | 0.66 | <0.0001 |

**Table 11.4** The correlation between contrast threshold, Csus and FACT chart scores.

*11.4 Conclusion*

The findings presented in this chapter indicate that deficits in Csus reflect deficits in the CSF. It may then follow that the relationship between Csus and the CSF explains any link observed between Csus and visual performance during everyday tasks such as driving.

Contrast threshold measurements made using the Pelli-Robson chart have received a great deal of attention in the recent literature as a useful means of gauging visual performance in everyday tasks. Evidence presented in this chapter suggests that deficits in contrast threshold are even more strongly linked to deficits in the CSF than is Csus. This, in turn, indicates that further research on the connection between contrast sensitivity and complex task performance might best be concentrated on contrast threshold rather than Csus. Nevertheless, Csus involves measurement of high contrast visual acuity; a measurement that is universally carried out during eye examination procedures.

# CHAPTER 12: SUMMARY AND FUTURE WORK

## *12.1 Summary*

Higher order tests of visual function are likely to offer the best means of predicting visual performance in everyday tasks such as driving (Chapter 2). Nevertheless, of the more basic tests of visual function, measurements of contrast sensitivity provide a useful link between mechanisms that underpin spatial vision and the effects that changes in the mechanisms have on visual performance (Chapter 3).

Pilot studies conducted at Aston University (The 1994 and 1995 surveys described in chapters 4, 5 and 6) have revealed that a particular contrast sensitivity test, referred to as contrast susceptibility (Csus) in this thesis but as normalised low contrast acuity by other researchers, was a strong predictor of driving accident involvement.

A large sample study (the 1996 survey described in chapters 5 and 6) failed to confirm the previously reported association between Csus and accident involvement. It appeared that earlier findings had been the result of spurious small sample variation in addition to biases in the driving population surveyed. Interestingly, in depth analysis of the pilot surveys revealed that the strength of the association between Csus and accident involvement was heavily influenced by the manner in which the accident history questionnaires had been carried out. This raises a major objection to the validity of self-reported accident histories – an objection that has also been raised by previous researchers (Chapter 2).

The large sample survey probed further into the issue of self-imposed driving situation avoidance (Chapter 7). Together with the evidence gleaned from a practice based survey conducted with the co-operation of the West Midlands police situation avoidance was shown to increase with reduced visibility. Furthermore, objects such as road signs and number plates were more likely to be used to judge whether situation avoidance was warranted.

A hypothesis emerging from earlier pilot studies stated that situation avoidance was based on high contrast vision and not low contrast vision. Hence, the relationship between high contrast vision and accidents would be confounded by situation avoidance. Also, drivers with low contrast vision deficits (i.e. poor Csus scores) would be more susceptible to accidents. Sophisticated statistical analysis (Chapter 7) failed to support this hypothesis. Situation avoidance exerted little influence on the relationships between age, vision and road accidents. However, it was found that drivers that did not practise situation avoidance were more likely to be involved in accidents if they also had an accompanying Csus deficit. Nevertheless, although this relationship did achieve statistical significance, it was too small to be of practical value in driver vision screening. As for self-reported accident histories, questions were raised about the validity of self-reported situation avoidance strategies.

Although Csus is unlikely to be a practical method for use in driver vision screening, this does not detract from its potential use as a means of detecting visual deterioration and the influence that this deterioration may have on the performance of other everyday tasks. It is for this reason that the remaining chapters of this thesis evaluated the Csus test in its own right.

Chapter 8 revealed that systematically worse Csus scores emerged from vision screeners compared to wall mounted charts. This discrepancy could not be attributed to variations in test luminance (Chapter 9) or instrument myopia (Chapter 10). The only remaining explanation was that degradation of vision screener test slides was responsible. This degradation was caused by either the optical system of the vision screener, or limitations in the manufacture of the slides used with the vision screener.

Given that the CSF provides a description of human contrast sensitivity, chapter 11 demonstrated that individual variation in both Csus and contrast threshold measurements exhibited strong correlations with CSF variations. Tests of Csus and contrast threshold are more useful in clinical applications than formal CSF measurements as they are relatively inexpensive, portable and rapidly administered. In addition, they reduce the amount of redundant information that may emerge from full CSF measurement. Although contrast threshold scores exhibited the strongest relationship with the CSF, it could be argued that the Csus test, involving measurement of high contrast visual acuity - a parameter universally measured during eye examination procedures, might be more readily integrated.

### *12.2 Critique and suggestions for future research*

The primary objection relating to the evidence presented in this thesis is that it places a great emphasis on self-reported accident histories and situation avoidance strategies. The limitations of this type of information have been discussed in chapter 2. One alternative would have been to use official records. However, in the UK, these records are generally unavailable. Another alternative would have been to use driving simulator, closed road or open road tests of driving performance. The relative merits of these have been discussed in chapter 2. Measuring performance during real driving tasks would also have the advantage that the occurrence of dangerous manoeuvres and situation avoidance may be assessed simultaneously.

A further objection relates to the research presented in chapter 11. A more sophisticated computational method, applying formal psychophysical procedures, should ideally have been employed to compare individual Csus and contrast threshold scores with the CSF. However, despite every effort being made to have customised software written for hardware that was already available in the Vision Science department, this task could not be completed in time for it to be included in this thesis.

