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INFLUENCE OF GRIDBOARD LINE WIDTH AND SPACING ON WINDSCREEN DISTORTION MEASUREMENTS

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FOR THE COMMANDER

CHARLES BATES, JR.
Chief
Human Engineering Division
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Optical distortions of aircraft windscreens are commonly measured on photographs taken through the windscreens of a large flat Cartesian grid called a gridboard. Presently there are no accepted standards for the width of the lines or the size of the squares on gridboards. This study measured the effects of these variables upon measurements of vertical and horizontal magnifications to aid in establishing standards.

Gridboards with 1/16" and with 1/32" wide lines and with 1/2", 3/4" and 1" squares were photographed through an optically excellent, a mediocre and a very

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poor windscreen from the pilot's design eye position with a gridboard distance of 202". Prior to testing, subjects were trained with photographs from a second set of windscreens. They measured vertical and horizontal magnifications and displacements and stated their preferences on line widths and square sizes. Line widths and square sizes had minute to nonexistent effects upon distortion measurements. Square size significantly influenced only vertical displacement measures, and the effect was very small. Measurement data indicated that the 1" squares were not desirable. Also, only 1 of the 6 subjects preferred them. The 1/2" squares and the 1/16" lines were least preferred. The 1/2" squares should be avoided due to strong observer objections. The optimum gridboard condition appears to be 3/4" squares with narrow (1/32") lines.

PREFACE

This report was prepared in the Human Engineering Division of the Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio. The work was performed under Project 7184, Man-Machine Integration Technology, Task 18, Visual Effects of Windscreens on Pilot Performance, and Work Unit 03, Visual Perception Through Windscreens. The work was accomplished under the auspices of the Improved Windshield Protection Development Program, Projects 2202 and 1926 of the Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio. The work directly supports the American Society for Testing and Materials, which has undertaken the task of formulating standards for the optical evaluation of aerospace transparencies.

Special thanks are due to TSgt John E. Skuya for preparing the grid board photographs that were used in this study. Thanks are also due to the School of Aerospace Medicine, Brooks Air Force Base, Texas, for supplying two of the test subjects. The authors also thank Mrs. Betty Reid, Mrs. Kathy Hauser, and Mrs. Phyllis Dennard for help in preparing the manuscript.

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2 GENERAL BACKGROUND

Aircraft windscreens are not precision optical devices: various optical defects are present. Optical perfection would be very difficult and expensive to obtain and is not necessary. A small amount of imperfection is acceptable. However, it is necessary to insure that the imperfections are within the contractually established specifications.

The most common method used to reveal optical defects and to make their measurement possible is a photographic one. A camera is mounted behind the windscreen at a location specified by the aircraft design as the pilot's design eye position. A photograph is taken through the windscreen of a large gridboard. The gridboard is a vertical panel covered with high contrast lines which form a Cartesian grid. A photographic enlargement or print is subsequently examined for areas of greatest distortion, and measurements are made on these areas of the print. If the windscreen is optically perfect and no distortions are present in the camera and enlarger equipment, all of the squares in the photograph would appear as uniform perfect squares whose size is the same as they would be as if no windscreen were present. If the windscreen changes the size of the squares, optical magnification is present. If distortion is present, the lines seen through the windscreen are no longer parallel to those seen around the windscreen frame.

At the present time, windscreen fabricators, aircraft manufacturers and Air Force quality inspectors may also use different line widths, square sizes, and camera to gridboard distances. This occurs because there are no industry-wide standards or specifications for gridboards. Some users have stated that small squares make it easier to see the distortions so that finding the areas of maximum distortion on windscreens becomes an easier task. Others have not agreed. It would not be surprising if measurement errors were to be larger or more numerous with some line widths and grid square sizes than with others. This would probably depend upon how the measurements were made and how much time was used in making them.

MEASUREMENT OF GEOMETRIC DISTORTION USING GRIDBOARDS

The image of a straight line represents a one dimensional sampling of distortion with respect to the transverse deviations of this line. The "thinner" the line, the more apparent are the small deviations induced upon it by the distortion. For a parallel array of these lines, the determining factor for their angular spacing in the field-of-view is that their spacing must be smaller than the smallest observed defect noted in the part under investigation. Adherence to this criterion will guarantee that every optical defect will be sampled by at least one line.

The limiting accuracy of measurements of lensing, displacement grade, and grid line slope made from photographs of gridboards is dependent upon the absolute error of the physical measurements made on the photographic print itself. In view of this, the larger the deviations are on the print, the less percentage error there will be in making these measurements. The measurement error should asymptotically approach zero as the print size increases. Therefore, the prints should be made as large as practically possible. To achieve a known level of accuracy for these measurements, the variation of measurement error with print size should be determined. The limit on thinness of grid lines is imposed by the aberrations inherent in the part, and the resolution of the whole photographic process. For a 35mm Nikon camera using a 55mm Nikkor lens and panatomic X film, measurements indicated that a linewidth of .01° is the practical limit. This corresponds to a 1/32-inch line at 17 feet.

An optical part, such as a windscreen, should be evaluated in the operational configuration for which it will be used. This is particularly important if the distortion specifications are derived from psychophysical methods. In practice, this required that the camera be placed at the design eye position of the part, and that the gridboard be placed as far away from the part as possible so as to approximate a target at optical infinity. By placing the camera at the design eye position, the photograph represents what the crew is actually seeing (subject to the qualifications discussed below.) The distance from the windscreen to the gridboard is equally important because as the gridboard distance is increased, the observed distortions will also increase.

Figure 1 shows how the camera and gridboard distances affect the apparent magnification of the gridboard image. In the theoretical analysis the local area on the windscreen through which the observer (or camera) is viewing a particular section of the gridboard has been treated as a weak spherical lens. This is a particularly accurate characterization for a

