In our aging society, visual impairment poses an increasing burden on the lives of many older adults. Evidence shows a decrease in health related quality of life,\textsuperscript{1} an increase in mortality,\textsuperscript{2} and one in three patients experience depression and/or anxiety.\textsuperscript{3} In our visually demanding society, reading is of great importance for participation in society and recreational activities and is one of the main reasons for visually impaired persons to seek low-vision rehabilitation.\textsuperscript{4} Visual impairment is most prevalent among people aged 50 years and older.\textsuperscript{5} With the aging population visual impairment will increase, which will result in more ophthalmic consultations,\textsuperscript{6} and an increased demand on visual rehabilitation services.

This thesis contributes to understanding the psychophysical aspects of continuous text reading tests and contrast sensitivity tests. Both types of tests are used in ophthalmic and optometric clinical practice and research to investigate visual functioning, such as (near) visual acuity (VA) or contrast sensitivity (CS), and to assess functional vision, such as the ability to read (see Figure 1).\textsuperscript{7} In clinical practice, these tests are important measurement tools to diagnose or monitor visual functioning of patients with visual impairment caused by various – often age-related – eye diseases.\textsuperscript{8-12} Reading performance tests have been used as the primary outcome measure for clinical trials on the effectiveness of low vision rehabilitation.\textsuperscript{13} CS tests have been used in cost-effectiveness studies of treatments of age-related macular degeneration,\textsuperscript{14} and provide a broader psychophysical understanding of the effects of treatment and benefits for patients.\textsuperscript{15} Both reading performance and CS are strongly related to vision- and health-related quality of life.\textsuperscript{16,17}

According to the Vision Loss Expert Group in 2015 worldwide 36.0 million people were blind, 216.6 million people had a moderate to severe visual impairment and 188.5 million people had mild (acuity $\geq$6/18 to $<$6/12) visual impairment.\textsuperscript{18} The absolute number of people who are blind or visually impaired is increasing worldwide due to population growth, aging of the population, and the higher demands of visual performance. However, after accounting for population growth and

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Visual function versus functional vision. Source: A. Colenbrander. Introduction to Visual Acuity Measurement. Available from the Precision Vision website (precision-vision.com).\textsuperscript{7}}
\end{figure}
ageing, the global prevalence of blindness decreased from 0.75% in 1990 to 0.48% in 2015. The age-standardised prevalence of blindness is highest (4% or greater) in developing or low-income regions, compared to high-income regions (0.5% or less). In the Netherlands in the year 2008 an estimated 311,000 people were at least moderately visually impaired, of whom 77,000 can be characterized as blind. An expected increase of 18% may lead to 367,000 people with at least moderate visual impairment in the year 2020.5

The current World Health Organisation (WHO) definitions of blindness and visual impairment in the International Statistical Classification of Diseases (ICD-10) are based on distance VA (Table 1).19 Besides distance VA, the WHO has recommended measurement of near vision in population-based surveys.20 Even though the importance of near vision has been acknowledged, the ICD-10 does not include a classification system for near vision.21 It has also been an uncommon criterion used in the “rapid assessments of avoidable blindness” to assess population status following the WHO’s initiative “Vision 2020” to eliminate avoidable blindness by the year 2020. However, reading tests to assess near vision impairment are increasingly included in (global) prevalence studies of blindness and visual impairment.18,21 When near vision impairment is included, uncorrected presbyopia is the most common cause of visual impairment worldwide.22 The current definition of blindness at near was agreed upon by the International Agency for Prevention of Blindness (IAPB) Refractive Error Program Committee in 2008 (Table 2).23 Near blindness was defined as presenting vision worse than N64 in the better eye when tested at the individual’s required

<table>
<thead>
<tr>
<th>Category</th>
<th>Presenting distance visual acuity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Worse than:</td>
</tr>
<tr>
<td>0 Mild or no visual impairment</td>
<td>6/18 (0.33)</td>
</tr>
<tr>
<td>1 Moderate visual impairment</td>
<td>6/18</td>
</tr>
<tr>
<td>2 Severe visual impairment</td>
<td>6/60</td>
</tr>
<tr>
<td>3 Blindness</td>
<td>3/60</td>
</tr>
<tr>
<td>4 Blindness</td>
<td>1/60*</td>
</tr>
<tr>
<td>5 Blindness</td>
<td>No light perception</td>
</tr>
<tr>
<td>9 Undetermined or unspecified</td>
<td>* or counting fingers (CF) at 1 meter</td>
</tr>
</tbody>
</table>