Future work should be planned to confirm the findings presented in this thesis, taking heed of the objections raised in the preceding paragraphs.

Discussions presented in chapter 2 reveal that basic visual functions are only likely to influence everyday task performance through their contribution to higher order functions such as visual search. Future research may, therefore, be most beneficially concentrated on higher level tests such as visual search, hazard perception and risk taking behaviour to gain a more holistic view of the visual and psychological parameters that might influence performance during everyday complex tasks such as driving.

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# APPENDIX A: PHOTOMETRIC EVALUATION OF CHARTS

## *A.1 Introduction*

It is known that contrast detection and visual acuity task performance are affected by changes in luminance (Hecht, 1928; Shlaer, 1937; Sheedy *et al.*, 1984; Brown *et al.*, 1987; Colletta and Clark, 1993; Rabin, 1994). With equal increments in luminance, the level of visual acuity (Hecht, 1928; Rabin, 1994) or contrast (DeValois *et al.*, 1974; Kelly, 1977; Rabin, 1994) increases at a diminishing rate. Consequently, comparisons between different test methods need to be conducted under identical luminance conditions. Hence, the aim of the lighting system described here was to produce uniform illumination for all charts.

## *A.2 Method*

### *A.2.1 Chart lighting requirements*

In the instructions for use of clinical test charts, a minimum standard of illumination is often specified under which the test should proceed. The recommendations for the charts used in this thesis are given in table A.1.

| **Test chart** | **Recommended luminance range (cdm$^{-2}$)** |
|---|---|
| Pelli-Robson Contrast Threshold | 60-120 |
| Functional Acuity Contrast Test | 68-240 |
| Bailey-Lovie chart | 120-150* |
| Landolt C chart | 120-150* |

**Table A.1** Recommended chart luminance levels. * This luminance is recommended in BS 4274 as suitable for distance acuity charts. The Landolt C chart is described in section 10.3.3.

*A.2.2 Lighting system*

A lighting system was built. The level of illumination was designed to broadly comply with the recommended luminance levels detailed by the chart manufacturers (Table A.1).

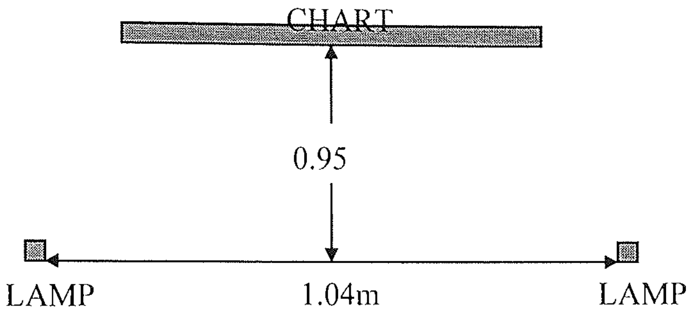


**Figure A.1** Plan view of the layout of the custom lighting system.

Charts were directly illuminated from the front. This allowed the charts to be changed easily and the disparity in chart sizes to be more readily accommodated (Table A.2).

| Chart | Height (m) | Width (m) | Area ($m^2$) |
|---|---|---|---|
| Pelli-Robson | 0.84 | 0.64 | 0.54 |
| Bailey-Lovie | 0.61 | 0.53 | 0.32 |
| FACT | 0.68 | 0.97 | 0.66 |
| Landolt C chart | 0.31 | 0.44 | 0.13 |

**Table A.2** Chart dimensions.

The chart mounting point (Figure A.1) consisted of a vertical wooden stand equipped with a small hook.

The configuration of the lamps and their position relative to the chart mounting point are illustrated in figure A.1. The lamps were 4ft, 36watt fluorescent tubes mounted vertically on individual moveable stands. Fluorescent tubes were chosen as they are considered to be the best method of producing long term stable lighting (Ferris and

Sperduto, 1982). The 4ft tube length was required to ensure even illumination down the whole length of the longest chart (Pelli-Robson chart) was achieved. The lamps were offset to eliminate specular reflection (Ferris and Sperduto, 1982). The fine positioning of the lamps was determined empirically to achieve optimal positioning for uniform chart illumination in the absence of glare. This procedure was made more difficult by the fact that there were differences in the shape and size of the three charts (Table A.2).

### *A.2.3 Photometric evaluation*

The chart luminance provided by the lighting system was assessed using a Minolta LS110 photometer. All measurements were carried out at a distance of 1m from the mounted chart surface with the photometer focused in the plane of the chart surface. Each chart used was individually assessed. Nine points on each chart were measured (Figure A.2). Three readings were taken and averaged for each point.

| | | |
|---|---|---|
| 1 | 2 | 3 |
| 4 | 5 | 6 |
| 7 | 8 | 9 |

**Figure A.2** Position of the luminance measurement points used in the photometric evaluation of charts.

The luminance of the charts during experimentation was monitored by repetition of the measurement procedure at the beginning of each experimental session.