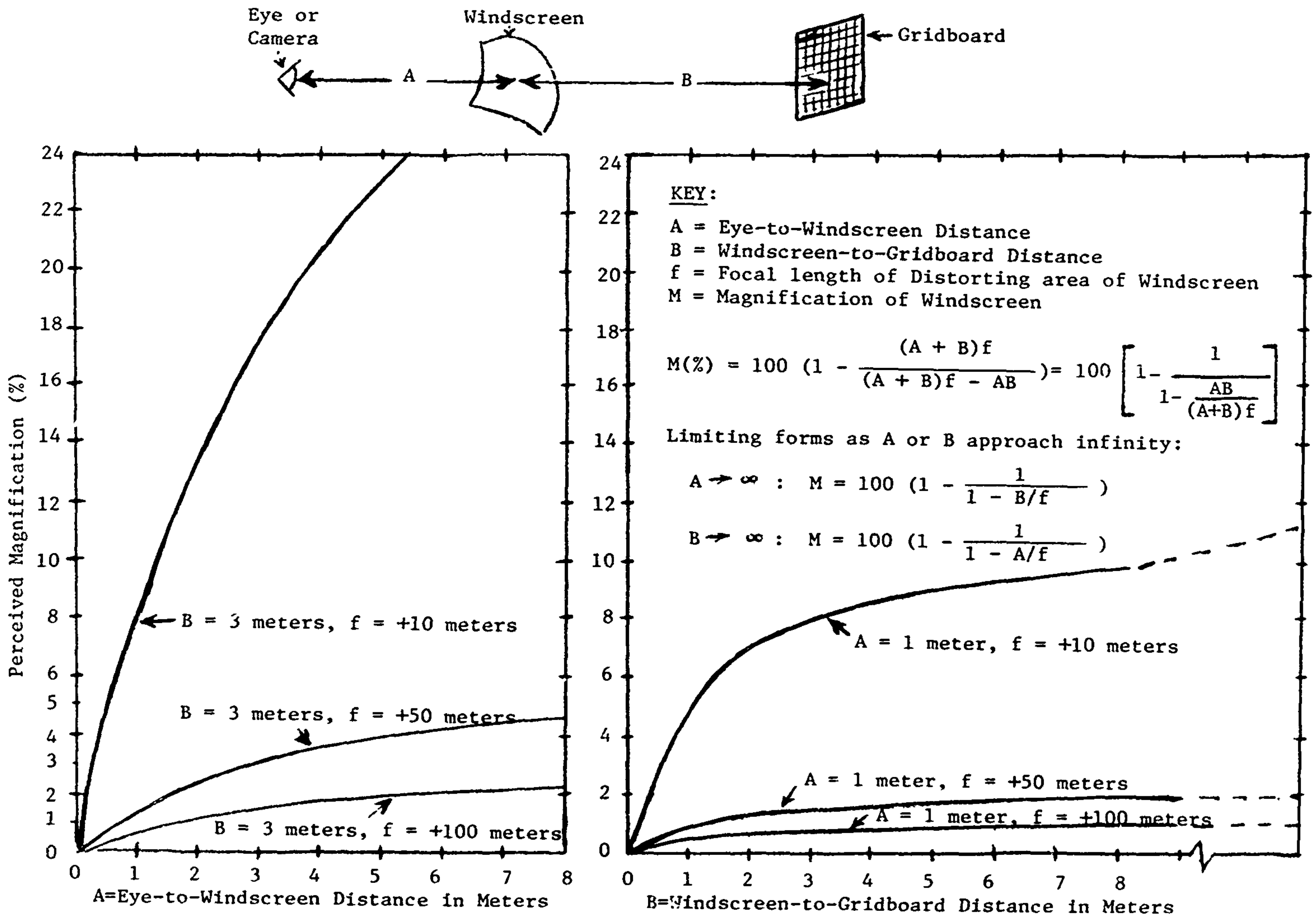


Figure 1. Gridboard Magnification produced by Windscreen Focusing Power at various Viewing Distances.

curved windscreen. It can be shown by geometrical ray tracing that there is optical power or magnification in curved windscreens, even when inside and outside surfaces are parallel. Because of the overall shape of curved windscreens, the local focal power (or magnification) smoothly changes through the clear aperture.

For this analysis, effective focal lengths from 10 to 100 meters were chosen to represent the optical power. A severe band would have a focal length of around 10 meters or less, while that of a relatively nonmagnifying or "clean" portion of the windscreen would be 100 meters or more. First, the gridboard distance, B, was held constant at three meters and the observer's position was moved further back from the windscreen. Note that while this movement slightly increases the observed magnification for areas of the windscreen with low optical power (long focal length), it greatly exaggerates the gridboard magnification seen through distorted areas of the windscreen. This is why experienced visual quality inspectors will back up from a windscreen in order to better judge its optical quality.

In the second part of this analysis, the eye distance, A, remained constant at one meter, and the gridboard distance, B, was varied. Here, the same phenomenon occurs, but the magnification increases are not as great. Note the limiting values of the magnification as B approaches infinity. While the areas of low optical power show little increase in magnification beyond a gridboard distance of a few meters, areas of strong optical power continue to increase significantly in magnification as B increases. The dependence of magnification on distance means that specifications derived from gridboard photographs must take into account the setup used to make the photographs.

A specific example will illustrate this point by showing how important gridboard distance can be. Suppose that gridboard photographs are taken with an eye distance (or camera-to-gridboard distance) of about one meter and a gridboard distance of about three meters. A windscreen measured for magnification with this setup that had an eight percent optical magnification would actually have a magnification for distant objects of 11 percent. This is apparent from examination of Figure 1. Thus, the testing setup can make windscreens appear better in testing than they would appear to a pilot looking through them at a distant scene. A contract for buying windscreens that does not specify the measurement setup under which its specifications apply may lead to the purchasing of optically unacceptable windscreens.

The above discussion applies even to the flat, parallel plate windscreens used in most commercial transport aircraft. With flat windscreens, the optical powers are much lower, and the observed magnification is less sensitive to the distances used, but the theory still applies. Normal optical deviation measurements made indoors at a factory will never present an accurate picture of what the world appears to be when viewing through these windscreens, because they do not reflect the manner in which the windscreens are used in the cockpit.

PROBLEM

Windscreens have many types of optical distortion, and all of them vary across the windscreen. The types of distortion of particular concern in the present study are horizontal magnification, vertical magnification, horizontal deviation and vertical deviation of the gridboard lines. When the values of these four distortions are specified, each value is given for that part of the windscreen where it is largest.

There are thus two distinct problems: (1) finding the areas where distortion is the greatest, and (2) making measurements with minimum error, or at least acceptable error. That combination of grid line width and grid square size most desirable for locating areas with maximum distortion may or may not be the same combination that is most desirable for minimizing measurement errors. The present study primarily examines the problem of minimizing the actual measurement error rather than in locating high distortion zones.

It seems reasonable to suppose that if a person performs many measurements from a photograph, he will either find the areas with maximum distortion or will come so close to them that the reported distortions will be almost the same as if he had not made an error in location. Since visual quality control inspectors outside of the laboratory do not necessarily have to rush through windscreen evaluations, it is assumed that they will take numerous measurements and will find or come close to the areas with the greatest optical distortion. The selection of a standard combination of grid line width and grid square size for industry-wide use, at least for photographic distortion evaluation, should be based on measurement error. If no particular line width-square size combination is advantageous for minimizing measurement error, then the combination that is selected as the standard should be the one that is preferred by users who have worked with various combinations of line width and grid square size.

APPROACH

This study wa. initiated in response to a request from the Distortion Task Force of the F7.08 Aerospace Transparent Enclosures and Materials Committee of the American Society for Testing and Materials. The group had reached an impasse on which of three grid sizes would provide the "best" target for gridboard photographs. In particular, AMRL was requested to investigate the effects of 1/2, 3/4, and 1-inch grids on the measurements of distortion made from photographs of these three grids. Since such a study would closely parallel on-going research, the Windscreen Laboratory at AMRL accepted the task and imposed the following additional criteria. First, a standard camera to gridboard distance of 202 inches was utilized. The grids were fabricated on clear acrylic sheets, 72" x 72" x 1/4", and back-illuminated by a large light box. The investigation further considered the role of line width on the detection of small scale distortion. Line widths of 1/16 and 1/32 inches were selected. Thus, the two line widths and three square sizes yielded six gridboards. Also, the prints used for analysis were the standard 8 x 10 inch size. The print scale on all of the prints was adjusted so that ten gridboard inches equaled one print inch.

