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Supporting the development of inclusive products: The effects of everyday ambient illumination levels and contrast on older adults' near visual acuity.

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Supporting the development of inclusive products: The effects of everyday ambient illumination levels and contrast on older adults' near visual acuity.

Current older adult capability datasets fail to account for the effects of everyday environmental conditions on capability. This paper details a study which investigates the effects of everyday ambient illumination conditions (overcast, 6000 lx; In-house lighting, 150 lx; and street lighting, 7.5 lx) and contrast (90%, 70%, 50% and 30% contrast) on the near visual acuity of older adults ($n=38$, 65-87 years). Visual acuity was measured at a one metre viewing distance using LogMAR acuity charts. Results from the study showed that for all contrast levels tested, visual acuity decreased by 0.2 log units between the overcast and street lighting conditions. On average, participants could detect detail around 1.6 times smaller on the LogMAR charts when under overcast conditions compared to street lighting. Visual acuity also significantly decreased when contrast was reduced from 70% to 50%, and from 50% to 30% in each of the ambient illumination conditions.

Practitioner summary: This paper presents an experimental study which investigates the impact of everyday ambient illumination levels and contrast on older adults' visual acuity. Results show both factors have a significant effect on their visual acuity. Findings suggest that environmental conditions need to be accounted for in older adult capability datasets/design.

Keywords: Inclusive design, capability data, visual acuity, ambient illumination, contrast.

1. Introduction

In order to support the development of inclusive (accessible and usable) products for the ageing population, accurate and relevant older adult capability data are needed by designers (Gyi *et al*, 2000). A range of older adult capability datasets exist, such as Older Adult Data (Smith *et al*, 2000), Bodyspace (Pheasant, 1986), and Humanscale (Diffrient *et al*, 1978, 1981a, 1981b). Also, inclusive design data tools which draw on

older adult capability datasets are available; these are the 'Exclusion Calculator' (University of Cambridge, 2011) and HADRIAN (Human Anthropometric Data Requirements Investigation and Analysis) (Marshall *et al*, 2010). However, one serious weakness with these capability datasets is that they fail to consider older adults' capabilities in real world day to day environmental conditions where products are used; see for example Gyi *et al*, 2004 and Grundy *et al*, 1999.

There are a number of studies which specifically report decrements in capability as a result of everyday environmental conditions. For example:

- Elton and Nicole (2013) found that an everyday cold temperature of 5°C had a significant effect on older adults' ability to carry out fine finger tasks and product interactions;
- Baker and Mansfield (2010) reported decrements in dexterity when participants were exposed to vibration which could be experienced on public transport;
- Hopkinson and Collins (1970) reported that the human eye can detect detail ten times as fine in daylight as it can under starlight.

Failure to consider the effect such everyday environmental conditions have on older adults' capabilities could easily result in products causing difficulties to, or excluding, those intended to be included.

Consideration of the impact such environmental conditions have on capability is even more important with today's ageing population as the Baby Boomer generation promises to be different from previous elder generations; they expect great things from design and technology. In particular, wireless information and communication technologies have become part of the fabric of their everyday lives (Morris *et al*, 2009). These advancements have allowed for the use of more everyday products when out of a

controlled home environment. For example, there is no restriction as to where mobile phones, mp3 players, digital cameras, PDAs, satellite navigation systems, signature recording devices, etc. can be used. It is not just technological devices that are used whilst out of the home environment; products such as flasks, keys, drinks bottles, maps, door handles, bus timetables, gardening products, packaging, etc. are also used in a wide range of different environments.

Vision is one of the key capabilities required to complete the majority of product interactions (Elton, 2012). More specifically, visual acuity (VA) (i.e. the eyes' ability to discriminate fine detail) is one of the main visual functions required for the successful perception of products (Owesley and Sloane, 1987; Persad *et al*, 2007). In particular, the perception of product symbols, markings and text all require VA. VA sets the minimum size for a target to be seen; target size along with contrast is the key aspects which define its visibility (IENSA, 2011).

Being able to successfully perceive product characteristics is essential, as they allow users to identify, understand and navigate through product functions to achieve their desired goal. VA capability is closely dependent on the ambient illumination (Weston, 1962), and the level of ambient illumination in everyday environments can change constantly. For example, on a bright sunny day illumination levels can reach +100,000 lx, on an overcast day it can drop to 6000 lx, and at night under starlight illumination can be as low as 0.001 lx (Department of Scientific and Industrial Research, 1935; Hopkinson and Collins, 1970). According to Hopkinson and Collins (1970) the human eye can detect detail around 10 times as fine in daylight as it can at night under starlight. A recent study by Dalke *et al*, (2010) found that the VA of Visually Impaired People (VIP) improved dramatically with an increasing light level when identifying signs and way finding information in the 'real world'. Thus, ambient

illumination is a critical factor which can affect the perception of 'real world' objects (Dalke *et al*, 2010).

2.0 Literature review

In the field of visual ergonomics there is a large volume of published studies describing the impact of ambient illumination on Visual Performance (VP), as opposed to Visual Acuity. VP is the performance level of the visual system as measured by the speed and accuracy with which a visual task is performed (CIE, 2002). VP therefore differs slightly from VA in that it is concerned with the speed as well as the accuracy by which a target is identified; however, VA is the basic visual function underlying VP (CIE, 2002). A strong relationship between VA and VP has been established (CIE, 2002).

