Low vision is defined as permanent vision loss that is not correctable with spectacles, contact lenses or surgical intervention and that interferes with normal daily life. Reading is one of the most highly-valued activities in human society. Any ocular disorder that deprives people of the ability to read causes severe restriction of daily activities. This disability may be improved by various low vision aids (LVA) such as hand-held, stand and spectacle-mounted magnifiers, telescopes or electronic reading aids. To provide the appropriate LVA to assist people with low vision to retain their reading ability, accurate and efficient calculation of the required magnification is necessary as part of low vision rehabilitation. Magnification for reading is most often prescribed in the form of simple plus lenses.
Previous calculations of required magnification

In the past, low vision rehabilitation practitioners measured patients’ distance and/or near visual acuity (VA) to calculate the required magnification for LVA by using simplified equations. These methods were Kestenbaum’s rule and the Lighthouse Method. Kestenbaum’s formula assumes that: distance VA and near reading can be equated, the reference addition is +2.50 D and the desired acuity level is 6/15 Snellen equivalent (0.4 logMAR) at near. Kestenbaum’s formula for calculating magnification is the reciprocal of distance VA divided by four. However, the Light-house Method considers near VA instead of distance VA. The desired acuity is assumed to be 1 M (6/15 Snellen equivalent at 40 cm) or 8 point print (N8) with a reference addition of +2.50 D. The equation for calculating magnification by the Lighthouse Method is 2.5 times near VA (M unit) divided by four. Cole found that magnification levels determined by these methods were usually under-estimated when compared with the final prescription. These equations consider only patients’ VA and ignore their desired reading material or assume that it is always 1 M (N8) print size. By taking patients’ target reading materials into account, for example, newspapers, magazines or large print books, appropriate magnification can be determined to meet patients’ reading requirements.

To improve the accuracy of the calculation of magnification, Cole introduced another equation: ‘reciprocal of vision’. This method predicts the magnification based on the patients’ distance VA and the required near VA, which can be predicted from the patients’ target reading materials. It assumes that the patients’ distance and near VA are equivalent and the refer-ence distance is 40 cm. Cole’s reciprocal of vision equation for calculating magnification is 2.5 times distance VA divided by four times the required near VA. However, magnification was still under-estimated by this method, when compared with the final magnification prescribed. This under-estimation may be due to a number of factors, which affect reading with magnification. The introduction of magnifiers can result in restricted field of view, reduced illumination and aberrations and patients may have difficulty in manipulating the magnifiers. The calculation of magnification needs to include some acuity reserve to help offset these difficulties in using magnifiers.

Importance of acuity reserve

A number of studies has demonstrated that reading rates of normally sighted and low vision subjects increase as print size increases from threshold. Regardless of the level of vision, it is not possible to read fluently if the print size is at or close to threshold. This implies that the print size of a reading task must be larger than threshold to achieve a fluent reading rate. For this reason, Whittaker and Lovie-Kitchin introduced the term ‘acuity reserve’. Acuity reserve was defined as the ratio of print size that the patient intends to read to threshold print size. For example, a person with 0.5 M (N4) threshold print size reads 1.0 M (N8) newspaper print at 40 cm, with an acuity reserve of 2:1. Watson suggested that one of the reasons that closed-circuit television (CCTV) or video magnifiers give better reading performance than optical magnifiers is the greater acuity reserve provided.

In the past, guidelines for prescribing magnification for reading with low vision suggested that minimum magnification should be prescribed to maximise the field of view available. However, Whittaker and Lovie-Kitchin showed that inadequate acuity reserve was one of the main impediments to reading with low vision. They have shown that field of view is not the limiting factor affecting reading rate if sufficient acuity reserve is given.

In the literature, there appear to be two different approaches for the provision of acuity reserve in determining required magnification to achieve fluent reading rate. Whittaker and Lovie-Kitchin suggested that print size that was two times larger than threshold was sufficient to
achieve fluent reading rate for normal and low vision subjects. They recommended using this fixed acuity reserve in the calculation of magnification for reading. They recommended using this fixed acuity reserve in the calculation of magnification for reading. For example, if a person’s target is to read the newspaper (N8 or 1 M print) fluently, a fixed acuity reserve of two times (0.3 log unit) means that the required threshold size will be N4 (0.5 M) so that the person can read N8 (1 M) fluently.

