ANGLIA RUSKIN UNIVERSITY

VISUAL ACUITY OF DRIVERS

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ANGLIA RUSKIN UNIVERSITY
ABSTRACT

FACULTY OF VISION AND HEARING SCIENCES

MASTER OF PHILOSOPHY

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PURPOSE

In May 2012 UK visual standards for driving changed, in order to comply with European laws. Drivers need to have both a visual acuity of 6/12 **AND** be able to read a number plate at 20 metres. Previously the number plate test was the only visual acuity test.

METHODS

Four different distance visual acuity charts were used (Snellen, logMAR letter-similar to ETDRS, logMAR Landolt ring, distance reading acuity- similar to MNRead chart) and were presented at 6m. 120 drivers were tested binocularly without refractive correction. Participants were taken outside to perform the number plate test at 20m. A second study was conducted, with 38 participants whose vision was impaired to approximately 6/12 using simulation spectacles.

RESULTS

Differences between the visual acuities as measured by the charts were statistically but not clinically significant. For all charts there is an overlap zone within which participants may pass only one of the two tests, outside this range, participants pass or fail both tests. The 6/12 cut-off provides reasonable sensitivity and specificity for Snellen and logMAR letter charts. A poorer acuity cut-off was needed with the Landolt chart to maximize the relationship with the number plate test.

CONCLUSIONS

The 6/12 visual cut-off and the number plate test will not always pass or fail the same drivers. Snellen and logMAR letter charts are recommended to be used to measure the visual acuity of drivers, but not Landolt rings. Fifteen percent of the sample could read a number plate at 20m, but was not able to achieve either 6/12 or +0.30 logMAR. The overlap zone is a helpful tool to identify those people who need advice from Eye Care Practitioners.

Key words: acuity, charts, number plate test, equivalence

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CHAPTER 1: VISUAL ACUITY

Adequate visual function is essential for driving performance and safety, and accidents can be caused due to poor vision. Eye Care Practitioners should be able to provide advice regarding the visual function of drivers in relation to current laws and have a duty to ensure that drivers will have adequate vision to drive safely on road, without injuring themselves or others.

In 2012, the DVLA (Driver and Vehicle Licensing Agency) introduced new regulations on visual standards for driving. The DVLA is an organisation responsible for keeping records of drivers and vehicles in UK and for introducing standards for driving, including visual requirements. Group 1 drivers of cars and motorcycles should now have a visual acuity of at least decimal 0.5 (6/12 measured on the Snellen scale) **AND** be able to read a number plate at 20 metres, with the aid of refractive correction where appropriate (GOV.UK, 2013b). Prior to 2012, the number plate test was the only visual acuity requirement.

The purpose of this thesis is firstly to investigate the relationship between the 6/12 visual acuity limit and the number plate test. Also, the new standards do not state which visual chart should be used to record visual acuity. Different visual acuity charts require different visual tasks and therefore may not record the same levels of visual acuity. This thesis will therefore also investigate if differences exist between visual acuity charts that might be used to assess drivers' acuity. In this initial chapter, concepts underpinning visual acuity and its measurement are described, in order to explain the importance of measuring visual acuity correctly.

Visual acuity is the ability of the eyes to discriminate or resolve spatially organised detail (Tunnacliffe, 2004). The angle at which the visual system can resolve two points as separate is the measurement of the discrimination of details (Tunnacliffe, 2004). Visual acuity is the reciprocal of that angle.

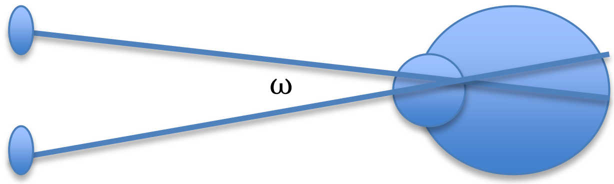


Figure 1.1: Figure indicates the visual acuity. If the separation of the two points is less than angle ω, then the two points cannot be resolved as separate (Tunnacliffe, 2004).

1.1 DIFFERENT TYPES OF VISUAL ACUITY

Visual acuity can be defined in different ways. Detection or visibility acuity occurs if a letter or a symbol can be detected against an illuminated background (Di Salvo, 2006), which constitutes the minimum detectable resolution. Meanwhile, the minimum separable resolution is the minimum separation between two neighboring points or lines that permits the two to be observed separately (Westheimer, 1979). In resolution acuity the main stimulus can be detected and it is a detail that needs to be identified, such as the position of a gap in a Landolt ring (Pointer, 2008). Recognition acuity involves the distinction and naming of symbols such as letters, words or symbols (Bailey and Lovie, 1976), so that patients can distinguish between similar or different letters, such as an A, H or O, C. Therefore, different visual acuity tasks can be used to analyse resolution: vernier acuity describes the ability of the visual system to detect a break between two objects when they are displaced (Rabbetts, 2007). Grating acuity describes the ability of a subject to recognise a series of parallel black and white lines, while in optotype acuity, subjects need to identify test targets which are consisted of letters or symbols (Kniestedt and Stamper, 2003). Snellen, logMAR letter and logMAR Landolt ring charts use optotypes and thus they are used for the measurement of foveal visual acuity. Visual acuity is a standard measure to assess visual function (Ricci et al., 1998).

In this thesis, resolution and recognition visual acuity will be considered. For the purposes of this thesis visual acuity is defined as the clinical measurement of spatial resolving power of the eye as measured by letters or symbols known as optotypes. Clinical visual acuity reflects the ability of the subjects to detect black optotypes against a white background (Visual Functions Committee, 1988), therefore assessing visual acuity. In order to better understand the importance of visual acuity its physiological basis needs to be explained.

1.1.1 Optical factors affecting visual acuity

A combination of optical and neural factors limits foveal visual acuity (Bailey, 2006). For a “normal” eye the effects of optical and neural limitations are approximately equal. Optical limitations arise because the eye does not image a point object as a point on the retina. This is not only due to problems related to focus, such as myopia, hypermetropia and astigmatism, which are common aberrations in the eyes (Vinas et al., 2013), inappropriate accommodation and aberrations of corrective ophthalmic lenses (Bailey, 2006), but also to higher order aberrations of the human eye. Aberrations in the human eye affect the performance of the visual system, by altering the appearance of a stimulus (Chen et al., 2006). Zernike polynomials describe the optical aberrations of the eyes by disintegrating complex wavefronts to fundamental shapes (Meister, 2010). Zernike polynomials consist of modes, which show how much the pupil size affects the shape of the wavefront. The second order aberrations (low order polynomials) include defocus, oblique astigmatism and with and against the rule astigmatism. They usually originate from uncorrected refractive error and cause reduced and blurry vision. They can be corrected by wearing the appropriate refractive correction. There are also “high order” aberrations which are those of third or higher order and describe more complex aberrations, such as vertical and horizontal coma.

Visual acuity is a way of evaluating the quality of an image (Meister, 2010). When optical aberrations are limited, the quality of an image is affected by diffraction (Meister, 2010). Diffraction affects the visual system, so that the eye perceives an image not as a point, but as a small round patch with hazy surrounding rings, even when the eye is optimally focused. The central round patch is the Airy disc. When the quality of an optical image is restricted only by diffraction, the Raleigh criterion for resolution is applied and states that “two Airy discs can just be resolved when the center of one lies at the edge of the other” (Bailey, 2006). Hence, two Airy discs should not be close to each other, in order for the observer to be capable of distinguishing the components of a stimulus (Bolte and Cordelieres, 2006). The optical limitation on resolution caused by very small pupils is due to diffraction (Campbell and Gubisch, 1966).

Airy disc size depends on pupil size: as pupil size is reduced, the blur circle formed at the retina is reduced (Wang and Ciuffreda, 2006), resulting in greater depth of focus (Atchison et al., 1997) and a clearer image (Charman and Whitefoot, 1977). As the pupil diameter increases, image degradation due to aberrations increases (Campbell and Green, 1965). For optimal visual acuity, the optimal pupil size is approximately 2.5mm (Westheimer, 1964), and according to Elliott et al. (1995) visual acuity is $6/4^{-1}$ in 25-29 years old and declines to $6/5^{+1}$ in 50-60 years old. A subject with 6/4 visual acuity will achieve 6/6 or 6/5 on truncated charts (Elliott et al., 1995).

Foveal acuity is optically limited, but neural factors also affect foveal visual acuity.

1.1.2 Neural factors affecting visual acuity

Neural factors restrict resolution acuity in the fovea, due to the density of receptors and the neural interactions which take place in the retina and the visual pathways (Bailey, 2006). Despite optimum optical resolution, reduced visual performance may be caused due to the finite number of cones in the retina (Charman and Chateau, 2003). The neural limit to resolution differs for each subject, since foveal cone density varies between individuals (Curcio et al., 1990). Curcio et al. (1990) found that cone densities in their sample varied between 98,000-324,000 cones/mm^{2}.

Visual resolution and recognition, which this thesis is considering, can be measured by the visual acuity (Campbell et al., 1966). Visual resolution and thus visual acuity are affected by different parameters, which are presented below.

1.2 THRESHOLD DETERMINATION

Different psychophysical threshold measurement techniques can be used to assess visual acuity, and the method used will affect the value of visual acuity (Camparini et al., 2001). In traditional psychophysical methods, subjects are given two alternatives from which to choose in order to demonstrate that a stimulus has been seen correctly. For example, they may have to choose if a stimulus was present or absent, or presented in the first or second of two time intervals. This is termed ‘forced choice’, and in the case of there being two options, ‘two alternative forced choice’ (2AFC) (Blake and Sekuler, 2006; Bogacz et al., 2006). In terms of acuity measurement, subjects usually have to correctly identify a letter or optotype orientation from a defined selection, such as 10 different letters. If the subject is told what letters are available and is restricted to making a choice from that set, then this represents a 10AFC task. If the subject can make a choice of any letter in the alphabet, it can be argued that this represents a 26AFC task.

Having outlined how determination of a correct response can be achieved, the way in which these responses can be dealt with to reach a threshold measure can vary. Fechner’s three behavioural methods to measure thresholds are the method of adjustment, the method of constant stimuli and the method of limits and are presented below in terms of visual acuity measurement (Blake and Sekuler, 2006).

Firstly, in the method of adjustment, the observer’s task is to adjust the size of a target so that it is just recognisable. Then, the size is reduced, so that the target is unrecognisable and finally the size is increased again till the point where the target is detectable. The size specified by the observer is a measurement of the threshold. The procedure is then repeated, by resetting the original size and the measurement of threshold will be the average of those repeated settings.

Another method of threshold determination is the constant stimuli method. Different fixed set of targets appear numerous times, sometimes the size is large and sometimes it is small. The task of the subject is to correctly recognise the target, according to its size. The threshold value is determined as the size of the target at the point at which a certain proportion of responses (e.g. 50%) are correct (Blake and Sekuler, 2006).

The method of limits is another way to determine the visual threshold for resolution or recognition. In the methods of limits there is a stimulus, which changes in size (Ehrenstein and Ehrenstein, 1999). If the stimulus starts at a small size that cannot be seen and enlarges to the point at which it can be seen, this is described as an ascending method of limits. However if the target starts at a larger size that can be identified and decreases to a smaller size that cannot be seen, then the method of limits is described as descending (Blake and Sekuler, 2006). The descending method of limits is used for the measurement of visual acuity for the purpose of this thesis. Targets are presented in size order from large to small and once the participant is not able to identify the target at the smaller sizes, the participant should stop reading.

The value of the smallest stimuli read is considered as the value of the visual acuity of the participant.

The method of limits is most commonly used in clinical acuity measurement. However, the staircase method is an alternative method sometimes used.

In the staircase method, the size of the target is larger than that of the expected threshold and it is decreased until the point at which the subject cannot identify the target. Then, the direction of the stimulus changes and the size increases until the response of the subject alters and then the procedure is repeated from the beginning. Threshold is measured as the average of all the sizes at which the response of the subject changed (Blake and Sekuler, 2006). However, the subject's responses may be affected by the fact that the pattern of the trial changes direction. In order to reduce this influence on the knowledge of the direction, Cornsweet (1962) introduced the idea of presenting various simultaneous interfering staircases, so that the subject does not know what to expect.

1.3 MEASUREMENT OF VISUAL ACUITY

Clinical visual acuity can be tested with charts constructed of optotypes (Arditi and Cagenello, 1993). In this thesis, distance visual acuity will be measured using Snellen, logMAR letter, logMAR Landolt ring and MNRead charts.

Visual acuity can be expressed in different ways. Snellen notation represents the viewing distance (often 6m) as the numerator and the distance at which the letters subtend 5 arc minutes (Keirl, 2007), or the detail of the letters subtends 1 arc minute (Rabbetts, 2007), as the denominator. Therefore, Snellen notation can be defined as

$$VA = \frac{TESTING\ DISTANCE\ IN\ METRES}{DISTANCE\ AT\ WHICH\ THE\ HEIGHT\ OF\ LETTERS\ ON\ THE\ SMALLEST\ ROW\ READ\ \ IS\ 5'}$$

As an example, a subject reading a Snellen chart at 6m and identifying letters which subtend 5 minutes of arc at a distance of 6m, will have a visual acuity of 6/6 (Tunnacliffe, 2004).

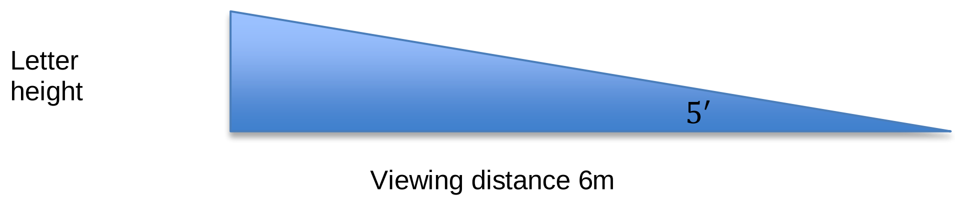


Figure 1.2: Figure shows that a letter subtends 5 min of arc at a viewing distance of 6m and thus the letter height can be determined (Tunnacliffe, 2004).

Decimal notation is derived simply by expressing the Snellen fraction as a decimal value.

LogMAR notation represents log_{10} of MAR, where MAR is the angular subtense of a limb of an optotype in arc minutes (Rabbetts, 2007). If the Snellen numerator is divided by the denominator, the result is the size of the letter in minutes of arc. If the letter is presented on a 5 unit high grid, the angular subtense of the limb of the optotype will be $1/5^{th}$ of this value.

Comparisons of these visual acuity notations are presented in Appendix 1.

The design principles of the different charts used in this study for measuring distance visual acuity are presented below.

1.3.1 Snellen chart

The Snellen chart was introduced in 1862 (Snellen, 1862) and is the most commonly used chart in UK optometric and ophthalmological practice (Elliott, 2007). The Snellen chart does not have a standard format: the choice, number and sizes of letters are different and depend on the manufacturer (Elliott, 2007). For example, some charts include a 6/7.5 line whereas others do not, and some charts truncate at 6/5 while others go to 6/4.

In spite of its popularity, the Snellen chart has limitations. The Snellen chart has an irregular progression of letter sizes. A typical visual chart constitutes of 10 lines of letters (Rabbetts, 2007), and the difference in size between each pair of lines differs. For example, a letter in the 6/36 line is 52.4mm in height, while a letter in the 6/24 line is 35.0mm in height. Thus, a letter in the 6/36 line is 1.50 times (50%) bigger than a letter in the 6/24 line. However, at the bottom of the chart, the 6/6 line has letters of 8.73mm height and the 6/5 line has letters of 7.27mm height. Hence, the letters in the 6/6 line are 1.2 times bigger (20%) than letters in the 6/5 line. Between 6/9 and 6/12 line there is a 30% jump in letter size and between 6/6 and 6/9 there is a 50% jump in letter size (Rosser, 2013). Therefore, the size progression is not linear, and there is a greater difference in height between the letters of some lines such as the 6/36 and 6/24 as compared to at the lower lines of the chart.

Usually a single letter is placed on the top of the chart and an additional letter is added to most lines (Tunnacliffe, 2004). The font style used for the original Snellen chart was serifed, in that the ends of the letter limbs have a cross-stroke (Tunnacliffe, 2004). However, current Snellen charts use sans serif letters and the design is on 5×4 grid (Tunnacliffe, 2004).

As mentioned above, the Snellen chart does not follow a specific format. However, it should comply with British Standard. The most recent standard is BS 4274-1 (2003), which states that letters should be presented on a 5×5 grid and the letter choice is C, D, E, F, H, K, N, R, P, U, V, Z. However, most Snellen charts are constructed following the previous British Standard BS 4274-1 (1968), which states that the chart construction should be based on a 5×4 grid and the letter selection is D, E, F, H, N, P, R, U, V, Z, excluding C and K. It is suggested that the minimum range of letter sizes should be between -0.1logMAR (6/4.8 Snellen) and 1.0logMAR (6/60 Snellen) (BS 4274-1:2003). The British Standard guidelines aim to reduce the drawbacks of the construction of the Snellen chart.

Some letters of the alphabet can be recognised more easily than others, for example D and E are easier to read compared to A, J or L (McMonnies and Ho, 2000). Therefore, the British Standard letter selection was chosen to minimise differences in ease of recognition. However, the letters used are not of equal recognisability. The ability to accurately identify letters or symbols and the ease of recognition of those characters is described by their legibility. Legibility can be measured in different ways, such as decreasing contrast to find the threshold (Luckiesh and Moss, 1939), increasing viewing distance to set the threshold

(Tinker, 1963), reducing time for which characters are viewed to find the threshold (Tinker, 1963) and defocus (Weiss, 1917). Luckiesh and Moss (1939) have rated some of the British letters according to their relative legibility. F was the least legible letter, followed by E and C. The letter D was the easiest letter to be recognised.

For the spacing of letters, BS 4274-1 (2003) suggests that letters should be presented at the centre of the chart. The space between the letters on each line should be equivalent to the width of the letters on the specific line. The spacing between lines should not be less than 20mm or less than the height of the letter in the line below, whichever of the two is the smallest.

The measurement of a patient's vision ought to be an equivalent task on each line of the chart. This is not the case with the Snellen chart, due to the difference in the number of letters and the irregular progression of letter sizes and spacing (Kaiser, 2009). The difference in spacing between the letters and rows are the main flaws of this chart (Falkenstein et al., 2008). Visual acuity is better for single letters than for lines of letters, due to contour interactions and fixational movements of the eye (Manny et al., 1987). Due to the crowding phenomenon, patients will recognise single letters more easily than many letters presented together (Kaiser, 2009), and crowding differs across a Snellen chart, due to the varying number of letters per line and the varying spacing on each line (more details will be given in section 1.4.5).

The advantages of measuring visual acuity with the Snellen chart are that assessment is simple and not time consuming. The process of recording visual acuity can be straightforward if it is done per line. Additionally, from a clinical perspective it can be easier to work out which line a patient is reading with a Snellen chart than with other designs, since there are different numbers of letters per line. It is easier to work out which line a patient is reading, since Snellen chart does not have the same number of letters on each line and thus if the patients reads more letters on a line, instantly the Eye Care Practitioner knows that the patient is reading one of the bottom lines of the chart.

The Snellen chart can be scored in various ways. The most common method of scoring is the 'line assignment' method, which attributes the value of the lowest line read on the chart on which at least half of the letters on the line are read correctly (Bailey et al., 1991; Vanden Bosch and Wall, 1997; Rosser et al., 2001; Laidlaw et al., 2003; Falkenstein et al., 2008; Kaiser, 2009). Another method of scoring the Snellen chart is by attributing the value of the lowest line read by subjects in which all the letters were correctly read. This is a more conservative approach to scoring, but is more consistent with the visual standard for driving of being able to achieve 6/12, which implies that all the letters on the line should be read correctly (personal communication, Geoff Roberson, Association of Optometrists). The latter method of scoring can provide more accurate results, since it is known that if the participant is attributed 6/12 visual acuity, then the participant has read five letters. With the line assignment method, participants may have read three, four or five letters out of 5 on a 6/12 line to be attributed the same acuity. The irregular size progression and the different number of letters on each line mean that it is not possible to find a standard value to attribute to each letter, if aiming to score the chart on a letter-by-letter basis.

Test-retest variability (TRV) (more details will be given in section 1.4.1) has been described using different terminology between studies in the literature. The variability in scores when multiple measurements are taken from the same subjects (Kaiser, 2009) is described in this thesis as the TRV for consistency, but terms such as repeatability or test-retest discrepancy have also been used in the literature for the same purpose. TRV and its importance will be presented for each chart, expressed in logMAR units.

The test-retest variability (TRV) for the Snellen chart has been defined by literature in terms of the line assignment method of scoring. The Snellen chart has been found to have a TRV of ± 0.33 logMAR (Rosser et al., 2001; Lim et al., 2010). Gibson and Sanderson (1980) reported that 13% of participants had a variation of 2 lines on repeated testing.

As will be seen by comparison to the other charts to be described, the TRV for the Snellen chart is high. In order to show that a genuine change in the visual acuity of participants has occurred, a relatively large change in acuity is required to be greater than the intrinsic variability of the chart.

1.3.2 LogMAR letter chart

LogMAR charts were first designed by Bailey and Lovie in 1976, as standardised charts for clinical trials and research that overcome many of the issues of the Snellen chart (Bailey and Lovie, 1976). In 1982 the Early Treatment Diabetic Retinopathy Study chart (ETDRS) was introduced, which followed the construction of Bailey-Lovie charts, but uses different letters (Ferris et al., 1982).

Bailey-Lovie and ETDRS charts are similar in several respects. Both have a progression of letter size between lines of 0.1 log units (Bailey and Lovie, 1976; Ferris et al., 1982). Moreover, each line of the chart contains five letters, the letter spacing is equal to the letter width, and the row spacing is equal to the letter height of the line below (Bailey and Lovie, 1976; Ferris et al., 1982).

The design of letters on visual acuity charts is usually on 5x4 or 5x5 grids. Therefore, on a 5x5 grid, the letter O has 1 unit line width, while the space at the center will be a diameter of 3 units (Rabbetts, 2007). However, on a 5x4 grid, the letter O has 2 units of central space. Thus, the legibility of the same letter will differ on different grids. On 5x5 grids, letters can be recognised more easily since they are wider compared to 5x4 grid (Figure 1.3).

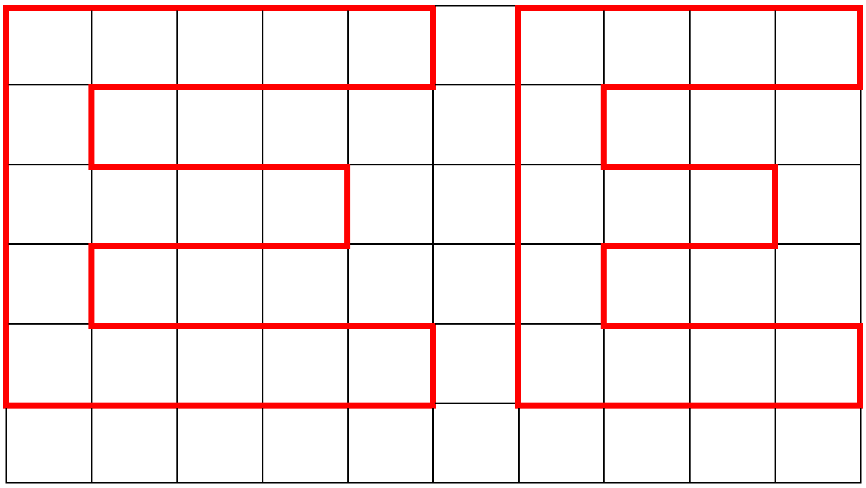


Figure 1.3: Left hand side: 5x5 non-serif E, right hand side: 5x4 non-serif E (Rabbetts, 2007).

Letters are more easily identified on the ETDRS chart than the Bailey-Lovie chart, since ETDRS letters are presented on a larger 5×5 grid compared to the 5×4 grid used in the Bailey-Lovie chart. Letters are slightly wider and so more legible and are less crowded.

The Bailey-Lovie chart (Bailey and Lovie, 1976) uses the 10 British Standard letters D, E, F, H, N, P, R, U, V, Z as stated in BS 4274-1 (1968), which are presented in a 5×4 non-serif format. The Early Treatment Diabetic Retinopathy Study (ETDRS) chart (Ferris et al., 1982) uses the Sloan letter set C, D, H, K, N, O, R, S, V, Z (Sloan et al., 1952). The letter construction is non-serifed and presented on a 5×5 rather than a 5×4 grid (Hazel and Elliott, 2002). In addition to Bailey-Lovie letters (5×4) being narrower compared to the ETDRS (5×5), the British Standard letters used in the Bailey-Lovie chart are more difficult to read compared to Sloan letters (Hazel and Elliott, 2002). The 10 Sloan letters have been accepted as standardised optotypes for the measurement of visual acuity in the United States (National Research Council Committee on Vision, 1980). These letters have similar legibility for emmetropes (Ferris et al., 1982) and the acuity levels obtained are similar to the acuities obtained with the elementary standard optotype, the Landolt ring (National Research Council Committee on Vision, 1980). The Landolt ring construction is also on a 5×5 grid (Rabbetts, 2007).

LogMAR charts are scored by attributing 0.02 logMAR for each letter read correctly (Bailey and Lovie, 1976), thus giving each line a value of 0.1 logMAR. Carkeet (2001) recommended for Bailey-Lovie and ETDRS charts to follow line-by-line termination rules, where the subjects should stop after four or more mistakes on a line are made.

Rosser et al. (2001) found a TRV of ± 0.18 logMAR for the ETDRS chart, therefore a smaller change in visual acuity is needed to show significant change compared to a Snellen chart. A change of at least five letters on an ETDRS chart is meaningful and thus letter-by-letter scoring will detect easier a change in visual acuity (Vanden Bosch and Wall, 1997). It has been observed that the Bailey- Lovie chart records poorer (worse) visual acuity than the ETDRS chart by almost 0.03 logMAR (Hazel and Elliott, 2002). Therefore, the charts differ by 1.5 letters, which is not a clinically significant difference. Kaiser (2009) reported a difference of 0.13 logMAR (6.5 letters) between Snellen and ETDRS charts in favour of ETDRS acuities. However, the ETDRS viewing distance was 4m, while the Snellen was at 6m which may have contributed to the discrepancy.

1.3.3. LogMAR Landolt ring chart

BS EN ISO 8596:2009 states that the standard optotype for visual acuity assessment is the Landolt ring. It is not suggested to use the Landolt ring as a standard for clinical trials (BS EN ISO 8596:1996 BS 4274-2:1996) but it is a standard to which other optotypes should be correlated. The Landolt ring optotype can be presented following either Snellen or logMAR chart designs, but for the purposes of this thesis the Landolt ring was presented in a logMAR chart design. The Landolt ring represents resolution rather than recognition acuity as letter identification is not required. The subject is trying to resolve the letter C and identify where there is a gap in the black circumference of the letter. Therefore, the Landolt ring represents a “purer” acuity test compared to charts that require letter identification. Subjects reading letter charts may be able to recognise letters because of their shape. With the Landolt ring, subjects need to use their vision to resolve the position of the gap, making this a more difficult task.

Another optotype that can be used to assess resolution acuity is the Tumbling E. The common feature of these optotypes is that subjects need to detect the orientation of the letter (Reich and Ekabutr, 2002) and since a single stimulus is presented, alteration in resolution is prevented (Schrauf and Stern, 2001). Bondarko and Danilova (1997) conducted an analysis regarding the comparison of the two and found that the Landolt ring can be resolved more easily than the Tumbling E. Therefore, the visual acuity levels recorded with Landolt ring will be better compared to those recorded with Tumbling E.

The outer diameter of a Landolt ring subtends an angle of 5 minutes of arc and is presented on a 5×5 grid. Its limb width and the gap subtend an angle of 1 minute of arc at a specified viewing distance (BS EN ISO 8596:2009). The letter size follows the construction of the logMAR charts. Therefore, there is logarithmic progression between lines of 0.1 log units (Bailey and Lovie, 1976, Ferris et al., 1982).

The spacing of the rings on the chart follows the rules of logMAR charts as well. The letter spacing is equivalent to the width of a letter C, while the line spacing is equal to the height of the C on the line below (Bailey and Lovie, 1976, Ferris et al., 1982, BS 4274-1:2003). Thus, the crowding phenomenon is constant across the chart, unlike with Snellen chart.

The Landolt ring can be presented in four positions (two vertical, two horizontal), or in eight positions (four orthogonal and four oblique). The eight position presentation of the Landolt ring can be affected more by complex astigmatic prescriptions (both oblique and orthogonal astigmatism) compared to a four position presentation. Additionally, subjects are less likely to be able to correctly guess the orientation in an 8AFC presentation. However, the four position presentation of the Landolt rings has advantages as well. It is easier to explain the procedure of the test to the subject and it is not difficult for the subject to identify the position of the rings, since all the positions are straight.

The Landolt ring's main advantage is that it includes a single aspect of detail that is characterised by the difference of its presentations (4 or 8 positions) (International Council of Ophthalmology, 1988) and that there is no impact regarding the shape recognition in comparison to letters or numbers (Grimm et al., 1994).

The drawback of the Landolt ring is that uncorrected astigmatism will affect the ability of subjects to identify the direction of the gap in the letter in some orientations more than in others, depending on the axis of astigmatism. Vertically and horizontally oriented stimuli are easier to recognise compared to oblique orientations (Appelle, 1972), as acuity for the principal meridians is better than oblique meridians. These differences are due to the neural architecture (Van Essen and Anderson, 1995): there are more cells in the visual cortex that deal with the vertical and horizontal targets and they are responsible for the better recognition of straight positions (Blakemore and Campbell, 1969). Therefore, subjects may find it more difficult to detect the gap in the oblique positions compared to the straight ones.

For each ring read correctly, a score of 0.02 logMAR units is attributed, which is the same scoring method as the logMAR letter charts. Since the Landolt ring chart follows the construction of ETDRS chart, Carkeet (2001) suggested to stop after four or more mistakes are made on a line (line-by-line termination rules).