Since it was not known if the optimum combination of grid square size and grid line width depended upon the amount of distortion in the windscreen being evaluated, the amount of distortion was varied. This was done by selecting an almost-flat clear plastic plate with a level of distortion that was quite low, and two F-111E windscreens. One windscreen was characterized by a medium level of distortion, while the other had an amount of distortion that made it unacceptable for use on an aircraft. The three square sizes, two line widths, and three windscreens yielded a total of 3 x 2 x 3 = 18 combinations of test conditions. Eighteen photographs were taken to cover the 18 conditions. Figure 2 shows the nominal values of displacement and magnification for the optical samples.

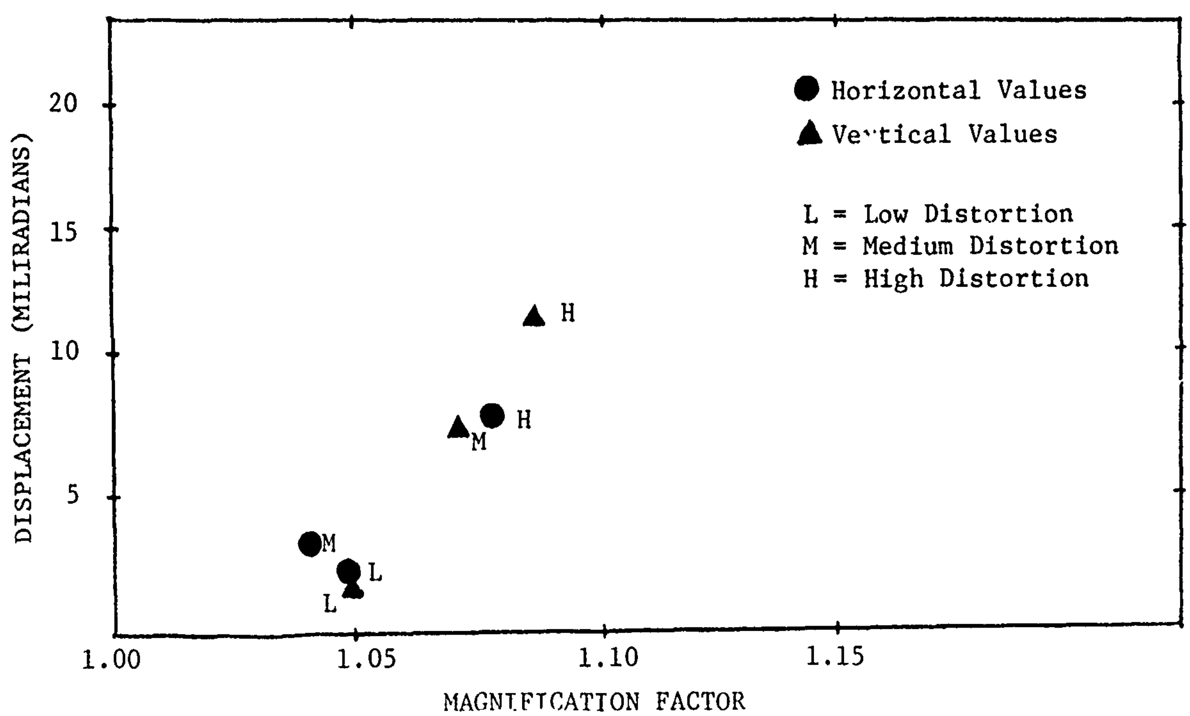


Figure 2. Nominal Values of Magnification and Displacement used in the Study

An additional set of six photographs were taken for calibration. These were made of the six gridboards with no windscreen or distorting medium between the camera and the gridboard. The magnification of the windscreens were evaluated by comparing photographed grid square size with and without the windscreens between the camera and the gridboard.

The 24 photographs were taken with Kodak Panatomic-X film which has high resolution and very small photographic grain size. The camera used was a Nikon F-2 35mm single lens reflex (SLR) camera with accurate shutter speeds. The lens used was a Nikon 55mm f/3.5 Micro-Nikkor which is noted for producing photographs with low optical distortion. The film was developed in Kodak D-76 developer. Glossy 8 x 10 inch photographic enlargements were made of the negatives through a 50mm f/4 Schneider Componon enlarging lens which also has low optical distortion and good optical resolution. Examples of the photographic prints or enlargements used by the six test subjects are given in Figures 3, 4, and 5.

Measurements made on the 8 x 10 inch prints used by the test subjects indicated that some line broadening occurred during the photographic process. The line widths on the prints were equivalent to those that would have been produced by an optically perfect system using gridboards with 1/16 inch and 1/8 inch lines rather than the 1/32 inch and 1/16 inch widths actually used.

An independent back up system with measurement accuracies exceeding the distortion measurement system actually used was not available. Such a system would have permitted selection of the most accurate width-spacing combination, if there was a superior one. If a choice has to be made between combinations which are significantly different by statistical test, then the choice would be a conservative one: select the combination with the largest amount of the indicated distortion, or else the one with the least measurement variability if the means are not significantly different.

DATA COLLECTION

Test subjects worked at a drafting table that had a parallel arm drafting machine. They used the drafting machine, a precision ruler calibrated in 1/100ths of an inch, and a pair of bow dividers with sharp steel points whose opening was adjusted by rotating a screw. For optical assistance they had a low power wide field magnifier mounted on the drafting table by a flexible arm. The magnifier contained a circular fluorescent lamp. Light was also provided by a battery of ceiling-mounted fluorescent lamps.

Test subjects first measured the six calibration prints to obtain a base for calculating magnification with the data obtained from the 18 windscreen photographs. After measuring the calibration prints, they took measurements on the 18 test prints. The 18 test prints were presented in quasi random order which was different for every test subject.

The typewritten instructions furnished to the test subjects presented detailed directions for making the measurements. Since the method for making the measurements could strongly influence the results of the study, the instructions presented to test subjects are given in the Appendix.

Vertical magnification is the ratio of two quantities: grid square height on the 8 x 10 inch photographic prints from pictures made with the windscreen in place and grid square height on the prints made from pictures taken with no windscreen present. The smaller of the two measurements is used in the denominator so that all magnification values are greater than unity. Horizontal magnification is a similar ratio, using the vertical line separations.

Horizontal and vertical displacement measures are made possible by the part of the gridboard that is visible outside of the windscreen area. This undeviated area in the photographic prints serves as a reference from which the displacement of the distorted grid lines may be measured. The displacement values that are reported in this document are in inches on the 8" x 10" photographic prints. The gridboard to camera distance was 202" which yielded, for one gridboard inch, 1/202 radians or 4.95 milliradians. The photographic print scale for all the prints was set at one print inch to 10 gridboard inches, so that one print inch equals 49.5 milliradians. Thus, the tabled and plotted displacement values may be converted to milliradians of displacement by multiplying by 49.5.