The fixed acuity reserve suggested by Whittaker and Lovie-Kitchin was generalised from data from groups of subjects with low vision. Some individuals might need more or less acuity reserve for fluent reading. Legge and colleagues suggested that acuity reserve (and therefore magnification) required for fluent reading should be determined on an individual basis. From the measurement of reading rates at different print sizes, an individual’s required acuity reserve for maximum reading rate is calculated as the ratio between critical print size (CPS)—the smallest print size that gives maximum reading rate—and the person’s threshold print size (Figure 1).

The fixed and individual acuity reserve methods each have their advantages and disadvantages. The fixed method can simplify the clinical procedures of calculating the required magnification, as only near visual acuity and the target print size of the person’s reading materials are required. However, this method may over- or under-estimate the required acuity reserve for different individuals. The individual assessment overcomes this disadvantage of the fixed acuity reserve method but it requires measurement of the patients’ reading rates at a number of different print sizes, which makes the clinical assessment more complicated. Lovie-Kitchin and Whittaker discussed the two methods of using acuity reserve to prescribe magnification for reading and suggested a combination of the two methods. However, there have been no studies comparing the two prescribing methods to support the suggestion of Lovie-Kitchin and Whittaker.

The aim of this study was to investigate if there is a significant difference between the fixed and individual acuity reserve methods for determining the required magnification for optimum reading performance.

Table 1. Subject details

<table>
<thead>
<tr>
<th>Subject number</th>
<th>Age (years)</th>
<th>Years since onset of vision impairment</th>
<th>LVA *</th>
<th>Target print size (N-point, M units)</th>
<th>Reading frequency †</th>
<th>Distance VA (logMAR) with +4 D (logMAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>§ 79</td>
<td>3</td>
<td>3</td>
<td>8 1.0</td>
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<td>1.10</td>
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<tr>
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<td>83</td>
<td>6</td>
<td>2</td>
<td>8 1.0</td>
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<td>3</td>
<td>3</td>
<td>8 1.0</td>
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</tr>
<tr>
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<td>§ 83</td>
<td>4</td>
<td>2</td>
<td>8 1.0</td>
<td>1</td>
<td>1.26</td>
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<tr>
<td>7</td>
<td>§ 68</td>
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<td>8 1.0</td>
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<tr>
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<td>9</td>
<td>2</td>
<td>10 1.3</td>
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<tr>
<td>9</td>
<td>§ 80</td>
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<td>8 1.0</td>
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<tr>
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<td>§ 76</td>
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<td>16 2.0</td>
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<td>0.60</td>
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<td>1</td>
<td>1</td>
<td>8 1.0</td>
<td>1</td>
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</tbody>
</table>

* Code for low vision aids (LVA) used at near: 1. High addition spectacles (+4 D addition or greater); 2. Hand-held magnifiers; 3. Stand magnifier
† Reading frequency: 1. Read daily; 2. 2–3 times per week; 3. Once per week; 4. Rarely
§ Subjects who participated in both the first and second visits
METHODS

Subjects
Nineteen subjects with low vision aged between 50 and 90 years (mean age 78.7 ± 8.83 years) were selected from the Queensland University of Technology (QUT) Vision Rehabilitation Centre (VRC). Distance VA in the better eye ranged from 0.38 logMAR (6/15+1) to 1.3 logMAR (6/120) (Table 1). All subjects were diagnosed by ophthalmologists to have age-related macular degeneration (AMD) and had been prescribed optical LVAs such as high additions, hand-held magnifiers or stand magnifiers (Table 1). The subjects had received a comprehensive vision examination or follow-up assessment of low vision aids during the 12 months preceding their recruitment. They were selected to have less than one line (0.1 log-unit) change in near VA since their last assessment. Subjects had used their low vision aids for three months or longer, had no known cognitive problem (as indicated from the clinical record) and all were fluent in English. Previous studies have stated that reading rate could be reduced due to difficulties with comprehension among people with normal26 or low vision.27 Therefore, it was important to ensure that subjects would have no difficulties understanding the reading materials.