A number of investigations have been conducted into the effects of illumination on VP. The initial studies focused on the level of illumination needed to optimise VP for set inspection tasks; these were conducted by Weston (1945, 1949, 1961) and Bodmann (1962, 1967). It was the investigations by Bodmann (1962, 1967) which focused on the relationship between illumination, VP and age. Findings from these studies revealed that VP for young adults ($n=48$, 20-30 years) increased with illumination up to 1000 lx; after this point diminishing returns applied. However, the same was not found for the older age group ($n=10$, 50-60 years), whose performance did not show such a pronounced reduction after 1000 lx. The results from Bodmann's (1962, 1967) investigations revealed that:

- The older age group clearly benefited from higher levels of illumination;
- Illumination cannot increase older adult's visual ability to that of younger adults;
- Low illumination levels can have a major effect on older adult's VP.

Several other studies broadly support these findings. Smith and Rea (1978), investigated proof reading under four different levels of illumination (10.76 lx, 107.6 lx, 1076 lx and approx. 7500 lx) with young adults ($n=4$, 18-22 years) and older adults ($n=4$, 49-62 years) adults. Findings showed that older adults were affected to a greater extent by low illumination levels and increased illumination had a stronger effect on their visual ability. However, caution needs to be exercised in terms of the generalisability of these results as there were only four older adults, the oldest being 62 years. Davis and Garza (2002) investigated the impact of illumination (54 lx, 323 lx and 1290 lx) on older ($n=17$, 62-76 years) adults' reading performance and preference. The study results showed that scores consistently improved with increased illumination. Charness and Dijkstra (1999) conducted field studies in homes, offices, and public places with younger and older adults to determine how legibility performance (in a proofreading and phone book search task) changed with age and luminance. The study found that performance not only declined with age but also with lower lighting levels. One of the interesting findings from this study was that added light helped both younger and older adults equally for most legibility tasks (i.e. in homes and public places). It is important to note that 'reading task performance' is different from VP (CIE, 2002); however, results from these studies show that older adults' visual ability to perform tasks can be significantly affected by varying levels of illumination. There are also further published studies (Blackwell and Blackwell, 1971; Boyce, 1973; Sorensen and Brunnstrom, 1995; Boyce, 2003) which report on the effects of illumination VP.

In relation to the numerous studies conducted into VP, it is the seminal work by Weston (1945) which has been deemed most comprehensive (CIE, 2002). As a result, this data has been used by the International Commission on Illumination (i.e., CIE - Commission Internationale De L'Eclairage) to create a mathematical model which can be used to theoretically calculate VP for a given task at a given luminance level, for a person of a given age (assuming they have fully corrected vision). The equation takes into account target size in minutes of arc (α), contrast (C), background luminance (L_b) and the age of the observer (AF). There are two variations of the equation, dependent on the contrast level of the target being viewed. For targets greater than 35% contrast ($C > 0.35$) the following mathematical model should be used (CIE, 2002):

$$VP = 0.5384(\alpha - 1.499)^x \cdot (\log L_b + 0.09196)^y \cdot (C - 0.2534)^z \cdot AF \quad (1)$$

For targets which are less than 35% contrast (i.e., $C < 0.35$) the following equation should be used:

$$VP = 0.6577(\alpha - 1.499)^x \cdot (\log L_b + 0.035)^y \cdot (C - 0.08521)^z \cdot AF \quad (2)$$

CIE (2002) specifies that the target size used in both equations must be greater than 1.5 minutes of arc ($\alpha > 1.5'$). The mathematical equations used to calculate X, Y, Z and AF can be found detailed within the CIE technical report (2002). These equations can thus be used to theoretically calculate older adults' VP ability for a given target in a given lighting condition. However, it is important to point out that even though VP and VA are strongly correlated measures, the measure of VA does not contain the variable time, which has been found to impact on accuracy (CIE, 2002; Boyce 2003). The consideration of speed/time to perform visual product tasks is less of a concern to this

study as product tasks are generally not time dependent/restricted by time. Although, a comparison of the VA data gathered in this study to the predicted VP data to determine the level of concordance that exists between the two factors is of importance, as ergonomists, engineers and designers may be able to utilise this model in the future to help determine the legibility of the visual characteristics of their designs.

Overall, this review has identified a range of studies which have focussed on determining either the extent to which different types and/or levels of illumination affect older adults' VP, the optimum lighting for a given task or environment, or the calculated VP for a given target under a given lighting level. What these studies do not do is 1) quantify older adults' VA capabilities at varying levels of ambient illumination; 2) determine the extent everyday ambient illumination levels affect older adults' VA; and 3) compare theoretically calculated older adult VP data (based on the CIE mathematical model) to actual older adult VA data to determine the level of concordance that exists. Findings from this review raised three key research questions which are addressed in this paper:

- (1) What are older adults' VA capabilities under typical everyday ambient illumination levels?
- (2) To what extent do everyday ambient illumination levels affect older adults' VA?
- (3) What level of concordance exists between older adults' actual VA data to that theoretically estimated by the standard VP model published by CIE (2002)?

The contributions of this paper are several fold: 1) an experimental methodology that can be used to obtain a reliable and valid measure of older adults' VA that is relevant to product interaction; 2) datasets which detail older adults' VA capabilities under a range of everyday ambient illumination conditions; 3) quantification of the extent to which everyday ambient illumination conditions can impact upon older adults'

VA capabilities and the implications for design; and 4) an evaluation of the standard VP mathematical model published by CIE (2002) . These contributions will help to ergonomists, human factors specialists, designers and engineers in developing products, technologies and/or services that are accessible and usable (inclusive) when used in everyday environments.

3.0 Materials and Methods

3.1 Measuring visual acuity

3.1.1 Type of visual acuity measured

Several different types of acuity are recognised, these include resolution acuity (the ability to detect that there are two stimuli, as opposed to one, in the visual field); vernier acuity (the ability to identify a misalignment between two lines; and, recognition acuity (the ability to identify visual targets such as letters) (IENSA, 2011). For the purpose of this experiment recognition acuity was measured, which typically involves the process of detection, recognition and discrimination. VA can also be measured in a number of different ways:

- One eye at a time (monocular vision);
- Both eyes together (binocular vision);
- Wearing contact lenses or glasses, if worn (presenting vision);
- After vision has been corrected by an optician (best corrected VA).

