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The Effect of microscope scale reticle design on variance of measurement

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THE EFFECT OF MICROSCOPE SCALE RETICLE DESIGN ON VARIANCE OF MEASUREMENT

by

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A thesis submitted in partial fulfillment of the requirements for the degree of Bachelor of Science in the School of Photographic Arts and Sciences in the College of Graphic Arts and Photography of the Rochester Institute of Technology

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ROCHESTER INSTITUTE OF TECHNOLOGY

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ABSTRACT

Little work has been documented regarding the design of optical instrument scale reticles. Reticle is the word used to describe both scales and crosshairs used in the eypiece of an optical instrument. An ergonomic (the relation of man to his working environment) experiment was performed in which thirteen different scale reticles were designed, manufactured and tested. The design parameters tested were scale spacing, line height, and line thickness. The testing consisted of thirty observers measuring a circular test object through a microscope with each scale reticles.

The results, taking into consideration both variance in measurement and observer comments, showed the following dimensions to be best. Scale spacing of 10.0 or 15.0 minutes of arc as subtended by the eye is best. Line heights of 20.0, 10.0, and 15.0 or, 50.0, 25.0, and 37.5 for major, minor and intermediate marks respectively are best. The best line thickness was determined to be 30 minutes of arc for major marks and baseline, minor and intermediate marks should be 2.0 and 2.5 minutes of arc respectively. Appendix C should be consulted for the dimensions of the other two paramters in use at the time the optimum for the third was being determined.

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to Mr. Gary Reif who supplied the idea for this project, his time, and guidance towards the success of this thesis.

A word of gratitude is in order for the Photographic Sciences Corporation, Webster, New York for the use of facilities and materials.

The author's fellow students deserve a thank you for participating in the observation tests. Certainly the thesis could not have been completed without their help.

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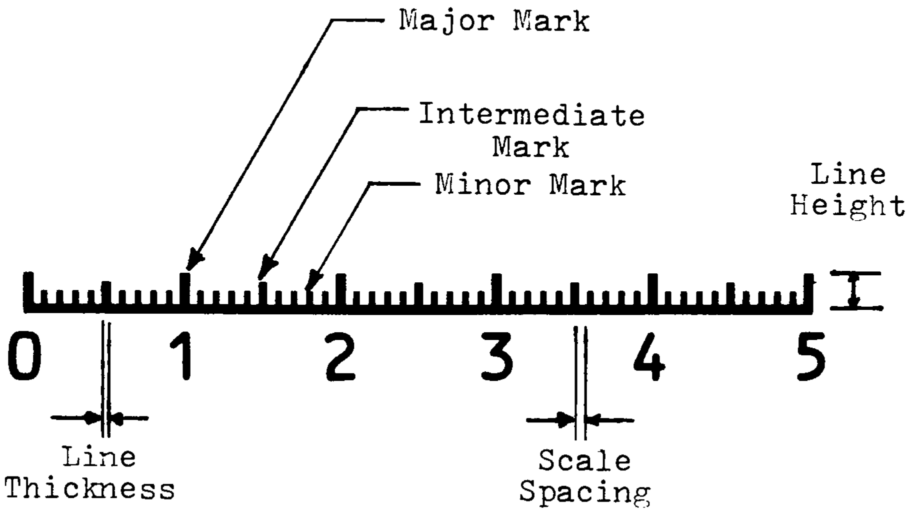
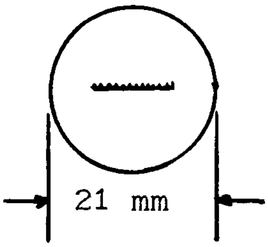


Figure 1. Scale Terminology



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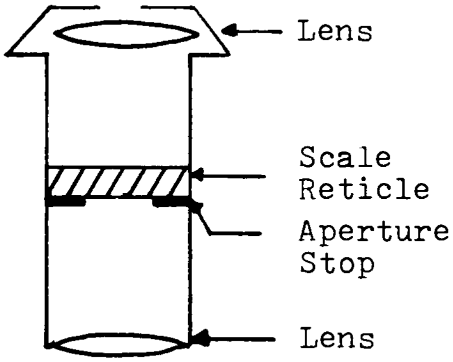

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I. INTRODUCTION

When one investigates the literature regarding reticles, he will find information on production methods,[1,2,3] but very little regarding the design of reticles. Reticle is the word used to describe both scales and crosshairs in the focus of the eyepiece of an optical instrument. In England the equivalent word graticule is used.

Reticles are used to determine (or aid in determining by serving as a reference) size, position, shape or distance of an object under observation. This project is concerned with which design attributes of a scale used in the eyepiece of an optical instrument will minimize the variability of measurements when used by a human observer. This experiment is therefore a study in ergonomics, the study of man in relation to his working environment.

Since the late 1950's, an increasing amount of attention has been given the area of ergonomics. Woodson[4] defines human engineering (ergonomics) as "the design of human tasks, man-machine systems, and specific items of man-operated equipment for the most effective accomplishment of the job, including displays for presenting information to the human senses . . ."

The objective of this experiment is to determine which scale spacing, line height, and line thickness for a scale used in the eyepiece of an optical instrument produces the least variance in measurement when used by a human observer. See Figure 1 for an illustration of terminology.

This will be the first time, to the author's knowledge, that specific research has been performed in the field of ergonomics regarding optical instrument scale reticles. Work has been done in the broader field of instrument displays such as pressure gauges, and aircraft instrumentation.[5] As exemplified below, this work further illustrates the need for research in the area of optical instrument scale reticle design.

Both McCormick[6] and Murrell[7] devote chapters of their books on ergonomics to visual displays. Murrell[7] defines a display as "devices which give information about an event or situation". Grether[8] performed a visual display test involving aircraft altimeter design; his results were surprising. He tested the accuracy of nine different designs, three of which were used in aircraft at the time, the other six were experimental types. He used two groups of observers for the experiment, 97 experienced United States Air Force pilots, and 79 male college students. He found that the design most commonly used had the least accuracy of the three designs in use at the time, and was ranked seventh in accuracy for all designs tested.

Although eyepiece reticles have been in existence since 1639,[9] knowing which design produces the least variance will not be known until ergonomic tests, similar to the altimeter experiment, are performed.

Authors who discuss visual displays usually give recommendations for designing scales. Unfortunately, in most cases, the authors do not agree among themselves. In *Ergonomics* Murrell contradicts himself on line thickness dimensions.[10] Literature recommendations were used as a starting point in designing the experimental scales, and can be found in Appendix A.

Below is a list of parameters Murrell gives as guidelines for designing scales. These recommendations were not contradicted by the other authors.

Number scale major marks in ones, twos, or fives (or decimal multiples of these numbers).[10]

One, three, or four minor marks may be used between each major mark, provided that the value of the minor marks fall into one of the three numbering systems recommended for the major marks.[11]

Interpolation of a scale space into fifths is best.[12]

There should not be less than five numbered divisions in a scale.[13]

Optimum numbers should have a thickness of stroke to height ratio of 1:6 to 1:8 for black on white. Ratio of height to width should be 2:1 to 0.77:1, and numbers should subtend a visual angle of 30 to 40 minutes of arc.[14]

Since these recommendations were consistent throughout the literature, they were used for designing the experimental scales where possible. The scope of this experiment was to test the parameters of scale spacing, line height and line thickness. This was because there was little agreement in the literature for the dimensions of these factors. Also, the dimensions which were given related to scales used on meters and gauges, not the small size needed for the eyepiece of an optical instrument.

II. EXPERIMENTAL

The experiment consisted of determining which range of dimensions for scale spacing, line height, and line thickness should be tested, then designing and manufacturing scale reticles with these dimensions. Thirty observers then measured a circular test object with a microscope equipped with an eyepiece in which the thirteen scale reticles were placed. Their data was recorded and analyzed. Below is a detailed explanation of the experimental procedure.