A simplified Neale Analysis of Reading Ability28 was used to confirm that all recruited subjects had Grade 6 or above reading ability. A short Grade 6 story was read to each subject and then four questions were asked to assess comprehension. Any subject who could not answer three of the four questions correctly was excluded from this study. All subjects gave signed informed consent to their participation in the study, which was approved by the QUT Human Research Ethics Committee. Vision and reading performance were assessed at one visit for 19 of the subjects and at a second visit for nine of the subjects (see below).

Table 2. Reading rate measures for first (n = 19) and second visits (n = 9)

<table>
<thead>
<tr>
<th>Visit</th>
<th>Reading Measures</th>
<th>Instrument used</th>
<th>Working distance</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>Large print reading rate without LVAs</td>
<td>Reading rate on sentences</td>
<td>Bailey-Lovie text chart</td>
<td>Working distance of near addition</td>
</tr>
<tr>
<td></td>
<td>Reading rate with LVAs</td>
<td>Reading rate with LVAs • Fixed method • Individual method • Own LVAs</td>
<td>Passages of texts with LVAs used in random order across subjects</td>
<td>Habital working distance with magnifiers; EVD calculated</td>
</tr>
<tr>
<td>Second</td>
<td>Large print reading rate without LVAs</td>
<td>Reading rate on sentences</td>
<td>Bailey-Lovie text chart</td>
<td>Working distance of near addition</td>
</tr>
<tr>
<td></td>
<td>Reading rate with LVAs</td>
<td>Reading rate with LVAs • Fixed method • Individual method • Own LVAs</td>
<td>Passages of text at CPS</td>
<td>Habital working distance with magnifiers; EVD calculated</td>
</tr>
</tbody>
</table>

Reading rate assessment
Reading rates were measured for single sentences on the Bailey-Lovie text reading chart and for short passages of text (see below). The level of text difficulty in both tests was well below the reading ability of the subjects to ensure that reading performance was not limited by text difficulty.31

The Bailey-Lovie text charts were modified MNRead charts32,33 suitable for measuring reading acuity and reading rate of people with normal or low vision at 25 cm. Print sizes ranged from 1.5 logMAR (8 M/N64) to 0.2 logMAR (0.4 M/N3) in 0.1 logarithmic steps with one sentence at
each print size. Each sentence contained 60 characters (10 standard words) including a space between each word and at the end of each line. All sentences used in this chart were selected from the MNRead Corpus with each sentence printed over two lines at each print size and left justified. Six charts were produced with Times New Roman font in black on white print and three charts were randomly selected for each subject.

Nine reading passages of approximately sixth grade reading level (263 ± 5.56 characters or 43.85 ± 0.93 standard words), selected from other reading tests (Sloan Reading Cards for low vision patients; University of Waterloo near vision test card; Maclure bar reading book for children—Clement Clarke International Ltd), were produced in various print sizes. These passages were used in a different order for each subject.

Reading rates were measured with the subjects’ habitual near additions (referred to as ‘without LVA’) and with LVA (Table 2). For all reading trials, subjects were instructed to read each sentence aloud at their normal reading rate to enable good understanding of the sentence or passage, that is, to read for understanding. Time to read each sentence was recorded with a Micronta LCD Stopwatch to ±0.5 second and any words missed or incorrectly read were recorded. Errors, in number of characters, were taken into account in calculating reading rate.

Oral reading rate (standard words per minute [wpm]) was calculated as follows:

\[
\text{Reading rate} = \frac{(\text{number of characters read } - \text{ errors}) \times 60}{\text{reading time (secs)}} \times 6.
\]

Reading rate for each sentence on the Bailey-Lovie text chart was plotted against print size. A smooth curve was fitted to the data and CPS was selected by eye (at N12 [1.6 M] in Figure 1). Text VA was the smallest print size the subject could read (N6 [0.8 M] in Figure 1).

Maximum reading rate (MRR) was taken as the mean of the reading rates for print sizes at and above CPS. For example, from Figure 1, MRR is the mean of reading rates at N12 and all print sizes larger. MRR and CPS without LVA were determined three times with different Bailey-Lovie text charts. The mean of the three measures of MRR was used for analyses, while mean CPS was selected to the nearest whole line.