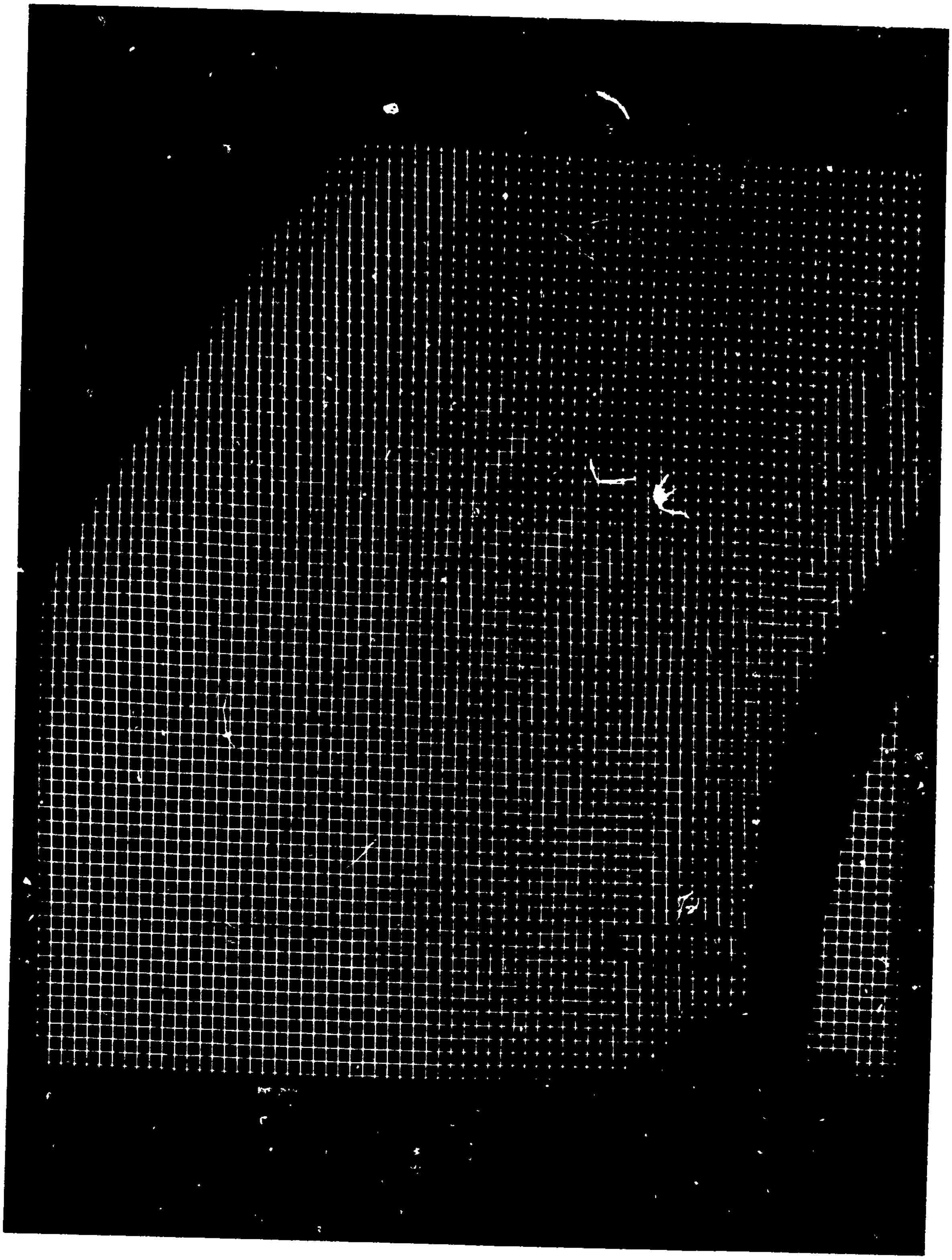


Figure 3. Grid Board Photograph: 1-inch grid and 1/16" line width taken through the low distortion windscreen

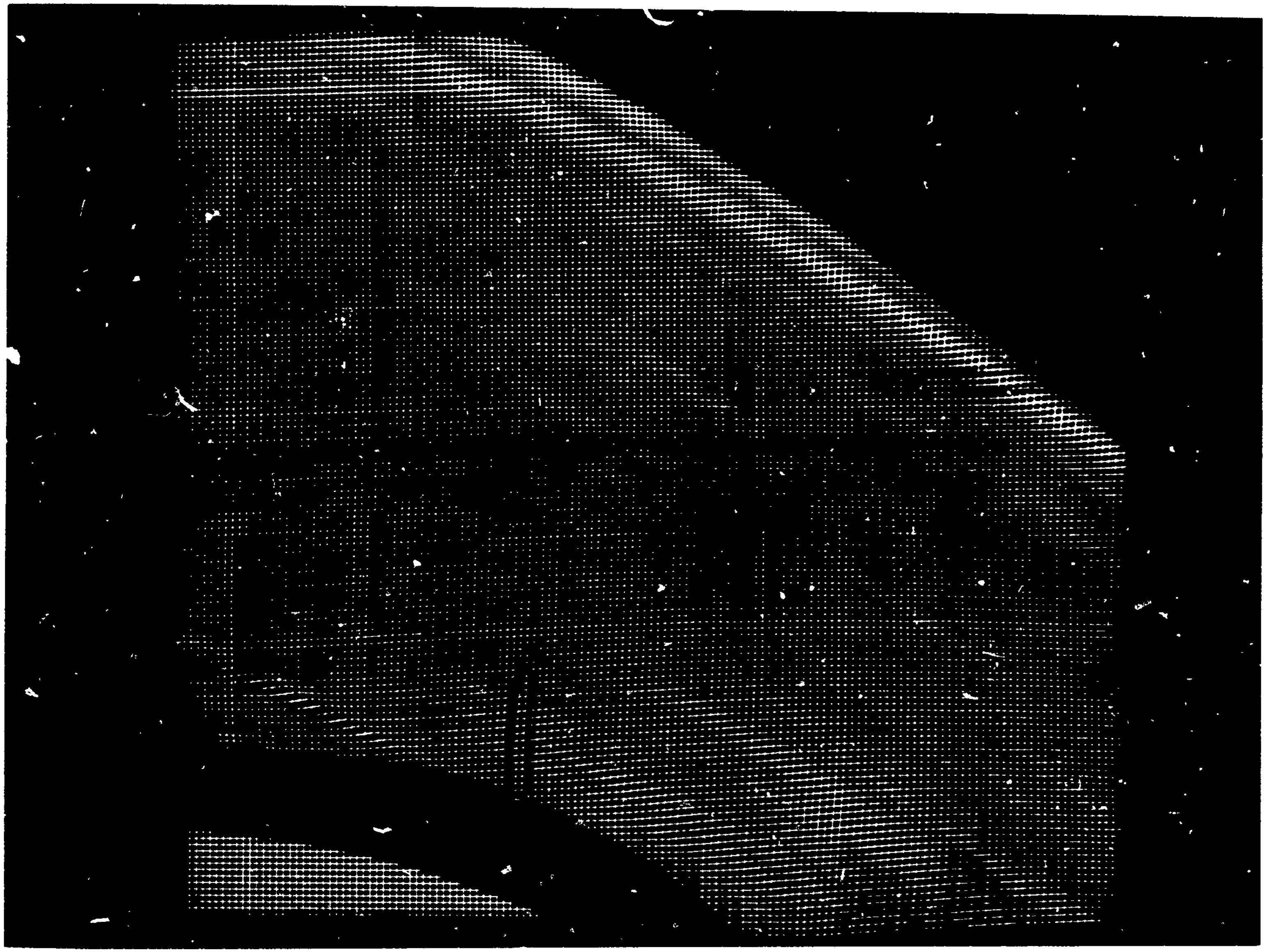


Figure 4. Grid Board Photograph: 1/2-inch grid and 1/32" line width taken through the medium distortion windscreen

