The DEM Test, Visagraph Eye Movement Recordings and Reading Ability in Children

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Short tile: Children's Reading Eye Movements and Reading Scores

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ABSTRACT

Purpose. To determine how Developmental Eye Movement (DEM) test results relate to reading eye movement patterns recorded with the Visagraph in visually normal children, and whether DEM results and recorded eye movement patterns relate to standardized reading achievement scores.

Methods. Fifty-nine school-age children (age = 9.7 ± 0.6y) completed the DEM test and had eye movements recorded with the Visagraph III test while reading for comprehension. Monocular visual acuity in each eye and random dot stereoacuity were measured and standardized scores on independently administered reading comprehension tests (Reading Progress Test) were obtained.

Results. Children with slower DEM horizontal adjusted times tended to have slower reading rates with the Visagraph (r = -0.547); those with slower DEM vertical adjusted times tended to have slower reading rates with the Visagraph (r = -0.414). While a significant correlation was also found between DEM Ratio and Visagraph reading rate (r = -0.368), the strength of the relationship was less than that between DEM Horizontal time and reading rate. DEM outcome scores were not significantly associated with Reading Progress Test scores. When the relative contribution of reading ability and DEM scores was accounted for in multivariate analysis, DEM outcomes did not significantly associate with reading rate. Reading Progress Test scores associated with Visagraph outcomes of duration of fixations (r = -0.403) and calculated reading rate (r = 0.366), but not with DEM outcomes.

Conclusions. DEM outcomes can identify children whose Visagraph recorded eye movement patterns show slow reading rates, however, when reading ability is accounted for, DEM outcomes are a poor predictor of reading rate. Visagraph outcomes duration of fixation and reading rate relate to standardized reading achievement scores, however DEM results do not.

Keywords: reading eye movements; visagraph; DEM

The optometric management of vision problems related to learning outcomes in children includes clinical assessment of visual acuity, refractive error and binocular vision status, plus assessment of the oculomotor system, with the aim of identifying and addressing vision problems that may interfere with the learning process. [1] Methods of evaluating oculomotor performance range in complexity from gross observation of pursuit and saccadic eye movements through to indirect measures of eye movements (such as the Developmental Eye Movement (DEM) test), to more complex direct measures of eye movements with infra-red recording systems.[2]

In optometric practice the method most frequently used to assess eye movements is observation and grading of fixation stability, pursuit and saccadic eye movements, where the smoothness and accuracy of these movements are rated on a scale from 1 to 4.[2] Normative data have been provided for some of these grading scales, including the North Eastern State University College of Optometry Oculomotor Test (NSUCO) and the Southern California College of Optometry (SCCO) rating system.[3] However, while the advantages of grading scales are that they are simple to administer and require no special equipment, their reliability, repeatability and ability to quantify clinical observations of eye movements has been questioned.[2, 3]

Other clinical approaches to evaluating eye movements involve the indirect assessment of saccadic eye movements during tasks that simulate reading. Some of these tests include the Pierce Saccadic Test, the King-Devick Saccadic Test and the DEM Test.[3] These tests share a similar design, with the patient being required to name a series of single digits arranged in rows as quickly as possible, without using a finger or pointer as a guide. The time taken to report the digits and the number of errors made are compared to normative data tables. Of these indirect tests of eye movements, clinically the DEM test is the most frequently used; it specifically measures the time taken to name numbers arranged irregularly in horizontal rows (horizontal time), and the time taken to name numbers arranged in vertical columns (vertical time), a measure of rapid automatized naming (RAN). RAN is the time it takes individuals to name aloud objects, pictures, colors, or symbols (letters or digits) as quickly as they can. Variations in rapid automatized naming time in children provide a strong predictor of their later ability to read, and does so independently of other predictors such as phonological awareness, verbal IQ, and existing reading skills.[4] The DEM Ratio, calculated by dividing the time taken to name the 80 numbers presented in horizontal rows by the time taken to name the 80 numbers presented in vertical columns, is intended to provide a measure of saccadic eye movements that factors out RAN.[5] The DEM is considered to be the best of the clinical indirect methods for evaluating saccadic eye movements because the test design aims to account for automaticity in number-naming skills.[3] By calculating the ratio between horizontal time and vertical time the variability in the rate at which children can automatically name numbers aloud is factored out.