Magnification calculation

Magnification was calculated from the reading measures without LVA using the two methods described above—the first, using a fixed 2:1 (0.3 log unit) acuity reserve for all subjects and the second using the acuity reserve determined individually for each subject from the CPS. Magnification was determined for a target print size selected according to each subject’s preferred reading material. For example, if the subjects indicated that they wanted to read newspaper print, the target print size was N8 (1 M), but if they wanted to read books, the target print size was N12 (1.6 M).

Magnification was calculated in terms of equivalent viewing distance (EVD) and using the fixed acuity reserve method.

Required EVD (cm) = (Target print size/2) x (Current viewing distance/Current threshold print size)

Using the individual acuity reserve method:

Required EVD (cm) = (Target print size/CPS) x Current viewing distance.

Based on the magnification calculated by the two methods, optical LVAs of the same type as the subjects’ own magnifiers (that is, high addition spectacles, handheld or stand magnifier) were chosen. In selecting an appropriate hand-held or stand magnifier of the required EVD, the eye-lens distance, image distance and the subject’s near spectacle addition were taken into account.

First visit

Reading rates with two optical LVAs determined as described above were measured by asking the subjects to read passages of their target print size three times. In addition, reading rate with each subject’s own optical aid was measured. The
three magnifiers were used in random order (Table 2). When measuring reading performance with the magnifiers selected by the fixed and individual acuity reserve methods, the subjects were instructed on the appropriate eye-lens distance to give the required EVD. They were allowed to adopt their own eye-lens distance when reading performance with their own magnifiers was measured; this eye-lens distance was measured to calculate the EVD of the subjects’ own magnifiers.34

As described above, MRR was calculated as the mean of the reading rates for print sizes at and above CPS (Figure 1). However, reading rate with LVA in some cases was reduced for large print sizes, because few characters were visible in the field of view (Figure 3). Therefore, when reading rates on large print sizes were less than 90 per cent of the reading rate at CPS, they were excluded from the calculation. For example, in Figure 3, MRR was the mean of reading rates at print sizes from N20 (2.5 M) to N8 (1.0 M).

Second visit
To assess repeatability of reading rate measurements over a period of time, nine of the 19 subjects returned for further reading rate measures approximately two months after the first measurement. These subjects reported that their vision had not changed during this time and this was confirmed from repeated vision measurements. There were no statistically significant differences in VA for distance or near (word and text) between the two visits (repeated measures ANOVA; \(F_{1,8} = 2.86, p = 0.13\); \(F_{1,8} = 0.29, p = 0.61\); \(F_{1,8} = 2.29; p = 0.17\) respectively). At this second visit, reading rates for sentences (Bailey-Lovie text charts) and passages were measured with and without LVAs (one trial each) as described in Table 2.

Data analysis
Data were analysed using the Statistical Package for the Social Sciences (SPSS)—version 10. As vision measures and reading rates were not significantly different from a normal distribution (Kolmogorov-Smirnov Goodness of Fit test, \(p > 0.1\)), parametric statistics were used—Pearson’s correlation, analysis of variance (ANOVA), repeated measures ANOVA and paired t-tests. Repeated measures ANOVA were used to test subjects’ distance and near visual acuities to ensure that there were no significant changes in vision between experimental visits. To compare the three reading rates with LVA and the maximum reading rate without LVA, one-way ANOVAs were performed. A probability of less than 0.05 was taken to indicate statistical significance for all analyses. However, the probability of finding a significant difference by chance alone increases rapidly with the number of statistical tests. Because the number of tests equalled the degrees
of freedom, a Bonferroni correction was applied to the probability associated with each test by dividing it by the number of tests executed. The adjusted probability was 0.006 as there were eight repeated measures at the second visit.

RESULTS

Method of determining magnification

There were no significant differences between the reading rates on passages with LVA determined by the two methods (the fixed or individual acuity reserve method) or with the subjects’ own-magnifier (Table 3). This was true at the initial visit and at the repeat visit ($F_{2,54} = 0.05, p = 0.95; F_{2,24} = 0.24, p = 0.79$ respectively) (Tables 3 and 4). Similarly, there were no significant differences in the required EVD calculated by the two different methods or the EVD of the subjects’ own magnifiers ($F_{2,54} = 0.69, p = 0.51$). The magnification of the LVAs prescribed for QUT VRC patients are determined initially on the basis of a fixed acuity reserve of 0.3 log unit. Reading performance is then assessed and the magnification may be modified. For this reason, it was not surprising to find no significant differences in EVD between that of the subjects’ own LVA and that calculated by the two different methods.