If the extent of the visual field is taken into account, patients with a field no greater than 10° but greater than 5° around central fixation should be placed in category 3. Patients with a field no greater than 5° around central fixation should be placed in category 4, even if the central acuity is not impaired.
working distance. This print size held at 40 cm corresponds with a distance VA of 3/60. The N point scale represents the body size of a letter (from the top of the ascenders to the bottom of the descenders). Size N8 to N10 resembles newsprint.

Not only in epidemiological studies, but also in clinical studies and in clinical practice near vision is increasingly measured using standardised tests or other reading materials, especially in patients with age-related macular degeneration (AMD). In 2011 the Dutch National Institute for Health and Environment estimated that 102,400 patients in the Netherlands had dry AMD (geographic atrophy) or neo vascular AMD in at least one eye.\textsuperscript{24,25} AMD is a heterogeneous degenerative disorder affecting the retinal pigment epithelium, Bruch’s membrane, and choriocapillaris of the macula, causing central vision loss.\textsuperscript{26} In patients with central retinal vision problems, reading tests are more informative than letter chart tests to assess distance VA, because these patients often experience scotoma interference while reading.\textsuperscript{27} Single optotype performance depends only on a small retinal area, usually the fovea, upon which each optotype is projected. Reading tests however require a larger retinal area for word recognition and for guiding successive fixations along the line.\textsuperscript{28,29} Given the high prevalence of AMD, the lack of treatment for most patients with dry AMD (about 90%)\textsuperscript{6}, and the high impact on reading and other activities of daily life, rehabilitation of people with AMD is an increasingly important public health issue. Reading problems, the effectiveness of low vision rehabilitation and optical needs can be assessed and analysed with reading performance tests.

**READING PERFORMANCE TESTS**

The determination of VA is the most important measurement of visual function in routine eye examination. VA defines the ability of the eye to resolve fine detail, in particular letters. Sometimes it is defined by the smallest distance to see two points
separately. Inspired by a formula of Donders (1861), Snellen published the principles of optotype construction in 1862 and introduced the scientifically based letter tests (“de Utrechtsche Optotypi”) to determine distance and near VA. This uniform standardised method is internationally recognised and has been used all over the world since then. Subsequently developed methods for measuring VA are often a modification of Snellen’s method. In 1867 and 1868, Green introduced the idea of logarithmic progression of optotype sizes. More than a century later in 1982, the National Eye Institute introduced the Early Treatment Diabetic Retinopathy Study (ETDRS) charts. The ETDRS charts have become the standard method for measuring distance VA in logMAR notation.

In contrast to distance acuity, for reading performance tests no such standards have been applied and there is no consensus on which tests should be used. For routine practice, in which patients mostly have normal vision, a reading test is often used to check the prescribed reading glasses and for this purpose almost any reading sample (e.g. newspaper article) can be used. However to obtain standardised and comparable outcomes in clinical practice and research, statistical evaluation and standardisation should be performed on every clinical method. This is certainly true also for function based vision tests such as reading tests, to allow a reliable and reproducible measurement. A reliable reading test can predict reading performance and optical needs, and provides a standardised measure of the visual component of reading performance.

A variety of (un-) standardised reading tests are currently used in clinical practice and research. The situation in 1969, as described in the Dutch Medical Journal is still valid in some situations: “The original reading acuity test of the Dutchman Snellen in 1862 is frequently changed, so that a true disarray of Snellen reading tests exists. The result is that measurements with different tests are not comparable.” It seems evident that reading tests should be developed according to a standard. In 1988 the Visual Function Committee of the International Council of Ophthalmology (ICO) published a standard for reading charts to establish calibrated reading acuity measures. A brief overview is given of some of the reading tests who are developed in accordance with this standard.