One of the key aims to this research was to gather data that mirrors a person's capability in the real world when interacting with products. To this end, presenting vision (wearing contact lenses or glasses if worn) was chosen as it is regarded as the

measurement that best reflects the everyday vision of the person (Tate *et al*, 2005). It also represents the actual impairment experienced by the individual in their everyday life (whether due to underlying disease such as cataract or due to uncorrected refractive error) (Tate *et al*, 2005).

3.1.2 Test distance

Products generally make demands on users' short sighted capability (near acuity), which is commonly measured by the distance at which newsprint can be read, usually 40cm (Tate *et al*, 2005). However, the viewing distance for a product is partly determined by a person's near point. Near point refers to the closest distance which the eyes can focus; this point moves further away with age and by 60 years of age the average near point increases to one metre (Grandjean, 1973). This condition (Presbyopia) can be corrected through lenses; however, statistics from the Department for Health show that over four million older people in the UK do not have regular eye tests, meaning such problems are not corrected (RNIB, 2005). These statistics imply that one metre would be the shortest distance a significant proportion (four million) of older adults could focus; thus a one metre testing distance was used to measure VA for the purposes of this study.

3.1.3 Visual acuity charts

Logarithm of Minimum Angle of Resolution (LogMAR) charts (see Figure 1) were developed for the purposes of this study to measure VA as they are regarded as the gold standard of VA tests (Bourne *et al*, 2003; Hazel and Elliot, 2002). The advantages of using these charts for assessment in clinical and population based surveys have been well documented (Bailey and Lovie, 1976; Ferris *et al*, 1982; Ferris and Bailey, 1996; Lovie-Kitchin, 1998; Colebrander, 2002; Bourne *et al*, 2003). In particular, their design/layout means that task difficulty increases in equal steps, letter size is the sole

determinant of difficulty on a given line, each letter has an equal chance of being recognised and the acuity data produced from the charts is classed as interval data which lends itself to parametric statistical analyses.

<<Figure 1. here>>

The charts were developed based on the principles detailed by Bailey and Lovie (1976) and British Standards Institution (2003a). Each chart had 9 rows of letters, which ranged from -0.3 log units (0.8mm) to 0.5 log units (4.7mm). Table 1 details the log unit values of the letters used, their size in millimetres² (mm²) and minutes of arc ('), their visual fraction and decimal notation.

<<Table 1 here>>

3.1.4 Contrast levels of charts

In order for the data to be of relevance to product design, VA was measured at a range of contrast levels from high to low (90%, 70%, 50% and 30% contrast). The contrast of the letters was calculated using the 'luminance contrast' ratio equation (British Standards Institution, 2003a):

$$Contrast = \frac{L1 - L2}{L1}$$

where: L1 = luminance of the background; L2 = luminance of the test letter.

3.1.5 Scoring method

LogMAR letter charts can be scored using different methods. Ferris *et al* (1982)

recommends a letter-by-letter method whereby the participant is asked to read the entire chart and is given a score for each letter read correctly. An alternative to this approach is the traditional line-by-line scoring method - whereby after a certain number of incorrect responses on a particular line ($\geq 25\%$ of letters read incorrectly) the test is terminated and the participant's acuity score is the row above (Carkeet, 2001).

However, neither approach was deemed suitable for the purposes of this study as each method either calculates threshold (i.e. the limits of a person's ability) or close to threshold VA. If design decisions were based on the limits of a person's capability (i.e. where a number of letters are read incorrectly) then it is unlikely that visual tasks with products could be completed independently without experiencing any difficulties. This viewpoint is supported by Porter *et al*, (2004) who suggest that a person's comfortable limit rather than their maximum is a more valid predictor for use in inclusive design datasets. Thus, for the purposes of this study, the acuity score was based on the smallest row of letters read correctly from start to finish, i.e. the smallest row the participant was able to read without making any mistakes. This method had the benefit of ensuring the data obtained from the acuity charts would detail what an older adult is independently capable of without making mistakes.

3.2 Everyday ambient illumination levels

A total of three everyday ambient illumination levels were simulated for the purposes of this study; these were:

- **Overcast:** An illumination intensity of 6000 lx was simulated; findings from an extensive 10 year study (1923-1933) (Department of Scientific and Industrial Research, 1935) showed that the lowest average illumination during overcast conditions is between late autumn and early spring, and was *not far from 555*

foot candles (5973 lx).

- **In-house at night:** An illumination level of 150 lx was the chosen light intensity for this condition. The Chartered Institute of Building Services Engineers (CIBSE) (1994) details guideline illumination levels for residential accommodation that houses elderly and disabled people; 150 lx is the standard minimum maintained illumination level for the kitchen, lounge and bathroom i.e. areas of the home where the majority of Activities of Daily Living (ADLs) are conducted.
- **Street lighting:** An illumination intensity of 7.5 lx was simulated; several UK regional councils (Leicestershire, Derbyshire, Nottinghamshire and Staffordshire) reported an average horizontal illumination at ground level for the majority of pedestrian and residential roads in these areas as being 7.5 lx.