While the DEM test was originally developed in the late 1980's to provide a simple way to assess saccadic eye movements related to reading in school-age children,[6] Ayton et al.[7] recently questioned its validity as an index of saccadic eye movements. Their study failed to find a significant relationship between DEM outcomes and objectively measured infra-red recordings of saccadic latency, gain, peak velocity or accuracy.[7]

The DEM is relatively inexpensive, easy to obtain and simple to use, however it is not clear how DEM outcome measures relate to the pattern of children's eye movements made during reading for comprehension. Given the widespread use of the DEM as a clinical measure of eye movements and the recommendation for its use in the optometric evaluation of children with learning-related problems,[1] it is important to have a clearer understanding of the relationship between DEM measures and direct measures of oculomotor function. It is also important to determine how these clinical eye movement measures relate to standardized reading test scores.

The Visagraph III Eye Movement recording system (Taylor Associates, New York) has been identified as one of the best clinical methods for direct eye movement recording,[2, 3] and has been commercially available for clinical use for over a decade. The Visagraph uses goggles containing infra-red sensors to record eye movements during reading, which are then described by a report that counts the number of fixations, regressions, return-sweep saccades, span of recognition, fixation duration and reading rate. An example of a recording is shown in Figure 1 and an example of a report is given in Figure 2. In the report fixations/100 words refer to the number of stationary periods between left-to-right progressive saccades of 1 to 2 degrees, while regressions/100 words refer to the number of times the eye movements are directed from right-to-left by "backward" saccades during reading. In established readers, about ten to fifteen percent of saccades made during reading are regressions, while children learning to read and poor readers make a larger number of regressions and have prolonged fixation durations.[8] However, when given material appropriate for their reading level, the overall reading eye movement pattern of inexperienced or poor readers tends to normalize, suggesting that the abnormal reading eye movement pattern had reflected difficulty with cognitive processing of the reading material.[8] Return-sweep saccades are the large right-to-left, slightly oblique saccadic eye movement that shift the eyes from near the end of one line to near the beginning of the next line of text and are typically 12 to 20 degrees in angular extent, with saccadic durations of 40 to 54 msec.[8]

In this study we investigated how the outcome measures of the DEM relate to the pattern of eye movements recorded with the Visagraph during reading for comprehension in children with normal visual development, and we also examined how these clinical measures of oculomotor function related to academic outcomes assessed by scores on standardized tests of reading.

METHODS

Participants

Visually normal participants (n=59; age = 9.7 ± 0.6y) were recruited from grades 4 and 5 of a local primary (elementary) school via a letter sent home to parents, which outlined the purpose of the study; 60% of invited students were granted parental consent to participate. Children recruited for this study also formed part of a control group for a study of motor and psychosocial skills in amblyopic children, the results of which have been published elsewhere.[9-11] For inclusion in the study, written information was obtained from parents that the child had no known neurological or ocular disorder (other than refractive error) and was carried in full-term pregnancy. All met the criteria of normal visual development with better than 0.1 logMAR VA in each eye and at least 60 seconds of arc stereoacuity.

Assessment of visual acuity and stereoacuity, fine motor skills, perceived self esteem and the DEM took about 45 minutes per subject and were completed within an initial test session by all participants. Infra-red recording of eye movements during reading for comprehension were made with the Visagraph III at a second session and took about 20 minutes per subject to complete. All data were collected within a one month period. Fifty-seven children had standardized tests of reading with the Reading Progress Test (RPT) conducted by the usual classroom teacher in class time at the start of the school year, two months prior to participation in the current study (two students were absent from the school on the day of testing).

All participants were given a full explanation of the experimental procedures and the option to withdraw from the study at any time was explained to both parent and child. Written informed consent for participation in the experimental procedures and for access to educational information from school records was obtained from the parent prior to participation in the study. The study was conducted in accordance with the requirements of the Queensland University of Technology Human Research Ethics Committee and all protocols concurred with the guidelines of the Declaration of Helsinki.