The method of using a fixed acuity reserve (prescribing for print size that was two times [0.3 log unit] smaller than target print size) satisfactorily determined the required magnification for almost all subjects. There was one exception in this sample—subject 8 was unable to read with the hand-held magnifier selected using the fixed acuity reserve method. Subject 8 had had AMD for the longest period of all the subjects and was well adapted to her own magnifier, which provided an acuity reserve of 0.5 log unit. While fluent reading was still possible with 0.4 log acuity reserve, it was not with 0.3 log acuity reserve. The fixed acuity reserve method in this case underestimated her required acuity reserve. She needed at least 0.4 log acuity reserve to achieve fluent reading with magnification.

Table 4. Comparison of the reading performance of (nine) subjects at two visits.

<table>
<thead>
<tr>
<th></th>
<th>First visit (n = 9)</th>
<th>Second visit (n = 9)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sentence</strong></td>
<td>Maximum reading rate without LVAs</td>
<td>104.35 ± 53.25 wpm</td>
</tr>
<tr>
<td></td>
<td>Reading rate with LVAs (by fixed method)</td>
<td>* 98.33 ± 47.5 wpm</td>
</tr>
<tr>
<td></td>
<td>Reading rate with LVAs (by individual method)</td>
<td>* 102.07 ± 50.81 wpm</td>
</tr>
<tr>
<td><strong>Passage</strong></td>
<td>Maximum reading rate without LVAs</td>
<td>* 67.37 ± 34.25 wpm</td>
</tr>
<tr>
<td></td>
<td>Reading rate with LVAs at target print size (by fixed method)</td>
<td>58.42 ± 30.2 wpm</td>
</tr>
<tr>
<td></td>
<td>Reading rate with LVAs at target print size (by individual method)</td>
<td>50.13 ± 31.3 wpm</td>
</tr>
<tr>
<td></td>
<td>Reading rate with own LVAs at target print size</td>
<td>53.2 ± 24.67 wpm</td>
</tr>
</tbody>
</table>

* The measurements were made at second visit only

Figure 4. Examples of reading rates as a function of print size with and without LVAs for sentences using the Bailey-Lovie text reading. Maximum reading rates were not significantly different with or without LVAs.
Repeatability of measurements

Reading rates were repeatable when measured in one session. At the first assessment, reading rate without LVA was highly repeatable with no statistically significant differences between the three trials ($F_{2,54} = 2.23, p = 0.12$). Ahn, Legge and Luebker $^{24}$ similarly found reading rates without LVA to be very repeatable across six measurements. This suggests that one measurement of reading rate on large print is sufficient to estimate a low vision subject's MRR without a low vision aid.

Reading rates between visits were also repeatable (Table 4). Maximum reading rate on large print without LVA at the second visit ($112 + 55.8$ wpm) was not significantly different from the first trial of maximum reading rate at the first visit ($104 + 53.25$ wpm) ($F_{1,8} = 2.76; p = 0.14$). Mean reading rates with LVA for passages at the subject's target print size were not significantly different between the two visits for the magnifiers determined by the fixed acuity reserve method or individual method ($t = -1.24; df = 8; p = 0.25; t = -3.36; df = 8; p = 0.01$ [not significant with Bonferroni correction] respectively) or using subject's own LVA ($t = 0.56; df = 8; p = 0.59$).

Comparison of reading performance with and without magnifiers

At the first visit, MRR without LVA was significantly faster than the reading rate with LVA at subject's target print size ($F_{2,37} = 0.89, p < 0.001$). This difference probably occurred because single sentences were used to measure MRR without LVA, but longer passages were used to measure reading rates with LVA. Carver $^{31}$ has suggested that reading rate for longer passages is lower than reading rate for short sentences. To confirm that the significant reduction in reading rate with magnifiers compared with large print was due to the different reading tasks, reading rate measures were made for similar tasks, both sentences and passages, with and without LVA at the second visit.