Raasch et al. (1998) compared British letters, Sloan letters and Landolt rings on charts following the construction principles of Bailey and Lovie. Five letters or symbols were presented in each row and each chart had seven rows of letters. The size progression was 0.1 logMAR. Participants did not suffer from pathology. Sloan letter acuity was better than that for Landolt rings by 0.038 logMAR (almost two letters). British standard letters were better than Landolt rings as well by 0.005 logMAR (0.25 letters) (Raasch et al., 1998). In terms of the TRV of each set of optotypes, the Test-Retest Discrepancy scores (SD) for Landolt rings was greatest (0.050 logMAR (2.5 letters)), while for Sloan letters TRV was 0.047 logMAR (2.4 letters) and for British letters was smallest at 0.036 logMAR (1.8 letters) (Raasch et al., 1998). Therefore, visual acuity charts using British Standard letters will have more repeatable acuities compared to Sloan and Landolt optotypes, since the difference in TRV for Sloan and Landolt optotypes is small (2 letters) (Raasch et al., 1998). The test- retest variability is comparing the response of individuals doing the same test twice, whereas the 95% LoA used in this study are comparing the response of individuals doing two different tests once. They are both calculated in the same way (2 x SD).

1.3.4 MNRead chart

Distance visual acuity is usually measured with letter charts, such as the Snellen or logMAR charts described, using letters or symbols, such as the Landolt ring. However, the driving task often requires distance word reading, for example reading road signs. Therefore, it is of interest to consider a distance word reading acuity task, in order to investigate how a driver's letter acuity relates to the ability to read road signs. To the author's knowledge, the relationship between letter and word acuity at distance has not previously been examined regarding driving.

When reading words, the acuity, or the smallest size that can be read, is not the only parameter that can be measured. At larger text sizes, reading speed is not limited by print size and an approximately constant maximum reading speed is maintained (Patel et al., 2011). Maximum reading speed (MRS) indicates how fast a subject can read: 80 words per minute is considered to be the borderline between reading slowly and fluently (Whittaker and Lovie-Kitchin, 1993). As print size decreases, a point is reached at which reading speed starts to become limited by print size and reading speed declines. This size of text is called the 'critical print size' (CPS; Cheung et al., 2008) and is the smallest size sentence for which the MRS is maintained (Patel et al., 2011).

The original MNRead chart (Ahn et al., 1995) is a card based reading chart designed for use at near. In Chapter 4 the creation of a distance reading acuity chart based on the MNRead will be described. In this section the construction and parameters of the near MNRead chart are introduced.

The MNRead chart consists of 19 sentences of size ranging between -0.5 and +1.3 logMAR. To quantify the print size the height of a lower case "x" is used (Mansfield and Legge, 1999). The sentences consist of 60 characters, which include the letters, a hidden period and the spacing between letters, presented across three lines. The text size follows a logarithmic progression of 0.1

logMAR steps, and the font is Times Roman in the English version, in order to represent everyday reading tasks. The sentences do not include complex words. Moreover, between the sentences on the different logarithmic steps there is no constant theme in the text and no punctuation. The chart has two versions with different sentences and has been constructed to comply with both American and British English (Mansfield and Legge, 1999).

Subjects are asked to read sentences aloud as quickly as they can (Legge et al., 1989) at a standard reading distance of 40cm and a stopwatch is used to record the time taken to read each sentence. The words incorrectly read are also recorded (Patel et al., 2011).

Therefore, from the MNRead data RA, CPS and MRS can be calculated.

The reading acuity (RA) in logMAR is estimated by:

RA= 1.4 - (sentences read×0.1) + (number of words read incorrectly× 0.01) (Legge et al., 1985), where 1.4 is one step larger than the largest text size on the chart.

For the purpose of this thesis only the RA data will be presented and analysed, since the analysis of CPS and MRS data are beyond the scope of this thesis.

Previous literature has not explored in great depth the variability of the MNRead chart. Subramanian and Pardhan (2006) provided the TRV using “normal” subjects. The near MNRead chart had a TRV of ±0.05 logMAR (five words or half a line) for reading acuity. The same study compared distance letter visual acuity using the Bailey-Lovie chart and near visual function with the MNRead chart at 40cm. The mean distance visual acuity was -0.07 logMAR (±0.07) and for near reading acuity was -0.12 logMAR (±0.06) (Subramanian and Pardhan 2006). Letter acuity at distance was better compared to near reading acuity, but they were tested in different viewing distances and thus do not reflect a direct comparison. A later study conducted by the same authors, involved participants who were visually impaired. In this case the TRV was higher compared to the normal participants of the previous study at ±0.10 logMAR for reading acuity (Subramanian and Pardhan, 2009).

1.3.5 Summary

In this chapter, four different charts to measure distance visual acuity have been introduced. These use different approaches in terms of chart design, and also different targets such as letters, symbols and sentences. This thesis will assess these approaches in order to investigate to what extent the measures provided by these charts are equivalent to each other and to the number plate test.

1.4 ASPECTS THAT AFFECT VISUAL ACUITY MEASUREMENTS

Visual acuity measurement is influenced by other statistical aspects, which are presented below.

1.4.1 Variation within a test

A stimulus and the neural response to that stimulus are intrinsically variable. However, this variability is essentially the limit to visual discrimination (Laming, 1991). If repeated measurements are taken using the same chart, the measurements will show variability. Therefore, variability will affect discrimination, resulting in differences in thresholds when tests are repeated.

When measuring visual acuity, even if no clinical change in acuity takes place, there will be a discrepancy between measurements, which is called test-retest variability (TRV) (Kaiser, 2009), or repeatability (Elliott, 2007). The greater the TRV, the greater a change in visual acuity is required before it can reliably be concluded that real change has occurred that is greater than the inherent variability of the chart (Kaiser, 2009).

1.4.2 Variation between tests

Agreement between two methods can be described by comparing the differences recorded between observations of the two methods on the same subject (Bland and Altman, 1999). Agreement characterises the degree to which one method differs from the other and if one method can be used instead of the other (Bland and Altman, 1999). The Correlation coefficient indicates the relationship between the two measurement methods (Field, 2009). A high correlation does not necessarily indicate good agreement between the two methods, since the correlation coefficient measures the association of the two methods (Bland and Altman, 1986). Correlation takes into account the range of valid measurements in a population, therefore if the range is huge, the correlation will be higher (Bland and Altman, 1986). Visual acuity can be measured and recorded using different methods, which may not be in agreement with each other. Bland and Altman (1986) suggested comparing the difference between two methods against their mean on a scatter plot. Using this method, the mean difference between two measurements can be determined. By drawing a regression line, it can be examined whether the difference is constant with mean measurement (flat) or if it varies (upward or downward slope). On such a graph the 95% Limits of Agreement (LoA) represent the amount of difference between the two measurements that can be expected given the variability of each measure with respect to the other one. The 95% Limits of Agreement are equal to the mean difference ± 1.96× standard deviation of the differences. The 95% LoA are dependent on the mean and standard deviation of differences being consistent throughout different measurements (Bland and Altman, 1986). The 95% LoA for two charts indicate that 95 out of 100 times the value of the data are expected to be included at those limits. The difference is plotted against the mean, and not each of them separately, because the plot will show whether there is a difference between those two methods, if this difference is consistent between measures and if this difference is significant. 95% LoA show an estimation of the data recorded for the whole population (Bland and Altman, 1986). The better the consistency of the observer, the sensitivity of detecting change will increase (Bailey et al., 1991). Confidence Intervals (C.I.) show the confidence in the precision of the position of the mean difference derived when calculating the 95% LoA.

1.4.3 Psychometric function

In relation to visual acuity, the psychometric function associates the frequency of correctly observing a stimulus to the stimulus size. As the size of the stimulus increases, the ‘frequency of seeing’ becomes greater (Laming, 1991). Figure 1.4. indicates the psychometric function from a hypothetical experiment, which aims to measure a contrast detection threshold (Kingdom and Prins, 2010).

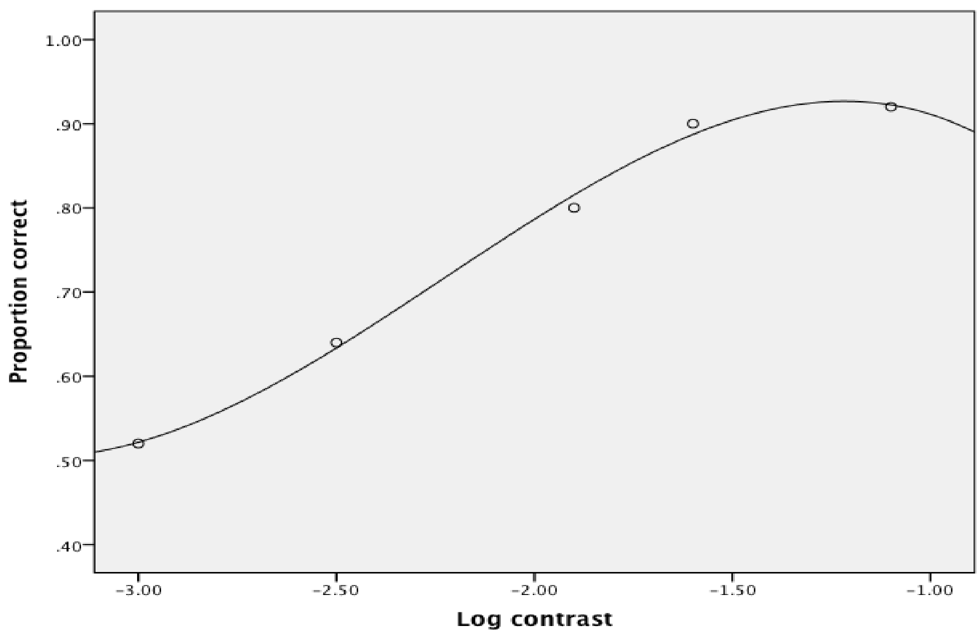


Figure 1.4: Psychometric function (Frequency of seeing curve) from a hypothetical experiment, aiming to measure a contrast detection threshold (Kingdom and Prins, 2010).

In Figure 1.4 the proportion of correct responses (for every stimulus contrast) is represented on the y-axis against the contrast on the x-axis. Fifty trials were performed for each stimulus and the contrast at which the proportion of correct responses reaches a criterion is described as the threshold contrast (Kingdom and Prins, 2010). In this hypothetical experiment, the threshold contrast is set at 0.75 or 75%. Thus, thresholds vary depending on which point on the psychometric function is chosen as representing threshold. In the present study with method of limits data and the Snellen chart, threshold is set either at 100% (full line method), in order to comply with the method of scoring suggested by the DVLA or at 60% (line assignment method), in order to comply with the method of scoring (3 of 5 correct) used by the previous literature.

1.4.4 Luminance

Visual acuity measurements change under different external and internal illumination conditions on visual acuity charts (Jackson and Bailey, 2004). The luminance of the chart should be even and not less than $120\ cd/m^2$ (BS 4274-1:2003). If the illumination across the chart is not even, the difference should not exceed 20%.

1.4.5 Crowding phenomenon

The closer that letters are placed together, the greater the crowding phenomenon, which is the difficulty faced by the subject in correctly identifying a target when other targets are near (Tripathy and Cavanagh, 2002). Flom et al. (1963a) investigated contour interaction both in normal and amblyopic patients by presenting a Landolt C ring with flanking contours horizontally and vertically. The closer the flanking contours were to the optotype, the more resolution was reduced, with a maximum effect reached when the flanking contours were 0.4 diameters of a letter away (Simmers et al., 1999). Therefore, when many optotypes are presented next to each other, they can act as distracters reducing the visual acuity.

The crowding phenomenon is not consistent across the Snellen chart, due to the different number of letters on each line. However, in logMAR charts the crowding phenomenon is consistent, due to the same number of letters on each line, apart from the upper lines. Even on a logMAR chart the end letters will be less crowded than the central ones, but at least the effect is much the same on each line.

1.4.6 Scoring systems

The charts have different scoring systems. Instead of using qualitative characteristics, such as high, moderate or low to describe the visual acuity, numeric scales or grading systems are available (Bailey et al., 1991). For example, the charts can be scored by attributing a specific value of units for each letter or by the smallest line that the subject was able to read.

As mentioned before, the Snellen chart can be scored by the line assignment method or the full line method, while ETDRS and Landolt ring charts are scored on a letter-by-letter basis. The MNRead chart is scored in a different way, by using the mathematical formula of Legge et al. (1985) (see section 1.3.4), since this chart is dealing with words and not optotypes. Although this is a way of providing a word by word scoring for the chart, is not dissimilar to logMAR.

The method of scoring impacts both on the score and the TRV (Raasch et al., 1998). Scoring systems that follow the full line method have smaller levels of TRV (Vanden Bosch and Wall, 1997).

1.4.7 Termination rules

Termination rules define when to stop asking the patient for further choices, and are a separate consideration from scoring rules. One common method of termination is to stop the patient once they have made a specific number of errors on a specific line (Carkeet, 2001). In this case, patients are permitted to attempt to finish reading the line (Carkeet, 2001). This type of termination rule is known as a line-by-line termination rule.

An alternative termination strategy is to apply letter-by-letter rules. There are two categories of letter-by-letter termination rules. If a patient completes a line of letters and makes a set number of errors on the chart, letter-by-letter (complete line) rules are applied (Carkeet, 2001). Nevertheless, true-letter-by-letter termination rules are applied when a patient is not allowed to complete a line after a set number of mistakes have been made (Carkeet, 2001).

It has been reported that letter-by-letter (complete line) rules provide similar results to line-by-line termination rules, but when the patients are forced to attempt all the letters or symbols on a chart, the appropriate termination rules ensure that threshold biases are eliminated (Carkeet, 2001). Additionally, letter-by-letter (complete line) rules provide greater average letter-by-letter scores.

Another type of termination rule that can be applied both to Snellen and logMAR charts is to stop when the subjects make a whole line of errors and cannot read further (Kaiser, 2009).

For the purpose of this thesis the termination rules followed for the Snellen chart were to stop if only one letter was correct on a line. For logMAR letter and logMAR Landolt ring, the termination rules were to stop after four mistakes on a line were made. Although the Snellen and logMAR charts have different numbers of letters on each line, the same termination rules were applied so that it is easier to compare the results obtained.

1.4.8 Guessing of letters

Subjects may become familiar with the letters used on acuity charts, since there is a fixed set of letters. Therefore, subjects with good levels of acuity may be able to guess the letters until they make it to the line of their threshold acuity (Raasch et al., 1998) or even go beyond the threshold line. Since there are groups of similar letters, for example the round shaped letters D, C, O (McMonnies, 1999) there is a good chance that the participant can guess such a letter from its shape.

For Snellen and Sloan charts that are comprised of 10 letters there is a 1 out of 10 (10%) chance for the participants to guess letters on the chart correctly. For Landolt symbols there is a 1 out of 8 (12.5%) chance of guessing the position correctly. Additionally, letters of similar legibility should be included on the charts and the greater the number of letters on the chart, the less is the chance for the participants to guess them correctly.

If the participants are not aware of which letters are used on the chart, in cases of Snellen and ETDRS charts, then they have to guess from all the letters of the alphabet, therefore they have 1/26= 3.85% chance of guessing correctly. It is really important to instruct appropriately the subjects, in order to obtain reliable results. In this study, participants were informed which letters were presented in the charts before they started reading.

CHAPTER 2: VISUAL ACUITY AND DRIVING

More than 90% of the sensory contribution while driving is thought to be visual (Hills, 1980), and drivers need to be able to respond quickly to different circumstances that may occur on the road (Chisholm et al., 2008). Driving is an important everyday task (Potamitis et al., 2000) and since vision is essential for driving, accidents caused while driving can be associated with problems related to vision (Johnson and Wilkinson, 2010; Owsley, 2010). However, since driving is a complicated task, it is difficult to estimate the appropriate visual acuity needed for safe driving (Chisholm et al., 2008). Nonetheless, visual standards of some level need to be in place to try to ensure that drivers have a level of vision that is compatible with safe driving. This chapter outlines the visual standards for driving in the UK and Europe.

Two main elements are usually tested in studies relating driving and vision: the driver's safety and performance. Safety is related to road accidents and injuries, while performance is associated with the reactions of a driver whilst driving (Owsley and McGwin, 2010). In terms of visual function, visual acuity is the basic test performed for drivers, in order to investigate whether or not they are eligible to drive (Wood, 2002). Having poor visual acuity is associated with a greater rate of road accidents (Hofstetter, 1976). In the study of Hofstetter (1976), drivers were divided into those with poor (if the scores were below the lower quartile) and those with good (if the scores achieved were above the median) visual acuity and they were asked to report the number of accidents that they were involved in over a period of one year. The number of drivers with poor acuity who were involved in three or more accidents was almost double the number of drivers with good acuity involved in the same number of accidents. Other studies have also related reduced vision with accident rates. Owsley et al. (1991) and Ball et al. (1993) found that older drivers with visual impairment had more chances of causing an accident compared to those who did not have reduced vision. Burg (1967, 1968) found that poor vision did not affect the accident rates for young and middle- aged drivers. However, for older drivers, visual acuity was related to accident rates. Gresset and Meyer (1994) observed that a higher rate of accidents occurred in drivers with reduced binocular vision. However, poor visual acuity may not significantly influence the ability to read road signs: Fonda (1989) found that eight people who were considered as partially sighted (6/60 visual acuity and 120 degrees of visual field) were able to read six traffic symbols from a distance at which a vehicle at 40mph (miles per hour) could stop safely.

Vision generally deteriorates with increasing age and thus driving performance maybe influenced (Keefe et al., 2002; Strong et al., 2008) although older drivers are likely to have more driving experience. Wood and Mallon (2001) assessed the relationship between vision and driving performance for drivers of different ages in traffic situations. A professional driving instructor and an occupational therapist scored the performance of drivers. Younger and middle- aged drivers with normal vision had better driving performance compared to older drivers with or without reduced vision. The driving instructor particularly scored older drivers with visual impairment as making more mistakes while driving compared to the other age groups (Wood and Mallon, 2001). The older visually impaired group of drivers was not able to detect signs, signals and other road users. Changes in vision happen at a gradual rate, therefore older drivers may not notice a reduction in their vision (Wood, 2002). However, Charman (1997) reported that younger drivers cause more accidents on the road, despite having generally better visual acuities than older drivers, which contradicts the previous mentioned studies. This may not be related to visual acuity, but to the fact that younger drivers may not be able to react to some road conditions, such as bad weather conditions, or due to lack of driving experience.

Higgins and Wood (2005) indicated that reduced acuity was responsible for 50% - 60% of the variance in sign recognition and the ability to avoid objects. In the same study optical blur was used to reduce acuity and observe driving performance. Reducing acuity with optical blur impacted on the driving time (slow driving) by 30%, on sign recognition by 58% and on hazard avoidance by 61% (Higgins and Wood, 2005). Thus, previous studies have shown that driving performance is associated with visual function.

Visual acuity is measured statically in the test room, but for on road conditions dynamic visual acuity is crucial. The ability of the visual system to analyse details of objects which are in motion declines with age, and dynamic visual acuity is associated with accident rates to a greater extent than other visual functions (Wood, 2002). However, in the case where uncorrected refractive error is the only origin of visual reduction, static acuity will be adequate to investigate the discrepancy of driver's performance in relation to sign recognition and hazard avoidance (Higgins and Wood, 2005).

Vision is crucial for driving performance and the reduction of accident rates as suggested by the above studies. Despite visual functions such as dynamic visual acuity being potentially more relevant to the driving situation, the need for visual standards that can easily be implemented and replicated means that stable visual acuity and static visual fields are the primary visual standards for driving around the world.

2.1 UK STANDARDS

In the UK there are different types of driving licences and the regulations differ according to the type of vehicle driven. Driving licences for road conditions are divided into two groups. Group 1 applies to drivers of cars, motor cycles and vehicles driven in private capacity (GOV.UK, 2013a). Group 2 applies to drivers of large lorries and buses and also vehicles driven commercially (GOV.UK, 2013a).

2.1.1 Group 1 standards

Drivers must ensure that they meet the standards set by the DVLA for visual fields and for visual acuity. When the eye does not move, the space around a person, which includes all the points that produce perception is defined as the visual field (Rabbetts, 2007). For Group 1 drivers the binocular visual field should be of at least 120 degrees width and should be at least 50 degrees to the right and to the left of fixation (AOP, 2013). A driver should not have a serious defect in the binocular field within 20 degrees of fixation above or below the horizontal meridian (The College of Optometrists, 2013).

The DVLA uses the Esterman binocular visual field test to assess the visual field of drivers (Esterman, 1982). The Esterman test presents an individual bright point at locations within the 120 degrees of the visual field and the candidate should identify when a stimulus is detected, usually by pressing a button (Chisholm et al., 2008). Candidates will fail the Esterman test if they miss a cluster of four or more adjacent points or if there are any lost points within the central 20 degrees (Chisholm et al., 2008). Detailed discussion of the visual field requirements for driving is beyond the scope of this thesis, but has been comprehensively reviewed by Chisholm et al. (2008).

In terms of visual acuity, changes have been made to the UK standard over time, and these are outlined below.

The Motor Car Act was introduced in 1903, in order to register cars and make sure that drivers held a driving licence, which they were eligible for at the age of 17. No test of vision or of driving ability was required to hold the driving licence (The Motor Car Act, 1903).

The number plate test, which was introduced in 1935, is the main visual standard that has been needed for those who want to acquire a Group 1 driving licence (Charman, 1997). The standard that applied from 1981 (Statutory Instrument No. 952, 1981) stated that the applicant should have the ability to read in good daylight, wearing spectacles or contact lenses if appropriate, a number plate, which has letters 79.4mm (3 1/8 inch) high at 20.5m (67 feet). An example of the style of number plate to which this standard refers is shown in Figure 2.1. The height of each symbol of the number plate (79.4mm) subtends a visual angle of around 13.3 minutes of arc at 20.5m, which is equivalent to a Snellen acuity of 6/15 (Charman, 1997). The Snellen acuity of 6/15 has been rounded, since the calculation for the geometric conversion of the number plate to the Snellen equivalent provides an acuity of 6/16, calculated by:

tan^{-1} (0.016/20.5)=0.045 degrees, 0.045×60=2.68 min of arc, 6/(2.68×6)= 6/16.08 Snellen acuity.

Figure 2.1: UK number plate of the type used between 1983-2001 (Performance Car Guide, 2013).

In September 2001, the design of the UK number plate was changed, as shown in Figure 2.2. The height of the letters reduced to 79.0mm, and the width of the letters is now specified and is 50.0mm. To compensate for the reduced letter size, revised regulations state that the number plate should be read at 20m, as opposed to the previous 20.5m (GOV.UK, 2013b). The stroke width of the symbols of the new number plate is 14 mm. The angular subtense of the stroke width at 20m = tan^{-1}(0.014/20) = 0.04 degrees, 0.04 degrees x 60= 2.41 minutes of arc, 6/ (2.41x6) = 6/14.4 Snellen acuity. Thus, the new style number plate (Figure 2.2) would appear to require slightly better visual acuity to read the symbols than the old style plate (Figure 2.1).

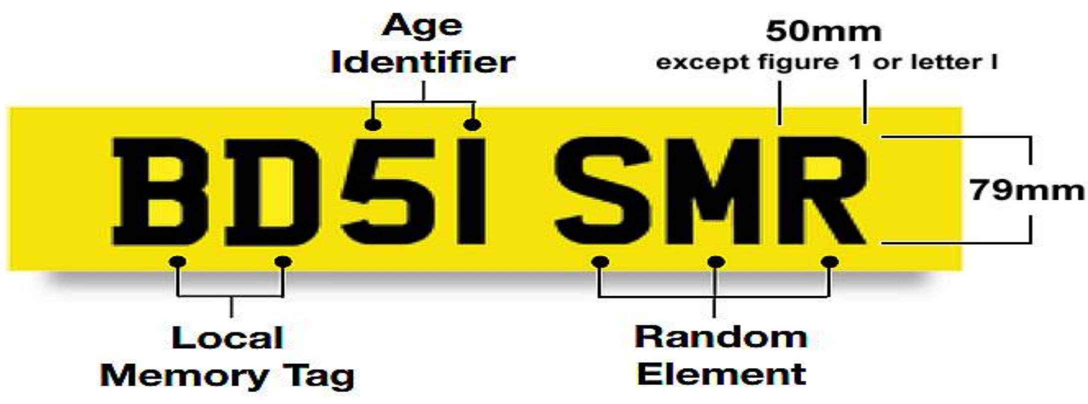


Figure 2.2: Current style of UK number plate (Paine, 2014).

Candidates for a driving licence must demonstrate that they are capable of reading a number plate at the appropriate distance. The ability to read a number plate is only confirmed by an examiner when the actual driving test is taken (Charman, 1997). Candidates must be able to read correctly one of three number plates. If the candidate does not manage to read the first number plate from a distance judged to be in excess of the standard, a second number plate should be read, but the candidate is allowed to move forward. If the second number plate is not read then a third number plate should be read and the examiner should measure the distance at which the candidate manages to read the number plate (Driving Standard Agency, 2013). After passing the driving test, it is the driver's responsibility to check that they can read a number plate at the appropriate distance, and to inform the DVLA if they no longer meet the standard. There are currently no regulations to specify that drivers must attend for eye examinations or have their eyesight checked once they have passed their driving test. The police are allowed to assess the ability of a driver to read a number plate at the prescribed distance, if they doubt that the driver can perform the task (Charman, 1997).

In 2012 the visual standards for driving were changed, partly in order to bring the UK more in line with European standards as will be presented in section 2.2. Drivers must be able to read a number plate constructed after 1st September 2001 at 20m (as defined above) at the beginning of their driving exam, **AND** additionally must have a binocular visual acuity of at least 0.5 decimal (6/12 Snellen) (DVLA, 2012). Spectacles or contact lenses should be worn if appropriate (DVLA, 2012). In 2013, it was specified that the 6/12 acuity should be measured on a Snellen scale (AOP, 2013; GOV.UK, 2013b; RNIB, 2013).

However, it is not specified whether the visual acuity should be measured on a Snellen chart or on other visual acuity charts and described in Snellen notation. In the case where candidates have monocular vision, they should achieve at least 6/12 in that eye (AOP, 2013). Low vision aids, such as a bioptic (telescope) are not allowed to be used while driving in the UK (GOV.UK, 2011).

Candidates who are unable to meet the 6/12 standard are responsible for informing the DVLA that they do not have adequate vision to drive. In a case where a driver is advised by the optometrist to stop driving and the candidate defies the advice, then the optometrist should consider informing the DVLA (The College of Optometrists, 2013).

2.1.2 Group 2 standards

In addition to the visual requirements for a Group 1 licence, candidates for a Group 2 licence (buses and lorries) should have a visual acuity of at least 6/7.5 in the better eye and at least 6/12 in the worse eye (DVLA, 2012). If refractive correction is used, then the visual acuity in each eye must be 3/60 unaided (DVLA, 2012).

In 2013, the following changes were introduced for Group 2 requirements. If refractive correction is worn, the power should not exceed +8.00 Dioptres and this applies only to spectacles, but not to contact lenses (AOP, 2013). The visual acuity should be 6/7.5 in the better eye, but the worse eye can be 6/60 (AOP, 2013). The field requirement is 160 degrees on the horizontal meridian and 30 degrees above and below fixation, with at least 70 degrees of field to the right and left sides of fixation (AOP, 2013). Appendix 2 presents the changes which occurred between 2012 and 2013 regarding the visual requirements for Group 1 and 2 drivers.

2.2 EUROPEAN STANDARDS

The European Union decided to adopt a common policy on driving licences with the aim that people could drive easily from one member state to another, without needing extra proof of their ability to drive. The Council Directive 91/439/EEC (1991) states in annex III that for Group 1 licences the visual acuity needed for driving should be at least 0.5 decimal (6/12 Snellen) binocularly, wearing refractive correction if appropriate, and that the visual fields must be no less than 120 degrees. Additionally, in cases of monocular vision due to loss of vision in one eye, visual acuity must be greater or equal to 6/10. If applicants have a progressive eye disease, they may still qualify for a licence, but they need to have regular eye examinations, in which medical practitioners examine visual function (Council of European Union, 1991). Annex III of the Directive 2006/126/EC (European Parliament, 2006) and the annex of Commission Directive 2009/113/EC (European Parliament, 2009), which amend the Directive 2006/126/EC and are the latest European Directives regarding driving state that candidates should have visual acuity of at least 0.5 decimal (6/12 Snellen) binocularly with the aid of refractive correction where appropriate, along with the other requirements for visual fields. Commission Directive 2009/113/EC (European Parliament, 2009) states that member states can apply stricter laws that the European minimum requirements for driving, but have to comply at least with these minimum requirements. If a member state does not comply with the European Directives, then anyone can make a complaint to the European Commission (European Commission, 2014). The Directive should be applied by the member state and the member state is able to decide how it will comply with the regulations of the Directive (European Commission, 2012). In the case that the date that the Directive should have been applied has passed and appropriate regulations have not been introduced, then the European Court of Justice can take action against the member state or advise how the member state can redress the situation (Europa, 2010).

Thus, the licences will comply both with the national rules of the member state at which they are issued and with the regulations of the European Directives, resulting in the ability to drive in all member states. The national visual requirements for some European countries are outlined below.

In Germany, visual acuity with refractive correction must not be below 6/12 in the better eye and 6/30 in the other eye (Anlagen zur Fahrerlaubnis-Verordnung, 1998). The visual field must be at least 120 degrees horizontally and must be perfect within 30 degrees, with no significant defects in the binocular visual field within 20 degrees of fixation above and below the horizontal meridian (Anlagen zur Fahrerlaubnis- Verordnung, 1998). In cases of monocular vision, or if the acuity of the worse eye is below 6/30, the better eye must have an acuity of at least 6/12 (Anlagen zur Fahrerlaubnis- Verordnung, 1998) and thus in cases of monocular vision the visual requirements stay the same. Therefore, both in binocular or monocular testing of visual acuity the better eye should achieve at least 6/12.

In France, visual acuity must not be less than 6/12 binocularly and the horizontal visual fields must be 60 degrees right and left and vertically must be

30 degrees above and below fixation (Ministere des transports de l'equipement du tourisme et de la mer, 2005). If visual acuity is tested monocularly or if the worse eye is below 6/60, the better eye must have at least 6/10 visual acuity. Night vision is mandatory, thus in order to hold the driving licence drivers should be able to see during night time, but some restricted day time licences can exclude this requirement (Ministere des transports de l'equipement du tourisme et de la mer, 2005).