Vision Assessment

Visual acuity was measured using a 3 metre Bailey-Lovie logMAR letter chart while the child wore their habitual refractive correction (if any). A screening/threshold procedure was used which was based on the Amblyopia Treatment Study VA protocol.[12] The child read the first letter of each row from the top of the logMAR chart until an error was made (screening). The child was then redirected to two rows above the screening error row and asked to attempt each letter until four incorrect responses were given (threshold). The resultant monocular VA for each eye was scored on a letter by letter basis. The level of binocular function was assessed with the Randot Preschool Stereoacuity test.[13, 14]

Reading Proficiency

The level of reading proficiency of the children was determined from outcome scores on standardized tests of reading performance, the Reading Progress Test (RPT).[15] The RPT is a series of seven tests for children aged 5 to 11 years and has high repeatability and validity.[15] Each test has cross-sectional norms based on Australian schools which give standardized scores for the interpretation of individual scores relative to the expected performance standards of students at the same school year level. The tests are made up of three main types of comprehension question: (1) identifying the meaning of individual words, (2) selecting the correct answer from a number of choices after reading a short story, non-fiction passage or poem, and (3) choosing, or supplying, missing words in a short story or non-fiction passage. The children work through the tests at their own pace after an initial explanation by the teacher, and generally require 45-50 minutes to complete the tests.[15] Raw scores were converted to standardized scores based upon Australian normative data of children at equivalent school grade level. Standardized scores of 71 to 88 suggest reading proficiency that is below average for grade level (less than 23rd percentile); scores between 89 and 111 indicate average performance ability; and scores between 112 and 126 suggest above average reading proficiency (above 77th percentile).

Developmental Eye Movement Test

The DEM test consists of a pre-test of number knowledge followed by two subtests with 40 numbers arranged in vertical columns (Tests A and B), and a subtest with 80 irregularly spaced numbers arranged in 16 horizontal rows (Test C). Participants were asked to name aloud the single digit numbers as quickly and accurately as possible and the time taken to read aloud the 80 numbers in both the four vertical columns (vertical time) and the sixteen line horizontal array (horizontal time) was recorded. The number of omissions and addition errors was recorded and test times were adjusted for errors made. Both the vertical and horizontal times were adjusted to account for the number of digits actually named by the child. That is, if a child skipped a line of digits in the horizontal test and therefore called out five fewer digits than required the horizontal time would be lower than expected. One second was added to the recorded time for each digit skipped; similarly one second was deducted for each digit called twice.

A ratio was calculated by dividing the time taken to read the 80 numbers in the horizontal array (test card C) by the total time for reading the 80 numbers in vertical subsets (test cards A and B). The outcome measures from the DEM test included Vertical time, Horizontal time, Number of Errors and Ratio (horizontal time/vertical time). Results were converted to standard scores and percentile ranks based on published age-normative data for the test.[6]

Visagraph

Eye movements were recorded with the Visagraph III recording system that uses goggles containing infra-red sensors to capture eye position information while the child reads a short grade level appropriate paragraph of text. A comprehension test involving ten questions with "yes" or "no" responses was administered following the recording to confirm that the child was reading for comprehension, rather than merely scanning through the text. All participants in this study had more than 70% correct on the multiple choice comprehension test, and thus met the Visagraph criterion for data acceptance. Figure 1 shows an example of the traces produced by the

Visagraph. Traces for both right (red) and left (blue) eye are shown. The right tracing of each pair represent the original data and the left of each pair are the computed traces from which the measures in the Reading Report are derived.

The outcome measures calculated by the Visagraph software include the number of fixations per 100 words, number of regressions per 100 words, span of recognition, average duration of fixations and reading rate. The average span of recognition refers to the amount of print perceived and processed with each fixation. It is specified in units of “words” and calculated by dividing the number of words in the specified paragraph by the number of fixations. Fixation duration refers to the length of time that the eye pauses or remains fixated on a word. Reading rate refers to the number of words read per unit time and is specified in words per minute. As the data obtained for each eye separately differed by less than five percent, results for the right and left eye were averaged for analysis of Visagraph outcomes for both the reading and number naming tasks. From the Visagraph recordings a number of measures of the eye movement pattern made during the reading task are summarized in a Reading Report (an example is shown in Figure 2).

Statistical Analysis

Pearson’s correlation co-efficients (*r*) were calculated to test for associations between DEM measures and the eye movement parameters derived from the Visagraph reports (Statistical Package for the Social Sciences – SPSS V16). The contribution of DEM and Visagraph variables to reading ability was investigated using multivariate analysis. In view of the extensive testing performed on this data set, we have adopted the more conservative criterion for statistically significance of $p=0.01$ for the analysis.