A. Research Layout Design for Scales

There are five different scales for each of the three test parameters: scale spacing, line height, and line thickness. This decision was based on two considerations, first, to provide a small difference in parameter dimensions so that there would not be wide gaps in the range of values being tested. Secondly, keep the number of reticles low enough so that observers do not become fatigued before they finish taking measurements. The experimental design requires that when testing one design parameter the dimensions for the other two parameters would remain constant at their assumed optimum value. This meant that the same scale could be used for testing the assumed optimum from each parameter. Therefore thirteen scale reticles were designed and tested.

Because no work has been published in the area of microscope scale reticle design, attention was turned to design guidelines for larger scales such as the type used in aircraft and pressure gauges. A detailed account of the pertinent data gathered from this literature search can be found in Appendix A. From this data the following values for each design parameter were decided upon.

Table 1. Values for Scale Spacing (in minutes of arc, measured from center to center of adjacent marks)

Design	Scale Spacing
A1	4.25
A2	7.50
A3*	10.00
A4	15.00
A5	20.00

* indicates assumed optimum

Table 2. Values for Line Height (in minutes of arc)

Design	Major Marks	Minor Marks	Intermediate Marks
B1	4.00	2.00	3.00
B2	8.00	4.00	6.00
B3*	20.00	10.00	15.00
B4	50.00	25.00	37.50
B5	100.00	50.00	75.00

* indicates assumed optimum

Table 3. Values for Line Thickness
(in minutes of arc)

Design	Major Marks	Minor Marks	Intermediate Marks	Baseline
C1	1.00	0.67	0.83	1.00
C2*	1.50	1.00	1.25	1.50
C3	3.00	2.00	2.50	3.00
C4	4.50	3.00	3.75	4.50
C5	6.00	4.00	5.00	6.00

* indicates assumed optimum

From a recommendation by Murrell,[15] the ratio of mark height to scale spacing was kept constant as follows: major mark to scale spacing 1:1, intermediate mark to scale spacing 0.75:1, and minor mark to scale spacing 0.50:1. This recommendation was followed for determining scale dimensions when testing line height and scale spacing.

When line thickness was varied the major marks and baseline were one and a half times as thick as the minor marks, and the intermediate marks were one and a quarter times as thick as the minor marks.

B. Manufacture of Reticles

The reticles were manufactured at Photographic Sciences Corporation, Webster, New York. Below is an outline and discussion of the production steps.

1. Design Artwork Sketches

Before artwork dimensions (artwork refers to the photo-plot, on film, of an enlarged scale which will be photographically reduced to produce the final reticle) could be determined, the magnification of the last lens in the optical system had to be calculated because this lens magnifies the reticle scale thereby affecting the angular size of the parameter dimensions as seen by the eye. A sample calculation and magnification values for the lenses used can be found in Appendix B. The slight differences in lens magnifications made no appreciable difference in the minutes of arc, as subtended by the eye, or the actual scale dimensions.

Artwork 44× times larger than the final reticle was used because only certain line widths could be produced using the photoplotter. With this magnification the widths needed for the final reticle could be accomplished using available photoplotter apertures. The reason for using a magnification of 44× is that this magnification yields very easily to a two step reduction, using available optics. Image quality and edge sharpness are increased at each reduction. A 2.2× followed by a 20× reduction were used to accomplish the needed 44× reduction.

Knowing the eyepiece lens magnification, and that a 44× artwork would be needed, artwork sketches, with dimensions, were drawn from the values determined from the literature search for scale spacing, line height, and line thickness. See Tables 1-3 for these values. The values were converted from minutes of arc to inches by dividing the minutes of arc by 60 minutes/degree, taking the tangent of this angle, multiplying by a viewing distance of ten inches, and dividing by the lens magnification. The answer was in inches and needed only to be multiplied by 44 to get final artwork dimensions.

2. Produce 44× Artwork of Scales

The dimensions from the artwork sketches were entered into a computer which controlled the movement of the exposing source on a photoplotter. In this method, a 44× artwork was produced for each scale design on Kodak LPF Precision Line Film.

OCR-B[16] numerals 0.246 inches high, with a stroke to height ratio of 1:8, were stripped on the 44× artwork. Every major mark was numbered consecutively starting at zero, except scales A1 and A2 where every other major mark was numbered because the small scale spacing did not permit every major mark to be numbered.

3. First Reduction

Using a Robertson Process Camera with a 610 mm APO Nikkor lens, the 44× artwork was reduced 2.2×. This reduction was made on Kodak LPF Precision Line Film, producing a negative. This piece of artwork, now 20 times larger than the final scale, was contact printed onto Kodak LPF Precision Line Film which produced a positive black scale on a clear background. This positive was placed in the center of a ring 420 millimeters in diameter (21 millimeters is the desired diameter of the reticle) and contact printed on Kodak LPF Precision Line Film, producing a negative which was opaqued to remove residual spots.

4. Final Reduction

Using the same Robertson Process Camera this time with a 114 mm Tropel Custom lens (diffraction limited at f/2.8, 550 nm) the 20× artwork (negative scale with the ring around it) was reduced 20× onto a two inch square Kodak High Resolution Plate, Type 1A. The resolution of this plate is above 2000 lines per millimeter.[17] The photoplate was then ground to a 21 millimeter diameter. Actual dimensions in millimeters of the final scale reticles can be found in Appendix D.

The test object which would be measured by the observers, was a circle 1.25 millimeters in diameter. This circle was produced by photoreduction onto a Kodak PFO glass photoplate.

C. Microscope

The microscope used was an Olympus Research Microscope Model FHA. The instrument was set up to produce a Kohler illumination.[18] An Olympus 4× objective (NA 0.1) and Bausch and Lomb Huygens type 10× eyepieces were used. The Bausch and Lomb eyepieces were used because they allowed for easy access to the reticles, and eight of them were available. Thirteen scale reticles were tested; this meant that five of the eyepieces each had a pair of reticles which used it. Each reticle was used in only one eyepiece.

Although this is a binocular microscope it was used as a monocular microscope for testing the scale reticles. Only the right side observation tube was used for the experiment. The diopter adjustment ring was turned all the way clockwise, and the interpupillary distance was set at 64. No filters were used in the light path. The voltage regulator was set at 4.25 volts throughout the experiment. The auxiliary lens shifting lever was placed in the low position, for use with the 4× objective. The condenser had a numerical aperture of 1.25; the aperture iris control ring was set at 12.

Test objective positioning could be facilitated by horizontal and vertical movement control knobs which moved the specimen holder across the stage.

D. Observer Testing

Thirty observers measured the test object with each of the thirteen scale reticles. The observers were instructed orally using the instructions for observers outline found on page 12. Explanations for these steps are given below.

INSTRUCTIONS FOR OBSERVERS

** If any instructions are unclear to you, ask for an explanation

1. Get your eyesight tested for whichever eye you will use during the experiment. You must use the same eye throughout the experiment.

2. Check and see that the number of the reticle you are viewing corresponds to the number of the reticle on the score sheet.

3. Take as much time as you like for measuring targets.

4. Turn entire eyepiece tube to level scale, and push eyepiece into tube. If needed, turn top lens of eyepiece to focus the scale reticle to your eye.

5. Focus microscope on the target circle.

6. The target circle may be positioned in relation to the scale by turning the horizontal and vertical control knobs located on the right side of the microscope stage.

7. Measure the <u>DIAMETER</u> of the target circle to the nearest fifth of a scale division. Interpolate into fifths, this means divide the smallest scale spacing into fifths by your eye. If the edge of the circle came at the first fifth it would be measured as .2, the second fifth as .4 and so on. See sample scale.

8. Record measured diameter and comments on score sheet.

9. Repeat steps 2-8 for each of the 13 reticles.

10. Finish filling out score sheet.

1. Eyesight Testing

Eyesight was tested using a Snellen type eye chart. The observer was asked to read line eight at twenty feet. If he could read the line with no more than three mistakes he was considered to have 20/20 vision.[19] Only observers with 20/20 vision were used for the test. If glasses were worn to take the Snellen test it was required that they also be worn while making measurements with the scales.