In Spain, the visual acuity requirements for driving are a best corrected visual acuity of at least 6/12 and the visual field must be "normal" (Disposiciones generales, 2008). Visual acuity cannot be tested monocularly, but there are some exceptions if the visual acuity is at least 6/10 monocularly and medical experts should decide if they will allow driving in cases where changes to mesopic vision or glare occurs (Disposiciones generales, 2008).

In Italy the driver licencing requirements are a binocular visual acuity of at least 6/6 with refractive correction and "normal" visual field, i.e. 120 degrees horizontally (Bron et al., 2010). If visual acuity is tested monocularly the worse eye must be at least 6/30 and candidates must have adequate chromatic sense and night vision (Bron et al., 2010). However, the International Council of Ophthalmology (2006) stated that Italy complies with the minimum visual acuity standard of 0.5 decimal (6/12 Snellen), which contradicts the requirements stated by Bron et al. (2010). Thus, the International Council of Ophthalmology (2006) stated that Italy complies with the minimum visual standards required by the European Union, whilst Bron et al. (2010) stated that drivers in Italy need a higher visual acuity of 6/6 to be able to hold a driving licence.

European countries measure visual acuity of drivers with letter charts, which contain letters which decrease in size and the recommended viewing distance is 3 to 6m (Eyesight Working Group, 2005), but there is no specific letter chart that should be used.

The countries in Europe try to adopt the requirements set by the European Union, but actually have set their own legislation regarding visual standards for driving. Some countries like Germany and France are specific on their requirements for the visual standards for driving, while other countries, such as Spain and Italy, do not specify what they mean by “normal”. It should also be noticed that most of the countries set the binocular visual acuity limit at 6/12. The Commission Directive 2009/113/EEC states that the member states should comply with the most recent directive within one year of the day of the issue of that Directive. The DVLA has already adopted the European 6/12 visual acuity limit whilst at the same time maintaining the UK number plate test, implying that there is equivalence between the visual acuity of 6/12 and the number plate test. The number plate test has been retained in order for drivers to be able to check their vision on their own at any time and in order for the police to be able to perform a quick eyesight test to check vision when they stop a vehicle (Chisholm et al., 2008).

2.3 REST OF EUROPE

All European countries should comply with the minimum requirements for driving. Apart from the UK, there are other countries which perform a number plate test, such as France, Cyprus, the Netherlands and Norway (ECOO et al., 2011).

2.4 REST OF WORLD

The 6/12 visual cut off limit is used worldwide. In Australia the visual acuity limit for the driving licence is 6/12 or 6/18 depending on the local authority (Austroads, 1998). Similarly, in United States 6/12 is the typical visual acuity standard (Fishbaugh, 1995).

2.5 DISCUSSION

Different European countries have different methods of assessing visual standards for drivers. For example, in order to hold a driving licence in UK the candidate needs to pass both a visual acuity test and the number plate test while in Italy the visual acuity test is the only requirement for the driving licence.

The recent change in the UK regulations means that drivers should be able to pass both visual acuity tests, rather than only the traditional number plate test. By making this change, the DVLA is bringing the UK more in line with European directives (Directive 2006/126/EC; Commission Directive 2009/113/EEC*)*. It also shows that the DVLA considers that a visual acuity of 6/12 is consistent with the visual ability required to pass the number plate test. Although the number plate test and the visual acuity test both assess recognition acuity, the tests are not equivalent to each other.

Additionally, the new standards introduced in 2012 did not specify the method of visual acuity measurement that should be used for drivers. In 2013 the DVLA stated that the 6/12 should be measured on a Snellen scale. Hospitals and optometric practices do not always use the same visual acuity charts and although the Snellen chart is one of the oldest and most commonly used charts, Bailey-Lovie and ETDRS charts are becoming more routinely used. In Chapter 1 it was shown that the charts for distance visual acuity are different in construction and thus the results obtained by each chart may make a difference to the visual acuity for the same subject. Therefore, it is important to understand the differences occurring by using different visual acuity measurement methods, as they may influence a driver's ability to meet the required standards.

The European standard for drivers is the visual acuity limit of 6/12 and by setting this as an additional requirement to the number plate test the UK government believes that the number plate test and 6/12 are equivalent (Taylor, 2012). However, it has been reported anecdotally that drivers with best binocular acuity of 6/24 have passed the number plate test (Taylor, 2012) therefore suggesting that, at least in some cases, equivalence of the two tests is not demonstrated. The equivalent visual cut off limit that will exclude, as far as possible, the same people from driving as the number plate test needs to be identified.

Surveys have shown that 2-4% (Culter and Davey, 1965a, Dunne, 1995) or 5-10% (Thomson, 1996) of UK drivers are not able to pass the number plate test and this fact has not altered significantly in the last 30 years. Other countries face the same problems with candidates for driving failing to meet visual standards (Harms et al., 1984). The Finnish Institute of Occupational Health and the Optical Information Centre (Taylor et al., 2010) reported that overall 2.9% of drivers did not achieve the visual requirements for driving and especially older drivers were found to be below the visual standards for the year of 2010. In Finland, 0.8% of drivers were reported with acuity less than 6/12 and 3.8% had acuities between 6/12- 6/9.5 (Taylor et al., 2010). In the same population visual field loss was detected in 0.9% of the population of age 25-44, 1.8% of age 45-69 and 6.3% of age 70 years and above. Furthermore, in France 12% of the driving population do not meet the visual standards stated on the Directives 2006/126/EC and 2009/113/EC for the same year (Taylor et al., 2010).

Slade et al. (2002) investigated whether or not drivers could read easily, without squinting, number plates and road signs under good daylight conditions. With good visibility during daylight hours, 32% found difficulties in identifying high contrast objects, 16% had difficulties reading a number plate and 14% of drivers knew that passengers managed to read road signs more quickly (Slade et al., 2002). An internet survey showed that 90% of 1000 drivers in UK could not recall the minimum legal visual requirements for Group 1, 52% of those drivers admitted they had not tested their vision using the number plate test on their own, and 70% could not state the legal viewing distance for the number plate test (RSA, 2012). Taylor (1997) also found that 97% of drivers questioned did not know the legal distance to perform the number plate test. A survey conducted by the RNIB, the AA, and Novartis Pharmaceuticals (2010) on people over 55 years, showed that 52% drive daily, but 45% had never discussed if their eyesight is adequate to drive with their optometrist. Thus, drivers should become aware of the visual requirements for driving and the importance of having adequate vision to perform such a complex task.

The following chapter will examine the current knowledge on the equivalence of the visual acuity and the number plate test.

CHAPTER 3: VISUAL ACUITY AND THE NUMBER PLATE TEST

As described in Chapter 2, the UK maintains the number plate test as a test of the visual ability of drivers, mainly because it is an easy eyesight test that drivers can perform on their own to check their vision at any time. Police can also test the vision of drivers when they stop a vehicle on road. Currently the UK uses both the visual acuity test and the number plate test for testing vision and thus it is of great interest to examine whether these two tests are equivalent.

People who are borderline for driving, with an acuity in the region of 6/12, are an appropriate group to examine whether, with this level of acuity, they will be able to pass the number plate test and by that means to investigate the equivalence of the visual acuity and the number plate test. Two groups of people may be borderline for driving: people with pathology, and people with uncorrected refractive error.

People with pathology may not have stable vision and thus should seek advice from Eye Care Practitioners on a regular basis, in order to ensure that they are still eligible to drive (Rathore et al., 2012). Studies have shown that ocular pathology has a negative impact in vision and driving (cataract, macular degeneration, retinitis pigmentosa, glaucoma) (McCloskey et al., 1994; Gutierrez and Wilson, 1997; Mangione et al., 1998; Owsley et al., 1999). Keeping refractive correction, such as spectacles and contact lenses, up to date may be crucial in maintaining best corrected vision adequate for driving for people with pathology. However, the majority of drivers who are likely to struggle with the visual acuity standards for driving are people with uncorrected refractive errors such as myopia, hypermetropia and astigmatism. Such drivers may consider that their vision for driving is “good enough” without correction. However, they may not know if this is actually the case. Wood et al. (2014) have found that even small levels of refractive blur negatively influences driving performance and thus driving safety.

A question that optometrists and dispensing opticians are frequently asked is whether people need to wear their refractive correction to drive. Subjects who are borderline cases may not know that they need to wear refractive correction to reach the legal visual standard to drive. Therefore, it is of interest to examine people with uncorrected refractive error, in order to investigate whether they will manage to achieve the legal visual limit with or without refractive correction. This thesis focuses on people with uncorrected refractive error and investigates whether those people who are able to read the 6/12 line on visual acuity charts without their refractive correction are also able to read the number plate test at 20m without refractive correction.

The following sections present the current literature on the ability of subjects with pathology and uncorrected refractive error to read a number plate at different levels of acuity.

3.1 COMPARISON BETWEEN VISUAL ACUITY AND THE NUMBER PLATE TEST

Several clinical studies have focused on comparing visual acuity and the number plate test using subjects with pathology. Only the study of Marsden and Packer (1966) examining the legibility of the number plates has used subjects who did not suffer from pathology but had uncorrected refractive error.

Marsden and Packer (1966) used number plates of 79.4mm high and 57.0mm width and the number plate style was ABC 123D (1963-1983 number plates). The contrast of the characters with the background was low and the characters were silver on a black background. The observers were 18-23 years old. They performed two experiments and on the second experiment, they tested the visual acuity needed to read a number plate at 23m (25 yards). Visual acuity of participants was measured in a darkened room, but the number plate test was performed outside. They suggested that a Snellen acuity of 6/7.5 will ensure success in passing the number plate test performed at 23m (25 yards) in daylight and that with an acuity of worse than 6/7.5 fewer errors will be made while reading a number plate with light characters on a dark background rather than the opposite. The acuity level of 6/7.5 suggested by this study does not seem reasonable, considering that visual acuity and the number plate test were measured under different light conditions and an inappropriate number plate viewing distance was adopted. They attributed an individual score to each character regarding its relative legibility (Table 3.1).

Table 3.1: Relative legibility of letters and numbers (Marsden and Packer, 1966), on a scale of 0-100%, where the greater the score the more legible the character is.

SYMBOL	LEGIBILITY SCORE	SYMBOL	LEGIBILITY SCORE
A	86	**U**	71
B	91	**V**	72
C	94	**W**	89
D	67	**X**	69
E	69	**Y**	61
F	77	**1**	97
G	81	**2**	83
H	73	**3**	85
K	52	**4**	91
L	83	**5**	81
M	74	**6**	73
N	82	**7**	91
O	52	**8**	71
P	85	**9**	78
R	86		
S	63		
T	84		

To the author’s knowledge, there is no other study apart from Marsden and Packer (1966), which has investigated the relative legibility for all the alphanumeric characters used on number plates. Sloan et al. (1952) and Reich and Bedell (2000) investigated the relative legibility of Sloan letters in the fovea, as shown in Table 3.2. McMonnies (1999) investigated the error percentages of a set of 21 characters, which were calculated by dividing the number of times that letter was read in error by the number of times that the letter appeared in the threshold acuity line (Table 3.3). None of these studies provides as much information relevant to this study as the Marsden and Packer (1966) study. However, the results of Marsden and Packer (1966) differ from Sloan et al. (1952) and Reich and Bedell (2000). Generally, Sloan et al. (1952) and Reich and Bedell (2000) attributed higher scores to the characters compared to Marsden and Packer (1966).

Table 3.2: Relative legibility of Sloan letters (Sloan et al., 1952; Reich and Bedell, 2000). The numbers represent the relative legibility of Sloan letters in percent correct identification.

LETTERS	**SLOAN ET AL. (1952)**	**REICH AND BEDELL (2000)**
Z	94.0	91.3
N	91.6	92.5
H	89.3	84.6
R	86.3	91.6
V	84.6	78.5
K	82.1	83.9
D	79.5	54.8
C	71.4	86.4
O	71.0	61.4
S	70.6	82.4

Table 3.3: Error percentage of characters (McMonnies, 1999). At the top of the Table the easiest characters appear and as we move towards the bottom the hardest is to recognize the characters. *0 and O were assessed in the study, but the paper reports both characters as O, making it not possible to tell which one is actually the 0.

CHARACTER	**ERROR PERCENTAGE (%)**
I	1.9
T	2.9
L	5.3
E	7.7
Z	7.8
U	10.5
S	19.2
R	19.6
O*	21.1
P	21.2
V	23.2
O*	23.7
H	24.9
F	26.7
D	36.8
Y	37.4
2	39.3
B	46.9
C	47.4
M	47.4
5	72.0

Drasdo and Haggerty (1981) conducted a study in order to find the visual limit that will ensure success in passing the number plate test using two groups of subjects (30 volunteers and 30 candidates) who had failed to meet the number plate standard. The volunteer group was divided further into 12 subjects who were considered to be visually normal, 10 subjects whose vision was reduced using diffusing goggles, and 8 subjects whose visual acuity was reduced using dioptric blur.

Participants read three British Snellen charts at 6m and also read a number plate. The letters on the number plates were chosen according to the relative legibility of the characters determined by Marsden and Packer (1966), and shown in Table 3.1, and number plates were categorised into high, medium and low legibility.

The number plates used by Drasdo and Haggerty (1981) were of style ABC 123A rather than the current style. The visual requirements for driving at the time of this study were reading the number plate at 20.5m and the character height was 79.4mm (Drasdo and Haggerty, 1981).

The subjects were placed outdoors at a distance at which it would be impossible to read the number plate and then approached the number plate until it was readable. Table 3.4 indicates the chance of passing at different acuity levels. Sensitivity and specificity were not calculated, and the cut offs provided are based on the probability of passing the number plate test.

Table 3.4: Chance of passing the number plate test at different Snellen acuities (Drasdo and Haggerty, 1981).

SNELLEN ACUITY	CHANCE OF PASSING
6/6	100%
6/7.5	99%
$6/12^{+2}$	50%
6/18	6%

The number plate test is criticised for its variability, due to the choice of characters, the changing weather conditions, the design and the contrast as a result of the testing distance (Smith, 1986). The number plate test and the visual acuity test will not fail all the same people, since the two tests are different (Drasdo and Haggerty, 1981). The $6/12^{+2}$ value derived by Drasdo and Haggerty (1981) has been widely used in optometric practice, but provides a 50% chance of passing the number plate test rather than ensuring a certain pass in the number plate test. The new visual acuity limit of 6/12 simplifies the advice that an optometrist gives in the test room, but the equivalence of 6/12 and the number plate test is not firmly established.

A Snellen acuity of 6/12 will fail 0.04% of applicants, while the number plate test will fail 0.1% (Drasdo and Haggerty, 1981). The percentage (0.04%) of applicants who will fail the number plate test with 6/12 acuity was calculated by a graph of the cumulative number of number plate vision test failures and estimated number of candidates against binocular Snellen visual acuity. The number plate test would fail 0.1% of that sample.

From the participants who were unsuccessful in passing the number plate test, 70% would have passed the visual acuity test and of the participants who were successful in the number plate test, 0.01% would have failed the visual acuity test (Drasdo and Haggerty, 1981). Thus, according to Drasdo and Haggerty (1981), in order to fail 0.1% of candidates, considering the cumulative frequency distribution, the most appropriate cut off is $6/9^{-2}$ Snellen acuity. Drasdo and Haggerty (1981) suggested the cut off of $6/9^{-2}$, in order to balance the failures of the number plate test. However, half of their candidates had already failed the official number plate test and thus half of their sample had acuities which would have not passed the number plate test. Therefore, their results do not reflect the different range of acuities that can be met in a driving population.

Currie et al. (2000) examined ophthalmic patients with a corrected visual acuity around 6/12, defined as seeing the full line on the Snellen chart binocularly and no more than two letters on the line below. They found that the chance of passing the number plate test with 6/7.5 acuity was 99% and with 6/18 acuity was 6%. 26% of participants with 6/9 binocular acuity were unsuccessful in reading the number plate test and 34% of participants with 6/12 visual acuity were successful in passing the number plate test (Currie et al., 2000). The number plate test was performed at 20.5m and the number plate style was A123 BCD. Therefore, it was a pre-2001 number plate style (1983-2001). Participants were allowed to attempt the number plate twice. The results of the study indicate that it is difficult to predict the visual acuity that will exclude the same people from driving as the number plate test. This study was performed with subjects who had an eye disease and they might not achieve similar results to normal subjects, although the kind of the ocular disease was not specified (Currie et al., 2000). Again this study did not calculate the sensitivity and specificity of the two tests, but based the results on the probability of passing/failing the number plate test. At the time of their study, the 6/12 visual acuity standard was not in existence and the only visual assessment for driving was the number plate test.

Kiel et al. (2003) conducted a study to assess whether the characters and the background colour used on number plates would affect the difficulty of reading them. They used number plates with 79.4mm high characters (1983-2001 number plate) and the appropriate legal viewing distance was 20.5m. Participants had a visual acuity of 6/9-6/12 (pathology participants), with refractive correction (if worn). The study does not define whether the full line or line assignment method for Snellen acuity was used. Participants read three different number plates starting from a distance of 27.3m and were allowed to move one foot closer to the number plate each time they made a mistake. The number plate test was performed outdoors on sunny days (Kiel et al., 2003). Two identical number plates were then read, one having characters on a white and the other on a yellow background. The results showed that 92.3% of participants read all the number plates at 20.5m, while 96.7% of participants managed to read one plate out of three correctly at the legal viewing distance. The number plate with the easiest legibility, as defined by data from McMonnies (1999), was read by more participants compared to the medium and harder legibility number plates, but the background colour did not have an impact on the participant's performance. Cut offs, sensitivity and specificity for the number plate test were not provided by this study.

A recent study by Rathore et al. (2012) aimed to examine the visual standards in patients with neovascular age-related macular degeneration. The study was conducted using the new style number plate read indoors at 20 m, under artificial light. This does not represent the weather conditions that a driver may face on the road. Three number plates were used for the study: two number plates with a yellow background of 1983-2001 style (A123 BCD) and one number plate with a white background, but the style is not equivalent with any UK number plate style (A12B CDE). Therefore, this study did not use the appropriate number plate style that should be tested at 20m according to the new regulations. Visual acuity was assessed monocularly with an ETDRS chart at 2m and binocularly with a standard Snellen chart at 6m. The charts were not placed at the same viewing distance, which may have affected the results, since one chart tested acuity in the distance, while the other chart measured acuity at a closer viewing distance than would generally be considered consistent with optical infinity. Snellen was scored by giving the value of the smallest line read with no more than two mistakes. Their results regarding the Snellen chart were that with greater or equal to 6/6 acuity, 100% of subjects passed the number plate test, with better or equal to 6/9 acuity there was 68% chance of passing the number plate test, with better or equal to 6/12 acuity there was a 63% chance of passing the number plate test and with less than or equal to 6/18, all subjects failed (Rathore et al., 2012).

Table 3.5: ETDRS acuity in L (letters), the Snellen equivalent and the chance of passing the number plate test (Rathore et al., 2012; Patel et al., 2008).

ACUITY IN LETTERS (L)	SNELLEN EQUIVALENT	CHANCE OF PASSING
At least 80L	6/15	100%
77L-79L	6/19-6/15	85%
70L-76L	6/24-6/19	70%
65L-69L	6/30-6/24	15%
Less or equal to 64L	$\leq 6/30$	0%

The study also suggested that an absolute cut off of 64L or worse (<6/30 Snellen) should be considered as the point where drivers would be advised not to drive (Table 3.5). An acuity of 77L (6/19) was the cut off where there was 85% chance of predicting correctly the ability of participants to be successful at the number plate test (Rathore et al., 2012). This acuity is worse than suggested by Drasdo and Haggerty (1981) and Currie et al. (2000), thus this study recommends to allow people with worse acuity than 6/12 to drive, whilst with 6/19 acuity there is uncertainty whether all the participants will be able to pass the number plate test as well.

The results from the study of Rathore et al., using Snellen chart data, shows that 6/9 Snellen acuity provides a better chance of passing the number plate test compared to 6/12. However, the ETDRS chart shows that a 6/15 Snellen acuity will be adequate to pass the number plate test. Since the DVLA suggested that 6/12 is the appropriate visual cut off limit that will exclude the same people from driving as the number plate test, the above results show a disagreement with the new regulations set by DVLA. 6/9-6/12 Snellen acuity is reasonably consistent with the number plate in the studies by Rathore et al. (2012), Drasdo and Haggerty (1981) and Currie et al. (2000). However, the study of Rathore et al. (2012) suggests a much poorer acuity equivalent to the number plate test (6/19-6/15). The discrepancy may have been caused due to the fact that ETDRS chart in this study measured visual acuity at a close working distance (2m) and not distance visual acuity.

3.2 DISCUSSION

The studies outlined above have mainly considered people with pathology as being borderline for driving and thus as the “best” subjects to examine for the equivalence between the visual acuity and the number plate test. The present study investigates people with uncorrected refractive error, in order to examine the equivalence between visual acuity and the number plate test, since a great number of drivers are people with uncorrected refractive error, who may not be aware that they need spectacles to drive.

The studies described have largely been done with Snellen charts only, and not with other more modern designs (outlined in Chapter 1). Table 3.6 summarises the different studies that have related visual acuity and the number plate test. As a whole, these studies show that the number plate test is unlikely to be passed with a Snellen acuity of 6/18 or worse, and extremely likely to be passed with an acuity of 6/7.5 or better. In the range in between (6/9-6/12) there are variations between studies. This is likely to be driven by differences in participant groups, number plate style, and definitions of assigning Snellen visual acuity. The number plates and the performance of the number plate test also differed in these studies. Some studies used very old number plates (before 1983), some used the old style number plates 1983-2001, such as Currie et al., (2000), Rathore et al., (2012) and Kiel et al., (2003) as described in Table 3.6. To the author's knowledge there is not a published study which investigates the equivalence between the visual acuity test and the new style number plate test (post 1st September 2001).

Table 3.6: Comparison of the studies about the visual acuity and the number plate test. Chance of passing for each acuity level is presented in %.

	Marsden & Packer (1966)	**Drasdo & Heggarty (1981)**	**Currie et al. (2000)**	**Kiel et al.,2003**	**Rathore et al. (2012)**
6/18		6%	6%		0%
6/12		50%	34%	92.3% of participants could read all number plates	63%
6/9			74%		68%
6/7.5	100%	99%	99%		
6/6		100%			100%
Participants	Uncorrected refractive error	normal and pathology	Ophthalmic patients	Ophthalmic patients	nAMD in one eye and 6/24 in the other eye
Number plate style	ABC 123D 1963-1983 very old	ABC 123A (1963-1983) very old	A123 BCD (1983-2001) old	A123 BCD (1983-2001) old	2 number plates A123 BCD (1983-2001) old and 1 number plate non-existing
Number plate conditions	outdoors	outdoors	outdoors	outdoors	indoors
Habitual correction or Best Correction	without	habitual	habitual	habitual	habitual
Definition of visual acuity	n/a	Proportion of letters read on a line by linear interpolation	Full line and no more than two letters on the line below	n/a	Smaller line read with no more than two mistakes

All studies involved people who wore their habitual refractive correction apart from Marsden and Packer (1966) where subjects were tested without refractive correction. Subjects were not refracted to find the best refractive correction, which may have affected the results on the above studies. Despite that, those subjects would have driven using their habitual correction and therefore, the choice to examine them with habitual correction was justified.

Prior to the introduction to the 2012 regulations requiring an acuity of 6/12, the majority of studies related to the visual standards for driving (Charman, 1997; Currie et al., 2000; Rathore et al., 2012) considered that the most appropriate visual acuity cut off point to pass the number plate test was the $6/9^{-2}$, as suggested by Drasdo and Haggerty (1981).

The change in the regulations of visual standards for drivers will be significant. Reading the number plate and having 6/12 visual acuity did not exclude the same people from driving in the studies discussed above (Drasdo and Haggerty, 1981, Currie et al., 2000, Rathore et al., 2012). A 6/12 visual acuity indicates an uncertainty about whether candidates would pass the number plate test. In most studies, a certain pass was ensured if the participants had an acuity of 6/7.5. There is a difference between the geometrical size of the number plate characters at the appropriate distance (6/15) (Charman, 1997) and the actual visual acuity found to be compatible with passing the number plate test in the study of Drasdo and Haggerty (1981) of $6/9^{-2}$.

The letters on the 6/12 line of the Snellen chart differ from the letters used on a number plate in several respects, including the letter size and spacing. As explained in section 2.1.1, the geometric conversion of the number plate characters result in a Snellen equivalent of 6/14.4. Thus, the characters on a number plate are slightly larger compared to those on the 6/12 Snellen line. The width of the letters in the 6/12 line are 13mm, subtending 7.45 min arc, while the width of the number plate characters are 50mm, or 8.59 min arc angular subtence. The spacing between the letters on the 6/12 line is 7.45- 8.02 min of arc, however the spacing between the number plate characters is 1.89 min of arc (DVLA, 2013). Thus, the number plate characters are closer together and more crowded compared to the letters of the 6/12 line.

Furthermore, the visual acuity test takes place indoors, under artificial lighting, while the number plate test is performed outdoors, under various weather conditions. Therefore, the number plate test lighting is not stable for each candidate; it may be performed under sunny, cloudy or dull conditions, where the candidates may have to face the varying effects of glare as well. The backgrounds of the two tests are also different. For the visual acuity charts, optotypes appear on a white background while, for number plates, characters can appear on a yellow background. Kiel et al. (2003) and Siderov et al. (2005) have shown that the background colour of the number plates does not affect the ability to pass the number plate test. Moreover, on the visual acuity test, candidates need to identify letters or symbols like the Landolt ring, but not numbers while, on a number plate, candidates have to identify numbers as well as letters. Thus, the task of reading a number plate becomes more difficult, since both numbers and letters are included.

Hence, the two tests are different, mainly due to their construction and the place that they are performed. It is difficult to consider the two tests as being equal for the above reasons. Therefore, candidates who are a borderline pass or fail on one test may not achieve the same result on the other test.

3.3 AIM OF THESIS

The aim of this thesis is to investigate the measurement of visual acuity for drivers. The new DVLA regulations specify that a visual acuity of 6/12 must be achieved, but do not specify which chart or measurement method should be used. In 2013, it was specified that 6/12 should be measured on a Snellen scale, however it was not specified if the 6/12 visual acuity should be measured on a Snellen chart or other visual acuity charts and described in Snellen notation. As outlined in Chapter 1, the different distance visual acuity charts available vary in their layout and design and therefore may produce differences in the scores they record. Therefore, the differences between the scoring recorded by the charts will be investigated.

Additionally, this thesis aims to examine if the number plate test is equivalent to the visual acuity cut off point of 6/12 on all or any of the charts. If this is not the case, as previously suggested (Drasdo and Haggerty, 1981), then how appropriate the visual acuity limit is with different charts for predicting performance on the number plate test will also be investigated.

This thesis aims to contribute to current knowledge by assessing the relationships between the current visual standards for driving and to provide evidence of the equivalence or otherwise of the ability to read a post-2001 UK number plate at 20m and a visual acuity of 6/12 as measured in various ways.

CHAPTER 4: METHODS

4.1 PARTICIPANTS

A sample of drivers was recruited from the staff and student populations of Anglia Ruskin University. Inclusion criteria were that the participants held a full or provisional driving licence and gave informed consent after the nature of the study had been explained. Recruitment of participants was aimed at people who thought that they were borderline for achieving the visual standard for driving without wearing refractive correction (around 6/9-6/12 Snellen visual acuity). Given the self-reported nature of recruitment, people with a wider range of acuities than expected were assessed. However, all volunteers were assessed and no one was excluded on the grounds of acuity. It was difficult to find participants around the 6/9-6/12 area, especially as many thought that their visual acuity was around that area, but actually it was not. Ethical approval was received from Anglia Ruskin University Faculty of Science and Technology Research Ethics Committee and the tenets of the declaration of Helsinki were observed.

Demographic information was obtained from the participants, including age, gender, date of last sight test and the correction worn for driving.

4.2 EQUIPMENT

For the measurement of drivers' distance visual acuity, three different optotype charts were used (Snellen, logMAR letter and logMAR Landolt ring). For distance reading acuity, a distance version following the principles of the MNRead chart was presented. The Snellen chart was chosen, since it is the traditional chart used in UK for the measurement of visual acuity, and the visual acuity standards for driving are described in terms of Snellen notation. A logMAR letter chart was used, since this type of chart is becoming more routinely used in both optometric and ophthalmological practice. A logMAR Landolt ring chart was chosen to test a different visual acuity task, and because some countries in Europe use this chart for visual acuity measurements. A distance reading acuity (MNRead) chart was chosen to compare the 6/12 standard with the performance of a task more similar to actual tasks such as reading motorway signs. Road signs would not be more appropriate, since most of them constitute of just numbers or a symbol and they have a variety of background colours.

All charts were presented using Thomson Test Chart 2000 Xpert software at 100% contrast. The display brightness of the screen was 300 cd $/ m^{-2}$ (Samsung, 2014) on a screen of size 300mm height × 520mm width (window position) and resolution of 1080 pixels height and 1920 pixels width. Distance visual acuity was measured indoors, using a clinical examination room in the Eye Clinic of Anglia Ruskin University. The room was illuminated with ceiling mounted fluorescent tubes.

4.3 PROCEDURES

Charts were presented, via a mirror, at a viewing distance of 6m. Participants viewed the charts binocularly, and acuity was assessed without refractive correction. Participants started to read from the largest size available and were stopped according to the termination rules applied to each chart. Before starting, participants were informed which letters were included in the chart.

Thus, they were aware of the letter choice and the chance of guessing was reduced to the 10 letters presented on the chart. The upper lines of the chart were presented individually on the screen, but as the size of the optotypes was reduced more lines were presented together. In that case the participant was asked to read the bottom line that appeared on the screen.

The charts were always presented in the same order: Snellen, logMAR letter, logMAR Landolt ring and distance reading acuity (MNRead) chart.

Participants were encouraged to guess if they were uncertain about an optotype or a word until they were unable to guess. Participants were told not to squint and it was checked during the study that they did not squint. In the case where participants changed their answer, the last answer given was recorded.

4.3.1 Snellen chart

The first chart presented was the Snellen chart. The upper line of the chart (6/60) had one letter and as the size decreased, more letters were included on each line (Table 4.1). The 6/4 line was the smallest line presented, as limited by the software. The letter choice used for the Snellen chart was sans-serif 5×4 format British Standard letters (D, E, F, H, N, P, R, U, V, Z) complying with BS 4274-1 (2003). The letters used were not repeated within any line.