A noteworthy development in clinical reading tests before 1988 was the introduction of the Sloan Continuous Text Read Cards in 1963. The Sloan reading cards present a short text passage. The amount of text varies from a few words for the bigger print sizes to an entire paragraph for the smaller print sizes. The next significant development in reading assessment was the introduction of the Bailey-Lovie Near Reading Card in 1980. These cards present two to six unrelated words per line. Print size decreases logarithmically; which means that the size decreases a constant percentage of change from line to line.

In 1989 Legge and colleagues were the first to introduce single sentences with continuous text (as advised by the ICO), first as a computer-based test and soon converted to a printed chart version called the Minnesota Low-vision Reading Test.
The test was designed to measure reading acuity and maximum reading speed simultaneously. The test consists of a series of three short lines logarithmically decreasing in print size. The MNread test is frequently used in scientific research and available in several languages but not in the Dutch language. Since the development of the MNread test other continuous text reading tests were developed in different languages of which some are specifically designed for cross language comparison.

Continuous text reading tests for out loud reading are feasible short duration tests, which resemble daily reading material and are suitable for clinical practice and research. These reading tests allow measuring reading parameters such as; reading acuity, critical print size, reading speed and reading mistakes. These parameters are the focus of this thesis. There are other types of reading tests, such as mixed-contrast tests and comprehension tests based on silent reading and there are other reading tests available for example with unrelated words. These tests all serve different purposes such as measuring CS, testing comprehension, and estimating the location of scotomas. These are beyond the scope of this thesis.

In the Dutch language several reading tests are commercially available and used in clinical practice and research: e.g. the Colenbrander Reading Card, the International Reading Speed Texts (IReST), the Laboratory of Experimental Ophthalmology (LEO), ‘de Nederlanders’ (meaning ‘the Dutchmen’), and the Radner Reading Charts (see figures 2 to 6). No validation studies are available for the Colenbrander Reading Card, the LEO, and ‘de Nederlanders’. For the IReST and the Radner Reading Charts there are several studies in which the content validity and internal consistency of the sentences or paragraphs were measured and well described. All tests except for the IReST are tests with single sentences and logarithmic progression in text size. The IReST tests consist of ten longer text paragraphs in one print size.

In general for standardised logarithmic reading tests, print size should be the only parameter affecting performance throughout the chart. To accomplish this, text properties and text content should be controlled for. There are local text properties; e.g. font, print size, letter spacing, and global text properties such as line length, line spacing and page format. Examples of text content that can be controlled for are lexical difficulty and syntactical structure of the text. It is unclear how text properties and text content for some reading tests have been controlled for, and if and how this possibly has influenced reading test reliability in comparison with the reliability of standardised reading tests.
Het gevaar opgegeten te worden is een van de vele gebeurtenissen die dieren en planten bedreigen. Veel dieren helpen zichzelf door zich te camoufleren, terwijl andere dieren zich verbergen. Een groot aantal van hen is zo snel dat zij voor de vijand kunnen vluchten. Planten die niet kunnen vluchten, hebben andere methoden ontwikkeld om zich te beschermen, zoals scherpe stekels en doornen. Andere planten en ook enkele dieren beschermen zich door middel van een gif dat zij in zich hebben. Dit gif hoeft niet noodzakelijk dodelijk te zijn. Het is voldoende als andere dieren tegengehouden worden om de giftige planten of dieren te eten. Veel dieren beschermen zich door er net zo uit te zien als andere dieren die wel giftige stoffen in zich hebben. Een erg opvallende kleur is in het dierenrijk meestal een signaal dat het dier oneetbaar is.

Figure 2. International Reading Speed Texts (IReST) (not at actual size or in printed contrast).