## *A.3 Results*

### *A.3.1 Mean chart luminance level*

| Statistic | Pelli-Robson | Bailey-Lovie | FACT | Landolt C Chart |
|---|---|---|---|---|
| Mean ($cdm^{-2}$) | 92 | 89 | 74 | 89 |
| Standard deviation ($cdm^{-2}$) | ± 1 | ± 2 | ± 2 | ± 2 |
| Minimum value ($cdm^{-2}$) | 90 | 87 | 70 | 85 |
| Maximum value ($cdm^{-2}$) | 96 | 93 | 78 | 95 |
| Range ($cdm^{-2}$) | 6 | 6 | 8 | 10 |

**Table A.3** Mean chart luminances obtained with lighting system.

The mean chart luminance level for each chart is given in table A.3. The difference in luminance between charts was significant ($F_{3,203}$ = 955.977, P <0.0001). The luminance of the Bailey-Lovie and Landolt C charts was slightly lower than recommended. However, within the luminance range of $80cdm^{-2}$ – $320cdm^{-2}$ the change in acuity would only be ± 1 letter (Sheedy *et al.*, 1984). Hence, although slightly low, the luminance of the Bailey-Lovie and Landolt C charts was within this tolerance. Luminance levels were also within the range that has the minimum effect upon contrast sensitivity (Rabin, 1994).

Although all four charts were illuminated by the same light sources, there was some variation in the mean level of luminance between charts. This variation probably arose through differences in chart reflectance.

### *A.3.2 Uniformity of chart luminance*

The variation in luminance over each chart was less than 10% (Table A.4). It was noted that the larger the chart, the greater was the variation in luminance. This reflected the increased difficulty of illuminating the larger charts evenly without glare. The variation of luminance with position was statistically significant (Table A.5). However, post hoc analysis (Fishers PLSD) revealed no particular pattern of luminance differences. Furthermore, the magnitude of these differences was small, being a maximum of $7cdm^{-2}$ (Table A.4).

| **Chart position** | **Mean luminance ± standard deviation ($cdm^{-2}$)** | | | |
|---|---|---|---|---|
| | ***Pelli-Robson*** | ***Bailey-Lovie*** | ***FACT*** | ***Landolt C*** |
| 1 | 91 ± 2 | 85 ± 2 | 74 ± 8 | 90 ± 3 |
| 2 | 90 ± 2 | 84 ± 2 | 65 ± 1 | - |
| 3 | 92 ± 2 | 86 ± 2 | 68 ± 3 | 90 ± 1 |
| 4 | 99 ± 2 | 91 ± 2 | 87 ± 9 | - |
| 5 | 98 ± 2 | 92 ± 2 | 67 ± 1 | 85 ± 5 |
| 6 | 102 ± 2 | 93 ± 2 | 82 ± 9 | - |
| 7 | 82 ± 3 | 89 ± 2 | 79 ± 3 | 90 ± 2 |
| 8 | 84 ± 2 | 89 ± 2 | 64 ± 4 | - |
| 9 | 90 ± 4 | 93 ± 2 | 79 ± 5 | 89 ± 4 |
| Overall mean luminance ($cdm^{-2}$) | 92 | 89 | 74 | 89 |
| Maximum difference from mean ($cdm^{-2}$) | 5 | 3 | 7 | 1 |
| % Luminance variation (max difference/mean) | 6 | 3 | 9 | 2 |

**Table A.4** Mean luminance at each chart position. Only 5 points were measured on the Landolt C chart because of its small size.

| **Factorial ANOVA** | **Pelli-Robson** | **Bailey-Lovie** | **FACT** | **Landolt C** |
|---|---|---|---|---|
| Degrees of freedom | 8,504 | 8,504 | 8,504 | 4,175 |
| F | 539.088 | 206.923 | 121.730 | 13.898 |
| Probability | <0.0001 | <0.0001 | <0.0001 | <0.0001 |

**Table A.5** Factorial ANOVA for luminance versus position of measurement.

### *A.3.3 Deterioration of chart luminance over time*

The deterioration of chart luminance over time was analysed using linear regression. From table A.6, it can be seen that the luminance level significantly decreased over the 9 months study duration.

On examination of the values involved in figure A.3, it was noticed that the magnitude of the decrease in luminance with time was approximately $5cdm^{-2}$. This was very small. Such a change was not unexpected given the possible effects of wear and tear on both lamps and chart surfaces under conditions of frequent use.

| | **Pelli-Robson** | **Bailey-Lovie** | **FACT** | **Landolt C** |
|---|---|---|---|---|
| Degrees of freedom | 1,55 | 1,55 | 1,55 | 1,34 |
| F | 7.478 | 25.310 | 59.797 | 10.257 |
| Probability | 0.0084 | <0.0001 | <0.0001 | 0.0030 |