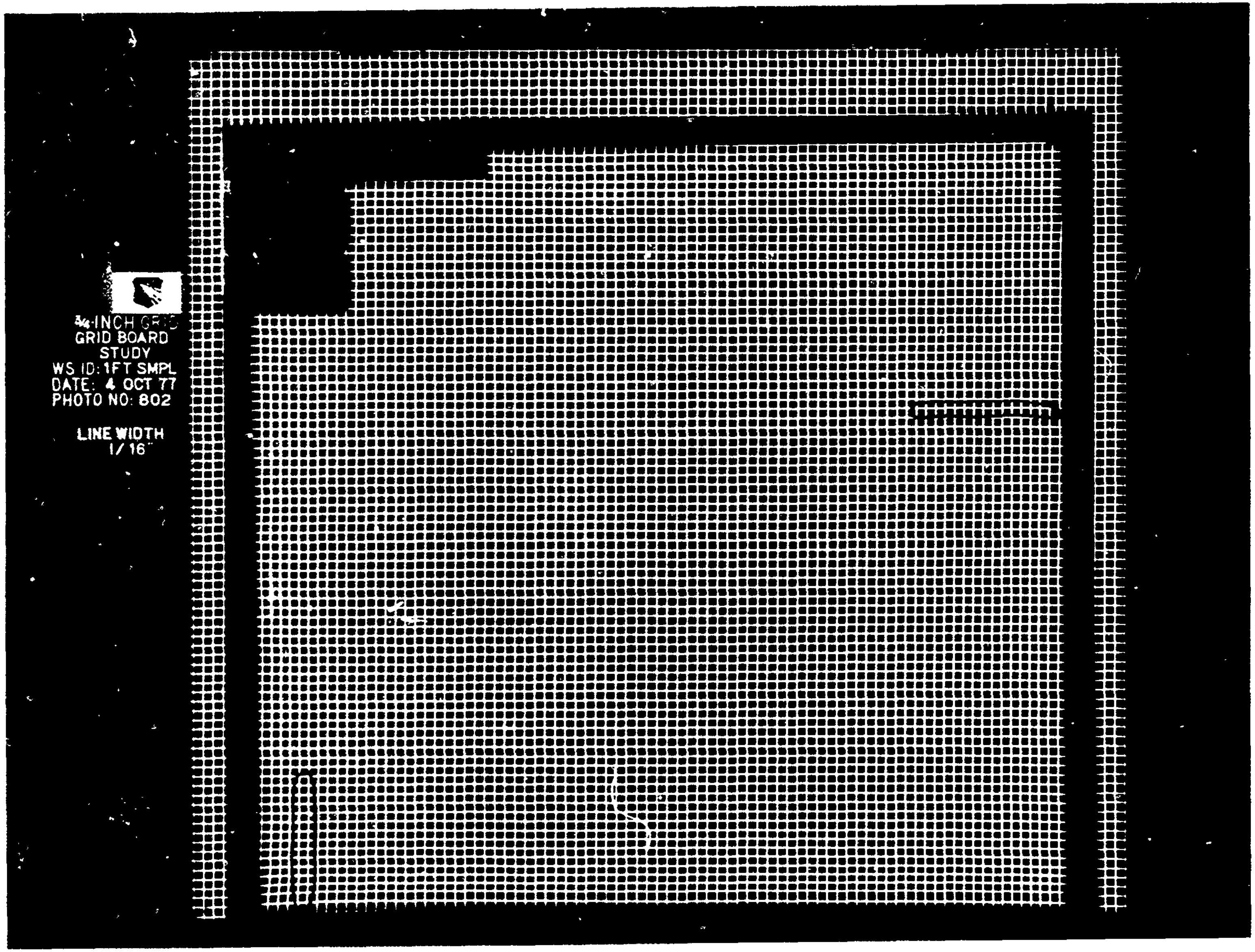


Figure 5. Grid Board Photograph: 3/4-inch grid and 1/16" line width taken through the high distortion windscreen

RESULTS

MEASUREMENT DATA

Table 1 lists the mean or average measurement data for individual test subjects for the three windscreens. Each data point is the average summed across six test conditions, i.e., three gridboard square sizes each at two grid line widths From this table it is apparent that the averages for the six subjects, while not precisely the same, are in good agreement.

Of particular interest are the data which show the effect upon magnification and displacement measures of the line spacing and line widths of the gridboards. These data are given in Tables 2 through 5 and are plotted in Figures 6 through 9. Note that in the bottom two graphs of each of these figures, the averages are plotted with ±1 standard deviation indicated about the means. In the top two graphs of each figure the standard deviations are plotted by themselves against test conditions.

In all of the figures the measurement values are plotted separately for the high, medium, and low distortion windscreen conditions. The size of the differences between the windscreens is not of concern in this report. What is of interest is the slope or inclination of the graph lines in going from a width of 1/32 inches to one of 1/16 inches or from 1/2 inches to 3/4 inches to one inch spacing. Significant inclination of the graph lines would indicate an effect upon measurement averages of grid line width or spacing.

From an examination of the bottom two graphs in each figure, it is apparent that, when the graph lines slope either up or down, the absolute amount of change is small. Note that the amount of change relative to the size of the standard deviations is almost invariably small. Also, while the slope may be slightly up for one distortion level (or windscreen), it is frequently either slightly down or level for another. From this visual inspection of the graphs, it appears that neither grid line width nor grid line spacing has any systematic effect upon the mean or average values of either the magnification or displacement measurements.

The top two graphs in each of the four figures plot the standard deviation, which is a measure of variability of the data, for the grid line spacings. Examination of these graphs of variability leads to essentially the same kind of conclusion: the width of grid lines and their spacing appear to exert no significant effect upon the variability of measurement data.

From a visual inspection of the graphs, one would thus tend to conclude that none of the grid line widths and grid line spacings appear to yield either averages or variabilities favoring any particular width or spacing. The hypothesis of no difference in averages may be statistically examined by means of Student's t test. One should, however, be aware of the probability of obtaining a few significant "$\underline{t}$'s" by chance in multiple testing.