Figure 3. Laboratory of Experimental Ophthalmology Groningen (LEO) (not at actual size or in printed contrast).
De Nederlanders ontlenen van de voorwerpen, die hen van jongs af aan omringen, vele denkbeeld en plooiën, waardoor zij beter geschikt zijn om, zoodra het hun lasten zal, tot zeelieden geworden te worden. Ons land, alons de ommuurd met wateren, rivieren, poelen en meeren, krits waar men zich wende, van kleine vaartuigen, waarop de boeren schippers zijn. Zij onderhouden door dat middel de gemeenschap van alle steden en dorpen, en hoe onmogelijk deze vergelijking ook moge schijnen, daartoe wordt in ver- schiedene opzichten dezelfde vaardigheid, zoo niet hetzelfde beleid vereischt, dat men van nood

\[ D = 0.5 \]

hoeft om op eenen zeetog geen nutteloos gezel te zijn. Geen Nederlandse boer, die ten minste niet van loeren en laveeren weet, weinige, die niet geleerd hebben een vaartuig te bestieren, te gissen hoewel wind het voeren kan, tegen wind en stroom te roeijen, dwarfwinden te voorzien, of zich te redden uit een onverwacht gevaar van zinken of vergaan. Velen onder hen, in hun geboorteplaats deze zaken lang genoeg voor tijdverdrijf en spel bijgewoond hebbeinde, kunnen de verzoeking niet nederstaan van ook eens op den

\[ D = 0.6 \]

ruimen Oceaan te zwerven, alwaar zij dan gemeenlijk voor al het overige geen trage leerlingen zijn. Ik kan niet nalaten hierbij te voegen, dat onze taal ook de kenteekenen draagt van onze gemeenzamenheid met de zeevaart: vooral onder het gemeen en in den dagelijkschen wandel is zij voor het grootste deel eene taal van zeelieden. Wij wenden het over dezen of genen boeg, zoeken eene reè, werpen ons anker, klampen elkander

\[ D = 0.8 \]

aan boord, haken naar het voorwerp onze begeerte, enz. Wij komen met eene zee aan land, of drijven op Gods genade. Kortom, geen uur op den dag, dat wij niet varen of bezig met ons getij te kavelen. Ontstaat er dan een oorlog ter zee, zoo levert zulk een Natie gemakkelijk een groot getal menschen, die, anders tot geene krijgsdienst geschikt zijnde, nogthans door den prikkel der eerzucht daartoe

\[ D = 1 \]

opgewekt worden, dewijl zij weten dat alles, wat hun ontbreekt om wel te dienen, ligtelijk door eene gemeene opmerkzaamheid zal vervuld worden. Onze Nederlanders in hun element, kunnen dus ten naaste bij gelijk gesteld worden met de Zwitsers, van jongs af aan op den wapenhandel afgerigt, te welde. Het

Medical Workshop b.v. Groningen

Figure 4. ‘de Nederlanders’ (not at actual size or in printed contrast).
Op de tafel stonden vroeger de theepotten, die Jan voor nette gasten gebruikten wilde

De grote hond stoette tegen de bierglazen, die net door onze dochter opgeruimd waren

Na schooltijd gingen ze naar de dierentuin, waar net twee bruine wolven geboren waren

De kleine zuster vertelde over de ziekenzaal, die zij voor arme mensen opzette wilde

De meester genoot altijd van de aardappels, die door mijn oude oma klaargemaakt werden

Op grote hoogte vlogen daar de roofvogels, die door mijn kleine zusje bekeken worden

De kluutens stonden bij in de winkelzaal, waar zij een leuke knuffel gekregen hadden

In vriendelijk hoeden vijf lezen de kinderen, die ondertussen goed keken naar een schaar en een bloem

Deichten leerden het in de klas, de vogel vloog tegen het raam toe

Afstandscorrectie:

Testafstand (cm): 50 40 30 20 15 10 8

LogRAD-correction: -0.1 -0.05 0.0 0.05 0.1 0.15 0.2

Table 1. Radner Reading Charts (not at actual size or in printed contrast).
CONTRAST SENSITIVITY TESTS