RESULTS

Participants had a group mean visual acuity of -0.03 logMAR in the better eye and -0.02 logMAR in the worst eye, with an average inter-ocular difference in acuity of 0.013 logMAR. Two subjects wore spectacles to correct hyperopic refractive error. All but one of the 59 participants had at least 40 sec of arc stereoacuity as measured with the Randot stereoacuity test, with the remaining subject having stereoacuity of 60 sec of arc.

The mean, standard deviation and range of DEM test outcomes and Visagraph outcome measures of number of fixations, number of regressions, duration of fixation, span of recognition and reading rate are presented in Table 1. The mean, standard deviation and range of RPT raw scores and age standardized scores are also included in Table 1.

Relationship between DEM outcomes and Visagraph Recorded Eye Movement Patterns

There was a wide range of reading ability within the sample (Reading standard score range 70 to 126: the scores are standardized to a value of 100 for each age group, Table 1). While the sample was skewed towards high reading scores, there were five students whose reading scores were more than two standard deviations below the mean of the group.

Bivariate correlation analysis showed a number of significant associations between the DEM and Visagraph outcomes. Pearson correlation coefficients are presented in Table 2. Children with slower reading rates measured with the Visagraph tended to have slower DEM horizontal adjusted (*r* = -0.547; p<0.000) and Vertical adjusted times (*r* = -0.414; p=0.001). The bivariate correlation between Visagraph reading rate and DEM horizontal adjusted time is shown in Figure 3; approximately thirty percent of the variation in reading rate could be predicted from the DEM horizontal time. While significant correlation was also found between DEM Ratio and Visagraph reading rate (wpm) (*r* = -0.368; p=0.004) (Figure 4), the strength of the relationship is less than that between DEM Horizontal time and reading rate (*r* = -0.547; p<0.000) (Figure 3). Children with a higher DEM Ratio had slower reading rates recorded during reading for comprehension (*r* = -0.368; p=0.004); however, as shown in Figure 5, only 13 percent of the variation in Visagraph reading rate could be predicted from the DEM Ratio outcome. The number of errors recorded during the DEM test was not significantly associated with any of the measures of reading fluency recorded by the Visagraph.

Relationship between DEM and Visagraph Outcomes and Reading Progress Test Score

Bivariate correlation analysis showed no significant association between DEM outcome scores and Reading Progress Test scores (Table 3). Performance on the Reading Progress Test was significantly related to both the duration of fixation (*r* = -0.403; p=0.002) and reading rate (*r* = 0.366; p=0.005) derived from the Visagraph recording of eye movement patterns during reading for comprehension.

Determinants of Reading Speed when Controlling for Reading Ability

In this study significant correlations were found both between DEM outcomes and Visagraph reading rate (Table 2) and between the measure of reading ability (RPT score) and reading rate

(Table 3). Multiple regression analysis was used to determine the relative contributions of DEM outcomes and RPT scores to reading rate. That is, to examine the correlation between DEM outcomes and Visagraph reading rate when the reading ability of the child, as measured by RPT score, is taken into account.

The multiple regression analysis indicated that when the inter-relationships between these measures was taken into account, reading rate as measured by Visagraph was significantly associated with RPT score (t=3.192; p=0.002) but not with DEM outcome measures (Table 4). Multiple regression analysis of the association between Visagraph eye movement parameters and reading rate was precluded due to unacceptably high inter-correlation between the Visagraph outcomes (multicollinearity). The variance inflation factors (VIF) were greater than 10 indicating that the variables are so highly related that it is not possible to obtain reliable estimates of the individual regression coefficients. Multiple regression models with RPT scores as outcome measures and either DEM or Visagraph measures as input parameters each had high VIF values, and so could not be applied to this data set.