2. Order of Testing

The scales were tested in a different random order for each observer. The observer was asked to check and make sure that the scale he was measuring corresponded to the number on his score sheet. Each scale had a letter-number combination below it for this purpose.

3. Observation Time

The observers were told they had as much time as they wanted for making the measurements. Total observation time for each observer was recorded so that an average observation time could be calculated. Many authors of ergonomic experiments feel that this is an important piece of data.

4. Reticle Position

Whichever scale reticle was being tested was dropped, emulsion side up, into its eyepiece where it came to rest against the aperture stop. The top lens was then replaced.

This eyepiece was then slid halfway down the observation tube, where the observer looked at the scale, and turned the eyepiece tube until the scale was horizontal, then slid the eyepiece in until it stopped. If needed, the observer was told he could turn the top lens of the eyepiece to focus the scale to his eye.

5. Focus Target

Observers were shown the location and use of the coarse and fine focusing knobs on the microscope. Observers were told that they may refocus at any time during the experiment.

6. Target positioning

The observers were shown how to use the horizontal and vertical control knobs, enabling them to position the target circle in relation to the scale. The observers were not told specifically where to line the circle up with the scale, this was left to their judgement.

7. Measurements

The observers were asked to measure the diameter of the target circle to the nearest fifth of a scale division. By using a sample scale, see Figure 1, the observers were shown that each scale mark equaled 0.1 units, and that interpolating the smallest scale spacing into fifths meant that each fifth would equal 0.02 units. The diameter of the target circle was approximately one half the total scale length.

8. Record Measured Diameter and Comments

The observers measured the target circle diameter with each of the scales and recorded their measurements on the observer score sheet (see Appendix E). They were also asked to comment on any factors which made the scale easy or difficult to use. It was suggested to them that these comments could include, but were not limited to, such factors as scale spacing, line height, and line thickness.

9. Finish Testing All Scales

Steps 2-8 were repeated for each of the thirteen scale reticles in the random order assigned that observer.

10. Complete Observer Score Sheet

After the observers had finished measuring the target circle with all the scale reticles, they were asked to answer the questions on the observer score sheet. At the beginning of the experiment, the observers were told that after they finished making measurements they would be shown a picture of all the scales they tested and asked to pick out which ones they found easiest to use. Their choice for easiest to use in each of the categories scale spacing, line height, line thickness, and easiest overall was recorded.

E. Measurement of Scales A1, A2, A3/B3/C2, A4 and A5

In order to compare variances and histograms, measurements from scales A1, A2, A3/B3/C2, A4 and A5 had to be converted to actual inches since the scale spacings are different. A 0.001 inch stage micrometer was used for this purpose. Dimensions for a 1.0 scale division for the scales are found in part C of the Results.

III. RESULTS

A. Format of Results

Each of the next thirteen pages contain the data collected from the observation tests for each scale. The following format is used for each scale.

1. A 20× reproduction of the scale is found at the top of the page. This helps the reader to visualize the scale under discussion.

2. Next is a histogram of the measurements made by the thirty observers with that scale. Measurements for scales A1, A2, A4 and A5 are reported in 10^{-2} inches, relative scale measurements are used for the other scales. A table of raw data can be found in Appendix E.

3. Any measurements made by the observer which were not interpolated to hundredths are listed below the histogram.

4. The number of good and bad comments made by the observers are recorded. This number is placed over thirty to remind the reader of the number of observers who could make comments. A sampling of the observers' comments are included in this section.

5. The number of observers who found the scale in question easiest to use of the five in its test parameter group, and easiest to use of all the scales tested are found in this section.

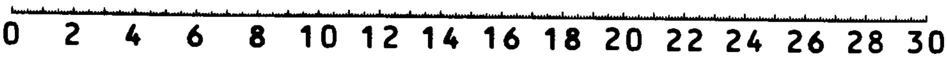

Figure 4. Scale A1
Testing Scale Spacing

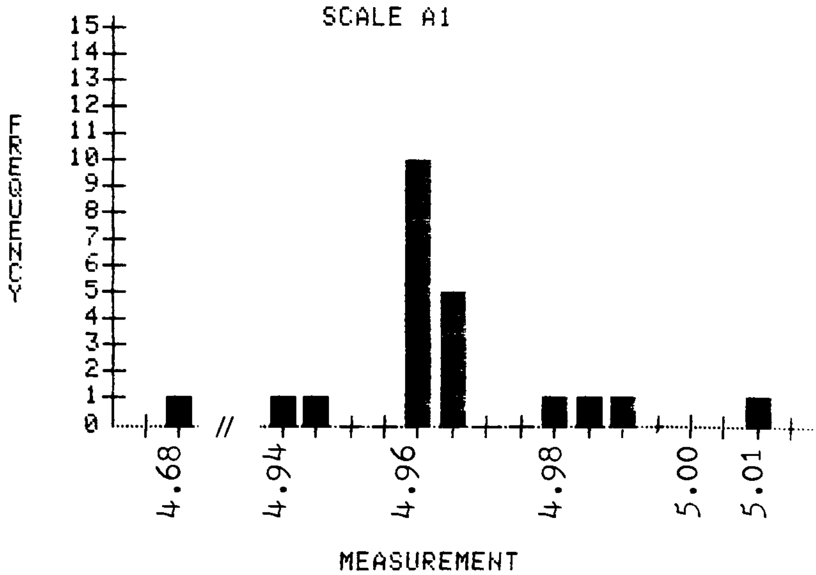

Figure 5. Histogram of Measurements
Made With Scale A1

Measurements Not Interpolated: 15.8, 15.8, 15.9, 16, 16.0, 16.0, 16.0, 16.1

Observers' Comments: Good 0/30 Bad 24/30

Sample of comments: lines too short, don't like increments going by two, could not interpolate between smallest spacing, very hard to read, scale spacing too small, difficult to see minor marks, unit divisions unclear, tiny

Judged Easiest to Use for Scale Spacing: 0

Judged Easiest to Use Overall: 0

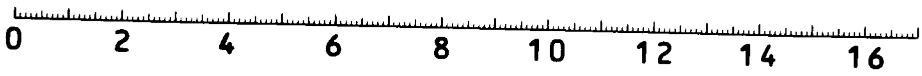

Figure 6. Scale A2
Testing Scale Spacing

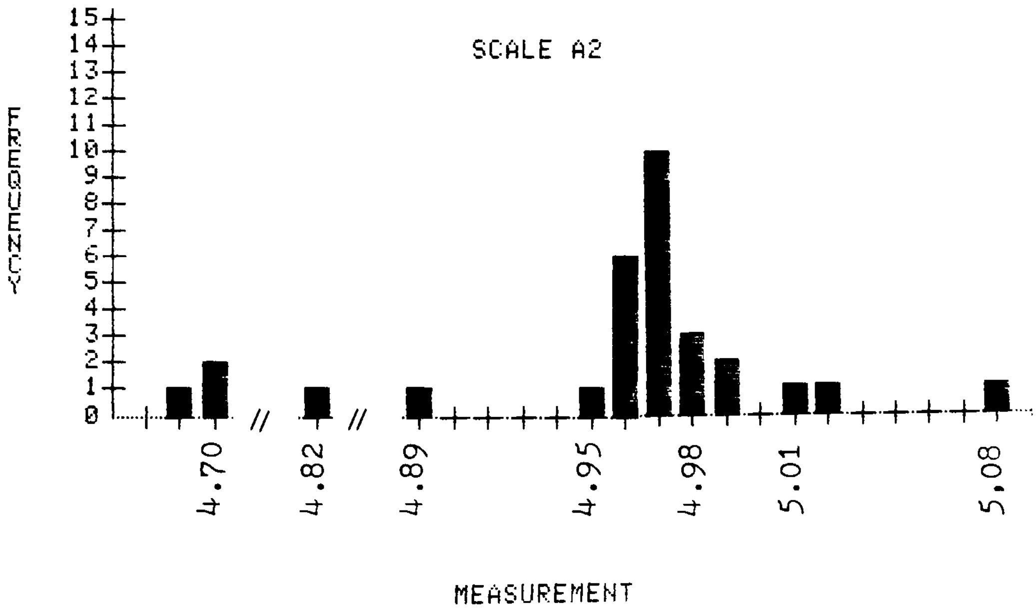

Figure 7. Histogram of Measurements
Made With Scale A2

Observers' Comments: Good 1/30 Bad 15/30

Sample of comments: difficult to interpolate, odd numbered lines should be more pronounced, don't like every other position numbered, lines too short, too many numbers missing, markings too fine, minor marks difficult to see, pretty good scale