The relative variation in luminance in a visual target is defined as the contrast. Contrast sensitivity tests are used to measure the smallest contrast that can be detected. Contrast threshold is typically reported as CS, which is the inverse of contrast threshold. For example, a difference of 5% contrast can just be detected; threshold expressed as fraction is 0.05 and CS is 20. The CS function shows the relation between CS thresholds and spatial frequencies (figure 7). This shows that also the size of the details within a target determines whether the target will be resolved. CS describes the ability to see low-contrast patterns. CS can be impaired in many ophthalmic conditions such as ambyopia, AMD and glaucoma, but can also be impaired in neurological conditions, and CS loss can be a side effect of prescription drugs. Instead of determining a whole CS function, contrast thresholds can be determined with letter charts such as the Pelli-Robson chart (figure 7). The outcome of such tests has been found to correspond more or less to CS at peak spatial frequency. Rubin et al. stated that an overall reduction in CS has a greater effect on for example reading performance than a small depression in sensitivity at particular spatial frequencies. Therefore, measuring peak CS is of clinical value and is practical because it is less time consuming.
CS, even though associated with VA, is considered to be an important additional measure of visual function and provides additional information on the aspect of visual performance.\textsuperscript{15,50-53} VA and CS are independently associated with difficulties in everyday activities.\textsuperscript{54,55} Someone with a good VA but with low CS can experience major problems with tasks in everyday life such as; face recognition,\textsuperscript{56} driving,\textsuperscript{57,58} and reading.\textsuperscript{54} Including CS assessment in clinical practice and research related to functional vision and quality of life provide a more complete understanding of the problems persons with visual impairment experience. The USA National Research Council committee on disability determination for individuals with visual impairments, recommends to assess CS as a supplementary basis for disability determination for people with decreased vision and/or self-report of visual impairment greater than would be expected from the acuity scores.\textsuperscript{59}

Contrast plays an important role in how well people can perceive text (distinguishing letters). This is especially true for persons with visual impairment, and in the prediction of reading speed.\textsuperscript{59,60-63} If the contrast ratio of text and background are at the limits of a person’s CS, the text is difficult to perceive for that person. If the contrast is well within the person’s visible range, the text is easy to distinguish. In turn, the way CS influences reading is complicated and cannot only be explained by the distinguishability of text. Reading speed for normally sighted people is nearly unaffected by contrast reduction.
down to about a critical value of about 10% or less, after which reading speed quickly declines. For visually impaired people, the critical contrast for reading is often much higher and can be predicted from standard measures of CS. Particularly for people with severe visual impairment reading performance may decline even for a small reduction in maximum text contrast, with a critical contrast as high as 80%.

To measure peak spatial CS, large letters which more or less correspond to the peak spatial frequency can be used (figure 7). In a clinical setting a letter spatial CS test, such as the Pelli-Robson is the preferred method of choice, as it is less time consuming and easy to administer compared with the gratings method. However even the Pelli-Robson test is sometimes considered time consuming or complex with regard to size of the test chart, working distance and special illumination needed. To overcome these issues the Mars Letter Contrast Sensitivity Test was developed to provide a small-format portable letter CS chart to measure spatial CS at peak sensitivity (figure 8). The Mars Letter Contrast Sensitivity Test has reasonable to good agreement with the Pelli-Robson chart and good repeatability.

Figure 8. Chart of the Mars Letter Contrast Sensitivity test. Figure courtesy of A. Arditi. The image is uncalibrated and does not show true contrast.
Another way of measuring CS is to measure flicker sensitivity or temporal CS by presenting a flicker stimulus to the eye. The concept of temporal CS is to better isolate neural function as temporal CS is not influenced by the optics of the eye. Although the usefulness of temporal CS has been shown for detecting and monitoring ocular diseases such as glaucoma, optic neuropathy, age-related maculopathy, and retinitis pigmentosa, it is not a widely used clinical test. There are several clinical devices described for measuring temporal CS, however these tests have often not been standardised and are unique to each specific research study. Recently a temporal CS test was developed by making an adaptation to the C-Quant device which was originally intended to measure straylight. With this temporal CS test the foveal (<2°) retinal deficiencies are assessed.

It is well documented that spatial CS is associated with reading speed, however the association between temporal CS and reading speed has not yet been described. Comparison between the role of spatial CS (optical and neural) and temporal CS (solely neural) in the association with reading speed may provide insight into how visual tasks (such as reading) are related to primary optical or neural or both effects.