The termination rules for the Snellen chart were to stop reading when the participants could not identify more than one letter correctly on a line. Since the lines of the Snellen chart have different number of letters, a fixed number of errors per line could not be applied.

Table 4.1: Snellen letters as presented on the screen.

P								6/60
E	N							6/36
U	Z	D						6/24
E	V	R	F					6/18
N	U	P	V	H				6/12
V	F	H	R	Z				6/9
U	R	D	H	F	P			6/7.5
N	P	H	U	E	R	V		6/6
P	F	N	E	H	D	V	U	6/5
F	D	H	N	P	Z	U	R	6/4

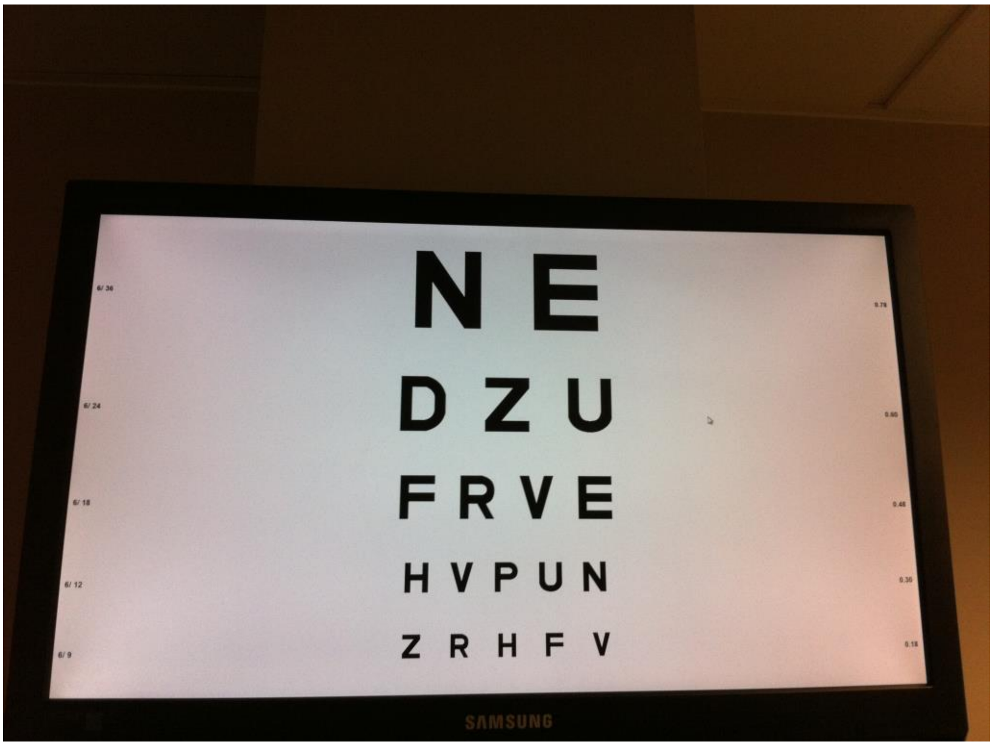


Figure 4.1: Picture of the Snellen chart used for the study.

The Snellen chart was firstly scored by the “full line method”, where the visual acuity was recorded as the smallest line for which the participant could read all the letters. This method was assessed since reading the entire 6/12 line is implied by the requirements of DVLA for the visual acuity standards. In cases where participants were unable to see the letter on the 6/60 line, their visual acuity was recorded as <6/60.

Scoring of the Snellen chart was also assessed using the “line assignment method”, in that the visual acuity of the driver was recorded as the lowest line on which at least half of the letters, e.g. 2 of 4 or 3 of 5, were correctly recognised, as used in several previous studies (Bailey et al., 1991; Vanden Bosch and Wall, 1997; Rosser et al., 2001; Laidlaw et al., 2003; Falkenstein et al., 2008; Kaiser, 2009).

For the Snellen chart, 120 measurements were recorded. For some analyses, the Snellen notation was converted to logMAR notation. In these analyses, 104 measurements were included, since 16 participants had acuities <6/60, which could not be converted to logMAR notation.

4.3.2 LogMAR letter chart

The second chart presented was a logMAR based chart utilizing 5×5 sans serif Sloan letters (Sloan et al., 1952) and replicating an ETDRS chart (Ferris et al., 1982). It is not an ETDRS chart, but was designed to have the same parameters as this chart. The chart included the following letters: C, D, H, K, N, O, R, S, V, Z. No letter was repeated within a line. The largest letter size presented was +1.40 logMAR and letter size decreased in 0.1 logMAR steps per line to a minimum of -0.40 logMAR. Each line was consisted of five letters, except the lines at large sizes, from +1.40 logMAR to +0.90 logMAR, as shown in Table 4.2. As with the Snellen chart the upper lines were presented on their own, while the lower lines were presented together on the screen.

Table 4.2: LogMAR letters as presented on the screen.

K					+1.40
R	N				+1.30
S	O				+1.20
C	R	Z			+1.10
V	O	R			+1.00
N	O	V	C		+0.90
C	R	K	O	D	+0.80
N	O	Z	R	V	+0.70
O	K	D	S	H	+0.60
Z	R	O	H	N	+0.50
H	S	N	C	K	+0.40
O	C	H	R	S	+0.30
S	H	V	N	C	+0.20
K	O	R	D	V	+0.10
D	V	N	O	K	0.00
C	S	O	R	N	-0.10
V	C	D	S	O	-0.20
R	D	S	N	K	-0.30
Z	N	V	O	H	-0.40

Figure 4.2: Picture of the logMAR letter chart used for the study.

Scoring of the logMAR letter chart followed a letter-by-letter approach. Therefore, 0.02 logMAR was attributed for each letter read correctly (five letters on each line). However, for the upper lines of the chart which consisted of smaller number of letters, the scoring for each letter (two letters) at +1.20 and +1.30 logMAR lines was 0.05 logMAR, at +1.10 and +1.0 logMAR lines (three letters) was 0.033 logMAR and at +0.90 logMAR line (four letters) was 0.025 logMAR.

The termination rules followed for the logMAR letter chart were the letter-by-letter (complete line) rules (Carkeet, 2001), where termination occurred when four mistakes were made on a line. The participants were allowed to complete the line and therefore attempt one more letter (five letters on each line).

If participants could not read the +1.40 logMAR line without refractive correction, they were considered as missing data, thus for the logMAR letter chart 117 measurements were recorded.

4.3.3 LogMAR Landolt ring chart

The final chart presented was a Landolt ring symbol chart presented in logMAR progression format. In accordance with BS EN ISO 8596 (2009) Landolt rings were presented in eight different positions; four straight (up, down, left and right) and four oblique (top right, top left, bottom right and bottom left). In each line of five Landolt rings, three were presented in straight positions and two at oblique positions in accordance with BS EN ISO 8596 (1996) and BS 4274-2 (1996). No orientation was repeated within a line (Table 4.3). The size range was +1.40 logMAR to -0.40logMAR.

For the logMAR Landolt ring chart, the participants were informed that they had to detect the orientation of the gap of the letter C and the possible oblique and straight positions were explained. Participants were told that they were allowed to use their hands to show the position of the gap, but simultaneously had to state using words the position of the gap.

Table 4.3: LogMAR Landolt ring directions as presented on the screen. UL is up-left, UR is up-right, DL is down-left, DR is down- right, R is right, L is left, U is up and D is down.

UL					+1.40
U					+1.30
DL	U				+1.20
R	UR				+1.10
U	DL	L			+1.00
R	UL	D	DR		+0.90
D	DL	L	UR	R	+0.80
L	UR	R	DR	U	+0.70
R	U	UL	D	DL	+0.60
UL	R	UR	L	D	+0.50
DR	U	L	D	UL	+0.40
UL	D	U	DL	L	+0.30
U	R	DR	L	DL	+0.20
D	DL	L	UR	R	+0.10
U	R	DR	D	UL	0.00
L	UL	R	UR	U	-0.10
D	DR	R	DL	U	-0.20
L	U	DR	D	UL	-0.30
R	UL	U	DR	D	-0.40

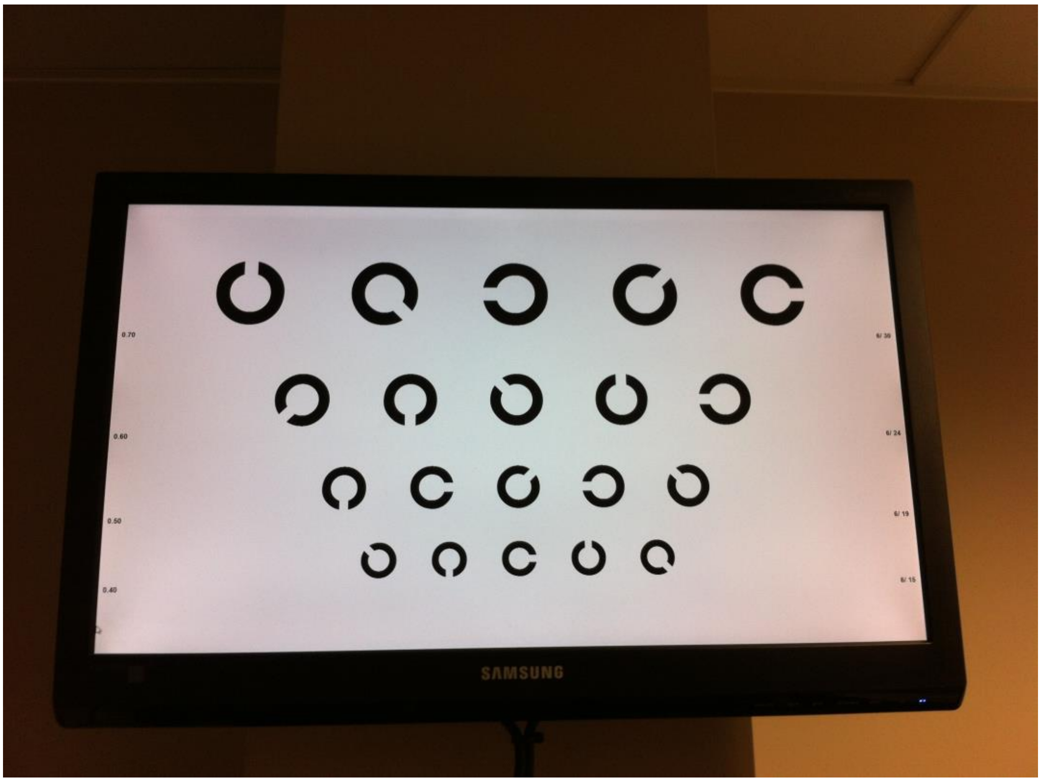


Figure 4.3: Picture of logMAR Landolt ring chart used for the study.

The scoring and termination rules for the Landolt ring chart were the same as those outlined for the logMAR letter chart above. If participants could not read the +1.40 logMAR line, they were recorded as missing data. Therefore, for the logMAR Landolt ring there were 119 measurements.

4.3.4 Distance reading acuity (MNRead) chart

Distance reading acuity was measured using a distance chart designed along the principles of the MNRead chart 1 (Ahn et al., 1995). The chart was designed by the supervisory team as part of a previous project (Conway et al., 2012). While the original MNRead chart is presented on printed cards, this distance reading acuity chart was constructed to be projected on the same screen as the other distance visual acuity charts at a 6m viewing distance. The text was presented in white Transport Medium sans serif font (Department for Transport et al., 2003) on a blue background (British Standard 381C No 109 (Middle Blue)). The presentation was designed to replicate the font and colours of a UK motorway road sign (Department for Transport et al., 1982). The largest text size presentable on the screen was +0.60 logMAR and text size decreased in 0.1 log unit steps to -0.50 logMAR units (Figure 4.4 and Table 4.4). The height for each size was calculated based on the x-height, which is the height of the lowercase “x” for charts which present sentences, or is the height of optotype when charts are consisted of upper case letters and symbols only (Legge, 2007). The formula $10^{LogMAR\ size}$ d/687.5 (Legge, 2007), where d is the viewing distance, was used to calculate the appropriate “x” height in mm for each logMAR step. Sentences were presented across three lines at each logMAR size apart from the +0.60 logMAR text size which was presented across four lines. The maximum font size was limited by the screen size (Figure 4.4). Some sentences had more words than others, but all sentences consisted of 60 characters, or six “standard” words.

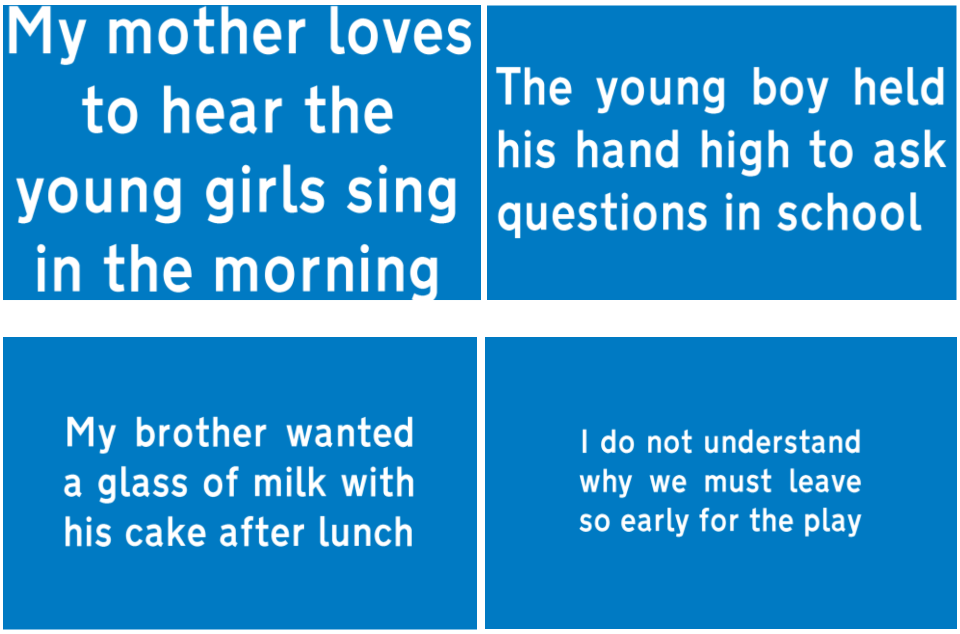


Figure 4.4: Examples of sentences from the distance reading acuity (MNRead) chart. Sizes of +0.60, +0.50, +0.40 and +0.30 logMAR are presented (not actual size).

Participants were informed that they would have to read sentences and that each sentence would appear on its own on the screen. Participants read each sentence aloud as quickly as they could. The participants were told that if they made an error or missed a word, they should finish the sentence and then go back and correct themselves (Mansfield and Legge, 1999). The time taken to read each sentence was recorded with a stopwatch. The mistakes that the participants made were recorded. Termination rules for the chart were to stop when participants were unable to identify any words in a sentence (Mansfield and Legge, 1999).

Table 4.4: Distance reading acuity (MNRead) sentences presented to participants.

My mother loves to hear the young girls sing in the morning	+0.60 logMAR
The young boy held his hand high to ask questions in school	+0.50 logMAR
My brother wanted a glass of milk with his cake after lunch	+0.40 logMAR
I do not understand why we must leave so early for the play	+0.30 logMAR
It is more than four hundred miles from my home to the city	+0.20 logMAR
Our father wants us to wash the clothes before he gets back	+0.10 logMAR
They would love to see you during your visit here this week	0.00 logMAR
The teacher showed the children how to draw pretty pictures	-0.10 logMAR
Nothing could ever be better than a hot fire to warm you up	-0.20 logMAR
The old man caught a fish here when he went out in his boat	-0.30 logMAR
Our mother tells us that we should wear heavy coats outside	-0.40 logMAR
One of my brothers went with his friend to climb a mountain	-0.50 logMAR

The reading acuity (RA) was calculated by the formula RA = 0.7 - (sentences read × 0.1) + (number of words read incorrectly × 0.01) (adapted from Patel et al., 2011).

The largest text size presented of +0.60 logMAR caused a ceiling effect in the data for the CPS and MRS, and these data is therefore not presented. For the RA, if participants could not read the +0.60 logMAR line, this was recorded as missing data and thus 91 measurements were recorded.

4.4 NUMBER PLATE TEST

To replicate the requirements of the number plate test, post 2001 style number plates with characters 79.0mm high and 50.0mm wide (as described in Chapter 2) were presented to each participant at a distance of 20m outdoors. All number plates had a yellow background and black characters and were UK number plates.

Table 4.5: Number plates used for the study.

									RELATIVE LEGIBILITY
1	L	F	7	6		R	X	C	81.86
2	B	C	7	2		T	O	H	81.14
3	A	V	6	3		N	J	Z	79.50
4	M	G	9	1		Y	V	T	78.14
5	H	D	8	4		P	S	A	76.57
6	K	E	9	5		W	U	F	73.86

Participants read three number plates (Driving Standards Agency, 2013) without correction, and were deemed to have passed if at least one of the number plates could be read without error. The time and the weather condition in which the number plate test took place were recorded.

Marsden and Packer (1966) provide data of the relative legibility of alphanumeric characters (Table 3.1), which were used to assess the relative legibility for these number plates. The average legibility for each number plate (Table 4.5) was determined by adding the legibility scores for each character together (higher numbers indicating greater legibility) and dividing by the number of characters for which data was available. This was done as no legibility score was available for the letter Z in number plate 3.

As the legibility score increases, the easier it should be for a participant to read the characters. Therefore, number plates 1 and 2 were considered to be more legible than the others, number plates 3 and 4 were of medium legibility and number plates 5 and 6 were of lower legibility compared to the other number plates. The number plates presented to each participant were random, since a hard, a medium and a low legibility number plate were presented in random order each time to each different participant.

The visual acuity recorded by the four distance visual acuity charts was compared to the results obtained from the number plates, in order to:

1) identify the most appropriate visual cut off limit that is most equivalent to the number plate test so that the two tests will exclude, as far as possible, the same people from driving and

2) determine the effect of the additional 6/12 requirement on the number of people passing/failing the visual standards for driving.

Furthermore, the four acuity charts were compared, in order to identify the differences recorded during the measurement of visual acuity. The four charts were compared using Bland-Altman plots, non- parametric statistics (Kolmogorov-Smirnov test, Kruskall-Wallis test), ROC curves (Park et al., 2004) and graphs (bar graphs, histograms). Statistical analysis used SPSS (version 20, IBM).

Other studies which have compared the visual acuity and the number plate test, as outlined in Chapter 3, have not used Bland-Altman plots, ROC curves and sensitivity and specificity values for each chart. At the time when those studies were published, the visual assessment for driving only comprised of the number plate test and analysis was provided in terms of the likelihood of passing the number plate test with a given acuity. Now that the two tests are required by law, optometrists need a direct comparison to be able to provide advice to candidates for a driving licence. These statistical tools will assist in examining the relationship between the required visual acuity and the number plate test and will allow comparison between the visual acuity charts.

CHAPTER 5: RESULTS

5.1 PARTICIPANTS

One hundred and twenty people took part in the study. There were 46 males and 74 females, with a mean age of 24.7±9.6 years, range 18-66 years. All subjects held a full or provisional driving licence. Participants were asked what type of refractive correction they wore most of the time while driving. 79 people wore spectacles for driving, 20 wore contact lenses and 21 did not have a refractive correction for driving. One hundred and two of the subjects had last had an eye examination within the last 2 years, and the other 18 had last had an eye examination between 3 and 10 years previously. None of the unaided acuity results represented a normal distribution (Komolgorov-Smirnov $p<0.05$ in all cases), and so non-parametric statistics are used throughout the analysis.

5.2 ACUITY CHARTS

5.2.1 Snellen acuities

As described in the methods, the Snellen chart was scored in two different ways: full line or line assignment. The differences in results achieved using the two methods are demonstrated in Table 5.1. Note that 56 participants achieved a visual acuity of 6/12 or better with the full line method as compared to 65 participants with line assignment method. The method used to determine 6/12 will be crucial in determining who meets the standard for driving. For the purposes of this thesis, the full line method for scoring the Snellen chart will initially be used, in order to be comparable with the DVLA method of determining visual acuity of drivers.

Table 5.1: A comparison of the frequency of subjects achieving various Snellen acuities using full line and line assignment methods.

ACUITY	FULL LINE RESULTS	LINE ASSIGNMENT RESULTS
<6/60	16	16
6/60	5	2
6/36	20	14
6/24	9	6
6/18	14	17
6/12	2	9
6/9	14	5
6/7.5	14	11
6/6	15	14
6/5	10	14
6/4	1	12

A letter-by-letter scoring method is also examined, in order to better understand which is the optimum visual cut- off limit that will reflect the equivalence with the number plate test. The approximate equivalence in logMAR units for the Snellen letters were calculated for the 6/12 line: 0.48 (6/18)-0.30(6/12)=0.18 logMAR; the 6/12 line has five letters, therefore 0.18 ×1/5=0.036 logMAR for each letter correctly identified in the 6/12 line. For the 6/9 line: 0.30(6/12)- 0.18(6/9)= 0.12 logMAR, the 6/9 line has five letters, thus 0.12× 1/5=0.024 logMAR for each letter correctly identified in the 6/9 line. The logMAR equivalence for Snellen letters is shown in Table 5.2:

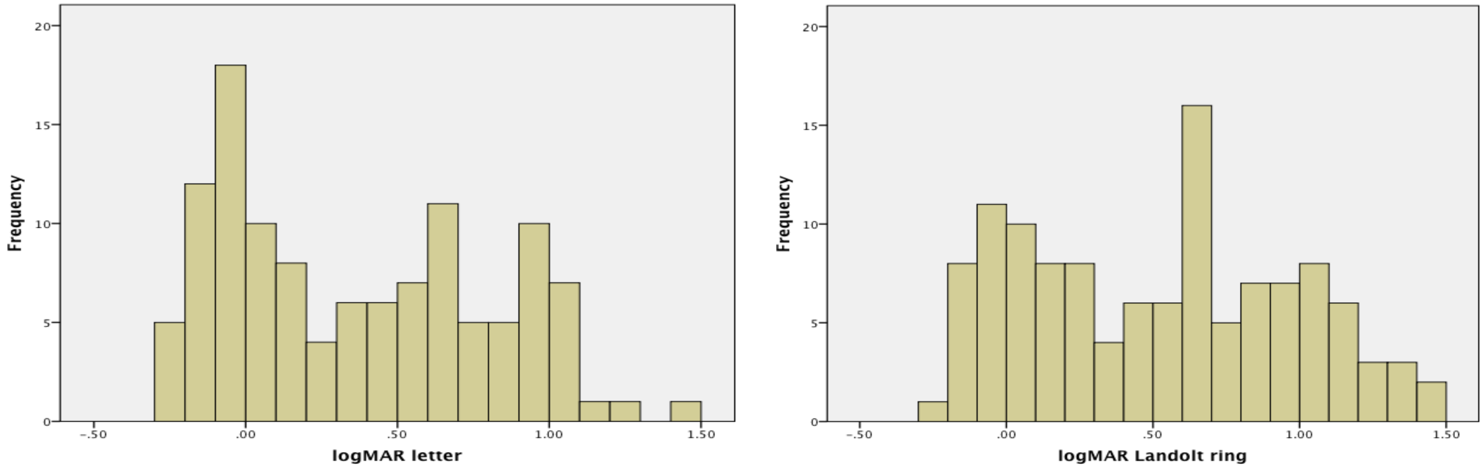
Table 5.2: Snellen acuity letter by letter analysis between 6/18 and 6/9, and their logMAR equivalent.

SNELLEN ACUITY	LOGMAR EQUIVALENT
6/18	+0.48
$6/12^{-4}$	+0.44
$6/12^{-3}$	+0.41
$6/12^{-2}$	+0.37
$6/12^{-1}$	+0.34
6/12	+0.30
$6/9^{-4}$	+0.28
$6/9^{-3}$	+0.25
$6/9^{-2}$	+0.23
$6/9^{-1}$	+0.20
6/9	+0.18

Snellen acuity notation does not reflect interval scoring since the progression between Snellen lines does not reflect equal intervals (Schacknow and Samples, 2010). Therefore, Snellen acuities should be described as ordinal data. Additionally, the Kolmogorov- Smirnov test showed that the full line data is not normally distributed ($p<.001$).

5.2.2 LogMAR letter and logMAR Landolt ring acuities

The range of logMAR letter and logMAR Landolt ring visual acuity scores achieved are shown in Figure 5.1. The Kolmogorov-Smirnov test was significant for both charts ($p<.001$), indicating that the distributions are non-normal. The median for logMAR letter results is +0.30 logMAR, the interquartile range is 0.73 logMAR and the range is 1.66 logMAR. The median for the logMAR Landolt ring results is +0.56 logMAR, the interquartile range is 0.82 logMAR and the range is 1.70 logMAR.



A **B**

Figure 5.1: Histograms of logMAR letter (A) (n=117) and logMAR Landolt ring (B) (n=119) acuities.

5.2.3 Distance reading acuity (MNRead) data

The reading acuity (RA) for the distance reading acuity (MNRead) chart is presented in Figure 5.2, determined as outlined in Chapter 4.

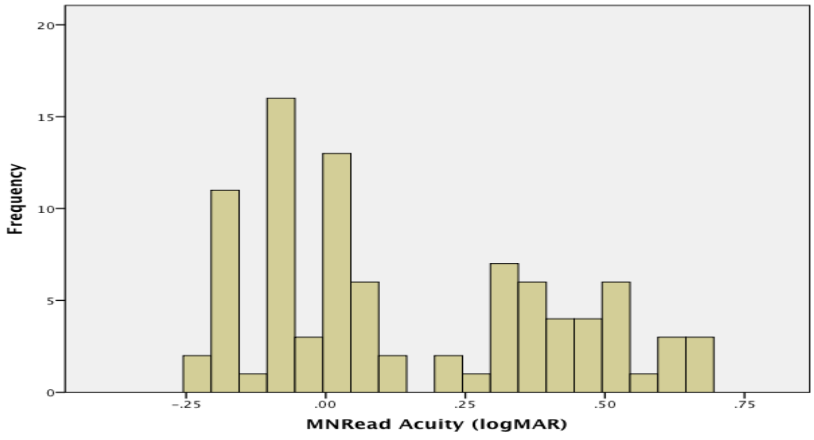


Figure 5.2: Histogram for distance reading acuity (n=91).

The parameters were not normally distributed (Kolmogorov-Smirnov indicated $p<.001$ for all parameters), thus non-parametric statistical treatment is required.

The median score for distance reading acuity (MNRead) is +0.04 logMAR, interquartile range is 0.47 logMAR, while range is 0.92 logMAR.

5.3 RELATIONSHIP BETWEEN DIFFERENT VISUAL ACUITY CHARTS

To investigate the relationship between the four different charts, Bland-Altman plots (Bland and Altman, 1986) are used. These present on the y-axis the difference in acuity between the two methods against the mean acuities being compared on the x-axis. It is not appropriate to just look at the correlation between the charts, because a correlation coefficient estimates how strong a relation between variables is, and does not take into account their agreement, which has to be investigated (Armstrong, et al., 2011). Bland-Altman plots show whether the difference between two measures varies with the level of acuity, whether there is a consistent difference between the acuity measures on the two charts and if this difference is significant, which would be shown by the 95% Limits of Agreement (LoA) excluding no mean difference (Bland and Altman, 1986).

The majority of differences will lie between d-1.96s and d+1.96s, where d is the mean difference and s the standard deviation (Bland and Altman, 1986). If the differences between d-1.96s and d+1.96s are not significant, one chart can be used instead of the other. The results from d-1.96s and d+1.96s are known as 95% LoA and will be presented on the Bland-Altman plots as dashed lines. In the case where the differences follow a normal distribution, 95% of differences in the sample will be between those limits (Bland and Altman, 1986), such that the 95% LoA indicate the limits within which two tests carried out on an individual might differ.

Confidence Intervals (C.I.) are calculated by d$\pm t_{n-1}$ s/ √n, where d is the mean difference, t is the t-statistic derived from the two-tailed test at p= 0.05 for the appropriate number of degrees of freedom (n-1), s is the standard deviation and n the size of the sample (University of Cambridge, 2009). The C.I. is applied to the mean difference and indicates the limits within which the true bias lies for a population, as opposed to that estimated from the sample.

5.3.1. Comparison between visual acuity charts

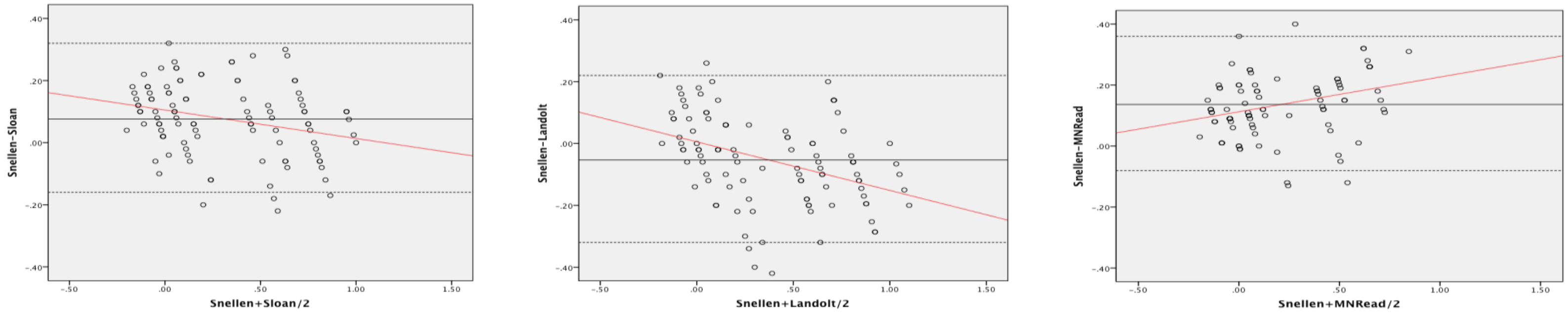
Comparisons between the four different charts are shown graphically in Figure 5.3.