**Table A.6** Results of ANOVA conducted on regression between luminance and time.

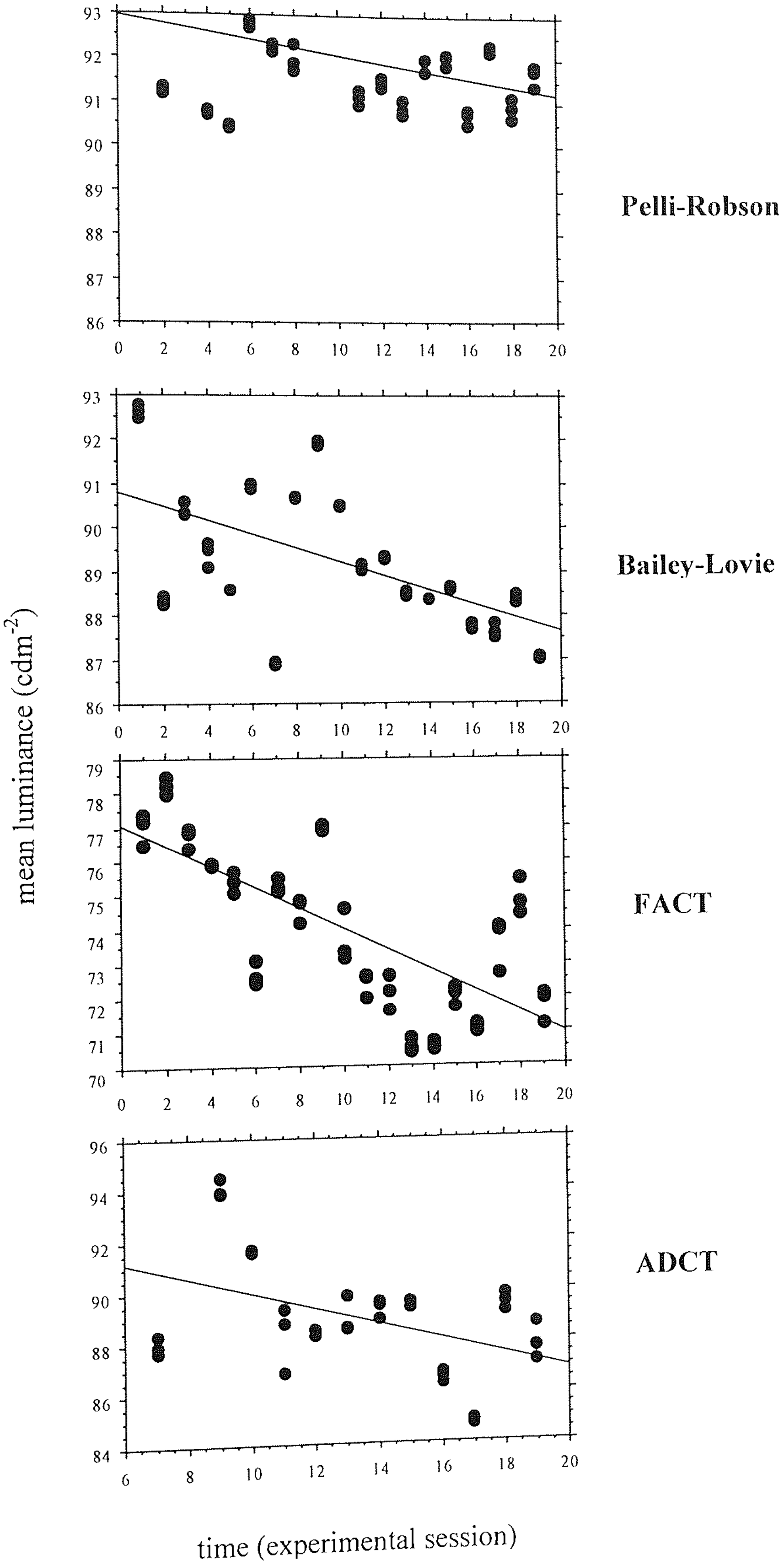


**Figure A.3** Regression plots showing the variation of mean luminance with time for each chart.

*A.4 Discussion*

In real terms, the small variation between the luminance of individual charts was unlikely to have a significant effect on the acuity and contrast results obtained from them. As already explained (Section A.3.1), the luminance variation between charts was unlikely to alter acuity by more than ± 1 letter (Sheedy, 1980). The magnitude of this variation in acuity is considerably smaller than the limits of reliability of each chart (Section 8.3.1).

Variations in luminance due to measurement position and time were likewise too small to have an adverse effect on visual acuity and contrast measurements.

*A.5 Conclusion*

The chart luminances provided by the lighting system complied with the guidelines set by the manufacturers to within ± 1 letter tolerance. Hence, although there were luminance differences between charts it was unlikely that these were of sufficient magnitude to affect visual acuity measurements given the known reliability of each chart (Section 8.3.1).

# APPENDIX B: PHOTOMETRIC EVALUATION OF VISION SCREENERS

## *B.1 Introduction*

All of the vision screeners used in experimentation (Ergovision, ADCT and Titmus) were internally illuminated. It was not possible to manipulate illumination levels within the vision screeners except through bulb replacement. Hence, photometric evaluation was conducted to monitor the luminance of the charts shown by each instrument throughout the experimental period.

This evaluation allowed any variation in the results of experimental comparisons to be investigated with respect to differences in vision screener luminance. As was described in appendix A, differences in luminance can give rise to differences in the level of acuity obtained with different instruments, although the magnitude of the effect on acuity is likely to be small.