Judged Easiest to Use for Scale Spacing: 2

Judged Easiest to Use Overall: 0

Figure 8. Scale A4
Testing Scale Spacing

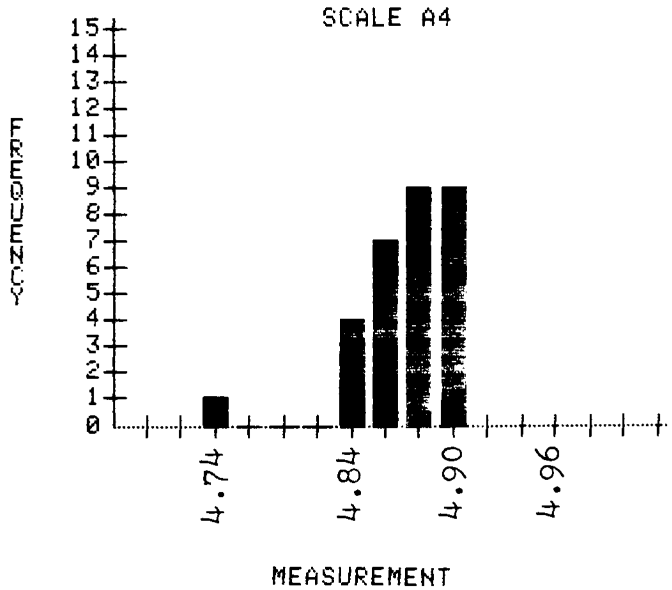

Figure 9. Histogram of Measurements
Made With Scale A4

Observers' Comments: Good 5/30 Bad 2/30

Sample of comments: height good, OK, good, easy to read markings, spacing just a little too close, spacing could be closer

Judged Best for Scale Spacing: 11

Judged Best Overall: 5

Figure 10. Scale A5
Testing Scale Spacing

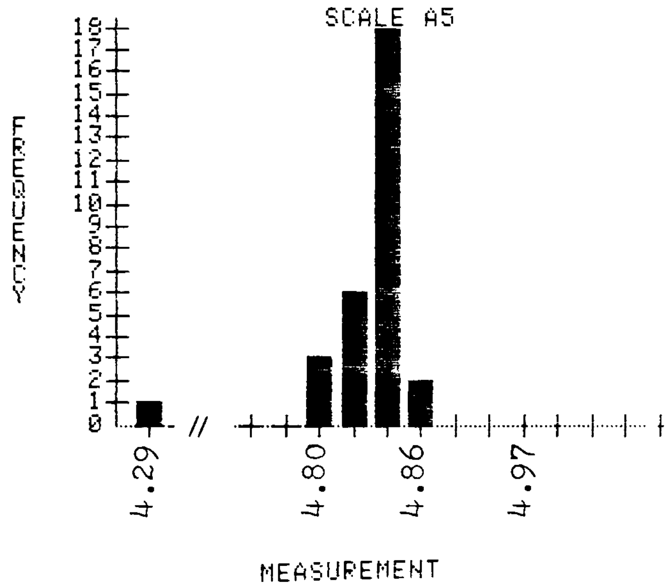

Figure 11. Histogram of Measurements
Made With Scale A5

Observers' Comments: Good 13/30 Bad 1/30

Sample of comments: height perfect, easy to interpolate, nice interval size, easy to read, nice, OK, good scale, spacing too wide

Judged Best for Scale Spacing: 14

Judged Best Overall: 4

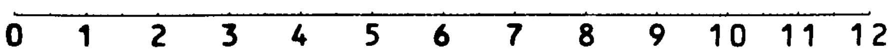

Figure 12. Scale B1
Testing Line Height

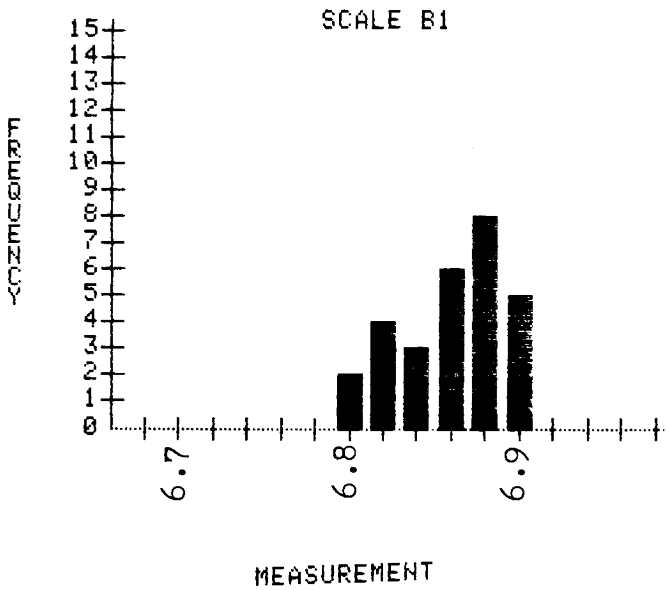

Figure 13. Histogram of Measurements
Made With Scale B1

Measurements Not Interpolated: 6.8, 6.7

Observers' Comments: Good 0/30 Bad 26/30

Sample of comments: line height too short, difficult to interpolate, almost unreadable, minor marks extremely fine, marks not varied enough, lines are hardly visible

Judged Best for Line Height: 0

Judged Best Overall: 0

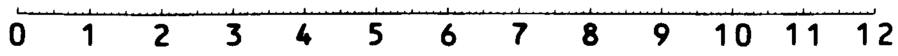

Figure 14. Scale B2
Testing Line Height

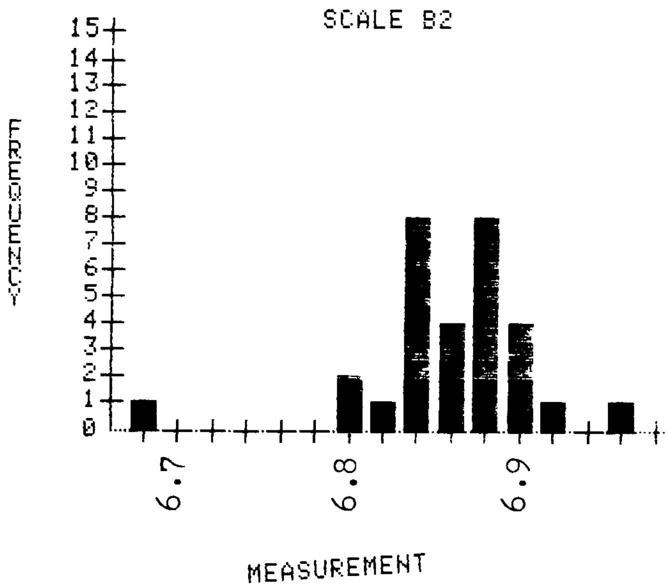

Figure 15. Histogram of Measurements
Made With Scale B2

Observers' Comments: Good 1/30 Bad 17/30

Sample of comments: line height too small (short), too thin, short lines difficult to separate intermediate marks hard to discern, hard to see minor marks, I like it