Figure 5.3 and Table 5.3, which shows values derived from the figures, shows firstly the mean difference between the different charts. Acuities achieved with the Sloan chart are better, or more acute, than those with the Snellen chart by 4 logMAR letters. Snellen acuities were better compared to Landolt acuities by 2.5 logMAR letters. MNRead acuities were better than Snellen acuities by 0.14 logMAR. Landolt acuities were worse compared to Sloan acuities by 6.5 letters, more than 1 line. MNRead acuities were better than Sloan acuities by 0.05 logMAR. MNRead acuities were better than Landolt by 0.18 logMAR, which was the biggest difference recorded between the charts.

The interval of the 95% LoA are presented in Table 5.4. Abbreviations have been used in Figure 5.3 -“Snellen” is used to describe the Snellen chart, “Sloan” is used to describe the logMAR letter chart. “Landolt” is used to describe the logMAR Landolt ring chart and “MNRead” describes the distance reading acuity chart. The 95% LoA include zero and therefore although there are differences between the charts, these differences are not clinically significantly different. The range of 95% LoA differ for each comparison of charts as shown in Table 5.4. The range of variations of results was wider for the Snellen- Landolt comparison (0.54 logMAR) and the narrowest variation of results was found between Sloan- MNRead comparison (0.36 logMAR).

SLOAN LANDOLT MNREAD

SNELLEN



SLOAN

LANDOLT

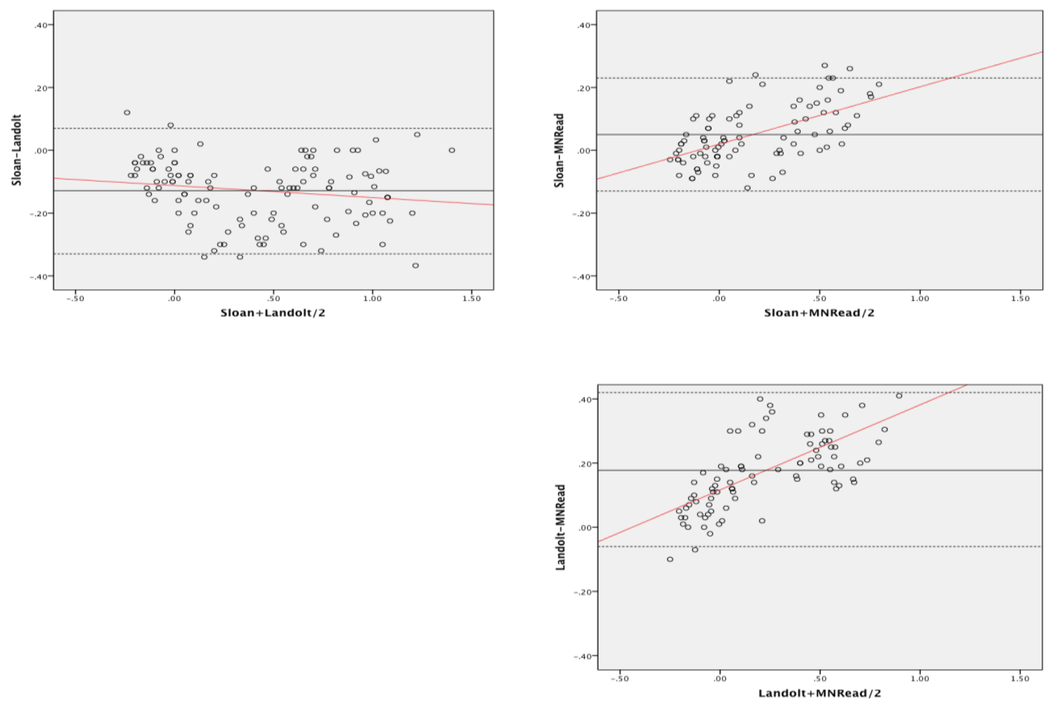


Figure 5.3: Bland-Altman plots for the four charts. See text for details. The Snellen full line scoring method is shown, but Snellen notation has been converted to a logMAR equivalent for comparison with the other charts. For the purposes of the comparison the logMAR letter chart is called "Sloan", the logMAR Landolt ring chart is called "Landolt" and the distance reading acuity chart is called "MNRead" chart. The solid lines in the Bland-Altman plots indicate the mean difference, while the dashed lines show the 95% LoA. Regression lines are presented in the graphs (red colour lines) and indicate whether the slope changes across mean acuity and which chart tends to be better at poor acuities.

Table 5.3: Statistical analysis of the comparison between the four different visual acuity charts. The mean difference, the 95% Limits of Agreement, the Confidence Intervals for the position of the mean difference and the slope of plots are presented.

COMPARISON	***MEAN DIFFERENCE***	***95% LoA***	***C.I.***	***SLOPE***
Snellen- Sloan	+0.08	-0.16 to +0.32	+0.06 to +0.10	Consistent
Snellen- Landolt	-0.05	-0.32 to +0.22	-0.08 to -0.02	Consistent
Snellen- MNRead	+0.14	-0.08 to +0.36	+0.12 to +0.16	Variation
Sloan-Landolt	-0.13	-0.33 to +0.07	-0.15 to -0.11	Consistent
Sloan-MNRead	+0.05	-0.13 to +0.23	+0.03 to +0.07	Variation
Landolt- MNRead	+0.18	-0.06 to +0.42	+0.16 to +0.21	Variation

Table 5.4: Interval between the 95% LoA for each comparison and how many participants each comparison included.

COMPARISON	**RANGE OF 95% LoA (LogMAR)**	**VALID NUMBER OF PARTICIPANTS (n)**
Snellen-Sloan	0.48	104
Snellen-Landolt	0.54	104
Snellen-MNRead	0.44	91
Sloan- Landolt	0.40	117
Sloan- MNRead	0.36	91
Landolt-MNRead	0.48	91

The slope of the plots has been described as being "consistent" or as having "variation" (Table 5.3). A slope with "variation" is one that changes across the range of mean acuities to the extent of, or more than, the 95% LoA. All the MNRead plots show a positive slope, with a tendency for differences to be more in favour of MNRead at worse acuities (right end of x-axis), i.e. MNRead acuities are better than those of the other charts at poorer acuities. Those plots with a negative slope are in favour of Snellen at worse acuities, e.g. in the Snellen-Landolt plot, at poorer mean acuities Snellen acuities are better than those with the Landolt chart. A "consistent" slope (e.g. Sloan- Landolt) is one which is essentially flat with no trend in terms of the difference varying with mean acuity.

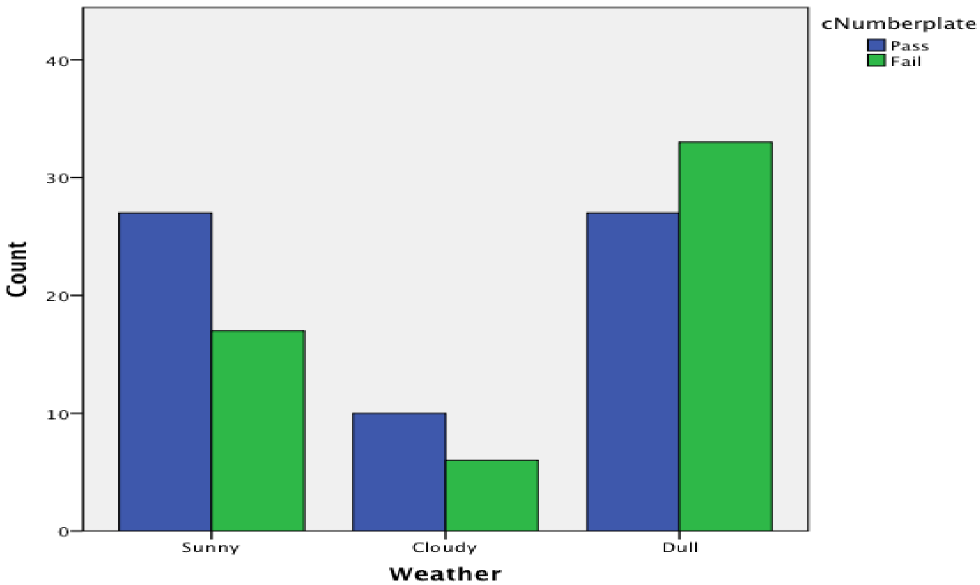
5.3.2 Summary

There are differences between the acuity charts in terms of mean difference in acuity measured, with Landolt ring acuities tending to be worse than Snellen, Sloan and MNRead acuities being better. These differences are statistically significant since the confidence intervals around the mean differences do not include zero in any case. However, the variability in measures means that the 95% LoA include zero, and the measured differences between charts are not clinically significant.

5.4 RELATIONSHIP BETWEEN VISUAL ACUITY AND THE NUMBER PLATE TEST

Of the 120 participants, 64 participants passed (53%) and 56 failed (47%) the number plate test.

The ability to read the number plate was assessed outdoors in daylight, in line with the visual standard (Taylor, 2012). Weather conditions were recorded as sunny, cloudy or dull (Figure 5.4). Conditions were considered as “cloudy” if there was no direct sunshine at the time the test was taken, and as “dull” in very heavy cloud or raining conditions.



	SUNNY	CLOUDY	DULL
PASS	27	10	27
FAIL	17	6	33

Figure 5.4: Frequency of number plate passes and fails under various weather conditions.

The Chi-square test showed that the relationship between weather conditions and the passing/failing rate of the number plate test was not statistically significant ($p>0.05$, chi-square = 3-35, df=2).

Performance with each chart is now compared to the number plate test, in order to investigate the relationship between the 6/12 visual cut off limit and the number plate test.

Analysis of sensitivity and specificity will be used to evaluate the relationship between the ability to read 6/12 and the ability to read a number plate at 20m. Sensitivity represents the correct identification of the participants who fail the number plate test by use of an acuity test, while specificity reflects the correct identification of participants who pass the number plate test by use of an acuity test. Data will also be examined to determine if a more appropriate cut off than 6/12 exists for each different chart.

Receiver Operating Characteristic (ROC) curves are also used, in order to assess the performance of the tests that this study investigates (Park et al., 2004). The ROC curves show the level of sensitivity and specificity. On the x-axis the false positive rate (1-specificity) is plotted, while on the y-axis sensitivity is shown (Park et al., 2004). The greater the area under the curve and the closer the curve is to 1, the greater the level of sensitivity and specificity. The ROC curve will not show the most appropriate cut off limit for the two tests, but the coordinates of the curve will show the level of sensitivity and specificity at each acuity level.

5.4.1 Snellen chart vs number plate test

Table 5.5 presents the results of the acuity level that participants achieved on the Snellen chart (full line method) and also indicates the chance of passing at each acuity level. This is calculated by dividing the participants who passed by all the participants who passed and failed the number plate test at each acuity level.

Table 5.5: Number of participants who passed/failed the number plate test and the Snellen acuity achieved. The chance of passing the number plate test at that acuity level is also presented.

SNELLEN ACUITY	NUMBER PLATE		CHANCE OF PASSING
	PASS	FAIL	
<6/60	0	16	0%
6/60	0	5	0%
6/36	3	17	15%
6/24	2	7	22%
6/18	4	10	29%
6/12	2	0	100%
6/9	13	1	93%
6/7.5	14	0	100%
6/6	15	0	100%
6/5	10	0	100%
6/4	1	0	100%

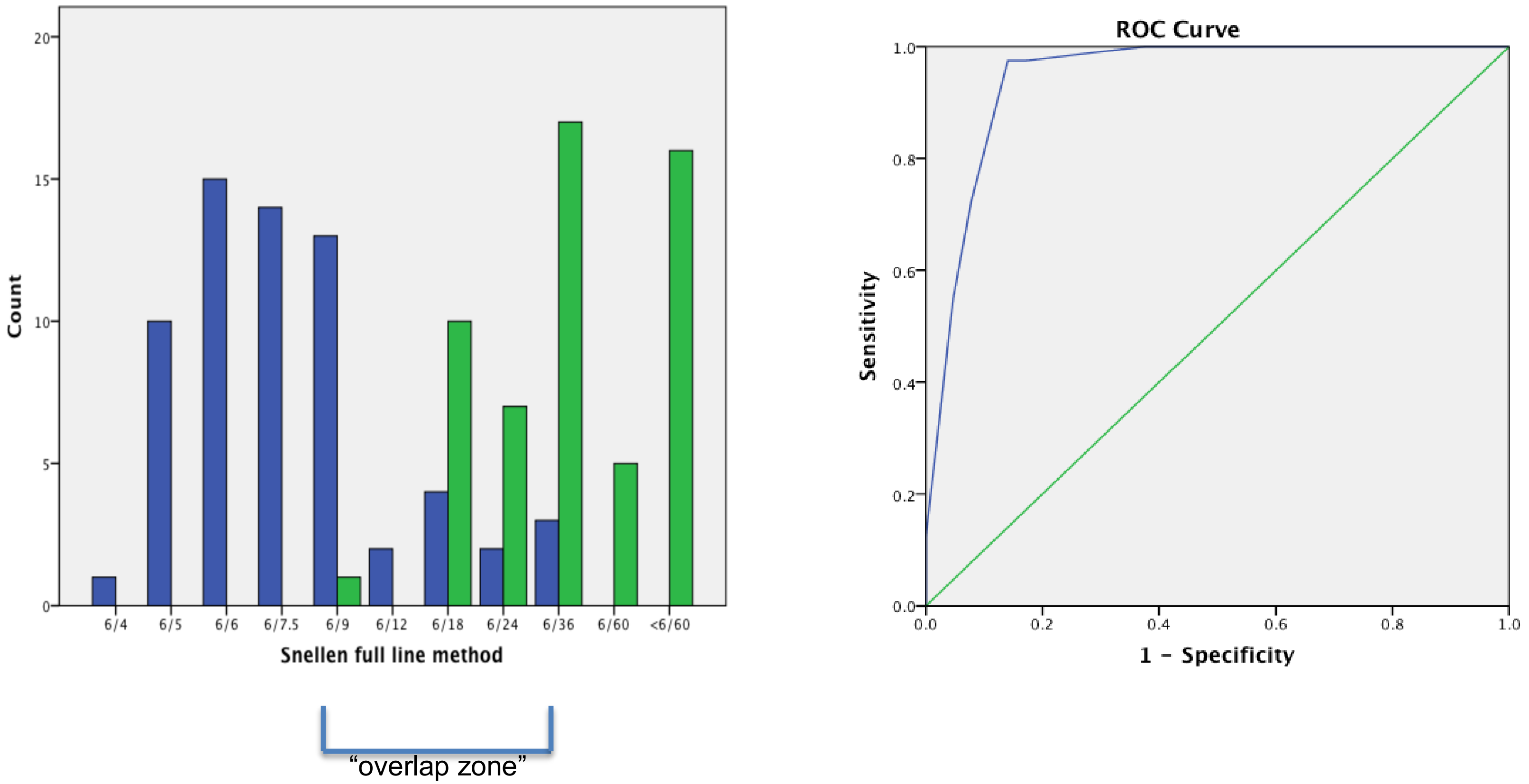


Figure 5.5: Left: performance on the number plate test (pass= blue, fail=green) compared to acuity measured using the Snellen chart (full line method). The blue lines show the "overlap zone" where there is an uncertainty whether participants will pass both tests. Right: the graph represents a ROC curve for the Snellen vs number plate comparison. The area under the curve is 0.95.

Table 5.5 and Figure 5.5 demonstrate that there is not a single visual cut off point in terms of the acuity required to pass the number plate test. Nine participants achieved acuities between 6/18-6/36 and managed to pass the number plate test and 1 participant with 6/9 visual acuity failed the number plate test. For the ROC curve analysis, the Snellen fraction has been converted to a logMAR fraction. The area under the curve is 0.95, which is close to 1, showing that the level of sensitivity and specificity is good. By looking at the coordinates of the curve, as depicted in Table 5.6, the visual acuity at which high sensitivity is maintained, while high specificity is also obtained is considered to be the most appropriate visual cut off point. The cut off point of +0.30 logMAR (6/12 Snellen) provides sensitivity of 98% and specificity of 86% and thus is an appropriate cut off point.

Table 5.6: The coordinates of the ROC curve for Snellen and the number plate test, which show level of sensitivity and specificity at each acuity level.

SNELLEN ACUITY (LOGMAR)	SENSITIVITY	SPECIFICITY
-0.13	100%	2%
-0.04	100%	17%
0.05	100%	41%
0.14	100%	63%
0.24	98%	83%
0.39	98%	86%
0.54	73%	92%
0.69	55%	95%
0.89	13%	100%

There is uncertainty as to whether participants with acuities recorded between 6/9 and 6/36 will pass both the number plate and acuity tests. All participants with worse acuities than 6/36 failed both tests, and all those with better acuities than 6/9 passed both tests. There were 59 participants in the “overlap zone”, between 6/9 and 6/36. This area is important, since these are the people who Eye Care Practitioners will have to advise carefully on whether they should drive or if they need to wear refractive correction while driving. Outside the "overlap zone" participants either pass or fail both tests.

Table 5.7: Participants in the "overlap zone". True Negative (TN), False Positive (FP), False Negative (FN) and True Positive (TP) are indicated on the table.

		NUMBER PLATE TEST	
6/12 SNELLEN ACUITY		**PASS**	**FAIL**
	PASS	15 (TN)	1 (FN)
	FAIL	9 (FP)	34 (TP)

Of the 59 participants in the "overlap zone", 49 passed or failed both tests, as shown in Table 5.7. One participant passed the visual acuity test, but failed the number plate test (1.7%). Nine participants could read the number plate test, but did not achieve the 6/12 visual standard without refractive correction (15.3%).

Sensitivity and specificity for the "overlap zone" (6/9-6/36) is indicated by an analysis of true positive, false positive, true negative and false negative counts (Elliott, 2007). Sensitivity shows the ability of the 6/12 cut off to identify those who will fail the number plate test. Specificity indicates the ability of the 6/12 cut off to identify those who will pass the number plate test. The False Positive Rate (FPR) indicates the proportion of participants incorrectly identified as likely to fail the number plate test by the 6/12 cut off and Positive Predictive Value (+PV) shows the proportion of participants in the sample failing both tests.

For the sample of participants in the overlap zone for the Snellen chart:

Sensitivity= (TP/TP+FN)×100= 97.1%

Specificity= (TN/TN+FP)×100= 62.5%

False Positive Rate= (1- specificity)×100=37.5%

Positive Predictive Value= (TP/TP+FP)×100= 79.1% (Elliott, 2007).

Sensitivity and specificity is different for the "overlap zone" compared to the whole dataset of participants but is considered more relevant because it focuses on participants with uncertainty of passing either the visual acuity test or the number plate test.

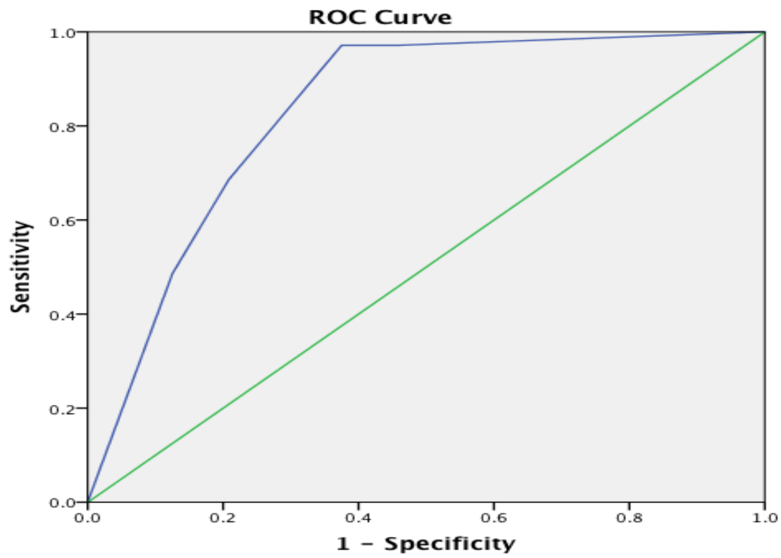


Figure 5.6: ROC curve for the "overlap zone". The area under the curve is 0.83.

The coordinates of the ROC curve (Table 5.8) indicate that the 6/12 cut off limit is an appropriate cut off point at which sensitivity is maximised (97%), while specificity remains high (63%). The point that the maximum sensitivity is obtained and a relatively high value of specificity is maintained is considered as an appropriate cut-off point.

Table 5.8: Coordinates of the ROC curve for the "overlap zone".

ACUITY	SENSITIVITY	SPECIFICITY
0.24	97%	54%
0.39	97%	63%
0.54	69%	79%
0.69	49%	88%

Further analysis of the nine participants who passed the number plate test with acuities worse than 6/12 is provided in Table 5.9.

Table 5.9: Analysis of the nine participants who passed the number plate test with worse acuities than 6/12, showing which legibility number plates they read under which weather conditions.

PARTICIPANTS	SNELLEN ACUITY	NUMBER PLATE LEGIBILITY			WEATHER
		HIGH	MEDIUM	LOW	
1	6/36	✓		✓	sunny
2	6/36		✓		sunny
3	6/36		✓		dull
4	6/24	✓			dull
5	6/24	✓	✓	✓	sunny
6	6/18	✓	✓	✓	cloudy
7	6/18	✓		✓	cloudy
8	6/18	✓	✓		sunny
9	6/18			✓	sunny

5.4.1.1 Snellen full line vs line assignment scoring methods

The full line method has been used to this point, but the line assignment method has previously been used to score Snellen visual acuity. A comparison of the two methods is presented, in order to evaluate which is the most appropriate to use to score the visual acuity of drivers. Figure 5.7 shows the relationship between acuity assessed by the two methods and the ability to pass the number plate test. For the full line method sensitivity of the 6/12 cut off within the overlap zone was 97.1%, whilst specificity was 62.5%. For the line assignment method sensitivity was 82.0% and specificity was 54.0%. Thus, the full line method has greater sensitivity and specificity compared to the line assignment method.

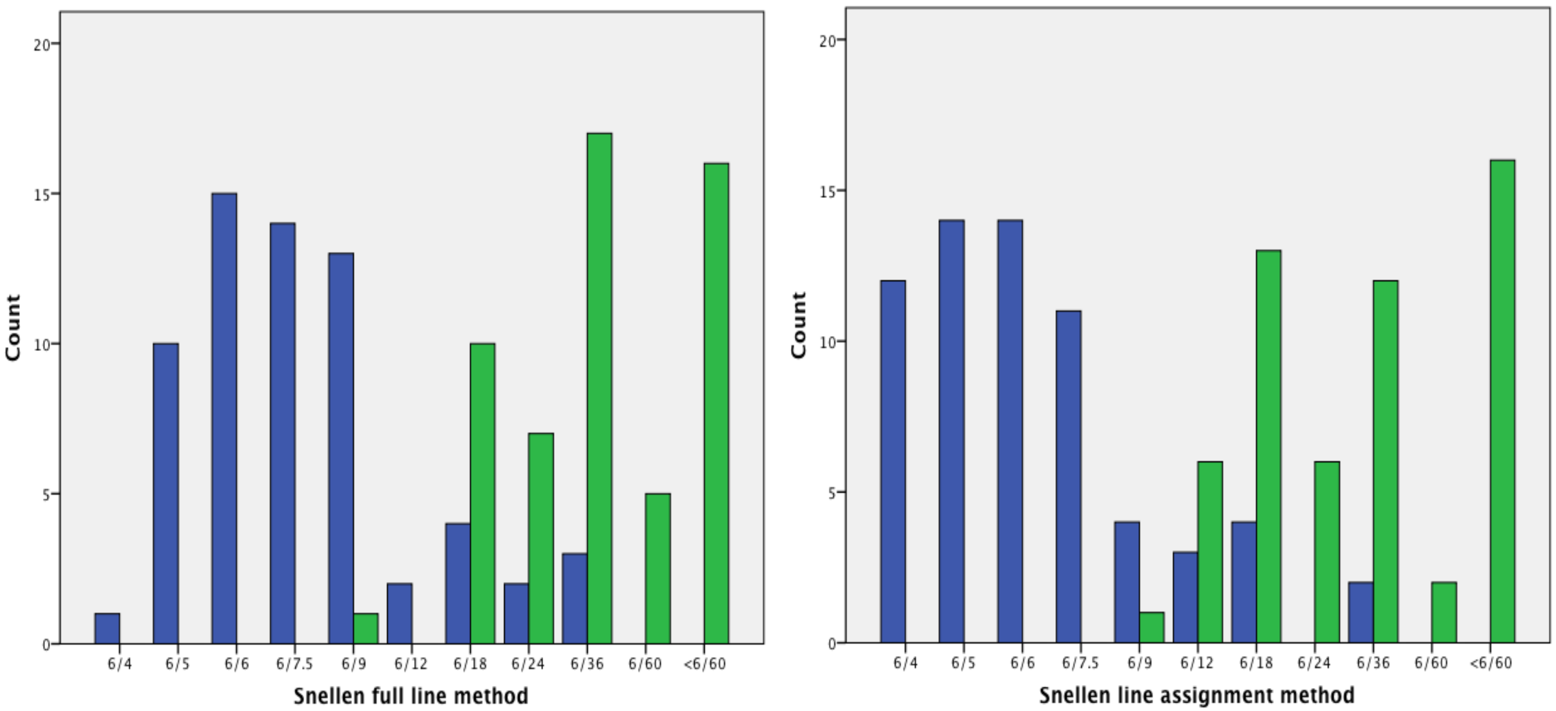


Figure 5.7: Bar graphs of Snellen full line and line assignment methods against the number plate test (pass= blue, fail= green).

5.4.1.2 Snellen letter analysis vs number plate test

To examine the findings further, this section analyses the Snellen acuity on a letter-by-letter basis. The 6/12 line on the Snellen chart has five letters. If participants read the 6/18 line, they may also manage to read some letters on the 6/12 line, but not the entire line as partially assessed above in the “line assignment” method. Figure 5.8 below represents the 22 participants whose Snellen acuity was between 6/18 and 6/9 on a letter-by-letter basis and whether they passed or failed the number plate test.

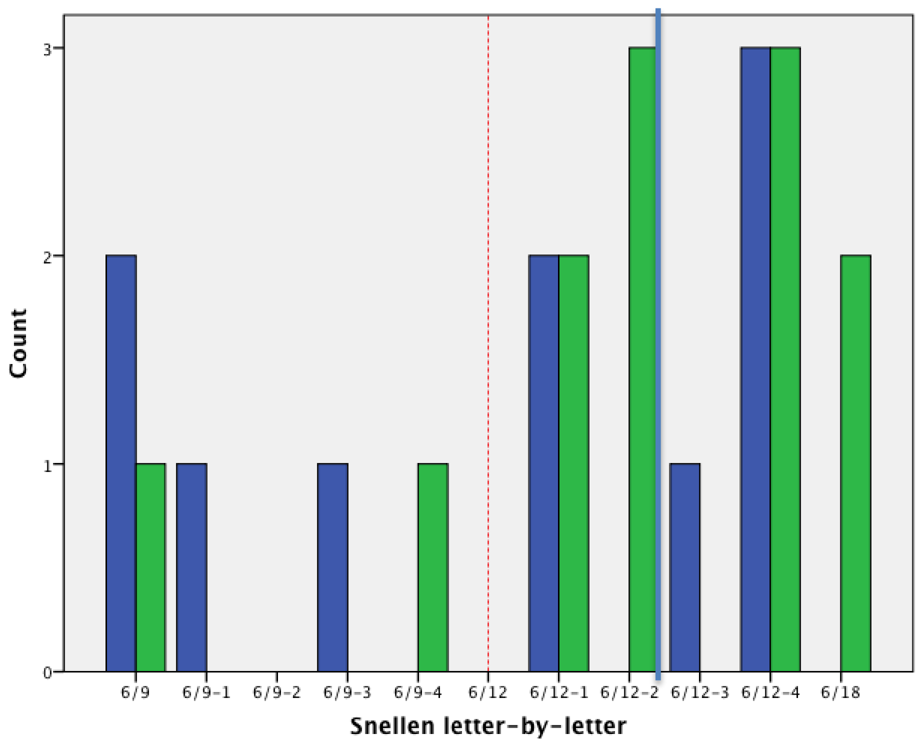


Figure 5.8: Illustration of the letter-by-letter acuity achieved by the 22 participants whose Snellen visual acuity was between 6/18 and 6/9. The 6/9 and 6/12 lines on the Snellen chart consist of five letters. Those who passed the number plate test are in blue, those who failed in green. The vertical red dashed line shows the point at which all the letters were achieved by participants (full line method), while the vertical light blue solid line indicates the point at which more than half of the letters on the 6/12 line were achieved (line assignment method).

Figure 5.8 indicates that no point on a letter-by-letter basis is any better than 6/12 full line. Analysis of sensitivity and specificity of the letter-by- letter data did not indicate that any improvements could be gained by giving the cut off on a letter-by-letter basis rather than by the full line method.

Therefore, the highest sensitivity, whilst maintaining high specificity is provided by the full line method as compared to either the line assignment method or letter-by-letter analysis.

5.4.2 LogMAR letter (Sloan) vs number plate test

The logMAR letter (Sloan) chart is compared in Table 5.10 and Figure 5.9 with the results from the number plate test. The 6/12 Snellen cut off limit is equal to +0.30 logMAR.

Table 5.10: Sloan scores and the frequency of subjects who passed/failed the number plate test. Chance of passing is also presented for each acuity level.