## *B.2 Method*

Ten points were measured on each vision screener (Figure B.1). Points 1-5 were measured with the photometer (Minolta LS-110) directed through the left eyepiece. Points 6-10 was measured with the photometer directed through the right eyepiece. Three readings were taken at each point and averaged to give a mean luminance level. For each vision screener, the photometer was focused in the plane of the chart viewed. This procedure was repeated for all the vision screeners at the beginning of each experimental session.

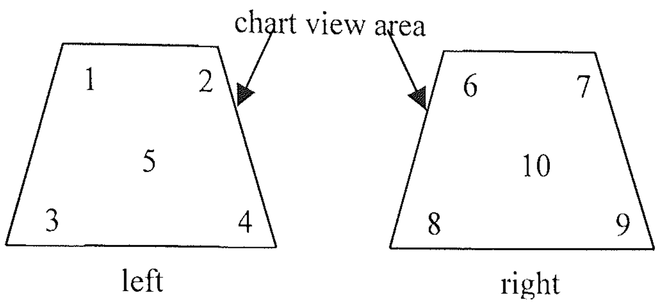


**Figure B.1** The position of the measurement points used for the photometric evaluation of vision screeners.

### *B.3 Results*

#### *B.3.1 Mean luminance of internally illuminated vision screeners*

The luminance values for all ten measured points were averaged to provide an overall mean luminance for each instrument (Table B.1). The differences in mean luminance between instruments were statistically significant ($F_{2,339} = 1083.981$, $P \leq 0.0001$). Post hoc testing (Fishers PLSD) showed that each vision screener was significantly different to the others at the 99% level.

| Statistic | Ergovision | ADCT | Titmus* |
|---|---|---|---|
| Mean ($cdm^{-2}$) | 65 | 52 | 16 |
| Standard deviation ($cdm^{-2}$) | 10 | 9 | 3 |
| Maximum value ($cdm^{-2}$) | 85 | 67 | 23 |
| Minimum value ($cdm^{-2}$) | 36 | 35 | 9 |
| Range ($cdm^{-2}$) | 49 | 32 | 14 |

**Table B.1** The mean luminance of vision screeners. *The Titmus screener used in the laboratory was screener R19395 used in the 1996 survey (appendix C).

#### *B.3.2 Uniformity of luminance*

The variation in luminance between measured points was less than 30% (Table B.2). Examination of the mean luminance for each chart position measured revealed that the centre of each chart (point 5) was brightest (Table B.2).

| Chart position | Mean luminance ($cdm^{-2}$) ± standard deviation | | |
|---|---|---|---|
| | *Ergovision* | *ADCT* | *Titmus* |
| 1 | 55 ± 13 | 56 ± 19 | 17 ± 6 |
| 2 | 55 ± 15 | 49 ± 14 | 19 ± 5 |
| 3 | 63 ± 14 | 41 ± 11 | 10 ± 3 |
| 4 | 56 ± 13 | 35 ± 11 | 11 ± 3 |
| 5 | 96 ± 17 | 80 ± 20 | 22 ± 5 |
| Overall mean luminance ($cdm^{-2}$) | 65 ± 10 | 52 ± 9 | 16 ± 3 |
| Average difference from mean ($cdm^{-2}$) | 12 | 13 | 4 |
| Average luminance variation (%) (average difference/mean) | 19 | 25 | 26 |

**Table B.2** Mean luminance at each measured point on the vision screeners. A central bright patch (position 5) was revealed for each instrument. The equivalent positions for each eyepiece were averaged to give a mean luminance for the five chart locations measured e.g. positions 1 and 6 were combined and so on.

| Factorial ANOVA | Ergovision | ADCT | Titmus |
|---|---|---|---|
| Degrees of freedom | 4,565 | 4,565 | 4,565 |
| F | 161.081 | 147.223 | 137.949 |
| Probability | <0.0001 | <0.0001 | <0.0001 |

**Table B.3** Factorial ANOVA for luminance versus position of measurement.

The difference in mean luminance between positions was significant (Table B.3). The magnitude of this variation was, on average, approximately 10$cdm^{-2}$. This was double the variation found for the charts illuminated with the lighting system (Appendix A).

### *B.3.3 Deterioration of luminance over time*

The deterioration of the mean luminance of each vision screener over time was analysed using linear regression (Table B.4).

It is seen in table B.4 and figure B.2 that both the Ergovision and Titmus showed a significant decrease in mean luminance over time. This was not the case for the ADCT. However, the ADCT bulb was replaced early in the experimental period. This could have been the reason for the unusual result obtained for the ADCT.

| | **Ergovision** | **ADCT** | **Titmus** |
|---|---|---|---|
| Degrees of freedom | 1,112 | 1,112 | 1,112 |
| F | 18.608 | 1.234 | 61.73 |
| Probability | <0.0001 | 0.2690 | <0.0001 |

**Table B.4** Variation in vision screener luminance over time.

From examination of the regression lines in figure B.2 it was seen that the change in luminance over time was about $7cdm^{-2}$. This was similar to that noted for chart luminance (Appendix A).