Judged Best for Line Height: 0

Judged Best Overall: 0

Figure 16. Scale B4
Testing Line Height

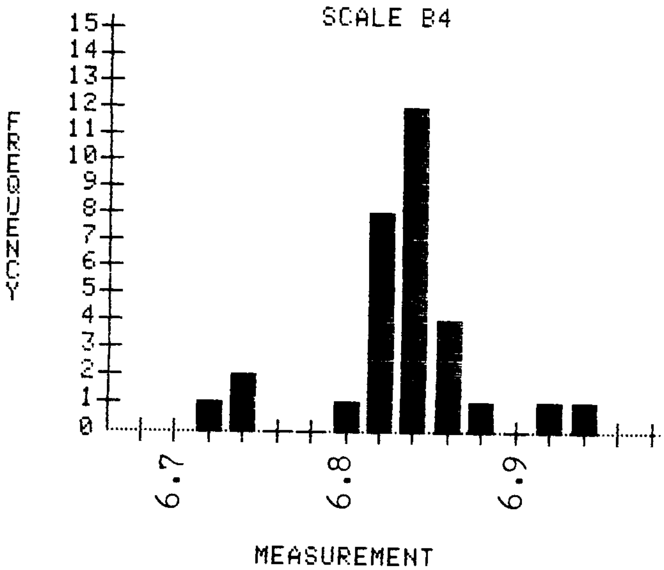

Figure 17. Histogram of Measurements
Made With Scale B4

Observers' Comments: Good 9/30 Bad 2/30

Sample of comments: the longer lines help in making measurements, pretty good, OK, easy to read, very easy to read markings, clear, good, height good, spacing could be closer

Judged Best for Line Height: 14

Judged Best Overall: 5

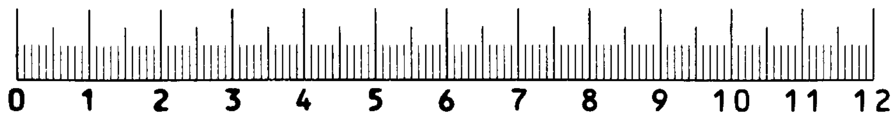

Figure 18. Scale B5
Testing Line Height

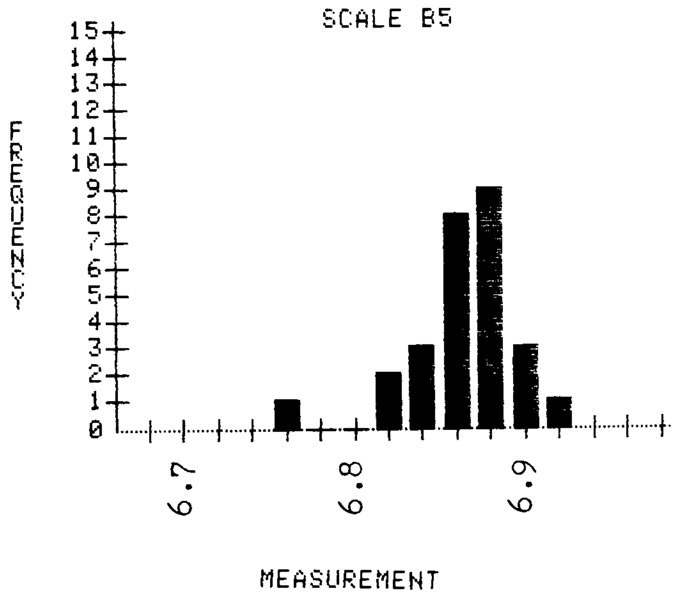

Figure 19. Histogram of Measurements
Made With Scale B5

Observers' Comments: Good 5/30 Bad 7/30

Sample of comments: long lines make it easy to read, long lines good for measuring circle, like tall major marks, OK, lines too high height is distracting, markings too close together, line height higher than necessary, tall scale not easy

Judged Best for Line Height: 3

Judged Best Overall: 2

Figure 20. Scale C1
Testing Line Thickness

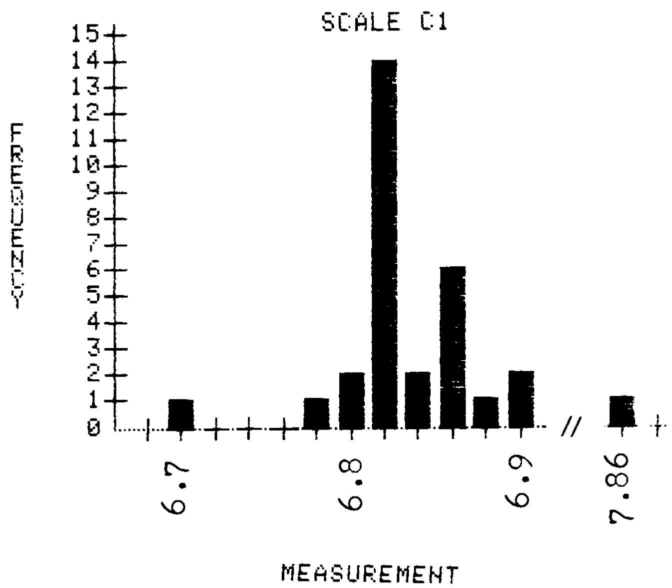

Figure 21. Histogram of Measurements
Made With Scale C1

Observers' Comments: Good 2/30 Bad 12/30

Sample of comments: too thin, minor marks a little light, lines too faint and thin, divisions small, good scale

Judged Best for Line Thickness: 1

Judged Best Overall: 1

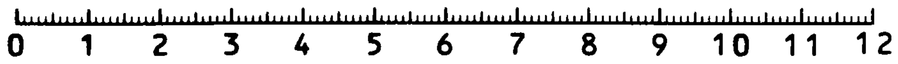

Figure 22. Scale C3
Testing Line Thickness

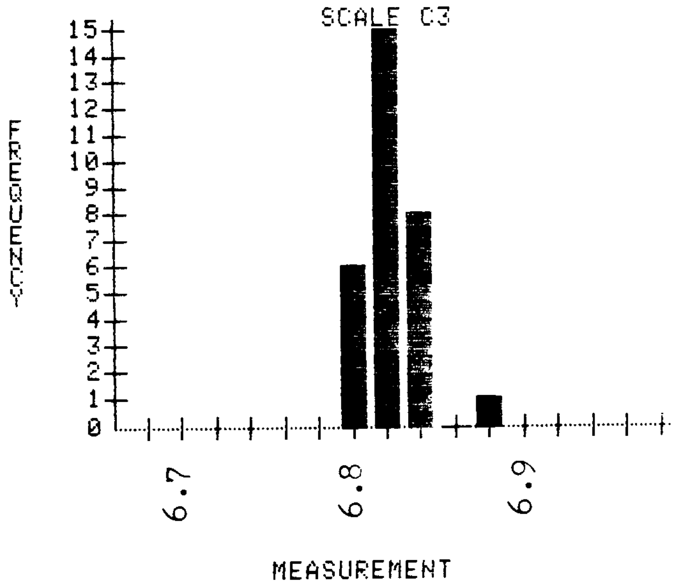

Figure 23. Histogram of Measurements
Made With Scale C3

Observers' Comments: Good 6/30 Bad 2/30

Sample of comments: pretty good scale, easy to read, OK, fine, need higher marks, marks too stubby