3.2.1 Representing real world ambient illumination

The selected lighting conditions were simulated in a lighting laboratory (2750mm x 4500mm) that was situated within the Environmental Ergonomics laboratories at Loughborough University. In order to accurately simulate the chosen ambient illumination conditions, both the intensity and the spectral distribution of the chosen environmental lighting were replicated. The following lights were used to achieve this:

- **Overcast:** Solar simulation lamp (1,000-W metal halide CSI lamp manufactured by GE Lighting) which produces light with a spectrum similar to that of daylight, and has been used widely across a number of industries including the automotive industry for this purpose (Beeson, 1978; Blazejczyk *et al*, 1992). A frosted screen was placed one metre in front of the light in order to diffuse the emitted illumination;

- **In-house lighting:** Over-head inbuilt incandescent light bulbs;
- **Street lighting:** A street lighting lantern (WRTL 2600 lantern) fitted with a 50w SON-T (high pressure sodium) ballast bulb.

Whilst this study is concerned with the impact of ambient illumination levels on VA, there are also further factors associated with the selected light sources, which may also impact on VA. In particular, there is the colour appearance of the light emitted by the light sources (i.e., the spectral distribution of energy emitted within the visual portion of the spectrum); this is known as the correlated colour temperature (T_c) (IENSA, 2011; Boyce, 2003). The metal halide lamp, used for the overcast condition, produces an intense white (natural) light of a similar spectral distribution to daylight. Incandescent light bulbs, used for the in-house condition, have a yellowish colour appearance as the spectral emissions are a continuum over the visible spectrum (Boyce, 2003). The high pressure sodium light, used for the street lighting condition, produces light with an orange colour appearance (Boyce, 2003). The emitted light from these sources have the potential to change the colour appearance of the surface colours being viewed (i.e., produce colourmetric shift); this is referred to as a lights colour rendering properties (Boyce, 2003; IENSA, 2011), and is quantified using the CIE Colour Rendering Index (CRI) (CIE, 1995). Out of the three lights used in this study, it is the high pressure sodium light which has the lowest CRI rating of 24, then the metal halide light which has a rating between 78-82, and then the incandescent bulbs which have a rating of a 100. Where the CRI ratings are close to 100, the variations in colour are unlikely to be large enough to produce a noticeable colour difference; however, as the number decreases from 100 the more likely a colour shift in surface appearance will appear (IENSA, 2011). These CRI ratings would therefore indicate that the street light (high pressure sodium) and to a lesser extent the overcast light (metal halide) are likely

to impact on the colour properties of the charts,. In particular, changing the colour difference between the characters and their background (i.e. contrast ratio) and changing the appearance of the colours (Boyce, 2003). The contrast ratio×text colour interaction has been shown to significantly affect (decrease) VP, especially at low contrast levels (Lin, 2003; Matthews, 1987).

3.3 Experimental methodology

The independent variables manipulated in this study were ambient illumination (6000 lx, 150 lx and 7.5 lx) and contrast (90%, 70%, 50% and 30%). In each ambient illumination condition the participant's VA (dependent variable) was measured using LogMAR acuity charts at each of the four specified contrast levels.

A repeated measures study design was used. Potential order and carry-over effects were balanced out through using a Latin and a Balanced Latin Square. More specifically, two Latin Squares (3x3), with the second Latin Square being a mirror image of the first, were used to determine the order that participants experienced the ambient illumination conditions; this method ensured each ambient illumination condition followed another on an equal number of occasions (Shuttleworth, 2009). A Balanced Latin Square (4x4) was used to determine the presentation order of the LogMAR charts in each ambient illumination condition.

3.4 Dark-light adaptation

Consideration was given to the adaptation time between each of the ambient illumination conditions as the human eye does not adjust instantaneously to different light intensities and adaptation speed slows with age (Hood and Finkelstein, 1986; Jackson *et al*, 1999). Failure to consider adaptation time could have meant that older

adults' VA was measured whilst the eye was still adapting; thus the capability data obtained would not have been an accurate representation of their VA capability at that ambient illumination level. Table 3 details the adaptation time given between each condition; adaptation timings were determined from the following literature: Hood and Finkelstein, 1986; Boyce, 2003; Coile and Baker, 1992; and Jackson *et al*, 1999.

<<insert Table 3 here>>

3.5 Procedure

Ethical approval was granted for the study from Loughborough University's Ethical Advisory Committee (Reference number: R08-P95). Prior to the study, each participant was provided with an information sheet which gave an overview of what the study involved, any questions were then answered, followed by the signing of an informed consent form. Participants were fully informed of their right to withdraw from the experiment at any time without reason or prejudice.

A measure of each participant's 'presenting' near (1m) VA was then recoded in accordance with the British Standards Institution (2003a); chart luminance was uniform at 120cd/m² and the line-by-line scoring method was used. A head rest fixture, with a chin support, was used to maintain the same distance between the eyes of participants and the acuity charts in all conditions. The ambient illumination level was then changed to the first test condition. Each participant was given the allocated adaptation time when the lighting levels were altered. Before reading the acuity charts, each participant was instructed to read the smallest row of letters on the chart they felt they could read correctly from start to finish. If read correctly, participants were asked to read the next row down the chart (smaller letters). This continued until the participants were unable to correctly identify the letters on the chart; the test was then terminated. However, if

participants read the first row they selected incorrectly, they were asked to read the row above (bigger letters); this procedure was continued until a full row was read correctly. After participants had completed the four LogMAR acuity charts the ambient illumination condition was changed, and this process was repeated until all ambient illumination conditions had been simulated.

3.6 Sample

A total of 38 older adults (19 male/19 female), ranging from 65-87 years (mean age 74 years) completed the experiment. The sample consisted of the following impairments: 7 (18%) age related macular degeneration, 5 (13%) cataracts, 3 (8%) had cataracts removed, 21 (55%) short sighted, 24 (63%) long-sighted and 4 (10.5%) Astigmatism. These figures are based on what each participant reported in the recruitment interview; participants were asked to confirm their impairments on arrival, prior to the study commencing. The 'presenting' near (1m) VA of the sample ($n=38$) ranged from -0.2 to 0.5 log units (mean 0.1); 29% had a VA ≤ 0.0 log units (1m/1m) and 13% of the sample had a near acuity score of between 0.4 to 0.5 log units, which is the equivalent of having mild sight loss i.e. a VA measure $<6/12$ but $\geq 6/18$ (RNIB, 2005).