LOGMAR SLOAN	NUMBER PLATES		CHANCE OF PASSING
	PASS	FAIL	
1.32-1.40	0	1	0%
1.22-1.30	0	1	0%
1.12-1.20	0	0	0%
1.02-1.10	0	4	0%
0.92-1.00	0	10	0%
0.82-0.90	1	7	13%
0.72-0.80	1	4	20%
0.62-0.70	1	10	9%
0.52-0.60	0	6	0%
0.42-0.50	3	4	43%
0.32-0.40	1	3	25%
0.22-0.30	5	2	71%
0.12-0.20	6	1	86%
0.02-0.10	9	0	100%
-0.08- 0.00	19	0	100%
-0.18- -0.10	11	0	100%
-0.28- -0.20	7	0	100%

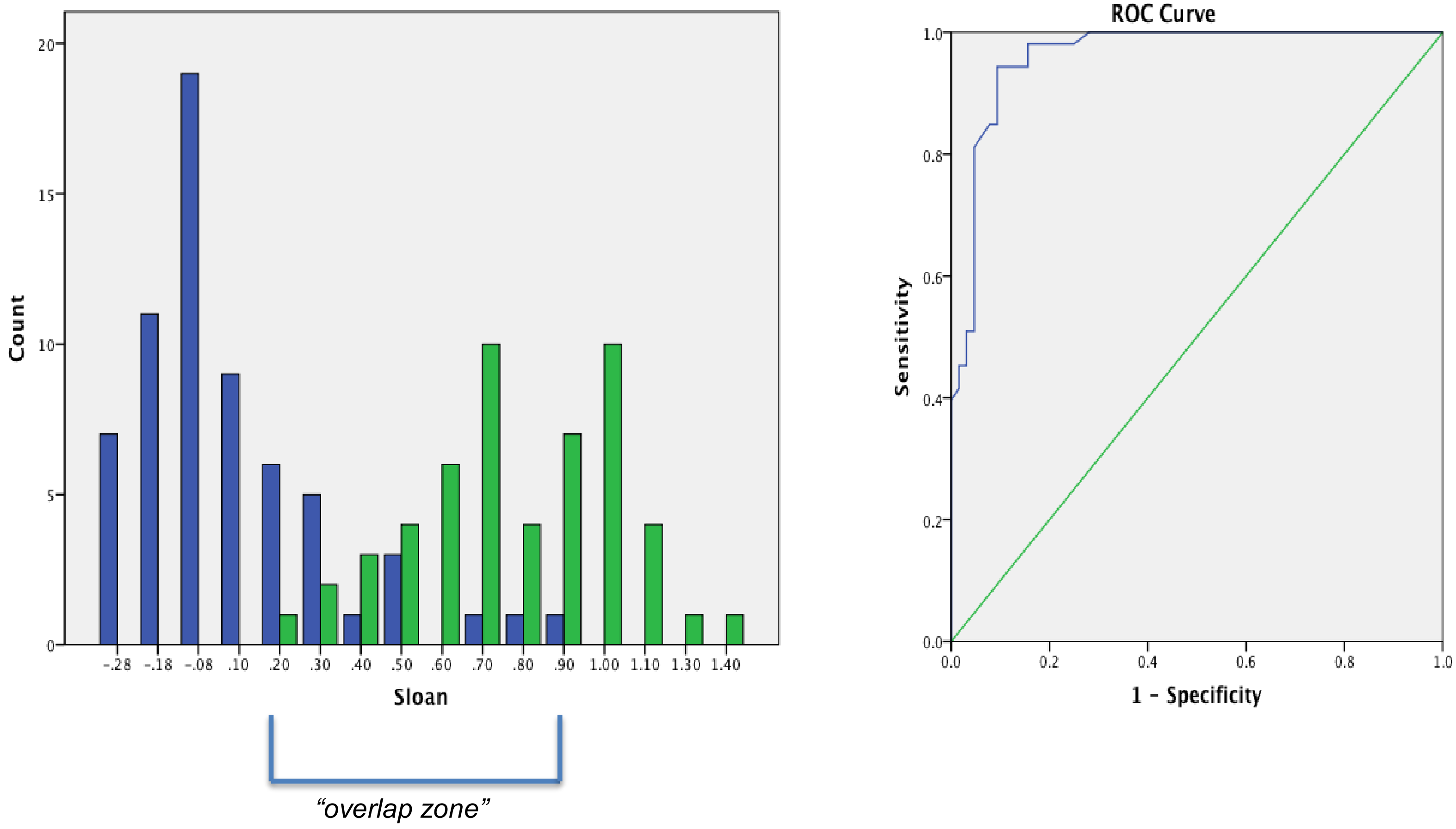


Figure 5.9: Left: Sloan acuity results as compared to the number plate test, those who passed the number plate test are represented by blue colour and those who failed by green. Blue lines show the "overlap zone" where there is uncertainty whether participants will pass both tests. The graph on the right represents a ROC curve for the Sloan vs number plate comparison. The area under the curve is 0.96.

Table 5.11: Coordinates of the ROC curve, which indicate the level of sensitivity and specificity at each acuity level.

SLOAN ACUITY	SENSITIVITY	SPECIFICITY
0.11	100%	72%
0.25	98%	84%
0.33	94%	91%
0.36	93%	91%
0.39	90%	91%
0.41	89%	91%

The coordinates of the ROC curve (Table 5.11) indicate that +0.30 logMAR is an appropriate cut off point that will exclude similar people from driving as the number plate test, since sensitivity is maximised (98%), while specificity remains high (91%).

The "overlap zone" indicates the range of Sloan acuities within which there is uncertainty over whether a participant will be able to pass both tests (Table 5.12).

Table 5.12: 50 participants in the "overlap zone" for Sloan chart.

<table>
<tr><th></th><th colspan="3">NUMBER PLATE TEST</th></tr>
<tr><td rowspan="3">+0.30 LOGMAR ACUITY</td><td></td><td>PASS</td><td>FAIL</td></tr>
<tr><td>PASS</td><td>11 (TN)</td><td>3 (FN)</td></tr>
<tr><td>FAIL</td><td>7 (FP)</td><td>29 (TP)</td></tr>
</table>

For the 50 participants in the "overlap zone" or +0.12 to +0.84logMAR, 40 passed or failed both tests. Three participants passed the visual acuity test, but failed the number plate test (6.0%). Seven participants passed the number plate test, but failed the visual acuity test (14.0%).

Sensitivity, specificity, FPR and +PV are indicated below for the 50 participants within the "overlap zone":

Sensitivity= (TP/TP+FN)×100= 90.6%

Specificity= (TN/TN+FP)×100= 61.1%

False Positive Rate= (1- specificity)×100=38.9%

Positive Predictive Value= (TP/TP+FP)×100= 80.6% (Elliott, 2007).

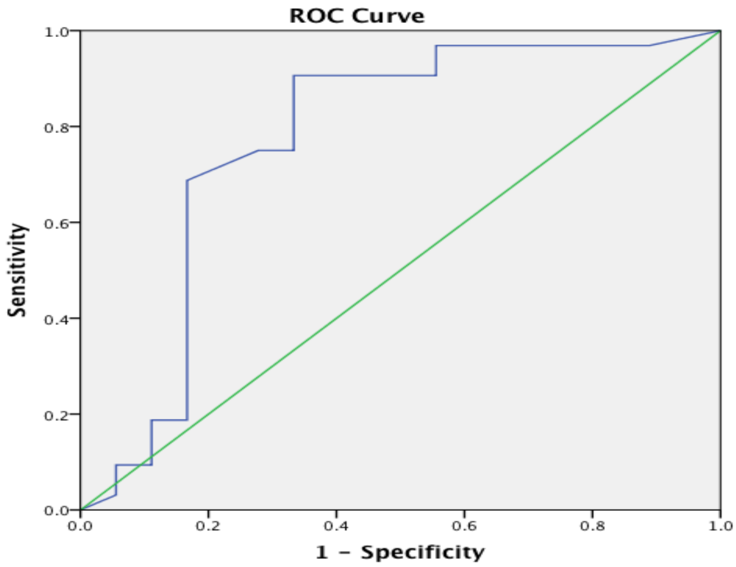


Figure 5.10: ROC curve for the "overlap zone" for the Sloan chart. Area under the curve is 0.77.

The coordinates of the ROC curve (Table 5.13) for the "overlap zone" indicate that +0.30 logMAR will exclude similar people from driving as the number plate test, since sensitivity is maximised (91.0%), while specificity is relatively high (67.0%).

Table 5.13: Coordinates of the ROC curve for the "overlap zone".

ACUITY	SENSITIVITY	SPECIFICITY
0.25	97%	44%
0.33	91%	67%
0.36	88%	67%
0.39	84%	67%
0.41	81%	67%
0.43	75%	67%

Table 5.14: Indicates the seven participants who passed the number plate test with worse acuities than +0.30 logMAR, which legibility number plates they read and under which weather conditions.

PARTICIPANTS	**ACUITY**	**NUMBER PLATE LEGIBILITY**			**WEATHER**
		HIGH	**MEDIUM**	**LOW**	
1	0.32	✓			dull
2	0.44			✓	sunny
3	0.48	✓	✓		sunny
4	0.50	✓		✓	sunny
5	0.70	✓	✓		sunny
6	0.78		✓		sunny
7	0.84		✓		dull

Further analysis of the seven participants who passed the number plate test with acuities worse than +0.30 logMAR is provided in Table 5.14. Participants more commonly read the medium and high legibility number plates, and more participants were tested under sunny conditions.

5.4.3 LogMAR Landolt ring vs number plate test

The results obtained from the logMAR Landolt ring chart and the number plate test are compared in Table 5.15.

Table 5.15: Landolt results compared to number plate results. Number of people who passed/ failed and the chance of passing the number plate test is presented.

LANDOLT	NUMBER PLATES		CHANCE OF PASSING
	PASS	FAIL	
1.32-1.40	0	2	0%
1.22-1.30	0	3	0%
1.12-1.20	0	7	0%
1.02-1.10	0	8	0%
0.92-1.0	2	5	29%
0.82-0.90	0	7	0%
0.72-0.80	0	4	0%
0.62-0.70	2	12	14%
0.52-0.60	3	5	38%
0.42-0.50	6	1	86%
0.32-0.40	5	0	100%
0.22-0.30	4	1	80%
0.12-0.20	11	0	100%
0.02-0.10	8	0	100%
0.08- -0.00	13	0	100%
-0.18- -0.10	9	0	100%
-0.28- -0.20	0	0	53%
-0.38- -0.30	1	0	100%

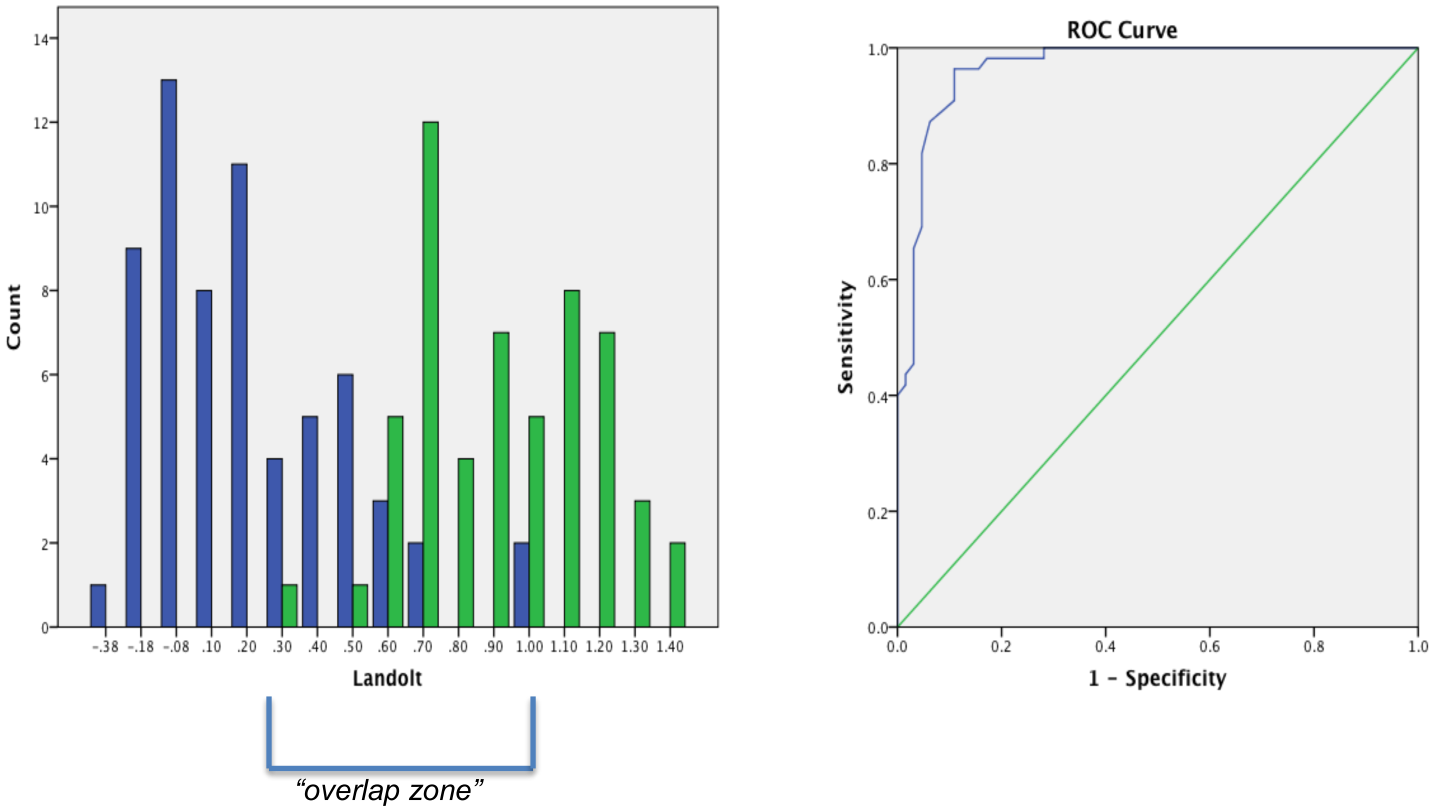


Figure 5.11: Left: Graphical representation of Landolt and number plate results. Blue lines show the "overlap zone" where there is an uncertainty if participants will pass both tests. Participants who passed the number plate test are represented with blue colour and those who failed by green. The graph on the right represents a ROC curve for the Landolt vs number plate comparison. The area under the curve is 0.97.

Table 5.15 and Figure 5.11 show that there are 18 participants who achieved worse than +0.30 logMAR and managed to pass the number plate test, but no one with an acuity better than +0.30 logMAR who passes the number plate test. As the previous section with the Bland- Altman plots indicated, acuities as measured with the Landolt chart tend to be worse than those measured with the other charts (Table 5.3). The area under the ROC curve is 0.97, which is the biggest of all the charts. It is closer to 1 compared to the other charts, which suggests that the test has good sensitivity and specificity if the most appropriate cut- off is used. The overlap zone identified for the Landolt chart is +0.30 to +0.98 logMAR.

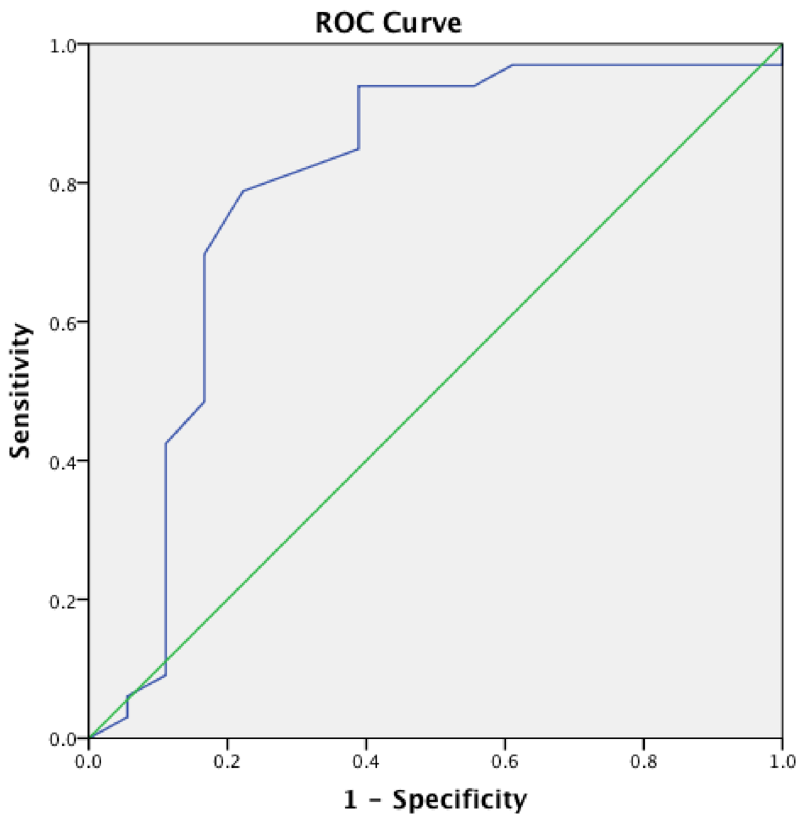


Figure 5.12: ROC curve for the overlap zone for Landolt chart. The area under the curve is 0.80.

Table 5.16: Coordinates of the ROC curve for the overlap zone of Landolt chart.

LANDOLT ACUITY	SENSITIVITY	SPECIFICITY
0.31	97%	5.6%
0.45	97%	38.9%
0.48	97%	44.4%
0.53	94%	61.1%
0.57	91%	61.1%

ROC analysis of the participants in the overlap zone (Figure 5.12 and Table 5.16), identifies that a cut off of +0.30 logMAR has a high sensitivity but no specificity, and that a cut off point of +0.50 logMAR is more appropriate to maximise sensitivity, whilst maintaining specificity. Therefore, the analysis of the overlap zone for this cut off is presented in Table 5.17.

Table 5.17: 51 participants in the "overlap zone" for Landolt chart.

		NUMBER PLATE TEST	
+0.50 LOGMAR ACUITY		**PASS**	**FAIL**
	PASS	11 (TN)	2 (FN)
	FAIL	7 (FP)	31 (TP)

Sensitivity, specificity, FPR and +PV are indicated below for the 51 participants within the "overlap zone" (+0.30- +0.98 logMAR).

Sensitivity= (TP/TP+FN)×100= 94.0%

Specificity= (TN/TN+FP)×100= 61.1%

False Positive Rate= (1- specificity)×100=39.0%

Positive Predictive Value= (TP/TP+FP)×100= 82.0% (Elliott, 2007).

Hence, the +0.50 logMAR cut off maximises sensitivity, whilst maintaining high specificity and thus similar people will be excluded from driving as the number plate test.

5.4.4 MNRead vs number plate test

Word acuities recorded with the MNRead chart and the results from the number plate test are presented in Table 5.18 below.

Table 5.18: MNRead acuity results and the frequency of participants who passed/failed the number plate test. Chance of passing is also presented.

MNREAD	NUMBER PLATES		CHANCE OF PASSING
	PASS	FAIL	
0.61-0.70	1	3	25%
0.51-0.60	2	6	25%
0.41-0.50	1	7	13%
0.31-0.40	3	8	27%
0.21-0.30	2	2	50%
0.11-0.20	3	0	100%
0.01-0.10	12	1	92%
0.00- -0.10	26	0	100%
-0.11- -0.20	12	0	100%
-0.21- -0.30	2	0	100%

Data are presented for 91 participants for whom valid acuity measures could be obtained given the ceiling imposed by a largest size of +0.60 logMAR (see Methods).

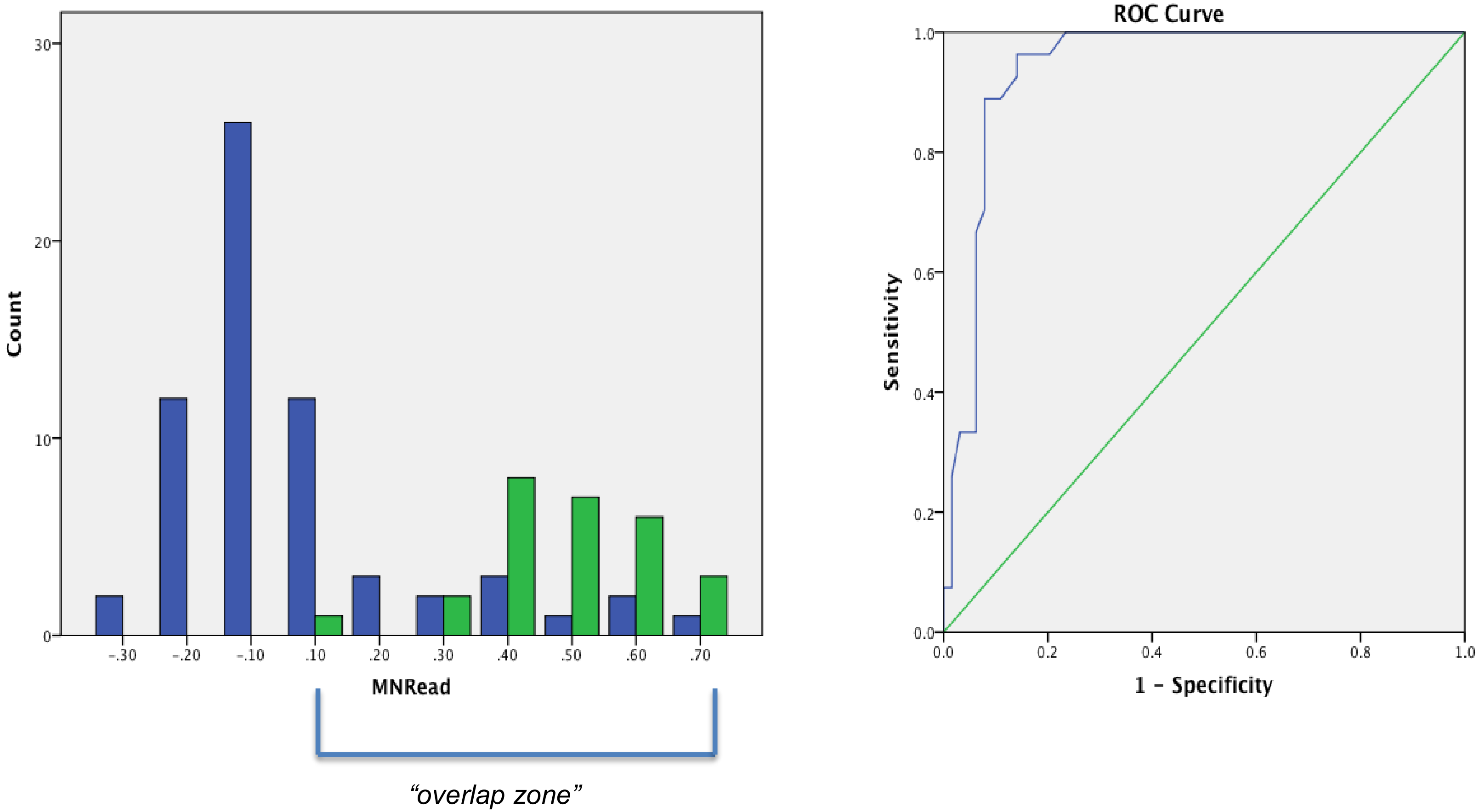


Figure 5.13: Left: Graphical representation of MNRead and number plate results. Blue lines show the "overlap zone" where there is an uncertainty if participants will pass both tests. Participants who passed the number plate test are indicated with blue colour and those who failed by green. The graph on the right represents a ROC curve for the MNRead vs number plate comparison. The area under the curve is 0.94.

There were seven participants with MNRead acuities worse than +0.30 logMAR who managed to pass the number plate test. The area under the ROC curve is 0.94, which is close to 1.0, thus showing good sensitivity and specificity for the chart. The overlap zone is between +0.08 to at least +0.70 logMAR, since data for acuities worse than +0.70 logMAR could not be collected due to the truncation of the chart.

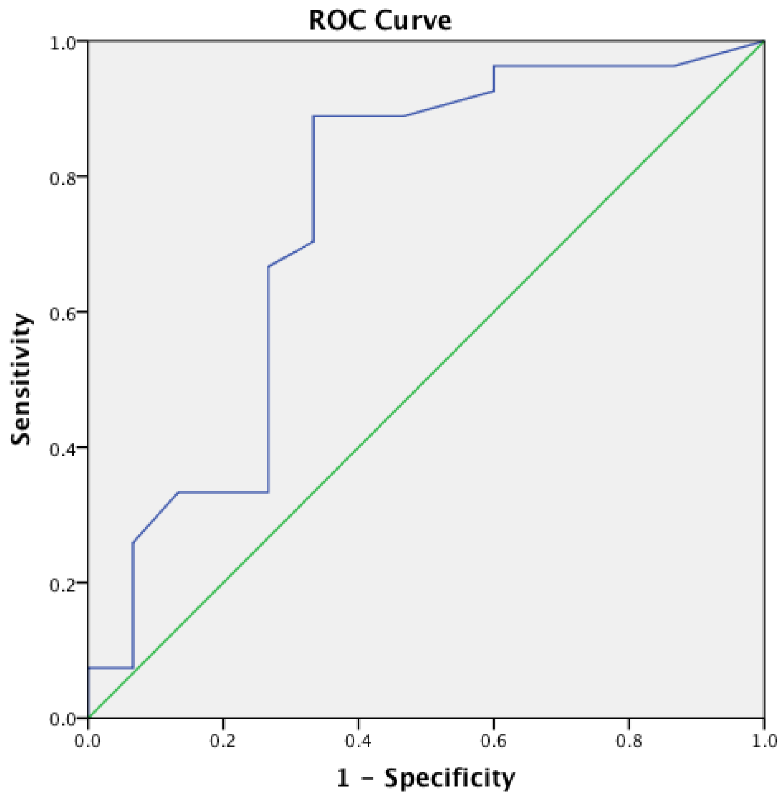


Figure 5.14: ROC curve for the overlap zone for MNRead chart. The area under the curve is 0.74.

The ROC analysis of the participants in the overlap zone (Figure 5.14 and Table 5.19) indicates that the +0.30 logMAR cut off is not quite the best performing, and that a slightly better value would be +0.25 logMAR.

Table 5.19: Coordinates of ROC curve for the overlap zone.

ACUITY	SENSITIVITY	SPECIFICITY
0.09	96%	13.3%
0.25	96%	40%
0.30	93%	40%
0.31	89%	53.3%

The most appropriate visual cut off point for distance reading acuity (MNRead chart) therefore appears to be at a slightly higher (+0.25 logMAR) acuity than the symbol acuity cut off of +0.30 logMAR, in order to exclude similar people from driving as the number plate test. With this cut off, there was one false negative and nine false positives within the overlap zone, giving sensitivity of 96.3% and specificity of 40.0%. The Bland-Altman plots (Figure 5.3) also showed that MNRead acuities were better compared to the acuities recorded by the other charts.

5.4.5 Summary

To summarise, the Bland-Altman plots show that the mean differences show trends, for example MNRead acuities are better at poor acuities compared to the other charts. The evaluation of whether the 6/12 Snellen or +0.30 logMAR cut off was an appropriate cut off point that will exclude similar people from driving as the number plate test was investigated with the use of ROC curves and the analysis of the "overlap zone". For Snellen and Sloan charts the 6/12 Snellen or +0.30 logMAR cut off was appropriate, for the Landolt chart a worse visual cut off point around +0.50 logMAR is needed and for MNRead chart the cut off point should be set at a higher acuity level of +0.25 logMAR to exclude similar people from driving as the number plate test. Thus, word acuity is slightly better compared to letter acuity. The overlap zones are a helpful tool, since they identify the people with uncertainty of passing both tests, who are actually those that Eye Care Practitioners will find it more difficult to advise.

CHAPTER 6: DISCUSSION

This thesis has investigated the relationship between the two current visual requirements for driving. The equivalence of the number plate test and the visual acuity test has been examined. Additionally, it has been investigated whether the four distance visual acuity charts used record similar levels of acuity.

6.1 COMPARISON OF VISUAL ACUITY CHARTS

The Bland-Altman plots (Figure 5.3) showed that letter and word acuities were better compared to symbol acuity and those differences were statistically significant, according to Bland-Altman plots (Table 5.3). The logMAR Landolt ring chart presents symbols and not letters, but follows the same construction rules as the logMAR letter chart. Despite this similar construction, they have the greatest mean difference (-0.13logMAR) between their acuities and the difference was found to be statistically significant. Participants found it more difficult to identify the orientation of letter C rather than identifying the letters presented on logMAR letter chart or on Snellen chart. Uncorrected astigmatism may affect the ability of participants to identify some of the positions of the gap of the letter C presented. Refractive correction was not collected as part of the data set, therefore it has not been possible to analyse the performance of those with uncorrected astigmatism specifically. Participants are also more familiar with letters rather than with different orientations of the letter C, since they use letters in their everyday life. For low luminance levels, Sloan et al. (1952) found approximately the same acuity levels were obtained with letters (Sloan) and Landolt rings. Reich and Bedell (2000) found that for low luminance levels the legibility threshold for Sloan letters was worse compared to Landolt rings by

0.05 log min arc in the fovea. At higher luminance levels Landolt rings were worse than British letters (Sheedy et al., 1984), which is similar to the findings of this study, where letters were better compared to symbol acuity.

The slope of the differences in Figure 5.3 is such that logMAR Landolt ring acuities become even worse, compared to letter acuities as vision gets worse. For example, in the Snellen-Landolt comparison, when mean acuity was 0.00 logMAR, the difference in acuities was +0.01 logMAR, but the difference was -0.15 logMAR when mean acuity was +1.00 logMAR. Similarly in the Sloan-Landolt comparison, when mean acuity was 0.00 logMAR, the difference was -0.11 logMAR, but when mean acuity was +1.00 logMAR, the difference was -0.15 logMAR.

Word acuity was found to be slightly better compared to letter and symbol acuity. The distance reading acuity (MNRead) chart represented a different visual task by requiring participants to read whole sentences and not just letters or symbols. Additionally, the words presented are related to one another in the sentences and participants can potentially use grammatical context to guess words correctly that they are on borderline of being able to see. The purpose of including the distance reading acuity (MNRead) chart was to compare letter and word acuities and it appears that the benefits of words over symbols seem to be increased at worse acuities. For the Snellen-MNRead comparison, when mean acuity was 0.00 logMAR, the difference in acuities was +0.11 logMAR in favour of MNRead and when mean acuity was +1.00 logMAR, the difference was +0.23 logMAR. The comparison of Sloan- MNRead and Landolt-MNRead showed a similar effect.

6.2 VISUAL ACUITY CHARTS AND THE NUMBER PLATE TEST

The comparison between the distance visual acuity charts and the number plate test showed that for the Snellen (full line scoring) and logMAR letter charts the 6/12 or +0.30 logMAR cut off provides reasonable sensitivity and specificity within the overlap zone (Snellen sensitivity= 97.1%, specificity= 62.5%, logMAR letter sensitivity=90.6%, specificity= 61.1%). Sensitivity indicates the ability of the 6/12 cut off to identify those who will fail the number plate test, while specificity identifies those who will pass the number plate test. Thus, these two charts can be used to measure the visual acuity of drivers, since the 6/12 or +0.30 logMAR cut off will exclude similar people from driving as the number plate test. The aim of this study was to investigate whether this cut- off maximises sensitivity, whilst specificity remains high. In order to provide appropriate advice, it is important to identify those who will fail the number plate test using visual acuity measurement and maximising sensitivity rather than specificity is therefore important.