Judged Best for Line Thickness: 10

Judged Best Overall: 2

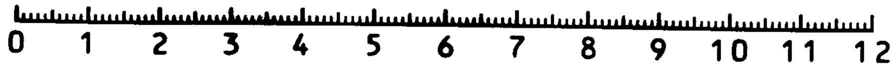

Figure 24. Scale C4
Testing Line Thickness

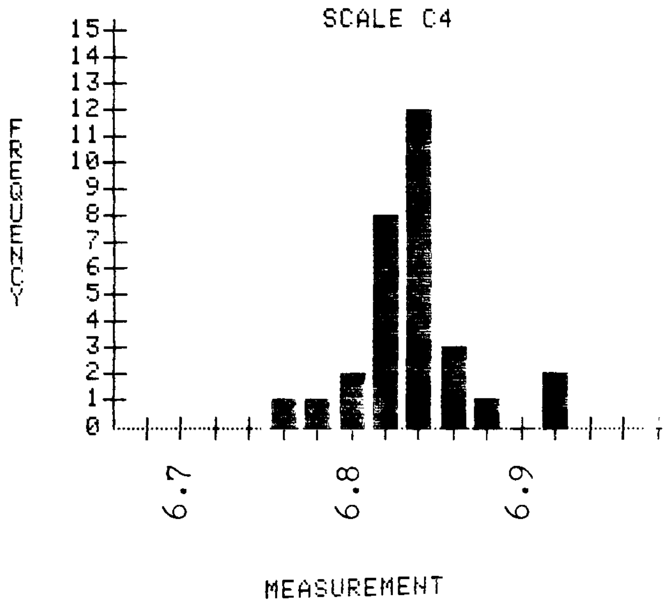

Figure 25. Histogram of Measurements
Made With Scale C4

Observers' Comments: Good 4/30 Bad 9/30

Sample of comments: lines too thick, lines too close together, not enough space between lines, minor marks a touch short, need higher marks, hard to interpolate hundredths, OK, good scale, easy to read

Judged Best for Line Thickness: 3

Judged Best Overall: 0

Figure 26. Scale C5
Testing Line Thickness

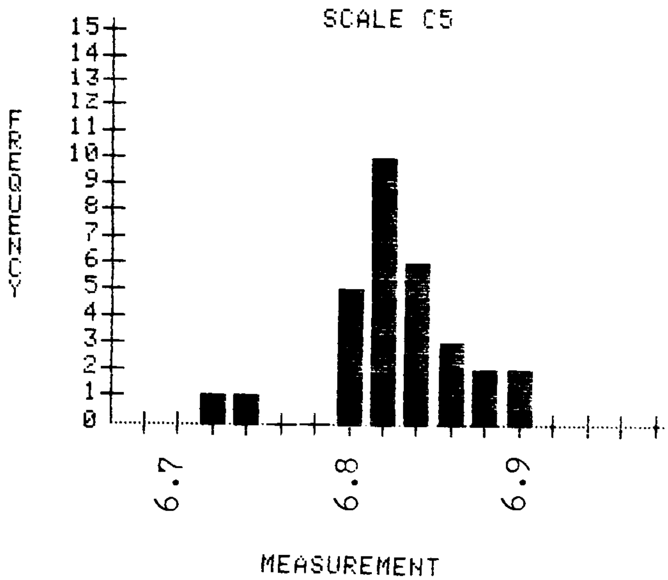

Figure 27. Histogram of Measurements
Made With Scale C5

Observers' Comments: Good 2/30 Bad 8/30

Sample of comments: lines too thick, tough on precise measurements, lines too short, not enough space between lines, major marks too thick other marks OK, thick marks make it difficult to interpolate, lines are easier to read because of contrast, good line thickness

Judged Best for Line Thickness: 2

Judged Best Overall: 0

Figure 28. Scale A3/B3/C2
Assumed Optimums

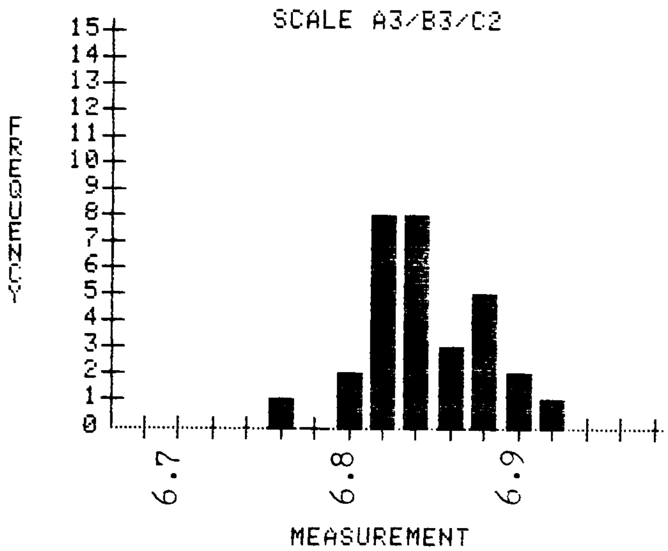

Figure 29. Histogram of Measurements
Made With Scale A3/B3/C2

Observers' Comments: Good 3/30 Bad 0/30

Sample of comments: good, pretty good scale easy to separate

Judged Best for Scale Spacing: 7

Judged Best for Line Height: 12

Judged Best for Line Thickness: 12

Judged Best Overall: 7

B. Observer Score Sheet Answers:

1. How many times a month do you use a microscope?
   0 = 16, 0-1 = 7, 1-5 = 2, more than 5 = 5

2. How many times a month do you use any optical instrument (including a microscope) which has a scale reticle?
   0 = 18, 0-1 = 4, 1-5 = 4, more than 5 = 4

3. What other experiences have you had using optical instruments equipped with a scale reticle?
   microdensitometer = 3
   measuring microscope = 4
   loupe = 2
   optical bench = 1
   aircraft instruments = 1

4. Average Total Observation Time: 19.26 minutes

C. Absolute Scale Dimensions (for experiment's optical system)

Table 4. Absolute Scale Dimensions

Scale	Absolute Dimension for 1.0 Scale Division
A1	3.1×10^{-3} inches
A2	5.4×10^{-3} inches
A4	10.7×10^{-3} inches
A5	14.2×10^{-3} inches
A3/B3/C2	7.1×10^{-3} inches

IV. DISCUSSION

A. Variance Tests

The variance in measurement for each of the scales was calculated and can be found below under the appropriate section. The variance values are listed in ascending order. An F test at 95% confidence level was used to compare the smallest variance to the others to determine it was significantly different. By dividing each variance one at a time by the smallest variance an "F calculated" value was obtained. If this value was greater than F critical (1.86 at 95% confidence level, 29,29 degrees of freedom) then the variances differed significantly. For simplicity, the scales will continue to be referred to as A1, A2, etc. For individual scale dimensions see Appendix C.

1. Scale Spacing

Table 5. Variance in Measurement for Scale Spacing

Scale	Variance
A3/B3/C2	6.104×10^{-8}
A4	1.100×10^{-7}
A1	3.161×10^{-7}
A2	8.552×10^{-7}
A5	1.085×10^{-6}

Comparison of scale A3/B3/C2 to scale A4 showed that they were not significantly different. An F test of scales A4 and A1 produced an F calculated value of 2.87, a significant difference. Since A3/B3/C2 was not significantly different from A4, both A3/B3/C2 and A4 are significantly different from A1, A2 and A5. Therefore, it is scales A3/B3/C2 and A4 which produce significantly lower variances when used by a human observer.

2. Line Height

Table 6. Variance in Measurement for Line Height

Scale	Variance
A3/B3/C2	1.205×10^{-3}
B5	1.754×10^{-3}
B1	1.858×10^{-3}
B4	1.972×10^{-3}
B2	2.331×10^{-3}

The variances which differed significantly from each other were scales A3/B3/C2 and scale B2. These were the lowest and highest variance values. This means that of the five scales tested for line height only scale B2 produces significantly higher variance than scale A3/B3/C2.

2. Line Thickness

Table 7. Variance in Measurement for Line Thickness

Scale	Variance
C3	3.060×10^{-4}
C4	1.087×10^{-3}
A3/B3/C2	1.205×10^{-3}
C5	1.506×10^{-3}
C1	3.674×10^{-2}

The F test calculation of the lowest variance, scale C3, versus the variances of the other scales showed that C3 produced significantly lower variance than the other designs tested for line thickness.

B. Observers' Comments and Ranking

The variance calculations and F test comparison of them is an excellent method of objectively ranking the scales and determining if there is a significant difference between them. However, because this is a study in ergonomics, the relationship of man to his working environment, observers' subjective comments and ranking must also be considered. Again each parameter will be discussed separately.