3.7 Statistics

All data were checked for errors and outliers. Outliers were identified statistically through the use of box plots; scores identified as extreme outliers, i.e. scores which extend more than three box-lengths ($z=3$) from the edge of the box were removed (Howitt and Cramer, 2008). Only one outlier was identified and removed (1 outlier - 30% contrast overcast lighting). All data were checked for normality using a significant skewness calculation detailed by Howitt and Cramer (2008) (i.e. skewness / standard

error of skewness = <1.96 normally distributed data). Out of the 12 datasets, only one (i.e. street lighting 70% contrast) was significantly skewed (i.e. sig. skew >1.96).

3.7.1 Statistical analysis techniques

Paired comparison analysis techniques (Paired t-tests and Wilcoxon Signed Ranks Tests) were used to determine whether significant differences in older adults' VA existed as a result of ambient illumination and contrast. Paired comparisons were used due to the variations in valid (n) scores across the dataset; a number of participants were unable to read the top row of letters correctly on certain charts, and therefore did not receive an acuity score (see table 5 for variations in valid scores across conditions). Paired comparison technique minimised the number of cases that were not considered in each analysis. The *Bonferonni* method was employed to avoid Type I error.

4.0 Results

One-tailed p -values are quoted as the directional relationship between the two independent variables (illumination and contrast) and the dependent variable (VA) has been established in previous studies (Weston 1945, 1949 and 1961; Bodmann, 1962 and 1967; Smith and Rea, 1978; Sanders and McCormick, 1993; Charness and Dijkstra, 1999; Davis and Garza, 2002; Howarth and Bullimore, 2005). In both cases, a negative relationship exists i.e. as ambient illumination and/or contrast is reduced so does VA.

4.1 Research question 1: What are older adults' visual acuity capabilities under typical everyday ambient illumination levels?

Three paired comparisons were carried out in each ambient illumination condition i.e. 90% to 70%, 70% to 50% and 50% to 30%. Applying the *Bonferroni* method (i.e. $p=0.05/3$) meant a p -value of <0.0167 was considered to be statistically significant.

Table 4 provides a summary of the statistical results obtained from this analysis.

<<insert Table 4 here>>

Table 5 presents the VA capabilities of the study participants under each of the everyday ambient illumination conditions at each of the tested contrast levels. For the overcast and street lighting conditions VA did not significantly decrease between 90% and 70% contrast; thus VA capability data is presented for $\geq 70\%$ contrast for this condition.

<<insert Table 5 here>>

The use of the coarse grading and scoring system (i.e. 0.1 log units) does not allow for interpolation between the log sizes measured (Bailey *et al*, 1991). Thus, rounded mean values have been reported for older adults' VA capability and capability decrements. Whilst this is not the true mean value of the datasets, the rounded mean provides the most accurate value in relation to the type of data gathered and the measuring scale used. Table 6 details the mean, rounded mean and letter size values for the sample's VA capabilities in each of the conditions tested.

<<insert Table 6 here>>

The rounded mean letter size (mm) values for each condition have been plotted in Figure 2 to illustrate the reduction in older adults' VA as a result of contrast.

<<insert Figure 2 here>>

4.2 Research question 2: To what extent do everyday ambient illumination levels affect older adults' visual acuity?

Two paired comparisons were made per contrast level between the overcast and in-house conditions, and the in-house and street lighting conditions. Applying the *Bonferonni* method (i.e. $p=0.05/2$) meant a p -value of <0.025 was considered to be statistically significant. Table 7 provides a summary of the statistical results obtained from this analysis.

<<insert Table 7 here>>

Table 8 details the VA capabilities of the study sample under each of the everyday illumination conditions. Again, the rounded mean values have been reported for older adults' VA capabilities and capability decrements due to the coarse grading and scoring system used.

<<insert Table 8 here>>

The rounded mean letter size (mm) values for each contrast level have been plotted in Figure 3 to illustrate the extent to which the older adults' VA capability was reduced as a result of ambient illumination.

<<insert Figure 3 here>>

4.3 Research question 3: What level of concordance exists between older adults' actual VA data to that theoretically estimated by the standard VP model published by CIE (2002)?

For the purposes of the VP equations (i.e. equation (1) and (2) detailed in section 2.0) the mean rounded acuity scores for each condition and the mean sample age (74 years) were used. Both equations require the photometric measure of light to be in luminance (cd/m^2) as opposed to illuminance (lx). The background luminance level of the white paper which the letters were printed on was measured in each condition: street lighting = 1.7cd/m^2 ; in-house lighting 35cd/m^2 ; and overcast = 1300cd/m^2 . Also, for the purposes the VP equations, letter height (in minutes of arc), as opposed to stroke width, were used to determine target size (see Table 1 for letter sizes). A VP score of 1 was assumed for the mean rounded older adult VA data for each condition, as accuracy was 100% (i.e. VA was based on the smallest row of letters identified correctly) and speed was not measured. The results from the VP calculations using the CIE (2002) mathematical model are detailed in figure 4.

<<insert Figure 4 here>>

5.0 Discussion

5.1 Research question 1: What are older adults' visual acuity capabilities under typical everyday ambient illumination levels?