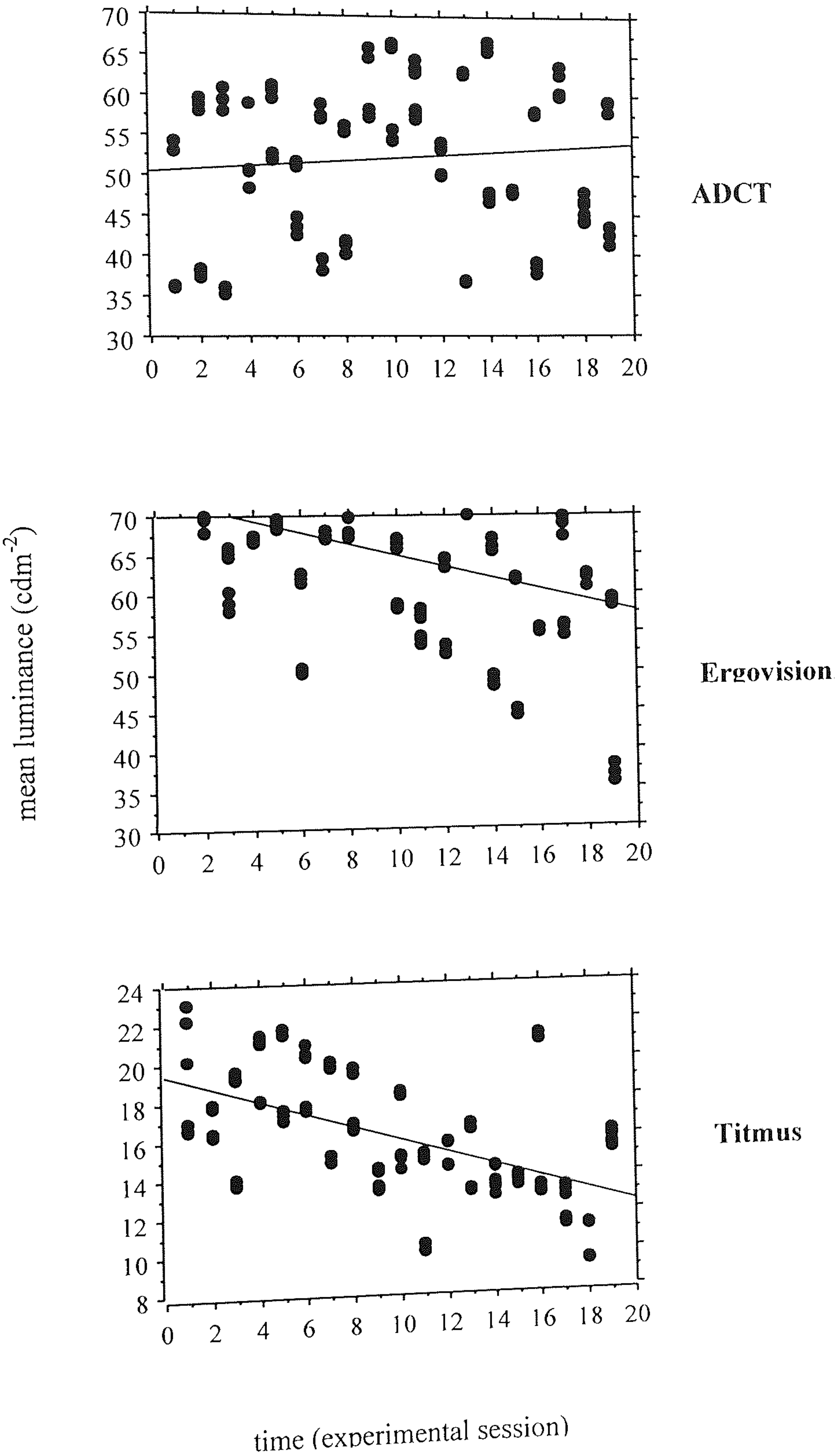


**Figure B.2** Regression plots showing the variation of mean luminance with time for each vision screener.

### *B.4 Discussion*

It has been demonstrated that doubling luminance produces a 1 letter change in acuity if conventional letters are used, or approximately ½ a letter change if Landolt C's are used (Sheedy *et al.*, 1984). Hence, the variation in mean luminance between screeners should produce a difference in acuity of approximately 1 letter between the Titmus and the ADCT and between the Titmus and the Ergovision (Table B.1). This is less than the ± 2 lines of acuity difference that can occur as a result of the limits of repeatability of these instruments (Section 8.3.1). Consequently, although the difference in luminance between vision screeners was statistically significant it may not result in a significant change in acuity.

Similarly, the statistically significant variations in luminance due to position of measurement and time were of small magnitude. Hence, following the same reasoning they were unlikely to produce an observable effect on measurements made with the vision screeners concerned.

### *B.5 Conclusion*

It may be concluded, that the luminance differences between vision screeners found would be unlikely to produce clinically observable effects on the Csus measurements made with these screeners.

# APPENDIX C: VERIFICATION OF TITMUS VISION SCREENER CHARACTERISTICS

## *C.1 Introduction*

The purpose of this experiment was to fully evaluate the 11 Titmus vision screeners (10 in use and 1 spare) used in the 1996 Survey (Chapter 5). This required photometric luminance measurements to be made on each screener shortly after survey completion.