Tables 2 through 5 list the values of "$\underline{t}$" and the probabilities of obtaining, by chance alone, values as large as were obtained. Table 2 on Horizontal and Vertical Magnification lists six values of "$\underline{t}$" and none are statistically significant. Clearly, a grid line width does not influence average horizontal or vertical magnification measurements. Table 3 on Horizontal and Vertical Displacement also contains six values of "$\underline{t}$," only one of which is statistically significant, with 1/16 inches yielding larger displacement means than 1/32 inches. Thus, line width appears, by statistical test, not to influence most displacement averages. In Table 4 on line spacing, only one of the 18 "$\underline{t}$" tests attained statistical significance, so that line spacing appears not to influence magnification averages. However, in Table 5 on the influence of line spacing on displacement averages, the case is not so clear. Five of the 36 tests attained statistical significance with all five having probabilities of .02 or lower: two out of nine for horizontal displacement means, and three out of nine for vertical means. Even allowing for the use of multiple "$\underline{t}$" testing, this result cannot readily be attributed to chance. The ratios of the significant means are tabled as follows:

TABLE 1

AVERAGE MEASUREMENT DATA FOR INDIVIDUAL OBSERVERS

Subject	*Magnification*		*Displacement (")*	
	Horizontal	*Vertical*	*Horizontal*	*Vertical*
Low Distortion				
1	1.044	1.048	.0342	.0292
2	1.044	1.053	.0417	.0268
3	1.044	1.046	.0375	.0308
4	1.051	1.044	.0325	.0263
5	1.044	1.042	.0322	.0380
6	1.048	1.044	.0317	.0365
Mean	1.046	1.046	.0350	.0313
Medium Distortion				
1	1.043	1.042	.0513	.1333
2	1.041	1.052	.0690	.1488
3	1.041	1.056	.0707	.1470
4	1.034	1.046	.0642	.1417
5	1.040	1.050	.0667	.1538
6	1.032	1.046	.0635	.1445
Mean	1.038	1.049	.0642	.1448
High Distortion				
1	1.078	1.123	.0967	.2207
2	1.086	1.117	.1028	.2232
3	1.073	1.129	.1208	.2232
4	1.064	1.107	.1172	.2142
5	1.085	1.132	.1182	.2160
6	1.064	1.112	.1097	.2147
Mean	1.075	1.085	.1109	.2187

TABLE 2

EFFECT OF LINE WIDTH ON MAGNIFICATION MEASUREMENTS

Distortion Panel	Grid Line Width	Windscreen Magnification							
		Horizontal				Vertical			
		Mean+	S.D.	t	P	Mean	S.D.	t	P
Low	1/32"	1.0455	.00338			1.0444	.00745		
	1/16"	1.0463	.00686	.57	.59	1.0482	.00651	1.76	.14
Medium	1/32"	1.0369	.00765			1.0478	.00982		
	1/16"	1.0404	.01248	1.47	.20	1.0508	.0120	1.02	.35
High	1/32"	1.0731	.01892			1.1211	.0146		
	1/16"	1.0772	.00686	.66	.54	1.1191	.0155	.92	.40

Note: None of the six "t" tests in the above table attained statistical significance.

TABLE 3

EFFECT OF LINE WIDTH ON DISPLACEMENT MEASUREMENTS

Distortion Panel	Grid Line Width	Windscreen Displacement							
		Horizontal				Vertical			
		Mean+	S.D.	t	P	Mean	S.D.	t	P
Low	1/32"	.0037	.00595			.0268	.00774		
	1/16"	.0362	.00737	1.77	.14	.0357	.01074	9.90*	<.001
Medium	1/32"	.0630	.01319			.1417	.01103		
	1/16"	.0654	.01221	.50	.62	.1481	.00878	1.96	.11
High	1/32"	.1123	.01125			.2228	.00967		
	1/16"	.1150	.01276	1.16	.29	.2145	.01506	1.94	.11

*Statistically Significant: Only one of the 6 "t" tests in the above table was statistically significant.

Note: In both of the above tables each mean is the mean or average for 6 observers. Each observer's score is the average of 3 scores, one for each of the 3 grid spaces. Thus each mean is the average of 18 scores or observations.

TABLE 4

EFFECT OF LINE SPACING ON MAGINIFICATION MEASUREMENTS

Distortion Panel	Grid Line Space	Windscreen Magnification: Horizontal Mean	Horizontal S.D.	Horizontal t	Horizontal P	Vertical Mean	Vertical S.D.	Vertical t	Vertical P
Low	a = 1/2"	1.0453	.00355	t_{ab} = .671	.52	1.0461	.00553	t_{ab} = .579	.58
	b = 3/4"	1.0442	.00480	t_{ac} = 1.26	.25	1.0449	.00618	t_{ac} = .628	.55
	c = 1"	1.0482	.00681	t_{bc} = 1.17	.29	1.0479	.00938	t_{bc} = .782	.46
Medium	a = 1/2"	1.0335	.00711	t_{ab} = 2.22	.08	1.0458	.0106	t_{ab} = 2.11	.09
	b = 3/4"	1.0431	.00947	t_{bc} = 1.32	.24	1.0532	.0066	t_{ac} = .461	.66
	c = 1"	1.0395	.01212	t_{bc} = .649	.54	1.0488	.0139	t_{bc} = .714	.50
High	a = 1/2"	1.0632	.01708	t_{ab} = 3.12	.02	1.1154	.0126	t_{ab} = 3.03*	.02
	b = 3/4"	1.0864	.01174	t_{ac} = 2.14	.08	1.1220	.0165	t_{ac} = 1.05	.36
	c = 1"	1.0758	.01945	t_{bc} = 2.33	.06	1.1226	.0155	t_{bc} = .055	.96

*ONLY one of the 18 "t" tests yielded statistically significant results.