At the second visit, there were no significant differences between MRR for sentences ($F_{1,32} = 0.12, p = 0.95$) and passages at critical print size ($F_{1,32} = 0.08, p = 0.97$) with or without LVA (Table 4 and Figure 4). This result agrees with the findings of Bowers, Lovk-Kitchin and Woods $^{37}$ who also reported no significant differences in reading rates with and without LVA for paragraph reading at critical print size. In addition, our results confirm that reading rate without magnifiers is a good predictor of reading rate with magnifiers ($r = 0.96; p < 0.0001$) as previously reported by Lovk-Kitchin, Bowers and Woods $^{38}$ and Ahn and Legge $^{39}$.

**DISCUSSION**

Our results and those of previous studies $^{37,39}$ indicate that, provided there is ample acuity reserve, LVAs do not reduce reading rate for experienced users. From the measurement of reading rate on large print without LVA, an estimation of the potential reading performance with LVA can be determined before optical aids are prescribed $^{39}$.

Numerous previous studies have found that reading rate is reduced by the use of magnifiers. $^{40-44}$ These studies recruited subjects who had normal vision, were highly educated and who had higher maximum reading rates without LVA than those achieved by people with low vision. These subjects were not experienced in using low vision aids and in some studies the retinal image sizes with and without LVA were different for the two conditions. Passages of the same print size were used to measure the reading rates with and without LVAs, giving different image sizes.

The results of our study showed that there was no significant difference between reading rate with and without LVAs for experienced subjects when performing similar reading tasks. However, these findings were for experienced magnifier users only. For inexperienced users, based on previous studies, $^{40,44}$ it is reasonable to expect a reduction in reading rate when the LVA is first prescribed. There are at least two possible reasons for this: they lack the experience to use the LVAs or they have given up reading for a long time because of their poor vision. Perhaps giving these low vision patients large print reading practice before prescribing the LVAs would enhance their reading performance with magnifiers. The results of this study suggest that reading rates with LVAs will reach large print reading rates, once the low vision subjects adapt to their LVAs. Previous studies have mainly concentrated on providing extensive training programs for the use of optical low vision aids. $^{45,46}$ However, there has been no study to evaluate subjects' adaptation to LVAs by monitoring reading performance over time. Therefore, further research to determine the effects of reading practice and/or training with magnifiers is needed.

**CONCLUSION**

Determining the appropriate magnification of low vision aids to assist people for reading is an important task in low vision rehabilitation. For clinical purposes, a method that is easy, efficient and accurate would be most useful. For the AMD subjects in this study, using the fixed acuity reserve method to determine magnification gave results similar to those of the individual acuity reserve method. The fixed acuity reserve method as described by Lovk-Kitchin and Whittaker $^{23,25}$ requires only the identification of the patient's target reading material and the assessment of near visual acuity; an acuity reserve of 2:1 (0.3 log-unit) is then used to determine magnitude. This study indicates that for most patients with AMD, this method gives magnification that meets their reading goals and is not significantly different from that which had been prescribed. Our clinical experience suggests that these results probably apply to patients with other causes of low vision. However, occasionally the reading rate achieved with the magnification calculated in this way was not satisfactory. In such cases, individual assessment of reading rates for different print sizes is needed to determine the acuity reserve required for fluent reading rate and calculate appropriate magnification $^{39}$.

We have confirmed Lovk-Kitchin and Whittaker's $^{23}$ suggestion that for clinical purposes the practitioner should determine the required magnification based on a required acuity reserve of three lines for fluency. If the reading performance is not satisfactory with this magnification, individual assessment of required acuity reserve for fluent reading rate is necessary.
By this prescribing regime, reading rates versus different print sizes do not need to be measured as a routine procedure in determining magnification. The patient’s near visual acuity and target print size are the only required information for calculating magnification.

ACKNOWLEDGEMENT

We would like to thank Professor Gordon Legge from University of Minnesota for supplying the sentences used to produce different versions of the Bailey-Lovie reading text charts. This work was supported by a QUT International Postgraduate Research Scholarship.

REFERENCES


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