The assessment included evaluation of:

1. Variation in mean luminance between vision screeners.
2. Variation in individual vision screener luminance across each test slide.
3. Variation in inter-eyepiece luminance. This may arise because the Titmus design uses two separate bulbs to illuminate the chart seen by each eye.
4. The effect on luminance arising from the cleaning of slides with the recommended cleaner.
5. The effect on luminance arising from bulb replacement.
6. Verification of the contrast of the test chart symbols relative to the background illumination.

### *C.2 Luminance measurements*

For all measurements, a Minolta LS-110 photometer was directed through the appropriate eyepiece of each vision screener. The photometer was always focused at infinity as the screeners were designed such that the charts were viewed at optical infinity. Three readings were taken at each measurement point (Figure C.1). These readings were averaged to give a mean reading for each measured point.

### *C.3 Variation of mean and positional luminance*

#### *C.3.1 Method*

All the vision screeners were run for 40 minutes duration before measurements were taken. Twelve points for each vision screener were measured (Figure C.1). The results were used for the assessment of variations in mean, positional and inter-eyepiece luminance.

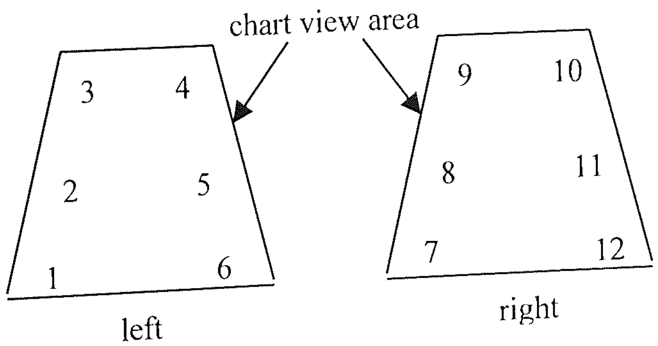


**Figure C.1** Diagram showing the points measured on each Titmus vision screener in the evaluation of mean luminance. Points 1-6 were measured with the photometer directed through the left eyepiece. Points 7-12 were measured with the photometer directed through the right eyepiece.

### *C.3.2 Results*

#### *C.3.2.1 Mean luminance*

The mean luminance across all the vision screeners is given in table C.1. The mean luminance for individual vision screeners is given in table C.2. A statistically significant difference in mean luminance was found between vision screeners ($F_{10}$ = 29.315, P <0.0001).

| Statistic | Luminance ($cdm^{-2}$) |
|---|---|
| Mean screener luminance ± standard deviation | 14 ± 6 |
| Minimum | 3 |
| Maximum | 34 |

**Table C.1** Mean luminance for all 11 Titmus vision screeners.

| Vision screener serial number | Mean luminance ± standard deviation ($cdm^{-2}$) |
|---|---|
| A30049 | 12 ± 3 |
| A30466 | 10 ± 2 |
| A30997 | 12 ± 3 |
| A30998 | 9 ± 3 |
| R19009 | 25 ± 7 |
| R19087 | 18 ± 6 |
| R19159 | 8 ± 4 |
| R19242 | 16 ± 5 |
| R19395 | 15 ± 5 |
| R20531 | 10 ± 2 |
| R8686 | 16 ± 4 |

**Table C.2** Mean luminance of individual Titmus vision screeners.

#### *C.3.2.2 Inter-eyepiece variation*

There was no significant difference found between the overall luminance values obtained through the left and right eyepieces of each vision screener (t-test: df = 261, t = -0.158, P = 0.8744).

### *C.3.2.3 Positional luminance variation*

A the luminance did not differ through each eyepiece (Section C.3.2.2) right and left eyepiece measurements for each position were averaged (For example, the results of position 1 were combined with the results of the corresponding point 7 from the other eyepiece and so on see figure C.1). Thus, positional variation in luminance was assessed for 6 points. The mean luminance at each of these points is given in table C.3. The difference between positions was found to be statistically significant ($F_{11}$ = 5.624, P = 0.0001).

Post hoc testing (Fishers PLSD) revealed that the luminance of point 1 was not significantly different to that of point 6. The luminances of both of these were significantly different to all the other points measured to at least the 95% level. This indicates that the luminance in the lower third of the chart view was significantly lower than in the other chart areas.

| Averaged position | Mean ± standard deviation ($cdm^{-2}$) |
|---|---|
| 1 | 11 ± 3 |
| 2 | 16 ± 6 |
| 3 | 15 ± 6 |
| 4 | 15 ± 6 |
| 5 | 16 ± 7 |
| 6 | 10 ± 4 |

**Table C.3** Mean positional luminance. Values were averaged across right and left eyepieces.

## *C.4 The effect of cleaning slides on luminance*

### *C.4.1 Method*

The chart luminance was measured at points 1, 4, 7 and 10 (Figure C.1) before and after cleaning the slides of a single vision screener. The slides were cleaned in accordance with instructions supplied by the manufacturer using a proprietary cleaner and soft cloth. This procedure was completed for both the high contrast chart slide and the low contrast chart slides of a single vision screener. This procedure was carried out in case the slides had become soiled during the survey, which would mean that test luminances would have been higher than the luminances measured at survey completion

### *C.4.2 Results*

There was no significant effect on luminance values after cleaning the slides in the chosen screener (t-test: df = 34, t = -1.174, P = 0.2487). Therefore, concerns about making the luminance measurements after completion of the survey were unfounded.