This study measured older adults' VA at four different contrast levels (90%, 70%, 50% and 30%), in three different everyday ambient illumination conditions (overcast = 6000 lx; in-house = 150 lx; street lighting = 7.5 lx). The purpose was to obtain accurate, reliable and valid measures of older adults' VA capabilities under each of these everyday ambient illumination conditions. The results obtained showed that older adults' VA capabilities can vary significantly under different everyday ambient illumination levels as a result of contrast. In all three ambient illumination conditions, VA significantly decreased when contrast was reduced from 70% to 50%, and from 50% to 30%. When contrast was reduced from 90% to 70% a significant reduction in VA was only observed in the in-house ambient illumination condition. It seems possible that the 90% to 70% results may be due to the colour rendering properties of the lights used. In particular, both the overcast light (metal halide) and the street light (high pressure sodium) have CRI ratings <100, indicating that they can produce a noticeable change to the colour appearance of the surface colours (IENSA, 2011). Thus, results would indicate that both the street and overcast lights produced a colourmetric shift in letters printed at high contrast levels (i.e. 90% to 70%), to the point where there is little discernable difference between the two to the older adult eye. This suggestion is supported by the results from the in-house condition, where a significant reduction in VA was observed between the two high contrast levels; incandescent bulbs have a CRI of 100, therefore unlikely to produce a noticeable colour difference in surface appearance (IENSA, 2011).

The results also showed that contrast affected older adults' VA capability to a greater extent at lower ambient illumination levels. Results from the study showed that, on average, under street lighting when contrast was increased from 30% to 70% letters that were 1.8mm smaller could be read, compared to overcast where the difference was only 1.1mm. This finding is consistent with studies that have investigated older adults' VP in a range of ambient illumination levels. For example, studies by Bodmann (1962, 1967) showed low illumination levels have a major effect on older adults' VP. Smith and Rea (1978) also found older adults were affected to a greater extent by low illumination levels and increased illumination had a stronger effect on their visual ability. Overall, these findings show that in order to accurately detail older adults' VA capabilities under different everyday ambient illumination conditions, it is essential that contrast is considered. Failure to consider the effect of contrast on VA under everyday ambient illumination conditions could easily result in older adults being unable to perceive the necessary product detail.

In answer to research question 1, Table 5 provides the raw statistics which detail the range of older adults' VA capabilities at each of the tested contrast levels under each of the simulated ambient illumination conditions. However, as discussed in section 4.1, the raw statistics produced from the analysis refer to letter sizes that were not tested, e.g. 0.12 log units, as the coarse grading and scoring system used (i.e. 0.1 log unit intervals) does not allow for interpolation between the log sizes (Bailey *et al*, 1991). Thus, Table 6 should be used to determine older adults' VA capabilities under the different everyday ambient illumination conditions simulated in this study.

5.2 Research question 2: To what extent do everyday ambient illumination levels affect older adults' visual acuity?

In order to answer this question, older adults' VA capabilities, at each contrast level,

were compared across the three simulated ambient illumination conditions. The results provide clear evidence that VA was significantly affected by everyday ambient illumination levels. Significant decreases in VA were observed between all conditions at each of the contrast levels tested. In terms of the extent to which VA decreased as a result of ambient illumination, based on the rounded mean values, it was found that:

- For all contrast levels tested, VA decreased by 0.2 log units between the overcast and street lighting conditions;
- For the 90%, 50% and 30% contrast charts, a 0.1 log unit mean decrease in acuity was observed between the overcast and in-house illumination condition, and between the in-house and street lighting condition;
- For the 70% contrast chart a 0.2 log unit decrease in VA was observed between the overcast and in-house condition and no decrease was observed between the in-house and street lighting condition.

In relation to actual letter size (mm), the most noticeable result to emerge from the analysis was the impact illumination had on letters printed at 30% contrast; under overcast illumination ($M = 2.9\text{mm}$), participants could, on average, read letters 1.8mm smaller than they could under street lighting ($M = 4.7\text{mm}$). For letters printed at 50% contrast, participants could read letters 1.4mm smaller under overcast illumination ($M = 2.3\text{mm}$) compared to street lighting ($M = 4.7\text{mm}$). For letters printed at both 70% and 90% contrast, participants could read letters 1.1mm smaller under overcast illumination ($M = 1.8\text{mm}$) compared to street lighting ($M = 2.9\text{mm}$). Thus, results suggest that everyday ambient illumination conditions have a lesser effect on letters printed at higher contrast levels i.e. 90% and 70% contrast. The impact of ambient illumination on letters printed at lower contrast levels (50% and 30% contrast) can be explained by the fact

that older adults have reduced contrast sensitivity as a result of ageing, i.e. older adults require a greater amount of contrast to see a target (Owsley *et al*, 1983). It is thought that the reduced retinal illumination characteristic of the ageing eye accounts for a large part of this, especially at lower illumination levels (Owsley *et al*, 1983).

One of the issues to emerge from the analysis was the implications of using a coarse grading scale and scoring system. In particular, it did not allow for interpolation between the log unit sizes used, which meant that mean statistics for each dataset had to be rounded to the nearest log value tested; this tended to increase the difference between the mean acuity values. Whilst the scale used was sensitive enough to detect changes in illumination and contrast, a slightly finer scale may have been more suitable. Another factor which influenced the study results was the range of letter sizes used on the LogMAR acuity charts; there were insufficient larger letter sizes on the charts which meant that the variability in the sample's VA across all test conditions could not be fully captured.

Results from this section of the study have shown that changes in everyday ambient illumination levels significantly affect older adults' VA capabilities. On average, participants could detect detail around 1.6 times smaller on the LogMAR charts when under overcast conditions compared to street lighting. This is much less than the 10 times statistic quoted by Hopkinson and Collins (1970) –*the human eye can detect detail ten times as fine in daylight compared to starlight*; however this statistic was based on a much greater illumination range (i.e. approximately 100,000 lx). Overall, this study has shown that there is a need to consider older adults' VA capabilities under differing everyday ambient illumination conditions when designing and developing inclusive products. Failure to do so could again result in older adults

experiencing difficulties or exclusion either completely or in certain everyday conditions.