Previous literature showed that a cut off around 6/9 acuity will exclude similar people from driving as the number plate test, though those studies used subjects with pathology and not uncorrected refractive error subjects and followed previous regulations (Drasdo and Haggerty, 1981; Currie et al., 2000). Currie et al. (2000) found that with 6/12 Snellen acuity, the chance of passing the number plate test was 34%, while with 6/9 Snellen acuity the chance of passing was 74%. Drasdo and Haggerty (1981) found a 50% chance of passing with $6/12^{+2}$ Snellen acuity based on their sample, while an acuity of $6/9^{-2}$ produced the same failure rate as the number plate test for their sample. Rathore et al. (2012) found that with 6/12 or better Snellen acuity there was

63% chance of passing the number plate test, while with 6/9 or better Snellen acuity the chances of passing were increased to 68%. In our sample, 98.3% of the overlap sample with 6/12 or 6/9 passed the number plate test, but our sample consisted of people with uncorrected refractive error and not ocular pathology.

The comparison of methods of scoring the Snellen chart resulted in the full line method (achieving all the letters on a line) providing the highest sensitivity (97.1%), whilst maintaining specificity (62.5%) for the overlap zone, as compared to the line assignment method or using letter-by-letter analysis. Thus, Eye Care Practitioners who use the Snellen chart in the test room should score the chart using the full line method.

The logMAR letter chart provided sensitivity of 90.6% and specificity of 61.1% (overlap zone). The logMAR letter chart can also be used to record the visual acuity of drivers, since sensitivity and specificity are high. The letter-by-letter scoring of that chart helps to identify accurately the level of acuity of the candidates for the driving licence.

Snellen and logMAR letter charts differ in construction, but the visual task that they require of participants is the same for both charts. The 6/12 line on the Snellen chart and the +0.30 logMAR line on the logMAR letter chart are similar: they both have five letters, the letters have the same height (17.5mm), letter spacing (around 14mm). Thus, although the construction and the letter choice between the two charts differ, factors such as the number of letters and height at this particular size are similar.

Table 6.1: Summary of findings.

CHART	OBSERVERS	OVERLAP ZONE	100% FAILURE (LEVEL OF ACUITY)	100% PASSING (LEVEL OF ACUITY)	SENSITIVITY OVERLAP ZONE	SPECIFICITY OVERLAP ZONE	CUT OFF
Snellen	120	6/9-6/36 (+0.18 - +0.78 logMAR)	6/60 (+1.00 logMAR)	6/7.5 (+0.10 logMAR)	97.1%	62.5%	6/12 OR +0.30 logMAR
LogMAR letter	117	+0.12- +0.84	+0.86 logMAR	+0.10 logMAR	90.6%	61.1%	+0.30 logMAR
LogMAR Landolt ring	119	+0.30- +0.98	+1.00 logMAR	+0.28 logMAR	94.0%	61.1%	+0.50 logMAR
Distance reading acuity (MNRead)	91	+0.08- at least +0.70	>+0.70 logMAR	+0.07 logMAR	96.3%	40.0%	+0.25 logMAR

People with acuity in the “overlap zone” may be able to pass the number plate test, but those with acuity worse than 6/12 are more likely to fail. However, those with 6/12 to 6/9 are more likely, to pass (Table 6.1). In the study of Rathore et al. (2012), an overlap zone between 6/6- 6/18 (Snellen chart) was found, where 6/6 represented a 100% pass rate with the number plate and 6/18 represented a 100% fail rate. Their zone differs from the overlap zones found for this study. This may be due to the fact, that Rathore et al. (2012) study used pathology subjects and followed the previous regulations. The overlap zones found for each chart differs slightly (Table 6.1). Drasdo and Haggerty (1981) found an overlap zone between 6/6- 6/18 (6/6 equals with almost certain pass). Currie et al. (2000) found an overlap zone between 6/7.5- 6/18. The overlap zone for the Snellen chart (6/9-6/36) found for this study is larger than those found in previous studies. The studies by Drasdo and Haggerty (1981) and Currie et al. (2000) did not concentrate on identifying the overlap zones, but in the acuities mentioned above there was an uncertainty of passing the number plate test. Again the difference in the overlap zone between previous literature and our study may be due to the different sample tested (people with uncorrected refractive error compared to people with pathology).

The overlap zones for the Snellen chart showed that 15.3% people failed the visual acuity test while they managed to pass the number plate test (false positives) and 1.7% failed the number plate test, whilst managing to pass the acuity test (false negative) (Table 5.7). For the logMAR letter chart there were 14.0% false positives and 6.0% false negatives (Table 5.12).

Therefore, Eye Care Practitioners will see candidates for the driving licence, who will be able to read 6/12 or better uncorrected, but they will not be able to read the number plate test. Those people, who were detected as false negatives (6/9 Snellen, up to +0.12 logMAR Sloan) should be advised that their acuity is acceptable for driving, but that they need to check their ability to read the number plate on their own, as the two tests differ. If they are unsure that they can read the number plate at 20m, then they should wear their refractive correction to drive. People achieving 6/7.5 Snellen acuity can be advised that they are fine to drive, however those with 6/9-6/12 acuity should be advised that the visual acuity part of the standard is fine, but it is their responsibility to check their ability to read a number plate. Eye Care Practitioners should advise patients to wear their refractive correction at all times while driving, even if they are certain that their unaided vision is adequate. Eye Care Practitioners should be careful with regard to the advice that they provide, because if they told a candidate that they are fine to drive, based on their acuity, and then the candidate could not read a number plate, then the candidate might consider that they had grounds to make a complaint against the practitioner.

There will also be patients who will be seen in the test room who will be unable to read 6/12, but they will be able to pass the number plate test (false positives). In our sample those candidates consisted a larger group than the false negatives (Snellen: 15.3%, Sloan: 14.0%). Under the old standards, where only the ability to read the number plate test was tested, these participants would have met the visual standard. However, under the new regulations they would fail to meet the standards, since they do not pass the visual acuity test. If patients are not able to achieve 6/12 with refractive correction they should be told not to drive and that they are responsible for informing the DVLA of their visual status. If the candidates defy the advice of the Eye Care Practitioners, then advice from the College of Optometrists (The College of Optometrists, 2013) and Association of Optometrists (AOP, 2013) should be sought. If candidates do not inform the DVLA that they do not meet the visual standards and they defy the advice of the Eye Care Practitioner, then the Eye Care Practitioner may need to inform the DVLA (The College of Optometrists, 2013). In such cases there is a conflict between the practitioner's duty of privacy to the patient and duty of care with regard to public safety, but the optometrist may need to prioritise the safety of the general public rather than the data protection of the patient.

The logMAR Landolt chart is not recommended to be used for the measurement of visual acuity of drivers. This chart needs a higher visual cut off level (+0.50 logMAR) to exclude similar people from driving with high sensitivity (94.0%) and good specificity (61.1%) (overlap zone). If people are tested with this chart their visual acuity will be recorded as being worse compared to other charts, since the logMAR Landolt ring chart tends to be not as precise in recording acuities as shown by the Bland- Altman plots in Chapter 5 (Table 5.3 and Figure 5.3). If Landolt rings are used by practitioners assessing visual fitness to drive, more people would be told not to drive, while actually they could if their acuity was measured with another chart. In this sample, 14 people got less than +0.30 logMAR on Landolt, but achieved +0.30 logMAR or better with a Sloan chart.

For distance reading acuity (MNRead) the most appropriate cut off was found to be at a slightly higher visual acuity level of +0.25 logMAR with a sensitivity of

96.3%, and specificity of 40.0% for the overlap zone to show equivalence with the number plate test. The MNRead chart was compared out of interest and it is not recommended to be used to measure the visual acuity of drivers, since word acuity does not comply with the visual standards required by DVLA. Further, limitations on font size have truncated this data and do not allow full analysis of the overlap zone for this chart.

Previous literature has not analysed the relationship between visual acuity and the number plate test with the use of ROC curves and sensitivity and specificity values. This thesis therefore makes a contribution to knowledge, by examining the relationship between these two tests in this way.

6.3 IMPLICATIONS FOR READING MOTORWAY SIGNS

The results of the study were also used to investigate the implications for reading a motorway sign with +0.30 logMAR or worse acuity. Text on motorway signs has an x-height of 300mm (Department of Transport et al., 1994). The following section will analyse the viewing distance at which a driver can see a motorway sign with a given acuity. The reaction time will also be estimated. This is of interest, because it can be examined whether a driver with 6/12 acuity (legal acuity to drive) will be able to read a motorway sign and come to a stop in time without risking safety.

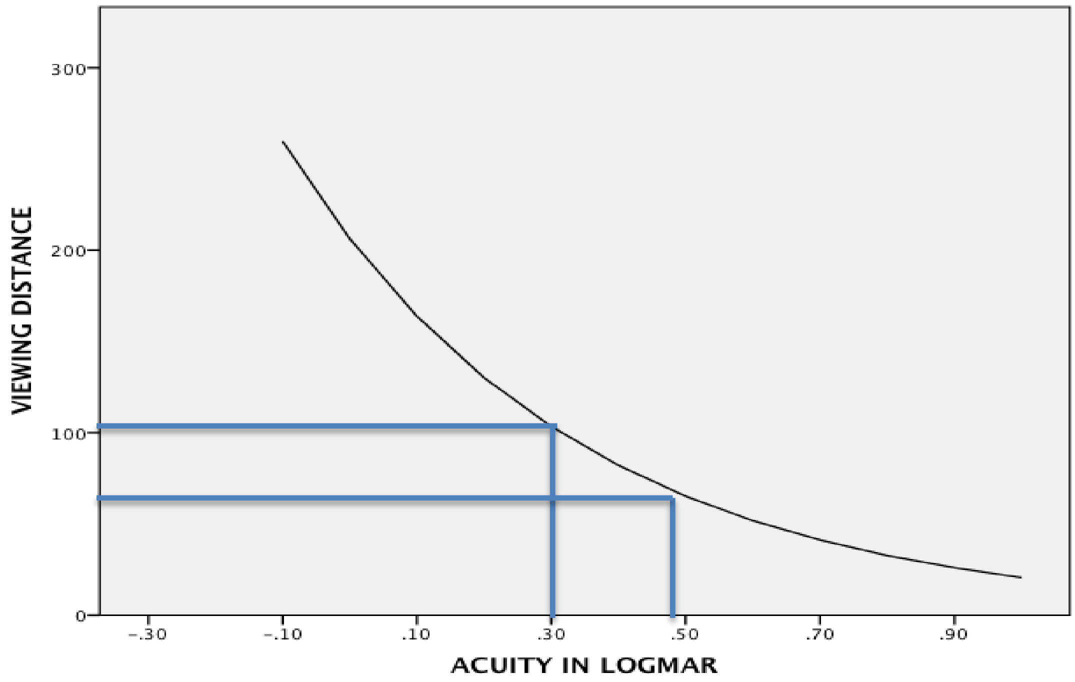


Figure 6.1: The viewing distance at which motorway signs can be seen with different levels of visual acuity (logMAR).

Figure 6.1 shows at what viewing distance motorway signs would be legible given different levels of acuity. In order to calculate the viewing distance the following formula was used: viewing distance= 687.5×30/ log^{-1} (logMAR) (Legge, 2007), where 30cm represents the 300mm x-height (Legge, 2007). Therefore, with a legal acuity to drive of +0.30 logMAR, a driver can see a motorway sign at 103m. With an acuity worse than the standard (e.g. +0.50 logMAR) a driver needs to be closer to a road sign for it to be visible (e.g. in this instance 65m). Since it was shown that +0.30 logMAR letter acuity is more equivalent to a word acuity of +0.25 logMAR, for this task a +0.25 logMAR limit will also be considered to present the differences between the letter and word cut offs.

Using the expression Time = Distance/ Speed, and assuming travel at the speed limit of 70 mph, with acuity of +0.30 logMAR the time taken to travel the

103m between first reading a road sign and reaching it is 3.3 seconds (Figure 6.2), with an acuity of +0.25 logMAR the time is 3.71 sec (viewing distance of 116m), and with a worse acuity of +0.50 logMAR, the time would be reduced to 2.08 seconds.

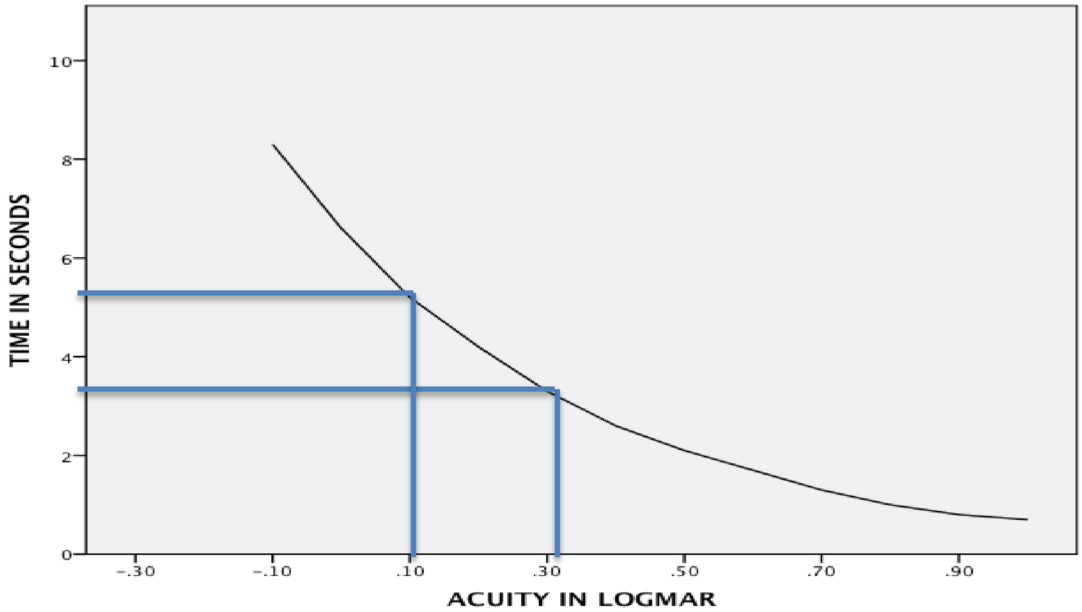


Figure 6.2: Shows the reaction time available between reading a motorway sign and reaching it at different acuity levels for a stable speed of 70mph.

The Highway Code (1993) states that at a stable speed of 70mph, a braking distance of 96m is required (GOV.UK, 2013c). Thus, with a legal acuity to drive of +0.25 or +0.30 logMAR, a driver will have a viewing distance of 116m or 103m respectively and thus would be able to come to a stop in the time between reading a sign and reaching it. Stopping time is important, since the driver needs to have adequate time to read the whole sign and have time to react without risking of causing an accident. With worse acuity of +0.50 logMAR, the driver would not be able to come to a complete stop between reading a sign 65m from it and reaching the sign, and the time available for taking other actions would be reduced. Therefore, the acuity standard and the size of the motorway signage are nicely matched regarding the ability to read a motorway sign and performance on road.

Previous literature estimated that a driver with visual acuity of 6/6, who travels at 60mph will have 3.9 seconds to read a road sign with letters of 6 inches (152.4mm) high (Allen, 1969). However, a driver with acuity of 6/12 will read the same road sign 1.95 seconds from it, while a driver with acuity of 6/36 will have only 0.65 seconds (Grundy, 1994). Therefore, lower acuities than 6/12 will not only result in failing the number plate test, but will also allow the driver to have less time to predict and react to what happens on the road.

6.4 LIMITATIONS OF STUDY

The study recruited people with wider range of acuities than 6/9-6/12 visual acuity, since a lot of participants thought that they were borderline for driving while they actually were not. Additionally, while uncorrected refractive error reduces visual acuity it may not affect other aspects of vision, such as contrast sensitivity, in the same way as for patients with pathology, such as cataract. The ability to read the number plate may be more affected in such individuals, due to outdoor conditions such as the effect of glare. In order to extend the findings beyond uncorrected refractive error and to obtain more data specifically within the overlap zone, a second study was performed, in which simulation spectacles were used, in order to reduce the visual acuity of participants to the level of the driving standard and to attempt to simulate ocular conditions, such as cataract.

CHAPTER 7: ADDITIONAL EXPERIMENT- SIMULATED VISUAL LOSS

The study described in Chapter 5 aimed to recruit people who had borderline vision for driving, therefore around 6/9 - 6/12 Snellen. However, only 13% of the 120 participants tested had vision within 6/9 - 6/12 and 27.1% had vision of 6/9-6/12 within the overlap zone. An additional experiment was therefore performed, aiming to provide more participants with visual acuities in this region. For this experiment, Cambridge University Simulation Spectacles (University of Cambridge, 2010) were used to reduce the vision of the participant to the level of vision necessary for driving. Simulation spectacles are intended to simulate loss of both visual acuity and contrast sensitivity (University of Cambridge, 2010), which are the effects accompanying most ocular pathology, and thus allows investigation of whether these participants behave differently compared to those with uncorrected refractive error which would predominantly influence visual acuity (Jackson and Bailey, 2004).

Contrast sensitivity (CS) provides useful information about the quality of an image that is separate to information about visual acuity (Elliott, 2006). With some forms of ocular pathology visual acuity may be relatively good, but visual quality is reduced due to CS loss. Cataracts, for example, increase light scattering in the human eye, resulting in a reduction of image contrast and thus has a negative impact on contrast sensitivity (American Academy of Ophthalmology, 1990), with contrast sensitivity often affected more than visual acuity (Terry and Brown, 1989). This can affect vision in outdoor daylight conditions, and people with cataract have been seen to have a reduction in visual acuity of as much as five lines of Snellen acuity outdoors as compared to measurements taken indoors (Neumann et al., 1988).

The hypothesis of this study was that people with pathology such as cataract, who experience reduced visual acuity and contrast sensitivity may not be able to perform well at the number plate test due to the outdoor conditions that may affect their visual functions.

Thus, this study aims firstly to provide additional data in the overlap zone, and secondly to investigate whether simulated visual loss affects visual acuity and the ability to read the number plate in the same way as uncorrected refractive error.

7.1 PARTICIPANTS

Thirty eight participants were recruited from the University population. There were 14 males and 24 females, with a mean age of 19.9 ± 3.8 years, range 17-36 years. All subjects held a provisional or full driving licence. Sixteen participants wore spectacles for driving, four wore contact lenses and eighteen wore no refractive correction. Twenty six participants had attended for an eye examination within the previous two years and the remaining twelve participants within the last eight years.

7.2 METHODS

The procedure followed for the additional experiment was the same as that followed for the original experiment (Section 4.3). Thus, participants read the four distance visual acuity charts at 6m. Participants were also taken outside to perform the number plate test at 20m.

Participants' presenting visual acuity was measured with correction using the Snellen chart (full line method). Simulation spectacles were then added, dependent on the initial acuity, to reduce the acuity to approximately 6/12.

The simulation spectacles used were developed by the Engineering Design Centre, University of Cambridge in order to "simulate a loss of the ability to see fine detail, but are not intended to represent any particular eye condition" (University of Cambridge, 2010). The simulation spectacles consist of translucent material mounted in a cardboard frame to reduce the visual acuity and contrast sensitivity of the wearer. The spectacles have been designed so that different levels of visual loss can be induced by wearing different 'levels' of blur. The reduction in visual acuity depends on the initial visual acuity of the wearer. A participant with 6/6 visual acuity should wear level 2 simulation spectacles, in order to reduce the visual acuity to 6/12 (University of Cambridge, 2010). If participants wear more sets of the simulation spectacles of either level 1 or level 2, they will experience a more severe visual loss.

Participants read the four distance visual acuity charts wearing the simulation spectacles over any refractive correction worn, and then they were taken outside where they read three number plates, again wearing the simulation spectacles.

7.3 RESULTS

7.3.1 Effect of simulation spectacles

Simulation spectacles were used to reduce the vision of the participants as outlined above. For sixteen of the 38 participants, acuity was reduced to within one line of 6/12 by the addition of level 2 simulation spectacles, as shown in the Table 7.1.

Table 7.1: Number of participants and the Snellen acuity achieved with simulation spectacles level 2, shown together with their natural Snellen acuity (n=16).

SNELLEN ACUITY WITH LEVEL 2 SIM SPECS	**PRESENTING SNELLEN ACUITY**			
	6/7.5	**6/6**	**6/5**	**6/4**
6/18	1	0	0	0
6/12	2	0	1	1
6/9	2	4	3	2

The level 2 simulation spectacles reduced acuity by between one and five lines of Snellen acuity, but did not reduce acuity to within a line of 6/12 for all subjects. The median reduction in lines is -2.5, the mode is -2.0 and the range is 4.0.

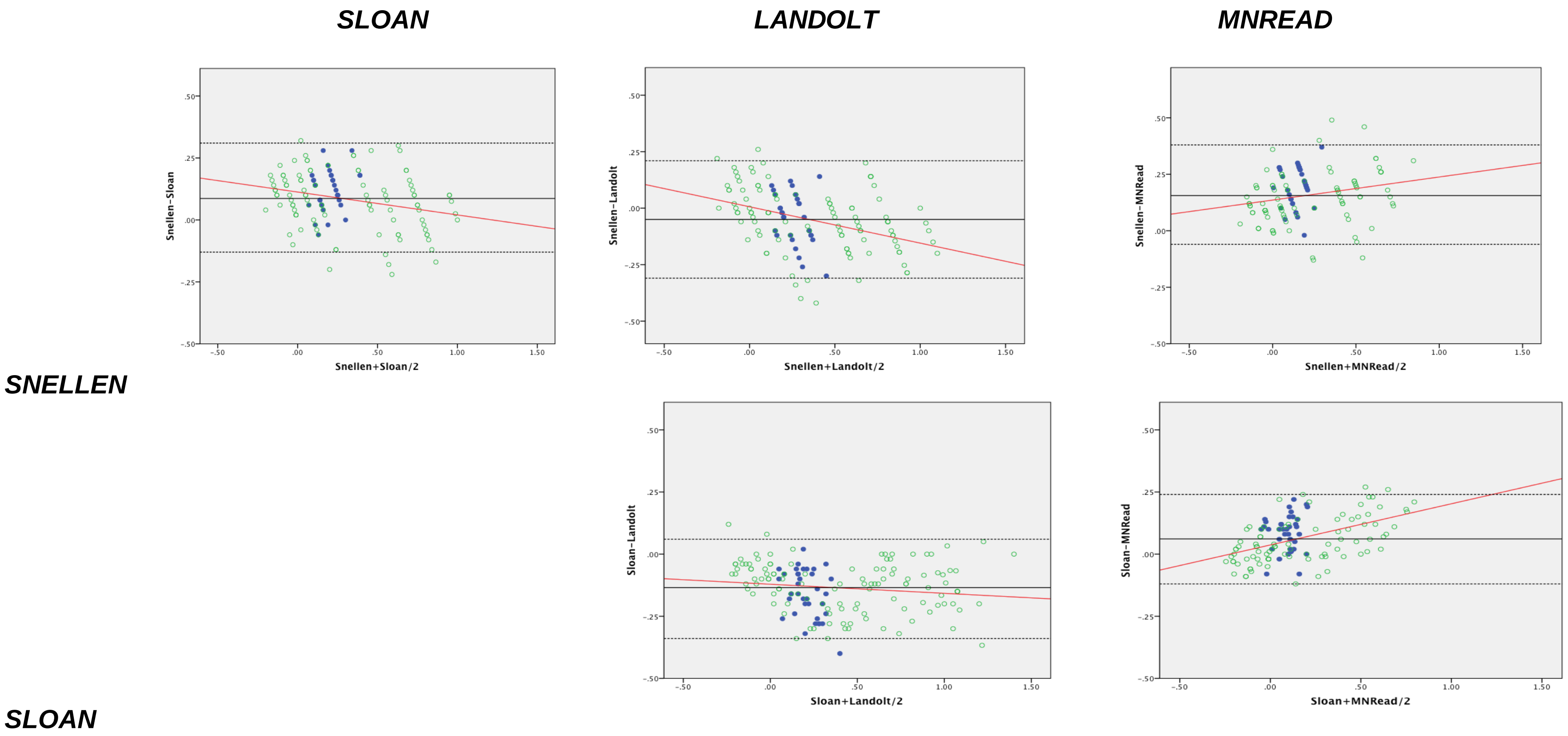
Table 7.2: Number of participants and the Snellen acuity achieved with simulation spectacles level 3, shown together with their natural Snellen acuity (n=22).

SNELLEN ACUITY WITH LEVEL 3 SIM SPECS	**PRESENTING SNELLEN ACUITY**			
	6/7.5	**6/6**	**6/5**	**6/4**
6/18	1	1	0	0
6/12	1	3	6	5
6/9	0	0	1	1
6/7.5	0	1	0	2

Level 3 simulation spectacles were needed for the remaining 22 participants to reduce acuity towards 6/12, as shown in Table 7.2. Again participants experienced between one and five lines reduction with the simulation spectacles from their presenting acuity. The median reduction in lines is -4.0, the mode is -4.0 and the range is 4.

7.3.2 Simulation spectacles and visual acuity charts

The results obtained with the simulation spectacles are combined with the original results that were presented in Chapter 5. The Bland- Altman plots (Figure 7.1) present how the simulation spectacles behave with the different visual acuity charts. The original data are in green, while the data obtained with the simulation spectacles are in blue. The blue dots fit well with the pattern of green data, indicating that the simulation spectacles are affecting the visual acuity in the same way on the different charts as uncorrected refractive error. Thus, it appears that the simulation spectacles are a valid way to reduce acuity to a desired level.



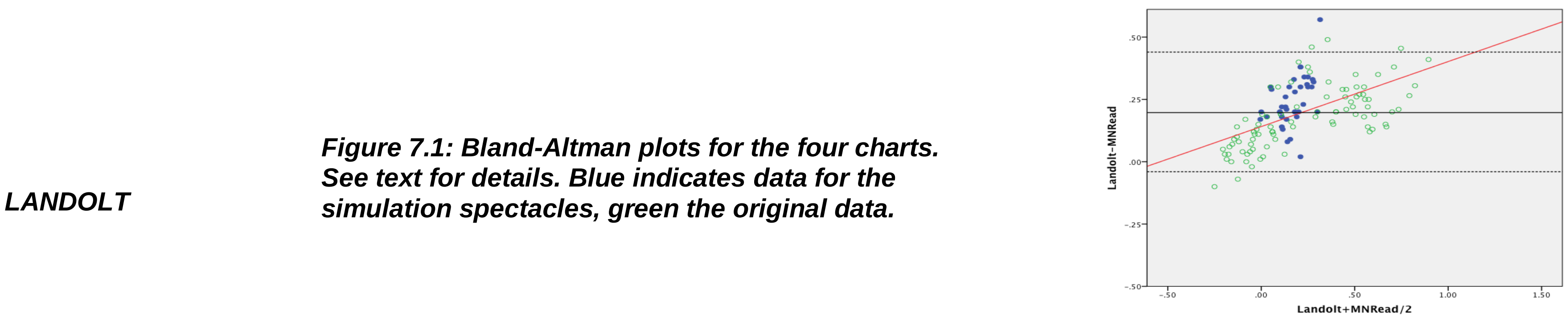


Figure 7.1: Bland-Altman plots for the four charts. See text for details. Blue indicates data for the simulation spectacles, green the original data.

The addition of the simulation spectacles data does not change the comparison between the visual acuity charts, with only minor changes in the mean difference (0.01- 0.02 logMAR) and 95% LoA observed.

7.4 RELATIONSHIP BETWEEN THE DATA FROM THE TWO STUDIES AND THE NUMBER PLATE TEST

Having determined that the simulation spectacles data results in visual acuities that change in the same way across the different acuity charts as the uncorrected refractive data did, the acuities obtained with the simulation spectacles was compared against the number plate test. The data used for this analysis was only that collected for the simulation spectacles. Since the number of participants is small, a clear cut off point for each chart at which sensitivity is maximised and specificity is maintained at a high level cannot be established, and the results concentrate on comparing the proportions of false positives and negatives within the data set.

7.4.1 Snellen chart and the number plate test

Simulation spectacle data for the Snellen chart are presented against the number plate test in Table 7.3 and Figure 7.2. Only the full line method of scoring Snellen chart is considered here, since it was found that this is the most appropriate method to score the Snellen chart, in terms of measuring the visual acuity of drivers.

Table 7.3: Shows the simulation spectacle data, how many participants pass/fail the number plate and the chance of passing at each acuity level for the Snellen chart.

PRESENTING SNELLEN ACUITY	**NUMBER PLATE TEST**		**CHANCE OF PASSING**
	PASS	**FAIL**	
6/18	3	0	100%
6/12	13	6	68%
6/9	13	0	100%
6/7.5	3	0	100%

Table 7.3 shows that with this smaller data set, everyone with acuity 6/9 or better could read the number plate. With 6/12 68% passed, however all three people with 6/18 vision passed the number plate test.

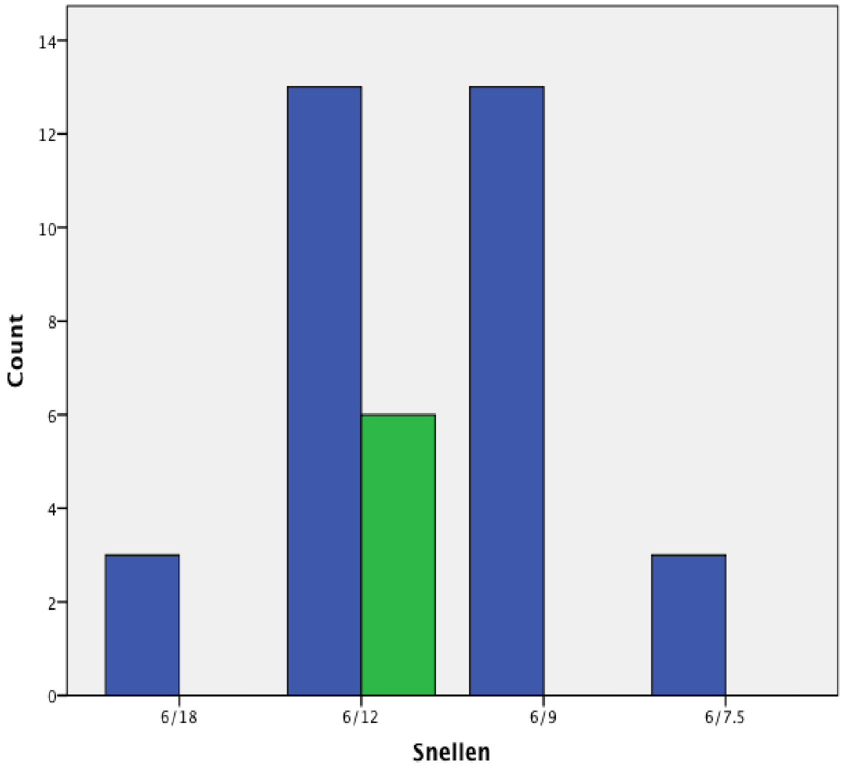


Figure 7.2: The bar graph shows how many people pass (blue) and fail (green) the number plate test at each acuity level.