**FACTORS INFLUENCING READING PERFORMANCE**

Reading performance is of interest to many groups of researchers in the fields of ophthalmology, optometry, vision science and in education or behavioural studies. Reading is a highly complex task involving perceptual processes (letter and word recognition), oculomotor control (eye movements along lines and up and down the page), and higher cognitive aspects of comprehension (use of semantic
and syntactic cues).\textsuperscript{27,83} It is difficult to predict how these factors influence reading performance. For example distance and near VA measured with single optotype tests are poor predictors for the actual reading performance.\textsuperscript{84-86} Therefore rather than relying on predictions from visual function testing, the best way to assess the impact of visual and non-visual factors on reading is to measure reading performance directly with a reading performance test.

Reading speed in words per minute has been used to study both educational and perceptual aspects of reading and has proven to be reproducible and sensitive to visual factors.\textsuperscript{27} Text properties and text content can be controlled for but it is well known that reading speed is influenced by patient characteristics as well. Several visual parameters (VA, CS, field of view such as scotomata) and non-visual parameters (age, education level, linguistic factors) have been reported to influence the reading process. Measurements of reading speed can be influenced by these individual variations. For example educational level and regular reading practice seem to be of significant influence on reading performance. Participants who received a higher level of education have been reported to read significantly faster and to make fewer reading errors.\textsuperscript{87-90}

Especially in educational research there are many studies on how reading performance is influenced by non-visual parameters such as person characteristics; e.g. reading habits, age, education level, practice effects, or linguistic factors and type of reading materials.\textsuperscript{91-93} In the field of ophthalmology, optometry and vision science there are several studies on how visual and non-visual parameters influence reading performance in low vision subjects as well,\textsuperscript{94-96} however there are just a few studies which have investigated these aspects in normally sighted persons.\textsuperscript{97,98} Despite the known influence of individual variation in patient characteristics on reading performance, it is often neglected in ophthalmic practice and research. In clinical practice there are restrictions in terms of time for the routine eye examination. It would therefore be helpful to identify those variables that are most relevant and easy to administer in the assessment of functional vision performance. Depending on the research question, certain variables can be included in the visual function assessment. Including relevant patient related characteristics that influence functional vision performance will help in the interpretation of results and comparison between studies.
AIM AND OUTLINE OF THE THESIS

The goal of this thesis is to contribute to understanding the psychophysical properties of continuous text reading tests and different types of CS tests. Five continuous text reading tests available in the Dutch language were analysed as were spatial and temporal CS tests.

The first section of the thesis gives an overview of measurement properties of available continuous reading performance tests and of tests that are available in the Dutch language, and evaluates variables influencing reading performance on these tests:

- In Chapter 2 an overview of the literature on available continuous text reading tests is provided and the measurement properties of these tests are described. A literature search was performed and subsequently, information on design and content of reading tests, study design and measurement properties were extracted using consensus-based standards for the selection of health measurement instruments.
- In Chapter 3 the reliability and equality of sentences and paragraphs of five (un-) standardised Dutch reading tests are investigated in a sample of normally sighted adults of various ages. The relative difficulty of sentences and paragraphs all in the same print size were evaluated with reading speed and mistakes as important outcomes.
- In Chapter 4 the norm scores, precision, agreement and feasibility of the five Dutch continuous text reading tests are evaluated in normally sighted and visually impaired participants.
- In Chapter 5 various visual and non-visual variables and their association with reading performance in normally sighted subjects are given. For each of the variables (distance and near VA, CS, straylight, age, sex, educational level, habitual reading hours and reading affinity), the association with reading performance was investigated.

The next section focuses specifically on the role of CS on reading performance and the reliability analysis of two CS tests. This section has the following chapters:

- In Chapter 6 insight into primary factors of CS and their association with reading performance is given. In addition the precision of spatial and temporal CS tests was assessed in a sample of normally sighted adults of various ages.
- In Chapter 7 the role of primary factors of CS in the reduction of reading capacity in visually impaired patients with macular disease is described. In addition, the precision of spatial and temporal CS tests was assessed.

The final part of this thesis consists of a summary and discussion of the outcomes of these chapters, the consequences for both clinical practice and research and recommendations for future research. The thesis is concluded with a summary in the Dutch language.
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