1. Scale Spacing

The observer found scales A1 and A2 to be of poor design because the scale spacing was too small, making interpolation into fifths difficult. There were seven people who could not interpolate scale A1 into fifths. They also indicated that they did not like only every other major mark numbered. Their first three choices for easiest to use were, A4, A5 and A3/B3/C2 with 11, 9, and 7 votes respectively. The observers indicated that these were easy to use because the wide scale spacing made interpolation easy. Many observers mentioned that they found it very distracting that scale A4 started at one instead of zero as the other scales do. This is consistent with Murrell's recommendation that scales begin with zero. The fact that the scale started at one instead of zero was pointed out to the observers before they made their measurement with it, and did not seem to affect measurement variability, see Figure 9.

2. Line Height

Although the F test comparison of variances showed that scales A3/B3/C2, B5, B1, and B4 were not significantly different, the observers definitely had a preference. Their ranking for easiest to use was, B4 and A3/B3/C2 well ahead of the others with 14 and 12 votes respectively. Scale B5 received three votes and scales B1 and C2 received zero votes each. More bad comments were given to scale B1 than any other scale. Two people could not interpolate scale B1 into fifths.

3. Line Thickness

Observers clearly indicated that they found scales A3/B3/C2 and C3 easier to use than any of the others in the line thickness group. They commented that the lines on scale C1 were too thin to be able to see them well, and that the line thicknesses for scales C4 and C5 were too thick, and crowded the space between them, making interpolation into fifths difficult.

The scale judged easiest to use overall was scale A3/B3/C2, the assumed optimum. There was a second place tie for easiest to use overall between scales A4 and B4.

C. Experimental Design

The experimental design, and testing procedure used were a valid method of obtaining the data necessary to achieve the objectives of the experiment. Actual field conditions were followed for microscope use, only observers with 20/20 vision participated, a large test sample (thirty people) was used, and both variance calculations and observer comments were used to determine the results. The fact that both variance calculations and observer comments were used to determine the results is an important point. What some observers felt was an asset others felt made the scale more difficult to use. An example of this is the tall lines on scale B5. Also, observers tended to make more negative comments than positive. There were a total of 124 bad comments compared to 51 good comments.

To the author's knowledge this is the first research done in this area. Any future work of this type should use the results of this experiment as its foundation.

V. CONCLUSION

Both variance rank and observer ranking were used to determine which dimension(s) from each parameter produced the "best" scale. Best is defined as the scale with the least variance, and most votes for easiest to use for that parameter if the scale with the least variance was not significantly better than the others of that parameter. Variance is ranked from lowest 1, to highest 5. Variance rank and the number of people who found that scale easiest to use for the parameter in question are listed next to each other in the tables for easy comparison. (**) means that this scale had significantly less variance than scales labeled (+) for that parameter. A box is placed around the best scale(s) in each parameter.

Table 8. Best Scale Spacing

Scale	Scale Spacing (in minutes of arc)	Variance Rank	Judged Easiest to Use
A1	4.25	3 +	0
A2	7.50	4 +	1
A3/B3/C2	10.00	1 **	7
A4	15.00	2 **	11
A5	20.00	5 +	9

The minor mark line height equaled the scale spacing, major marks were twice and intermediate marks were 1.5 times the scale spacing. Dimensions for line thickness can be found in Appendix C. Scales A3/B3/C2 and A4 with scale spacings of 10.00 and 15.00 minutes of arc respectively were determined best for scale spacing.

Table 9. Best Line Height

Scale	Minor Mark Line Height (in minutes of arc)	Variance Rank	Judged Easiest to Use
B1	2.00	3	0
B2	4.00	5 +	0
A3/B3/C2	10.00	1 **	12
B4	25.00	4	14
B5	50.00	2	3

The height of the major and intermediate marks were 2, and 1.5 times the minor mark height respectively. Dimensions for scale spacing and line thickness can be found in Appendix C. Scales A3/B3/C2 and B4 with minor mark line heights of 4.00 and 10.00 minutes of arc were determined best for line height. Their variances did not differ significantly from each other and approximately the same number of people judged them easiest to use.

Table 10. Best Line Thickness

Scale	Minor Mark Line Thickness (in minutes of arc)	Variance Rank	Judged Easiest to Use
C1	0.67	5 +	1
A3/B3/C2	1.00	3 +	13
C3	2.00	1 **	10
C4	3.00	2 +	3
C5	4.00	4 +	2

Major marks and baseline thicknesses were 1.5 times the minor mark thickness. Intermediate marks were 1.25 times the minor mark thickness. Dimensions for scale spacing and line height can be found in Appendix C. Scale C3, with a minor mark line thickness of 2.0 minutes of arc, was determined best because its variance was significantly less than the others of that parameter.

This thesis has set the groundwork for future pursuits concerning what effects optical instrumental scale design has on variance of measurement. It has significantly narrowed the range of values for each parameter which should be considered if future work in the area is performed. Researchers may turn their attention to other design factors. These would include; line height and line thickness ratios, different interpolations, measuring different shaped test objects, and testing the interaction between parameters.

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APPENDIX A

Scale spacing, line height and line thickness dimensions from literature.

Scale Spacing: measured center to center of adjoining lines (measured in minutes of arc)

Reference	Scale Spacing
Chapanis[20]	8.59
McCormick[21]	6.14 minimum 8.59 optimum 12.27 maximum
Murrell[22]	10.00
Murrell[23]	4.23 if interpolated into fifths 8.47 if interpolated into tenths

Line Height: (measured in minutes of arc)

Reference	Major Mark	Minor Mark	Intermediate Mark
Chapanis[20]	27.00	17.19	19.64
McCormick[24]	27.00	17.19	19.64
Reif[25]	20.00	10.00	15.00
Murrell[15]	10.00	5.00	7.50
Murrell[26]	3.41	1.71	---

APPENDIX A (continued)

Line Thickness: (measured in minutes of arc)

Reference	
Rheinberg[27]	0.33 too narrow for comfort 0.67 lower tolerable limit 2.00 upper limit
Chapanis[20]	major = 4.30 minor = 3.07 intermediate = 3.68
McCormick[24]	major = 4.30 minor = 3.07 intermediate = 3.68
Murrell[15]	between 5 and 10% of scale spacing for instruments with tolerance greater than 1% between 0.57 and 0.95 for instrument with tolerance greater than 1%
Murrell[26]	major = 0.0035 × reading distance minor = 0.0028 × reading distance

APPENDIX B

Calculation for Magnification of the Last Lens of the Optical System, (first lens of eyepiece)

An optical bench was used to find the relative positions of the first nodal point, and the first local point of the first (nearest the eye) lens of the eyepiece. The focal length was then calculated by subtracting the distance to the first focal point from the distance to the first nodal point. Magnification was calculated as, viewing distance (10 inches) divided by the focal length, plus one. Below is a list of the lenses used for each reticle scale, corresponding focal lengths, and magnifications.

Eyepiece	Used with Scale(s)	Focal Length	Magnification
1	A1 and A4	17.4 mm	15.60
2	A2 and A5	17.3 mm	15.68
3	B1	17.4 mm	15.60
4	B4	17.4 mm	15.60
5	B2 and B5	17.7 mm	15.35
6	C1 and C4	17.4 mm	15.60
7	C3 and C5	17.6 mm	15.43
8	A3/B3/C2	17.5 mm	15.51

APPENDIX C

Individual scale dimensions (in minutes of arc) based on eyepiece used

Scale Reticle	Scale Spacing	Line Height major	Line Height minor	Line Height inter.	Line Thickness major	Line Thickness minor	Line Thickness inter.	Line Thickness base
A1	4.25	8.50	4.25	6.375	1.5	1.0	1.25	1.5
A2	7.5	15.0	7.5	11.25	1.5	1.0	1.25	1.5
A4	15.0	30.0	15.0	22.5	1.5	1.0	1.25	1.5
A5	20.0	40.0	20.0	30.0	1.5	1.0	1.25	1.5
B1	10.0	4.0	2.0	3.0	1.5	1.0	1.25	1.5
B2	10.0	8.0	4.0	6.0	1.5	1.0	1.25	1.5
B4	10.0	50.0	25.0	37.5	1.5	1.0	1.25	1.5
B5	10.0	100.0	50.0	75.0	1.5	1.0	1.25	1.5
C1	10.0	20.0	10.0	15.0	1.0	0.667	0.883	1.0
C3	10.0	20.0	10.0	15.0	3.0	2.0	2.50	3.0
C4	10.0	20.0	10.0	15.0	4.5	3.0	3.75	4.5
C5	10.0	20.0	10.0	15.0	6.0	4.0	5.0	6.0
A3/B3/C2*	10.0	20.0	10.0	15.0	1.5	1.0	1.25	1.5

*assumed optimum

APPENDIX D

Dimensions measured from center to center of marks, in millimeters, of scale reticles. Measured on a Nikon comparator, Model 6C, at Photographic Sciences Corporation.