DISCUSSION

We examined the relationship between the outcome measures of the DEM and parameters derived from Visagraph III clinical recordings of reading eye movement patterns and determined how these measures relate to a standardized test of reading achievement (Reading Progress Test). Bivariate analysis demonstrated a number of significant relationships between these two tests which are used clinically to assess eye movements in children. The DEM outcome measure of horizontal adjusted time, rather than DEM Ratio, showed the most significant associations with

Visagraph outcome measures. While the associations found between DEM outcomes measures and the pattern of eye movements obtained from the Visagraph recording suggest that the DEM may be clinically useful to identify children with slow reading rates, the data suggest that it is the DEM timed outcomes, rather than the Ratio, that are the most useful measures in terms of their relationship to objective measures of eye movement patterns. When the relative contribution of reading ability and DEM scores to reading rate was accounted for in multivariate analysis, reading rate was associated with RPT score, but not to DEM outcomes.

DEM Ratio scores are calculated by dividing horizontal time by vertical time and the Ratio score is intended to differentiate between poor saccadic function and a primary rapid naming deficit.[16] High Ratio scores are the result of abnormally increased time to complete the horizontal test relative to the time taken to complete the vertical test and are reported by the DEM test authors to be characteristic of oculomotor dysfunction.[6] A high Ratio score is purported to indicate poor saccadic eye movement competence which, in turn, has been suggested to explain poor reading fluency.[6] If this were the case then we would expect that the Ratio outcome would have the strongest relationship with the pattern of eye movements recorded during reading. However, in our data, the DEM Ratio accounted for only thirteen percent of the variation in Visagraph measured reading rate and was a poorer predictor of reading rate than Horizontal time. Similarly, the DEM Ratio did not correlate with the number of fixations or regressions made during either the reading for comprehension. The number of errors made during the DEM, which generally resulted from skipping a row of numbers on the horizontal task, showed no correlation with infra-red recording of reading rates. The DEM examiner's booklet advises that error scores should not be taken into account in their clinical response categories and advises clinicians to consider error scores independently. Similarly, our data suggests that error scores alone are not useful for the identification of children with slower Visagraph recorded reading rates.

Correlation between DEM horizontal time and reading rate has been reported in dyslexic[17] and in poor readers[18]. In our study, when we controlled for the level of reading ability of the child using multiple regression analysis, DEM outcomes did not significantly associate with reading rate ($p>0.01$).

The findings of this study support the conclusions of Ayton et al.[7] and Ciuffreda[19] that the DEM does not evaluate basic components of eye movement control. Ayton et al.[7] recently reported no significant correlation between DEM test performance and quantitative eye movement parameters (gain, latency, asymptotic peak velocity and number of corrective saccades) in their sample of 158 children aged 8 to 11 years from a normal, unselected school-based cohort and advised that the DEM should not be described as an eye movement assessment tool.

We found that the duration of fixation and reading rate determined by Visagraph associated with scores achieved on the standardized test of reading achievement (RPT), however DEM outcome measures did not relate to this measure of reading ability. A number of studies suggest that poor outcomes on the DEM may identify children with poor academic performance.[6, 7, 20, 21] In the initial validation study of the DEM (n=58; mean age 8.9 years) reading scores on the Wide Range Achievement Test (WRAT) correlated with both DEM horizontal time (r=-0.78) and Ratio (r=-0.55)[6] and the timed outcomes of the DEM were found to predict performance on a test of academic achievement (n=60; age = 11y 7m ± 5m), the English Language Arts section of the

Test of New York State Standards.[20] Poor performance on the DEM test has also been reported to correlate with parental observation of reading errors, such as losing one's place or omitting words when reading or re-reading lines unknowingly [21] and, while their findings indicate that the DEM is not a valid measure of saccadic eye movements, Ayton et al.[7] also report that DEM outcome scores significantly correlate with a measure of reading age (Burt reading test) and with measures of visual processing speed (RSVP task).[7] However, our data suggest that DEM outcomes do not predict performance on standardized tests of reading ability that assess comprehension of read passages of text, while the Visagraph measures of duration of fixation and calculated reading rate were related to these standardized measures of reading ability.

In summary, slow DEM outcomes appear to identify children whose Visagraph recorded eye movement patterns show slow reading rate, however, DEM outcomes do not associate with results on independently administered tests of reading ability (RPT score). Clinicians need to be aware that, while the DEM can be used to identify children with poor automaticity in number naming, the DEM is not a measure of saccadic eye movements. The strongest bivariate correlation with RPT reading achievement score was found with Visagraph recorded duration of fixation, that is, the length of time that the eye movement pattern paused during a fixation. This suggests that the time taken to process the text information is controlling reading speed, rather than reading speed being limited by the mechanics of saccadic eye movement control. These findings support the argument that the cognitive aspects of reading, rather than the motor aspects, control reading rate when reading for comprehension.