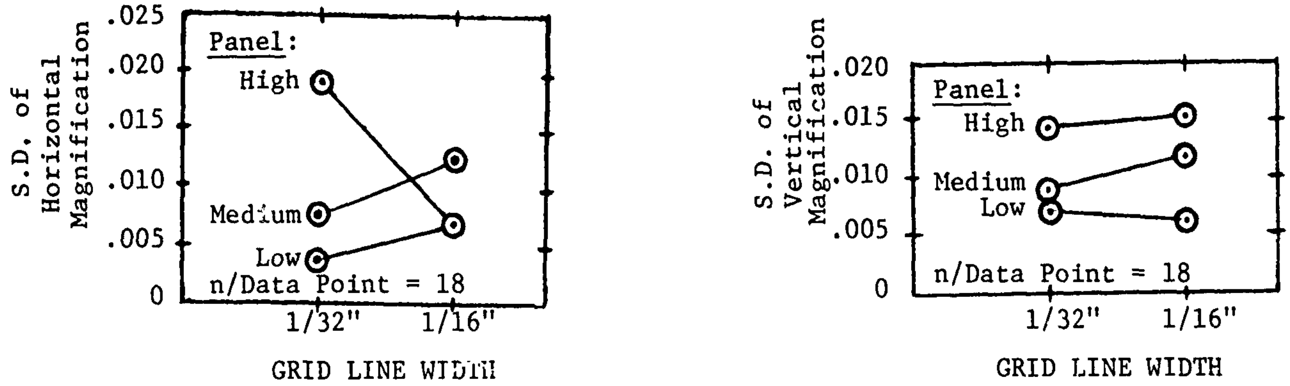
TABLE 5

EFFECT OF LINE SPACING ON DISPLACEMENT MEASUREMENTS

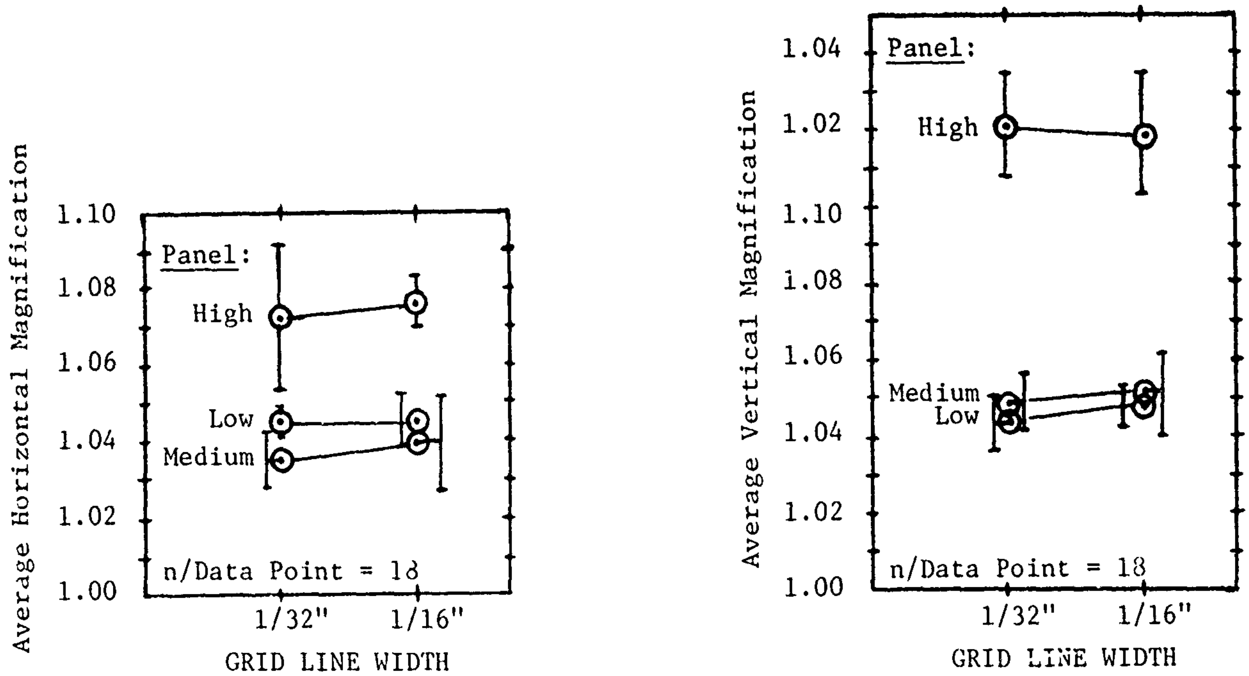
Distortion Panel	Grid Low Space	Windscreen Displacement: Horizontal Mean	Horizontal S.D.	Horizontal t	Horizontal P	Vertical Mean	Vertical S.D.	Vertical t	Vertical P
Low	a = 1/2"	.0364	.00592	t_{ab} = .328	.75	.0361	.0122	t_{ab} = 5.23*	.01
	b = 3/4"	.0350	.00745	t_{ac} = .771	.47	.0302	.0068	t_{ac} = 5.17*	.01
	c = 1"	.0334	.00694	t_{bc} = 5.84*	<.01	.0275	.0099	t_{bc} = 1.98	.10
Medium	a = 1/2"	.0595	.01275	t_{ab} = 1.73	.19	.1410	.0098	t_{ab} = 1.62	.16
	b = 3/4"	.0656	.01285	t_{ac} = 3.22*	.02	.1478	.0090	t_{ac} = 1.58	.17
	c = 1"	.0676	.01175	t_{bc} = .473	.65	.1458	.0117	t_{bc} = .650	.54
High	a = 1/2"	.1136	.0140	t_{ab} = .915	.40	.2268	.0074	t_{ab} = 2.48	.05+
	b = 3/4"	.1168	.0112	t_{ac} = 1.02	.35	.2146	.0131	t_{ac} = 3.76*	.01+
	c = 1"	.1106	.0104	t_{bc} = 1.76	.14	.2145	.0146	t_{bc} = .016	.99

*Statistically significant "t" test· 5 of the 36 attained statistical significance.

Note: Every entry in the above two tables is based on 1/32" and 1/16" grid line widths for 6 subjects or observers, thus every tabled value is the average of 12 measurements.

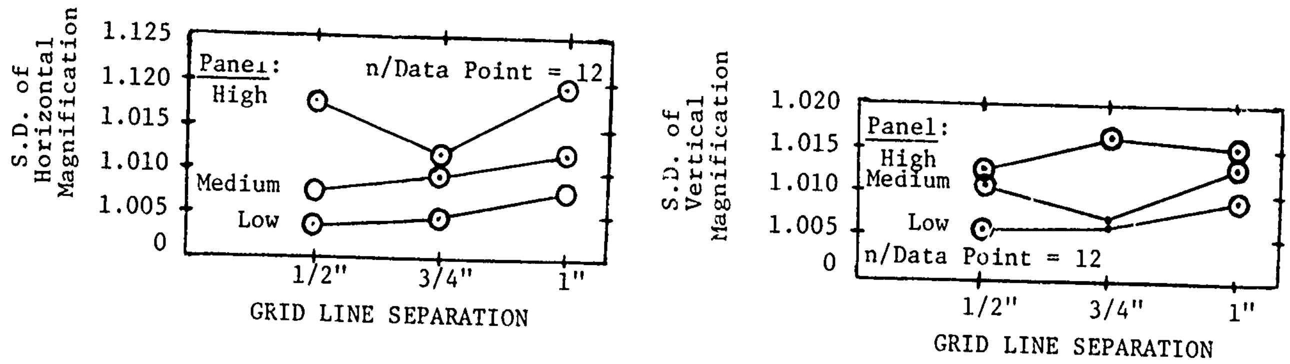


(A) Effect on Measurement Variability.