5.3 Research question 3: What level of concordance exists between older adults' actual VA data to that theoretically estimated by the standard VP model published by CIE (2002)?

As detailed in the literature review, a mathematical model has been published by the CIE (2002), which can be used to theoretically calculate VP for a given task at a given luminance level, for people of a given age. The mean rounded VA data for each lighting condition and contrast level were entered into the mathematical models (see equations (1) and (2) in section 2.0) for the mean sample age (74 years), in order to determine the level of concordance which exists between the older adult VA data gathered in this study and that estimated by the CIE model (2002). The purpose of this comparison was to determine whether the model may be something that could be used by ergonomists, engineers and/or designers in the future to help determine the legibility of the visual characteristics of their designs to older adults.

A VP score of 1 (VP scores range from 0 to 1) was assumed for the mean rounded older adult VA data for each condition, as accuracy was 100% (i.e. VA was based on the smallest row of letters identified correctly) and speed was not measured. Using this method as a basis to compare the VA data to the estimated VP data, results showed there to be a varied level of concordance between two measures. The highest level of concordance existed with the 90% acuity data; in all conditions VP was estimated to be >0.6 for targets of 90% contrast. However, theoretically estimated VP dramatically decreased when target contrast was reduced, even though target size increased; the CIE model suggested a VP level of 0.3 to 0.4 for targets of 30% contrast

in each of the simulated conditions. These results therefore indicate that the lowest level of concordance exists between VA and estimated VP with visual targets of low contrast (i.e. 30% contrast). It seems possible that the lack of overall concordance between the VA data and calculated VP data may be due to the variable time/speed. As the VP calculations are based on both speed and accuracy, whereas time/speed restrictions were not placed on participants when viewing each of the VA charts, as everyday product tasks are generally not time dependent/restricted by time. These findings further support the notion that viewing time can significantly impact on visual accuracy (CIE, 2002; Boyce 2003).

Also, the CIE mathematical model estimated that a decrease in VP would occur between 90% and 70% contrast in all conditions; however, a significant decrease in VA only occurred between these two contrast levels under the in-house lighting condition. The calculated results from the CIE model showed that VP is likely to in fact decrease least under the in-house lighting condition between these two levels of contrast. As previously stated, it would appear that the correlated colour temperature of the lights, along with their Colour Rendering Index (CRI) properties can impact on VA, specifically with targets that are of higher contrast (i.e. $\geq 70\%$ contrast). Therefore, a further factor that may need to be incorporated into the CIE mathematical model, in order for it to theoretically estimate real world VP, is either the correlated colour temperature (T_c), or, Colour Rendering Index properties (CRI) of the lights under which the visual task(s) is being performed.

6.0 Conclusion

The present study confirms that typical everyday ambient illumination levels can significantly impact on an older adults' VA capability. Also, the study confirms that the

contrast of letters is an important design consideration too. Failure to consider the effect of both ambient illumination and contrast on older adults' VA capability could easily result in their being unable to perceive the necessary product detail and therefore experience difficulties and frustration, or potentially become excluded from product use. A practical approach to offsetting the effects of ambient illumination on VA is to manipulate the visual stimuli being presented; in particular, study results indicate that increasing the size and/or contrast of the letters produces an improvement in visual accuracy. Thus, consideration and application of this data by designers will help to ensure the effects of ambient illumination on product interaction are mitigated.

The CIE (2002) mathematical model for estimating VP showed a moderate level concordance with the older adult VA data obtained in this study, particularly at a high contrast levels (90% contrast); however, as target contrast reduced so did the level of concordance between the two measures. A comparison of the VP results to the VA data would suggest that viewing time can significantly impact on visual accuracy. Also a future mathematical model for calculating VP may need to consider the impact that lighting properties (i.e. correlated colour temperature and Colour Rendering Index) can have on older adults' VP.

The capability data generated from this study will be used to generate analytical design metrics which detail the percentage of older adults able to distinguish certain letter size contrast combinations under different everyday lighting conditions. Translating the data into this format will allow designers to make informed design decisions about how inclusive the visual characteristics of their designs are. For example, a 2.3mm letter at 50% contrast may be distinguishable by 60% of older adults under in-house lighting, whereas a letter of the same size but greater contrast (i.e. 90%) may be distinguishable by 85% of older adults.

The VA capability data presented within this paper was gathered in a laboratory experimental setting. Whilst this type of testing environment allows for a significant level of control over illumination levels, it lacks contextual factors from the real world which may impact on an individual's level of VA. For example, factors such as glare, visual noise, colour, etc. were not investigated/replicated in this experiment. Thus, whilst the results obtained from this study provide a reliable and valid measure of older adults' VA capabilities under a range of typical everyday ambient illumination levels, the data does not account for additional variables which may also impact upon an individual's level of VA in the real world.