Scale	Length Overall	Length of 1.0 units	Length of 0.1 units
A1	6.072	0.203	0.020
A2	5.993	0.353	0.036
A4	7.113	0.711	0.071
A5	5.688	0.949	0.095
B1	5.688	0.474	0.047
B2	5.688	0.475	0.047
B4	5.688	0.474	0.047
B5	5.688	0.475	0.047
C1	5.691	0.475	0.047
C3	5.688	0.475	0.047
C4	5.688	0.474	0.047
C5	5.687	0.474	0.047
A3/B3/C2	5.687	0.474	0.046

APPENDIX E

OBSERVER SCORE SHEET

Name: ______________________________

Phone Number: ______________________

Eysight Score (for eye that will be used in test): __________

Questions:

1. How many times a month do you use a microscope?

   ____

2. How many times a month do you use any optical instrument (including a microscope) which has a scale reticle?

   ____

3. What other experiences have you had using optical instruments equipped with a scale reticle?

   ____

Any other comments you would like to make about any aspect of the experiment:

Observer's Signature: ______________________________

Date: ____________________

Thank you for helping with this experiment.

APPENDIX E (continued)

MEASUREMENTS:

Diameter of Target: interpolated to the nearest fifth

Comments: In this column describe any factors which made this scale difficult or easy to use. Including, but not limited to, such factrs as: scale spacing, line height, and line thickness.

Reticle	Diameter of Target	Comments

end time __________

start time __________

total time __________

APPENDIX F

Observers' Raw Data

SCALE

Observer	A1	A2	A4	A5	B1	B2	B4	B5
1	16.	9.18	4.58	3.42	6.88	6.88	6.82	6.88
2	16.02	9.20	4.56	3.42	6.88	6.84	6.84	6.88
3	16.0	9.18	4.58	3.40	6.88	6.68	6.82	6.84
4	16.00	9.20	4.56	3.40	6.86	6.88	6.82	6.86
5	16.1	8.68	4.54	3.38	6.8	6.84	6.82	6.82
6	16.0	8.92	4.43	3.42	6.86	6.80	6.74	6.74
7	16.00	9.28	4.52	3.40	6.82	6.84	6.82	6.96
8	16.10	8.70	4.52	3.42	6.86	6.88	6.84	6.86
9	16.02	9.20	4.58	3.42	6.90	6.88	6.86	6.88
10	15.10	8.70	4.56	3.42	6.90	6.90	6.84	6.86
11	16.20	9.22	4.58	3.42	6.90	6.90	6.88	6.90
12	16.0	9.20	4.56	3.40	6.82	6.86	6.84	6.84
13	16.02	9.24	4.58	3.02	6.82	6.86	6.84	6.88
14	16.00	9.40	4.54	3.42	6.88	6.88	6.84	6.88
15	16.00	9.20	4.58	3.40	6.88	6.84	6.84	6.90
16	16.02	9.20	4.56	3.42	6.86	6.88	6.86	6.86
17	16.02	9.20	4.56	3.42	6.88	6.88	6.86	6.84
18	15.8	9.30	4.56	3.44	6.80	6.84	6.84	6.86
19	15.92	9.22	4.54	3.42	6.86	6.84	6.72	6.86
20	16.00	9.24	4.58	3.42	6.90	6.90	6.92	6.88
21	16.12	9.22	4.56	3.42	6.86	6.92	6.84	6.96
22	16.00	9.18	4.54	3.42	6.80	6.96	6.82	6.86
23	15.8	9.16	4.52	3.42	6.7	6.84	6.74	6.88
24	16.00	9.18	4.54	3.42	6.88	6.84	6.82	6.88
25	16.00	9.18	4.54	3.42	6.88	6.84	6.82	6.88
26	15.94	9.18	4.58	3.40	6.84	6.86	6.82	6.86
27	15.9	9.06	4.52	3.38	6.84	6.82	6.80	6.78
28	16.00	9.20	4.56	3.42	6.88	6.86	6.86	6.84
29	16.08	9.18	4.58	3.44	6.82	6.88	6.94	6.92
30	16.00	9.20	4.54	3.38	6.84	6.80	6.84	6.82

APPENDIX F (continued)

Observers' Raw Data

SCALE

Observer	C1	C3	C4	C5	ABC	eyesight score		time (min)
1	6.82	6.82	6.84	6.82	6.82	20/20	L	20
2	6.82	6.82	6.84	6.84	6.84	20/20	R	--
3	6.86	6.80	6.76	6.86	6.82	20/20-1	R	17
4	6.86	6.84	6.84	6.82	6.88	20/20	R	19
5	6.82	6.84	6.78	6.84	6.84	20/20	R	20
6	6.70	6.82	6.84	6.72	6.82	20/20	R	18
7	6.82	6.82	6.92	6.80	6.82	20/20	L	--
8	6.86	6.82	6.84	6.82	6.86	20/20	R	21
9	6.82	6.84	6.84	6.82	6.84	20/20	R	18
10	7.86	6.82	6.86	6.82	6.88	20/20	L	19
11	6.86	6.84	6.84	6.84	6.88	20/20-1	L	--
12	6.82	6.80	6.82	6.86	6.84	20/20-1	R	28
13	6.82	6.80	6.86	6.82	6.88	20/20-1	L	25
14	6.82	6.82	6.82	6.80	6.82	20/20	R	25
15	6.82	6.80	6.90	6.86	6.86	20/20	L	12
16	6.82	6.82	6.82	6.82	6.86	20/20	L	25
17	6.84	6.84	6.84	6.88	6.84	20/20	R	24
18	6.90	6.84	6.84	6.90	6.88	20/20	L	17
19	6.82	6.80	6.82	6.82	6.82	20/20-3	R	20
20	6.90	6.88	6.92	6.90	6.90	20/20	R	20
21	6.88	6.82	6.82	6.88	6.90	20/20	R	20
22	6.86	6.84	6.86	6.80	6.82	20/20-1	R	21
23	6.82	6.82	6.84	6.74	6.76	20/20	R	23
24	6.82	6.82	6.84	6.84	6.84	20/20	R	19
25	6.80	6.82	6.82	6.84	6.84	20/20	L	13
26	6.80	6.82	6.82	6.80	6.80	20/20	R	20
27	6.86	6.84	6.84	6.82	6.80	20/20	L	20
28	6.84	6.82	6.82	6.82	6.84	20/20	R	14
29	6.82	6.82	6.88	6.84	6.92	20/20	R	14
30	6.78	6.80	6.80	6.80	6.82	20/20-2	L	15

R - Used Right Eye

L - Used Left Eye

VITA

David Rockafellow is a native Rochesterian. After completing his secondary education in the Greece Central School District, Rochester, New York, he entered the Photographic Science and Instrumentation program at RIT.

He has worked for the Photographic Technology Division of Eastman Kodak, in Rochester, for two summers while at RIT. At the time of this writing David and his fiancée, Cheryl McPherson, are considering employment offers from various firms.