A potential limitation of our study was that participants were not selected based upon their academic ability. Our sample had RPT standardized scores that ranged from 70 to 126, and was skewed towards higher RPT scores (Table 1). Four children in our sample had RPT standardized scores less than or equal to 88 suggesting reading proficiency that is below average for grade level (less than 23rd percentile). We plan future studies which will further explore recorded eye movement patterns in children from a broader range of academic ability, with particular regard to those children whose reading ability is below average for school grade level.

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Table 1. DEM and Visagraph outcome measures and Reading Progress Test scores.

	Outcome measure	Mean (Std. Deviation)	Range
Developmental Eye Movement Test (DEM) (n=59)	Vertical adjusted time (seconds)	40.4 (7.0)	29 - 65
	Horizontal adjusted time (seconds)	51.2 (11.1)	30 - 85
	Number of Errors	1.3 (2.9)	0 - 10
	Ratio Horizontal Time/Vertical Time	1.26 (0.17)	1.0 - 1.8
Visagraph Recording during silent reading for comprehension (n=59)	Average number of Fixations per 100 words	168 (37.3)	101.5 - 257
	Average number of Regressions per 100 words	29 (14)	5 - 74
	Average span of recognition	0.62 (0.14)	0.39 - 0.99
	Average duration of fixation (seconds)	0.29 (0.05)	0.22 - 0.46
	Average reading rate (words per minute)	130 (34)	70 - 231
Reading Progress Test (n=57)	Raw Score	27.91 (6.77)	11 - 38
	Standard Score	108.02 (12.99)	70 – 126

Table 2. Pearson correlation co-efficients calculated between DEM and Visagraph.

	Visagraph Silent reading for comprehension				
DEM Test	Number Fixations	Number Regressions	Span Recognition	Duration Fixation	Reading Rate (wpm)
Vertical Adjusted Time	.277 (0.033)	.301 (0.021)	-.296 (0.023)	.300 (0.021)	***-.414 (0.001)***
Horizontal Adjusted Time	***.407 (0.001)***	.263 (0.044)	***-.418 (0.001)***	***.355 (0.006)***	***-.547 (<0.001))***
Number of Errors	-.042 (0.750)	-.087 (0.512)	-.004 (0.974)	.247 (0.060)	-.138 (0.298)
Ratio (Vertical Time /Horz Time)	.317 (0.015)	.048 (0.720)	-.306 (0.018)	.184 (0.162)	***-.368 (0.004)***

Bold italics indicate correlation is significant at the 0.01 level.

Table 3. Pearson correlation co-efficients calculated between Reading Progress Test scores and DEM and Visagraph outcomes.

		Reading Progress Test Standard Score
Developmental Eye Movement Test Outcomes	Vertical Adjusted Time	-.015 (0.912)
	Horizontal Adjusted Time	-.048 (0.724)
	Number of Errors	.052 (0.702)
	Ratio (Vertical Time /Horz Time)	-.111 (0.411)
Visagraph recording Eye Movement Pattern Parameters	Number of Fixations	-.139 (0.302)
	Number of Regressions	.080 (0.556)
	Span of Recognition	.109 (0.420)
	Duration of Fixation	***-.403 (0.002)***
	Reading Rate (WPM)	***.366 (0.005)***

Bold Italics indicates correlation is significant at the 0.01 level (2-tailed).

Table 4. Multiple regression analysis of contributors to Reading Rate.

	Regression coefficient	t		Collinearity Statistics		
	B	Std. Error	Sig.		Tolerance	VIF
DEM Vertical Time (sec)	-.086	.902	-.095	.925	.324	3.089
DEM Horizontal Time (sec)	-1.516	.618	-2.454	.018	.298	3.352
DEM number of errors	.232	1.328	.174	.862	.879	1.138
RPT Score	1.754	.550	3.192	.002	.967	1.034

FIGURE LEGENDS

Figure 1. Original tracing for left eye (left column) and right eye (right column) from which Visagraph measures are derived. A color version of this figure is available online at www.optvissci.com.

Figure 2. Reading report generated by Visagraph.