## *C.5 Effect of bulb replacement on luminance*

### *C.5.1 Method*

Mean luminance was measured before and after replacement of the existing vision screener bulbs. Positions 1, 4, 7 and 10 were measured as for section C.4 (Figure C.1). This procedure was, again, completed for both the high and low contrast chart slides of a single vision screener. This procedure was carried out for the same reasons as are given in section C.4.

### *C.5.2 Results*

No significant effect on luminance was found after bulb replacement in the chosen vision screener (t-test: df = 22, t = 0.878, P = 0.3896). Again, concerns about checking luminance after survey completion were unfounded.

### *C.6 Verification of symbol contrast*

### *C.6.1 Method*

#### *C.6.1.1 Calibration slide design*

For these measurements a new slide design was produced that consisted of a checkerboard pattern of alternating light and dark squares (Figure C.3). This was necessary, as the symbols on the survey test slides were too small to allow accurate evaluation of their contrast.

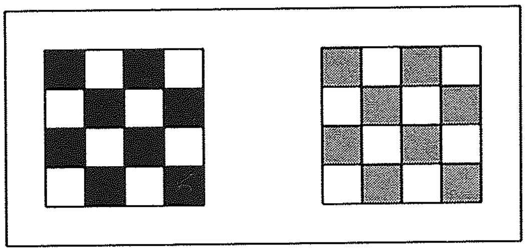

**Figure C.3** The calibration slide developed for the purpose of verifying Titmus vision screener symbol contrast. Each small square was 6mm x 6mm. The dark and light shaded target squares matched the contrast of the high and low contrast Landolt C symbols.

Square patches were produced in the same manner as the high and low contrast symbols (Section C.3.2.3). The checkerboard design permitted evaluation of the variation in luminance with chart position.

Two slides of this design were produced so that verification of the consistency of slide manufacture could be conducted.

#### *C.6.1.2 Testing procedure*

Three photometry measurements were taken in each square. The low contrast squares were measured through one eyepiece; the high contrast squares were measured with the photometer directed through the other eyepiece.

The slide was then rotated 180 degrees and replaced and the measurement procedure repeated. Consequently, the high and low contrast squares were each measured through each eyepiece.

The whole test procedure was then repeated with the second slide.

#### *C.6.1.3 Calculation of contrast*

The Weber contrast of the high and low contrast squares relative to the background was calculated using equation 3.2 (p48). Each high or low contrast square was compared to the background squares adjacent to it.

### *C.6.2 Results*

#### *C.6.2.1 Consistency of slide manufacture*

There was no statistically significant difference between the luminance measurements taken from slides 1 and 2 (t-test: df = 190, t = 0.611, P = 0.5417). This suggests that the two slides were manufactured to a similar standard.

#### *C.6.2.2 Inter-eyepiece differences*

There was no significant difference between the luminance measurements taken through the right and left vision screener eyepieces respectively (t-test: df = 190, t = -0.002, P = 0.9981). This was not unexpected in view of the results of section C.3.2.2.

*C.6.2.3 Mean contrast*

As the same luminance arose from both eyepieces (Section C.6.2.2) and both slides (Section C.6.2.1), luminance measurements were averaged across both of these conditions. The mean symbol contrast for the high and low contrast squares is given in table C.4.

| Contrast | Mean Weber contrast ± standard deviation (%) |
|---|---|
| High (dark grey squares) | 99 ± 0 |
| Low (light grey squares) | 9 ± 3 |

**Table C.4** The Weber contrast of high and low contrast Titmus vision screener symbols.

***C.7 General discussion and conclusions***

A number of conclusions about the Titmus vision screener may be drawn from the results given in the preceding sections.

1. The luminance of the charts viewed through the right and left eyepieces was not significantly different, although separate bulbs illuminated both the charts. This suggested that the bulbs supplied were generally of consistent standard. This conclusion was supported by the fact that there was no significant improvement in luminance found when the bulbs were changed.

2. The luminance of each chart was found to be significantly lower in the lower third compared to the upper portion. The magnitude of this drop, however, was approximately 5-6cdm$^{-2}$. Much larger luminance changes would be needed if acuity were to be affected (Sheedy *et al.*, 1984). Furthermore, luminance was lowest where the symbols were largest. Hence, the targets in the low luminance

area were likely to be well above the resolution limit of the subject. This would further reduce any possible effect of luminance on acuity.

3. It is more difficult to explain the significant variation in mean luminance found between vision screeners. This was possibly not a result of bulb aging, as there was no significant change in luminance found with bulb replacement. However, there was a chance that the spare bulb set available was of a similar age and condition to those already in use. Furthermore, the differences did not appear to occur as a consequence of differences in slide cleanliness, as cleaning the slide had no significant effect on overall chart luminance.

   It is possible that the variation arose from differences in the optical properties of the screeners themselves. This may have occurred as a consequence of vision screener aging. This factor could not be investigated, as the age of the vision screeners was unknown.