Table 7.4: Shows the True Negatives, False Negatives, True Positives and False Positives for the Snellen chart.

	NUMBER PLATE TEST		
6/12 SNELLEN ACUITY		**PASS**	**FAIL**
	PASS	29 (TN)	6 (FN)
	FAIL	3 (FP)	0 (TP)

For the simulation spectacles data six participants (15.8%) failed the number plate test, but passed the visual acuity test (false negatives), compared to 1.7% in the original study. Three participants (7.9%) failed the visual acuity test and passed the number plate test (false positives), compared to 15.3% in the original study. Twenty nine participants manage to pass both tests.

7.4.2 LogMAR letter chart and the number plate test

Table 7.5 presents the ability to read a number plate with different levels of logMAR letter acuity with the simulation spectacles.

Table 7.5: Acuities achieved by participants and how many participants passed/ failed the number plate test. Chance of passing at each acuity level is also presented for logMAR letter chart.

PRESENTING LOGMAR LETTER ACUITY	NUMBER PLATE TEST		CHANCE OF PASSING
	PASS	FAIL	
+0.22- +0.30	4	1	80%
+0.12- +0.20	17	4	81%
+0.00- +0.10	11	1	92%

With the levels of blur provided by the simulation spectacles, all participants were able to achieve a logMAR letter acuity of +0.30 logMAR or better. However, only 32 out of the 38 (84.0%) were able to pass the number plate test.

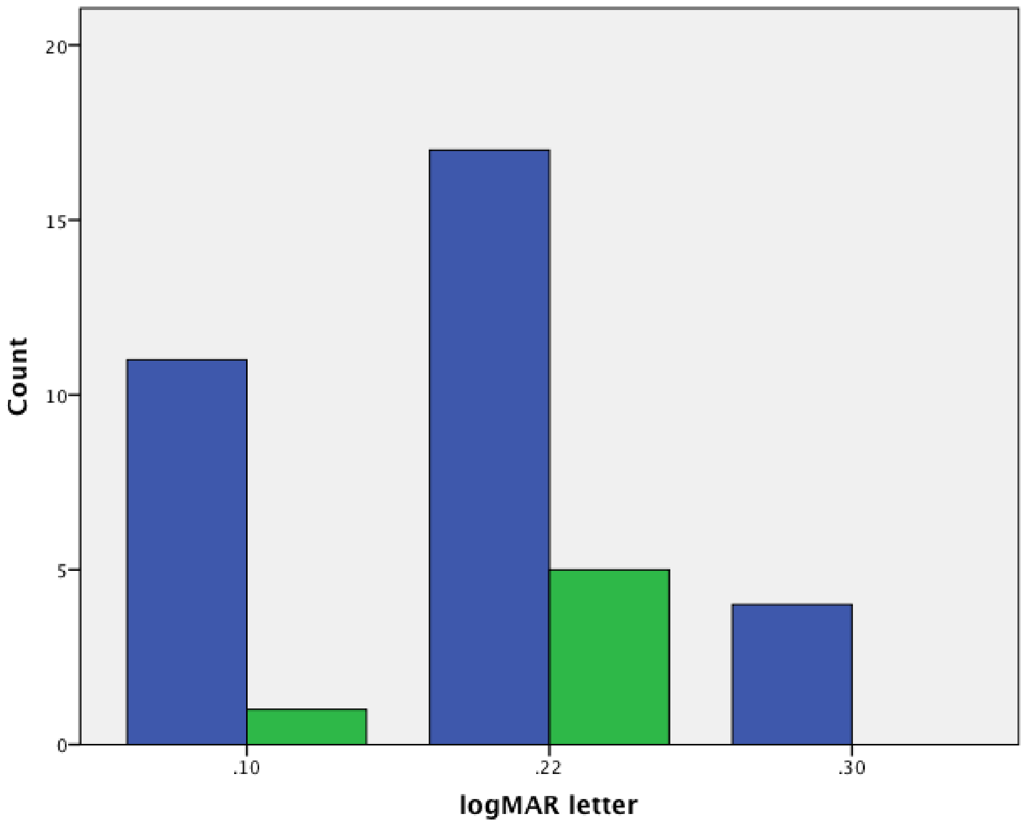


Figure 7.3: The bar graph shows how many people pass (blue) and fail (green) the number plate test at each acuity level.

Table 7.6: Shows the True Negatives, False Negatives, True Positives and False Positives for the logMAR letter chart.

		NUMBER PLATE TEST	
+0.30 LOGMAR ACUITY		**PASS**	**FAIL**
	PASS	32 (TN)	6 (FN)
	FAIL	0 (FP)	0 (TP)

There were six people (15.8%) who failed the number plate test but achieved the visual acuity standard, as opposed to 6.0% of false negatives in the original study. No one in this study was recorded as a false positive, compared to the original study, where 14.0% were recorded as false positives.

7.4.3 LogMAR Landolt chart and the number plate test

Simulation spectacle data recorded with the logMAR Landolt ring chart against the number plate test are presented below.

Table 7.7: Landolt acuities achieved by participants and number of participants passed/failed the number plate test. Chance of passing for each acuity level is also presented for the logMAR Landolt ring chart.

PRESENTING LOGMAR LANDOLT RING ACUITY	**NUMBER PLATE TEST**		**CHANCE OF PASSING**
	PASS	**FAIL**	
+0.52- +0.60	2	0	100%
+0.42- +0.50	3	2	60%
+0.32- +0.40	7	2	78%
+0.22- +0.30	8	2	80%
+0.12- +0.20	10	0	100%
+0.08- +0.10	2	0	100%

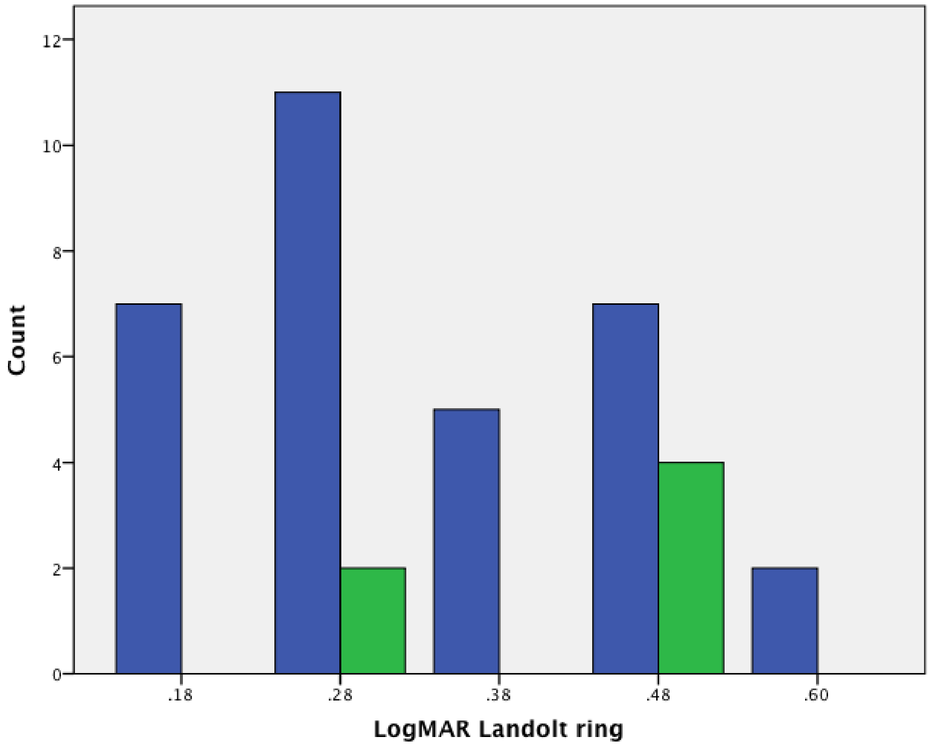


Figure 7.4: The bar graph shows how many people pass (blue) and fail (green) the number plate test at each acuity level.

Table 7.7 indicates that with a visual acuity cut off of +0.30 logMAR, two people managed to pass the acuity test but failed the number plate test, unlike with the original sample, where only one participant achieved +0.30 logMAR acuity, but failed the number plate test.

Table 7.8: Shows the True Negatives, False Negatives, True Positives and False Positives for the logMAR Landolt ring chart.

		NUMBER PLATE TEST	
+0.50 LOGMAR ACUITY		**PASS**	**FAIL**
	PASS	30 (TN)	6 (FN)
	FAIL	2 (FP)	0 (TP)

Considering a +0.50 logMAR cut off point, and compared to the original sample, the proportion of false negatives in the simulation spectacles sample was 15.8%, compared to 6.5% of the overlap zone in the original sample. The proportion of false positives in the simulation spectacle sample was 5.3%, as opposed to 13.7% in the overlap zone of the original sample.

7.4.4 Distance reading acuity (MNRead) chart and the number plate test

The chance of passing the number plate test for simulation spectacles data for the distance reading acuity (MNRead) chart is presented below.

Table 7.9: How many participants pass/fail and chance of passing at each acuity level is also presented for the distance reading acuity (MNRead).

PRESENTING DISTANCE READING ACUITY (MNREAD)	**NUMBER PLATE TEST**		**CHANCE OF PASSING**
	PASS	**FAIL**	
+0.11- +0.22	7	3	70%
+0.01- +0.10	15	3	83%
-0.10- 0.00	10	0	100%

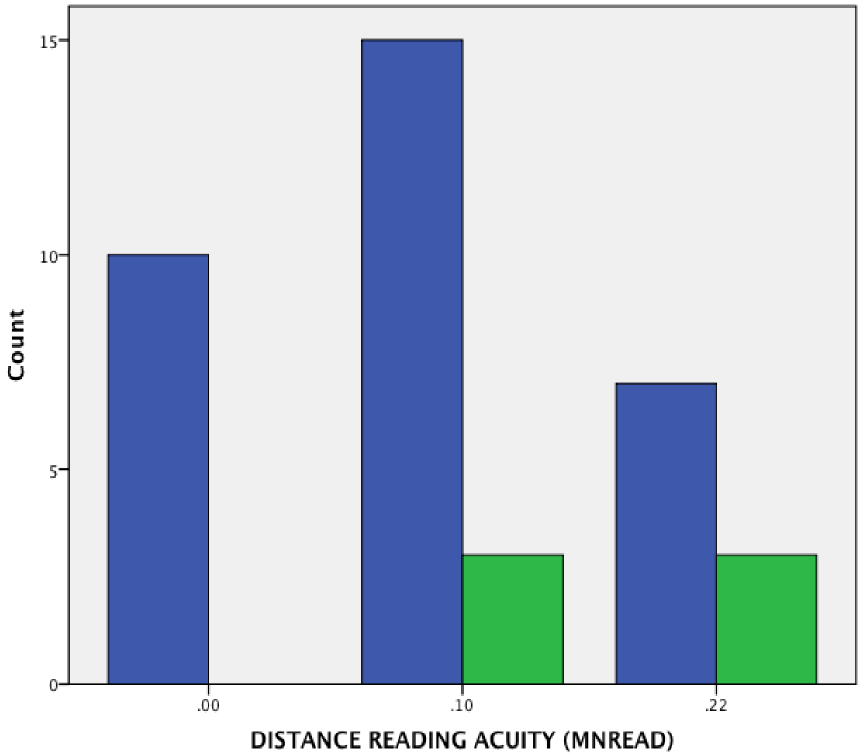


Figure 7.5: The bar graph shows how many people pass (blue) and fail (green) the number plate test at each acuity level.

The simulation spectacles reduce word acuity, however the reduction is not as great as it is with the Snellen chart, since no one achieves below +0.30 logMAR. Although better acuities than +0.30 logMAR were achieved, six people failed the number plate test.

Table 7.10: Shows the True Negatives, False Negatives, True Positives and False Positives for the distance reading acuity (MNRead) chart.

		NUMBER PLATE TEST	
+0.25 LOGMAR ACUITY		**PASS**	**FAIL**
	PASS	32 (TN)	6 (FN)
	FAIL	0 (FP)	0 (TP)

The proportion of false negatives in the simulation spectacles sample was 15.8%, compared to 2.4% of the overlap zone in the original sample. The proportion of false positives in the simulation spectacle sample was 0%, as opposed to 21.4% in the overlap zone of the original sample. The proportion of false negatives was higher compared to the original study.

7.4.5 Summary

Simulation spectacles reduced the visual acuity of the participants recruited for the study. The comparison between the acuity charts showed that the additional data behaved in the same way in the test room as the original data, resulting in no significant changes in the results. Comparing the visual acuity chart results with the number plate test, the proportion of false negatives increased in all charts, and the proportion of false positives generally decreased.

CHAPTER 8: DISCUSSION OF SIMULATION SPECTACLES STUDY

The acuity data collected from the simulation spectacles study were combined with the data from the original study, to determine whether the simulation spectacles reduced acuity in a similar way to uncorrected refractive error for each chart and that the simulation of 6/9-6/12 visual acuity had the same effects as unaided acuity of 6/9-6/12. Table 8.1 indicates that addition of the simulation spectacle data did not significantly influence the findings of the initial study (Snellen- MNRead +0.14 logMAR, SD: 0.11, simulation spectacles study +0.16 logMAR, SD: 0.11).

Table 8.1: Mean differences for the comparisons between charts from both studies and the difference detected between the two studies.

COMPARISON	ORIGINAL STUDY (LOGMAR)	COMBINED DATA (LOGMAR)	DIFFERENCE BETWEEN STUDIES (LOGMAR)
Snellen- Sloan	+0.08	+0.09	0.01
Snellen-Landolt	-0.05	-0.05	0.00
Snellen-MNRead	+0.14	+0.16	0.02
Sloan- Landolt	-0.13	-0.14	0.01
Sloan-MNRead	+0.05	+0.06	0.01
Landolt- MNRead	+0.18	+0.20	0.02

Thus, the results obtained from simulated visual loss and from uncorrected refractive error do not behave differently in relation to the measurement of visual acuity by the specific charts.

8.1 SIMULATION SPECTACLES DATA AND THE NUMBER PLATE TEST

The aim of this study was also to investigate whether the simulation spectacles made it more difficult to read a number plate compared to people with uncorrected refractive error.

It was found that the simulation spectacles data act differently compared to uncorrected refractive data. The proportion of false positives in the sample generally decreased and the proportion of false negatives in the sample increased with the simulation spectacles data compared to those in the overlap zone of the original study (Table 8.2). There were a greater proportion of people who were able to pass the visual acuity test, but failed the number plate test. Thus, the intended simulated visual loss resulted in more people facing problems in reading the number plates at 20m, perhaps due to the outdoor conditions being more problematic with reduced contrast sensitivity and increased glare. This suggests that visual loss that affects contrast sensitivity as well as visual acuity may result in candidates being able to pass the acuity test, but the number plate test is harder for them to read. Patients with reduced contrast sensitivity due to cataracts, who do not have cataract surgery, may have legal acuity to drive (Chapter 7), but in the outdoor conditions of the number plate test, they may not be able to identify the characters. The outdoor conditions in which the number plate test is performed may affect the performance of pathology subjects, since they not only have reduced visual acuity, but also reduced contrast sensitivity in most cases and thus they differ from the uncorrected refractive error sample, which had “normal” contrast sensitivity.

Table 8.2: Proportions of False Negatives and False Positives for subjects with vision in the overlap zones found in the two studies. In all cases the second study has higher numbers of False Negatives.

CHARTS	**FN ORIGINAL STUDY**	**FN SIMULATION SPECTACLES STUDY**	**FP ORIGINAL STUDY**	**FP SIMULATION SPECTACLES STUDY**
Snellen	1.7%	15.8%	15.3%	7.9%
logMAR letter	6.0%	15.8%	14.0%	0%
logMAR Landolt ring	6.5%	15.8%	13.7%	5.3%
Distance reading acuity (MNRead)	2.4%	15.8%	21.4%	0%

The increase in false negatives in the simulation spectacle data compared to uncorrected refractive error appears to provide some support for this suggestion.

People identified here as false negatives will not be able to pass the number plate test, but they will be able to pass the visual acuity test. Therefore, Eye Care Practitioners need to be careful with their advice as they might tell these patients that they are eligible to drive, yet they are at risk of failing the number plate test, since the visual acuity tests carried out indoors do not have the outdoor factors, such as glare. Sugar et al. (2002) found that in early stages of cataract, contrast sensitivity can be at reduced, whilst visual acuity is normal. Visual acuity and contrast sensitivity loss are not necessarily similar, and the level of visual acuity loss cannot predict the amount of contrast sensitivity loss (Elliott, 2006). The 6/12 recommended visual limit for cataract surgery (The Royal College of Ophthalmologists, 2014) is also the legal limit for driving. Those people with 6/12 acuity or better may be able to pass the visual acuity test, but may not be able to pass the number plate test, due to the outdoor effects of glare.

As was explained in the beginning of Chapter 7, this may consisted a problem in areas where cataract surgery is restricted to those whose visual acuity is reduced to 6/12 or worse in both first and second eye surgery, such as in Cambridge and Peterborough (NHS, 2013; The Royal College of Ophthalmologists, 2014). The LogMAR letter chart detected six people (15.8%) who were able to achieve better than +0.30 logMAR, thus those people would not have been qualified for the cataract surgery, but they were unable to read a number plate and thus also unable to drive.

One limitation of this second study is that, by using the Snellen chart as the basis for determining the appropriate amount of blur to induce with the simulation spectacles, no one has worse acuities than +0.30 logMAR on the logMAR letter chart.

Participants with induced simulated visual loss acted in the same way at the measurement of visual acuity, but differently against the number plate test. This suggests that the findings with uncorrected refractive error may not exactly reflect the findings with those with ocular pathology reducing best corrected acuity. Thus, other visual assessments should be considered during eye examination for those candidates, such as an assessment of contrast sensitivity. It is crucial to identify the needs of the candidates for the driving licence and ensure that nobody who is eligible to drive will be told otherwise.

CHAPTER 9: CONCLUSIONS AND RECOMMENDATIONS

The aim of this thesis was to investigate the new regulations for the visual acuity of drivers of being able to achieve 6/12 visual acuity and pass the number plate test at 20m. The way of measuring this visual cut off was assessed by using four distance visual acuity charts. The equivalence between visual acuity and the number plate test was also assessed. The study focused on people with uncorrected refractive error, since they constitute the majority of drivers, who are likely to fail the visual standards and thus need to be advised, in order to be able to drive safely and because previous literature has not used these people before.

The main study included people whose acuity was reduced due to uncorrected refractive blur. These people need advice on whether to wear their refractive correction for driving. The follow up study used simulation spectacles to try to reduce both visual acuity and contrast sensitivity, more like age-related or pathological changes in best corrected function. This second study (Chapter 7) was also conducted with the aim of recruiting more participants around the 6/9-6/12 area, since the first study ended up with wider range of acuities than expected.

9.1 RECOMMENDATIONS

The ability to read a number plate at 20m is not exactly equivalent to an acuity of 6/12 Snellen or +0.30 logMAR. Drivers may fail one or other of the two tests if their vision falls within a range around 6/12 (overlap zone for Snellen 6/9-6/36, and for a logMAR letter chart +0.12 to +0.84 logMAR).

LogMAR Landolt ring acuities are poorer than those for Snellen or logMAR letter charts and the +0.30 logMAR cut off is poor at predicting the ability to pass the number plate test. This chart is not recommended if assessing visual fitness to drive, since more people will be told that they are not eligible to drive, while they actually could if their visual acuity was measured with another visual acuity chart.

Although MNRead acuities were better compared to those recorded by the other charts, the distance reading acuity (MNRead) chart was compared to the other charts out of interest, in order to investigate how word reading in the distance is related to letter reading. It was not examined as a recommended method for the measurement of the visual acuity of drivers. A word acuity cut-off of +0.25 logMAR best reflected the ability to read a number plate. It was shown that a +0.25 or +0.30 logMAR cut off is nicely matched with the ability to read and react to motorway signs (section 6.3).

For Snellen and logMAR letter charts, an acuity of 6/12 or +0.30logMAR provides reasonable sensitivity and specificity (for the ‘overlap zone’: Snellen sensitivity 97.1%, specificity 62.5%, logMAR letter chart sensitivity 90.6%, specificity 61.1%) for predicting performance in the number plate test, but not all drivers achieving 6/12 will be able to pass the number plate test. Eye Care Practitioners should advise patients with vision that is only slightly better than the 6/12 standard (6/9 Snellen, +0.12 to +0.28 logMAR letter) to test their ability to read a number plate at 20m on their own regularly. The proportion of people in this category for the simulation spectacle data was higher for Snellen (1.7% original, 15.8% follow up) and logMAR letter charts (6.0% original, 15.8% follow up; Table 8.2). Thus, it is suggested that people with ocular pathology may be more likely to fail the number plate test even with 6/12 acuity compared to people with uncorrected refractive error, due to problems related to other visual functions (e.g. contrast sensitivity).

Additionally, in the original study approximately 15% of our sample could read a number plate at 20m, but failed to achieve 6/12 Snellen or +0.30 logMAR letter. These individuals would have been perfectly legal to drive prior to 2012, but under the new regulations now fail to meet one of the two criteria. Therefore, under the new regulations, Eye Care Practitioners will see more patients who fail to meet visual standards for driving.

Drivers who will not achieve 6/12 uncorrected but whose acuity can be improved with refractive correction should be advised to wear refractive correction for driving at all times. Drivers who do not achieve 6/12 with best correction should be advised that it is their legal duty to inform the DVLA of this (GOV.UK, 2013b). If a patient is unwilling to do so, Eye Care Practitioners should consult the College of Optometrists' (The College of Optometrists, 2013) and the Association of Optometrists' guidance (AOP, 2013). These sources suggest that if Eye Care Practitioners are aware that patients that were advised not to drive are still driving, they should inform the DVLA, but they should try to inform the patient about this action.

This thesis contributes to knowledge by determining that Snellen or logMAR letter charts are the most appropriate to use for assessing the visual acuity of drivers. Additionally, it is recommended that Snellen charts use full line scoring in order to best predict the ability to read a number plate at 20m. In the absence of guidance from the DVLA, these findings are relevant to providing practitioners with advice on best practice when determining visual fitness to drive. The overlap zones for Snellen and logMAR letter chart include the 6/12 and +0.30 logMAR cut offs respectively, which means that even if participants achieve those acuity levels, there is an uncertainty if they will be able to pass the number plate test. For those charts the visual cut off defined by the DVLA provides reasonable sensitivity and specificity. If Eye Care Practitioners record uncorrected acuity worse than the 6/12 or +0.30 logMAR cut off, but close to that area they may need to measure candidates with their refractive correction to ensure that they are able to achieve the visual cut off with refractive correction and therefore that they are still eligible to drive. Thus, they will ensure the drivers will be safe on road.

9.2 FUTURE WORK

Future work may include assessing more participants with their vision reduced with the simulation spectacles, since the present sample was relatively small (38 participants). The study should be replicated to a large sample of people who actually have cataracts, and other ocular pathologies, in order to investigate whether the level of false negatives with the 6/12 cut off increases with pathology compared to uncorrected refractive error and what the implications are for cataract operation restrictions on that matter.

The 6/12 cut off limit and the number plate test differ in many respects as outlined in this thesis. This thesis provides recommendations on which visual acuity chart Eye Care Practitioners should use and what kind of advice they should provide to drivers in relation to their vision. Therefore, they will ensure that drivers have adequate vision to drive safely on road.

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PUBLICATIONS

K Latham, MF Katsou, S Rae. Changes in visual standards for driving: implications for drivers and optometrists. Faculty of Science & Technology Research Conference, Anglia Ruskin University, May 2014. Paper presentation.

S Rae, MF Katsou, K Latham. How does the visual standard for driving relate to reading words on road signs? Faculty of Science & Technology Research Conference, Anglia Ruskin University, May 2014. Poster presentation.

MF Katsou, K Latham, S Rae. Visual acuity of drivers. Optometry Tomorrow Conference: York UK, March 2014. Poster presentation.

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S Rae, K Latham, T Sharp, M Katsou. Landolt C vs UK Road Sign Word Acuity. European Academy of Optometry and Optics, Malaga, April 2013. Poster presenation.

APPENDIX 1: COMPARISON OF VISUAL ACUITY NOTATIONS

SNELLEN	***LOGMAR***	***DECIMAL***	***MINUTES OF ARC***
6/60	1.0	0.10	10.0
6/48	0.90	0.125	7.9
6/38	0.80	0.16	6.3
6/30	0.70	0.20	5.0
6/24	0.60	0.25	4.0
6/19	0.50	0.32	3.15
6/15	0.40	0.40	2.5
6/12	0.30	0.50	2.0
6/9.5	0.20	0.63	1.6
6/7.5	0.10	0.80	1.25
6/6	0.00	1.00	1.0
6/4.8	-0.10	1.25	0.79
6/3.8	-0.20	1.60	0.63
6/3	-0.30	2.0	0.50

APPENDIX 2: CHANGES IN VISUAL STANDARDS FOR DRIVING IN UK FROM 2012-2013

The new visual requirements for driving introduced on 1st May 2012, though in 2013 and 2014 there were updates to these regulations. The visual standards required and the updates are presented in chronological order below.

2012 (AOP, 2013 Vision Standards Motor Vehicle Drivers)

Class 1 (Cars and light vans) Licences

The standard for ALL drivers is the ability to read in good daylight (with the aid of glasses or contact lenses, if worn) a registration mark fixed to a motor vehicle and containing characters 79mm high and 50mm wide from 20meters OR characters 79 millimetres high and 57mm wide from 20.5 metres [NB the former refers to a post-1/9/2001 plate and the latter to an older style plate].

AND

Visual acuity (with the aid of glasses or contact lenses, if worn) must be at least 6/12 with both eyes open.

Visual Fields

The standard for the visual field remains the same at 120 degrees horizontally with at least 20 degrees above and below fixation. From 1st May 2012 an extra condition was added that there must be at least 50 degrees to each side. There should be no significant defects within the central 20 degrees.

1st May 2012 (DVLA, 2013 Visual disorders panel updates Changes to the medical standards for driving and visual disorders)

Changes to the Group 1 and Group 2driver licensing standards for vision came into effect from the 1st May 2012.

The changes mean that:

Group 1 (cars and motorcycles):

Applicants and licence holders, will need to have a visual acuity of 6/12 (0.5 decimal) as well as being able to read the number plate from the prescribed distance.

Visual field:

The present standard of a total field width of 120 degrees remains but in addition, there will need to be a field of at least 50 degrees on each side.

Group 2 (buses and lorries):

Applicants and licence holders must have a visual acuity, using corrective lenses if necessary, of at least 6/7.5 (0.8 decimal) in the better eye and at least 6/12 (0.5 decimal) in the other eye. If corrective lenses are worn, an uncorrected acuity in each eye of at least 3/60 (0.05 decimal) is needed. All Group 2 drivers must also meet all the Group 1 visual acuity standards as outlined above. Where glasses are worn to meet the minimum standard for driving, they should have a corrective power of no more than plus eight (+8) dioptres.

Important changes to vision medical standards- latest update 15th March 2013

There are important changes to the minimum medical standards for driving in the UK. These changes affect the minimum eyesight standards for driving. These changes followed a public consultation on the proposals which ended on 28 April 2011 and apply to drivers of cars and motorcycles (Group 1) and lorries and buses (Group 2).

Vision all drivers

- Must still be able to read a number plate (post-1.9.2001 font) from 20 metres with corrective lenses if necessary.
- Must also have a binocular visual acuity of 0.5 (6/12), with corrective lenses if necessary, but we will not require drivers to have their eyesight tested as part of the application process for a car/motorcycle licence.
- If a driver has been advised by their doctor or optometrist that they cannot meet 0.5 (6/12) with corrective lenses they must tell DVLA
- Drivers who cannot meet this standard will not be licensed.
- Bioptic (telescope) devices are still not permitted for driving in the UK.

Vision Group 2 (lorry and bus) drivers

- Must have a visual acuity of 6/7.5 in the better eye and the worse eye standard has reduced to 6/60.
- If glasses are worn, this must have a power no greater than +8 dioptres (dioptres= strength of the glasses lens)
- If a doctor completing a medical examination required for lorry and bus driver glasses prescription (where glasses are worn), the driver

will need to have the vision assessment section of the D4 examination report completed by an optician.

- Any fees associated with the completion of the D4 examination report must be paid by the driver.

Driving eyesight rules (GOV.UK, 2013)

Standards of vision for driving

You must be able to read (with glasses or contact lenses, if necessary) a car number plate made after 1 September 2001 from 20 metres.

You must also meet the minimum eyesight standard for driving by having a visual acuity of at least decimal 0.5 (6/12) measured on the Snellen scale (with glasses or contact lenses, if necessary) using both eyes together or, if you have sight in one eye only, in that eye.

You must also have an adequate field of vision- your optician can tell you about this and do the test.

Lorry and bus drivers

You must have a visual acuity at least 0.8 (6/7.5) measured in the Snellen scale in the other eye. You can reach this standard using glasses with a corrective power not more than (+) 8 dioptres, or with contact lenses. There's no specific limit for the corrective power of contact lenses.

You must have a horizontal visual field of at least 160 degrees, the extension should be at least 70 degrees left and right and 30 degrees up and down. No defects should be present within a radius of the central 30 degrees.

You must tell DVLA if you've got any problem with your eyesight that affects either eye.