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Table 1. Letter log values, sizes and visual fraction for 1m test distance

LogMAR value	Letter size mm ² (5x5)	Letter size (mins of arc)	Visual fraction	Decimal	Snellen fraction
0.5	4.7	16.25'	1m/3.20m	0.32	20/63
0.4	3.7	12.75'	1m/2.5m	0.4	20/50
0.3	2.9	10'	1m/2m	0.5	20/40
0.2	2.3	7.95'	1m/1.6m	0.63	20/32
0.1	1.8	6.2'	1m/1.25m	0.8	20/25
0	1.45	5'	1m/1m	1	20/20
- 0.1	1.2	4.15'	1m/0.8m	1.25	20/16
- 0.2	1.0	3.4'	1m/0.65m	1.5	20/13
- 0.3	0.8	2.75'	1m/0.55m	1.8	20/11

Table 3. Adaptation time given to participants between conditions

Order 1	Sequence	1	2	3
	Lighting condition	Overcast	In-house	Street lighting
	Adaptation time	5 mins	5 mins	7.5 mins
Order 2	Sequence	3	1	2
	Lighting condition	Street lighting	Overcast	In-house
	Adaptation time	7.5 mins	12.5 mins	5 mins
Order 3	Sequence	2	3	1
	Lighting condition	In-house	Street lighting	Overcast
	Adaptation time	5 mins	7.5 mins	12.5 mins
Order 4	Sequence	3	2	1
	Lighting condition	Street lighting	In-house	Overcast
	Adaptation time	7.5 mins	7.5 mins	5 mins
Order 5	Sequence	2	1	3
	Lighting condition	In-house	Overcast	Street lighting
	Adaptation time	5 mins	5 mins	12.5 mins
Order 6	Sequence	1	3	2
	Lighting condition	Overcast	Street lighting	In-house
	Adaptation time	5 mins	12.5 mins	7.5 mins

Table 4. Summary of paired comparison results for contrast levels in each illumination condition

Illumination condition	Paired comparisons (contrasts)		
	90%-70%	70%-50%	50%-30%
Overcast	t(36)=-1.466, $p=.076$ Not significant	t(35)=-3.82, $p=.000$ Significant	t(30)=-3.76, $p=.000$ Significant
In-house	t(31)=-4.776, $p=.000$ Significant	t(30)=-3.102, $p=.002$ Significant	t(22)=-5.391, $p=.000$ Significant
Street lighting	z=-1.689, $p=.046$ Not significant	z=-3.328, $p=.000$ Significant	z=-3.358, $p=.000$ Significant

Table 5. Older adults' log visual acuity capabilities under different everyday ambient illumination levels – effect of contrast

Condition	Contrast	<i>n</i>	Mean	SD	Median	IQR	Min	Max
Overcast	≥70%	37	0.12	0.18	0.1	0.2	-0.2	0.5
	50%	36	0.18	0.13	0.2	0.2	-0.1	0.4
	30%	31	0.26	0.12	0.3	0.1	0.0	0.5
In-house	90%	36	0.23	0.16	0.2	0.275	-0.2	0.5
	70%	33	0.28	0.16	0.3	0.25	0.0	0.5
	50%	31	0.32	0.13	0.3	0.2	0.1	0.5
	30%	23	0.38	0.08	0.4	0.1	0.2	0.5
Street lighting	≥70%*	30	0.27	0.16	0.25	0.3	0.0	0.5
	50%	26	0.38	0.1	0.4	0.2	0.2	0.5
	30%	17	0.45	0.05	0.5	0.1	0.4	0.5

*90% contrast dataset has been used as 70% contrast street lighting dataset was skewed. There was no significant difference between these two conditions.

Table 6. Older adults' visual acuity capabilities - rounded mean and letter size (mm) values for each illumination condition

Illumination condition	Contrast	Mean (log units)	Rounded mean (log units)	Letter size (mm)	Decimal	Snellen fraction
Overcast	≥70%	0.12	0.1	1.8mm	0.8	20/25
	50%	0.18	0.2	2.3mm	0.63	20/32
	30%	0.26	0.3	2.9mm	0.5	20/40
In-house	90%	0.23	0.2	2.3mm	0.63	20/32
	70%	0.28	0.3	2.9mm	0.5	20/40
	50%	0.32	0.3	2.9mm	0.5	20/40
	30%	0.38	0.4	3.7mm	0.4	20/50
Street lighting	≥70%*	0.27	0.3	2.9mm	0.5	20/40
	50%	0.38	0.4	3.7mm	0.4	20/50
	30%	0.45	0.5	4.7mm	0.32	20/63

*90% contrast dataset has been used as 70% contrast street lighting dataset was skewed. There was no significant difference between these two conditions.

Table 7. Summary of paired comparison results for illumination conditions across all contrast levels

Contrast level	Paired comparisons	
	Overcast - In-house	In-house - Street
90% contrast	t(35)=6.614, $p=.000$ Significant	t(29)=-3.633, $p=.000$ Significant
70% contrast	z=-4.922, $p=.000$ Significant	z=-2.03, $p=.021$ Significant
50% contrast	t(30)=-6.839, $p=.000$ Significant	t(24)=-5.136, $p=.000$ Significant
30% contrast	t(20)=6.614, $p=.000$ Significant	t(15)=-4.484, $p=.000$ Significant

Table 8. Older adults' visual acuity capabilities – effects of ambient illumination on visual acuity

Contrast	Illumination condition	Mean (log units)	Rounded mean (log units)	Letter size (mm)
90%	Overcast	0.1	0.1	1.8mm
	In-house	0.23	0.2	2.3mm
	Street lighting	0.27	0.3	2.9mm
70%	Overcast	0.12	0.1	1.8mm
	In-house	0.28	0.3	2.9mm
	Street lighting	0.3*	0.3*	2.9mm*
50%	Overcast	0.18	0.2	2.3mm
	In-house	0.32	0.3	2.9mm
	Street lighting	0.38	0.4	3.7mm
30%	Overcast	0.26	0.3	2.9mm
	In-house	0.38	0.4	3.7mm
	Street lighting	0.45	0.5	4.7mm

*Median value presented as dataset was significantly skewed

Figure 1. LogMAR acuity chart developed and used in study.

Figure 2. Rounded mean letter size (mm) visual acuity for each ambient illumination condition – effects of contrast

Figure 3. Rounded mean letter size (mm) visual acuity values for each contrast level – effects of ambient illumination

Figure 4. Calculated VP scores based on the CIE (2002) mathematical model using mean rounded VA data