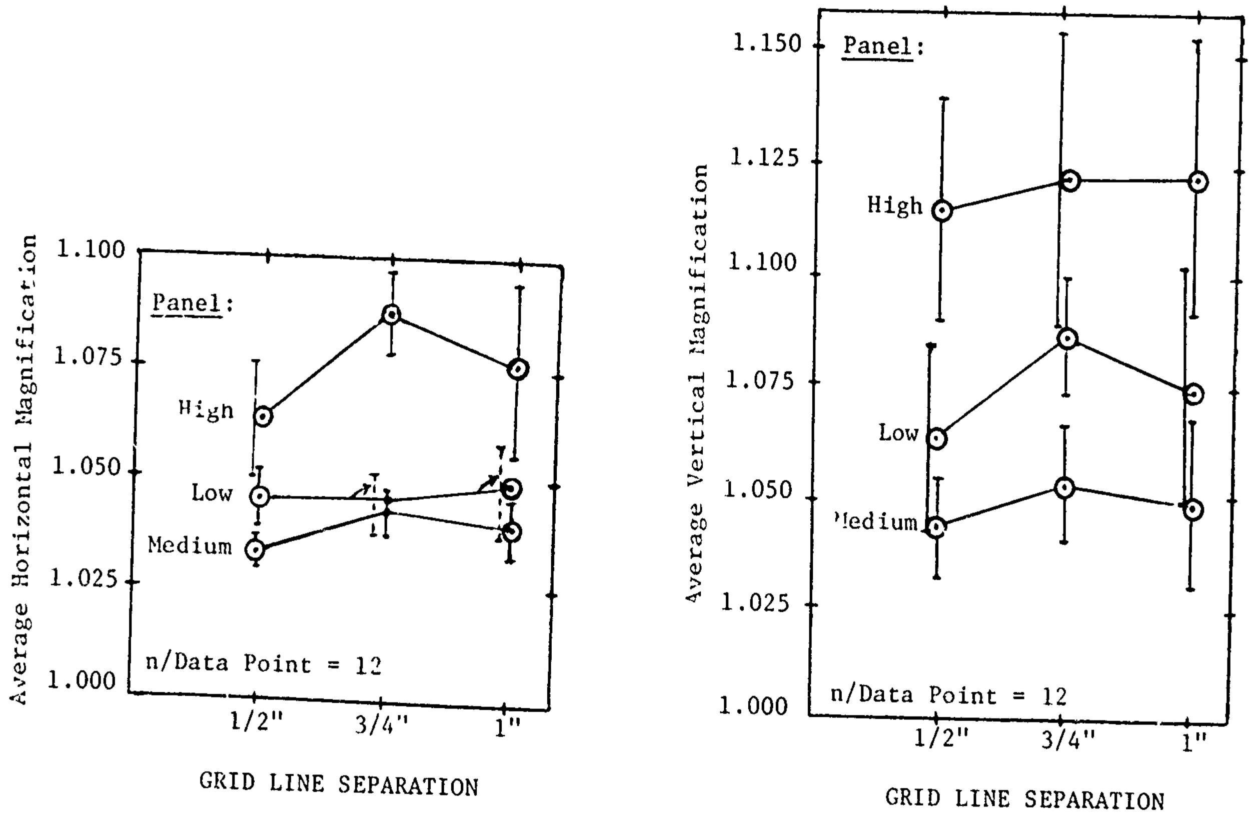


(B) Effect on Measurement Averages.

Figure 6. The Effect of Grid Line *Width* on Magnification Measurements.

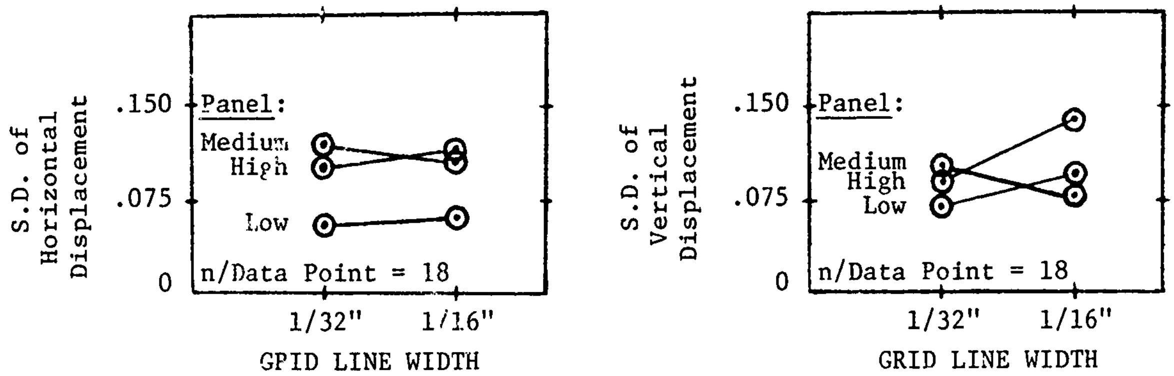


(A) Effect on Measurement Variability.

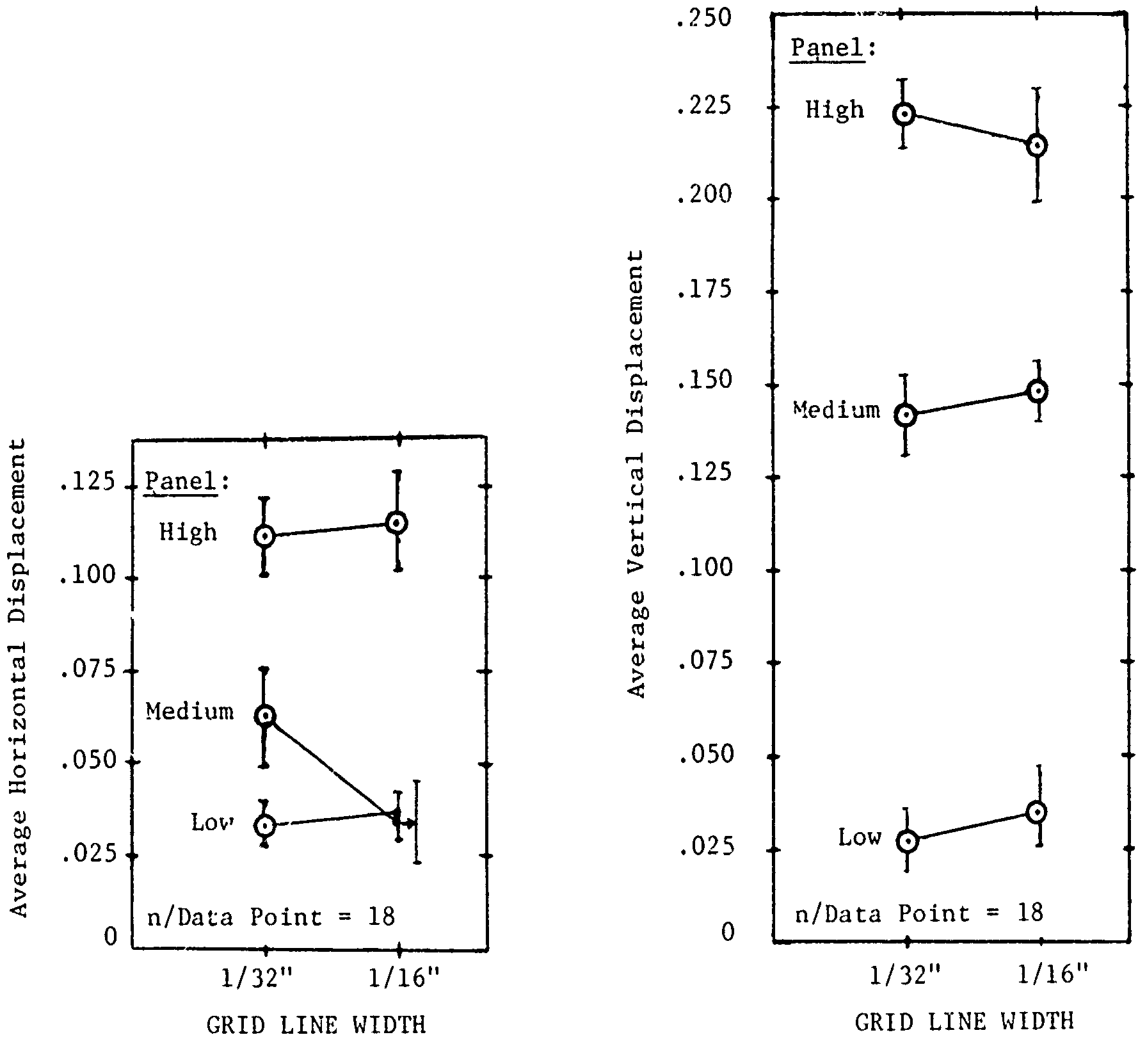


(B) Effect on Measurement Averages

Figure 7. The Effect of Grid Line *Spacing* on Magnification Measurements.



(A) Effect on Measurement Variability



(B) Effect on Measurement Averages

Figure 8. The Effect of Grid Line *Width* on Displacement Measurements.

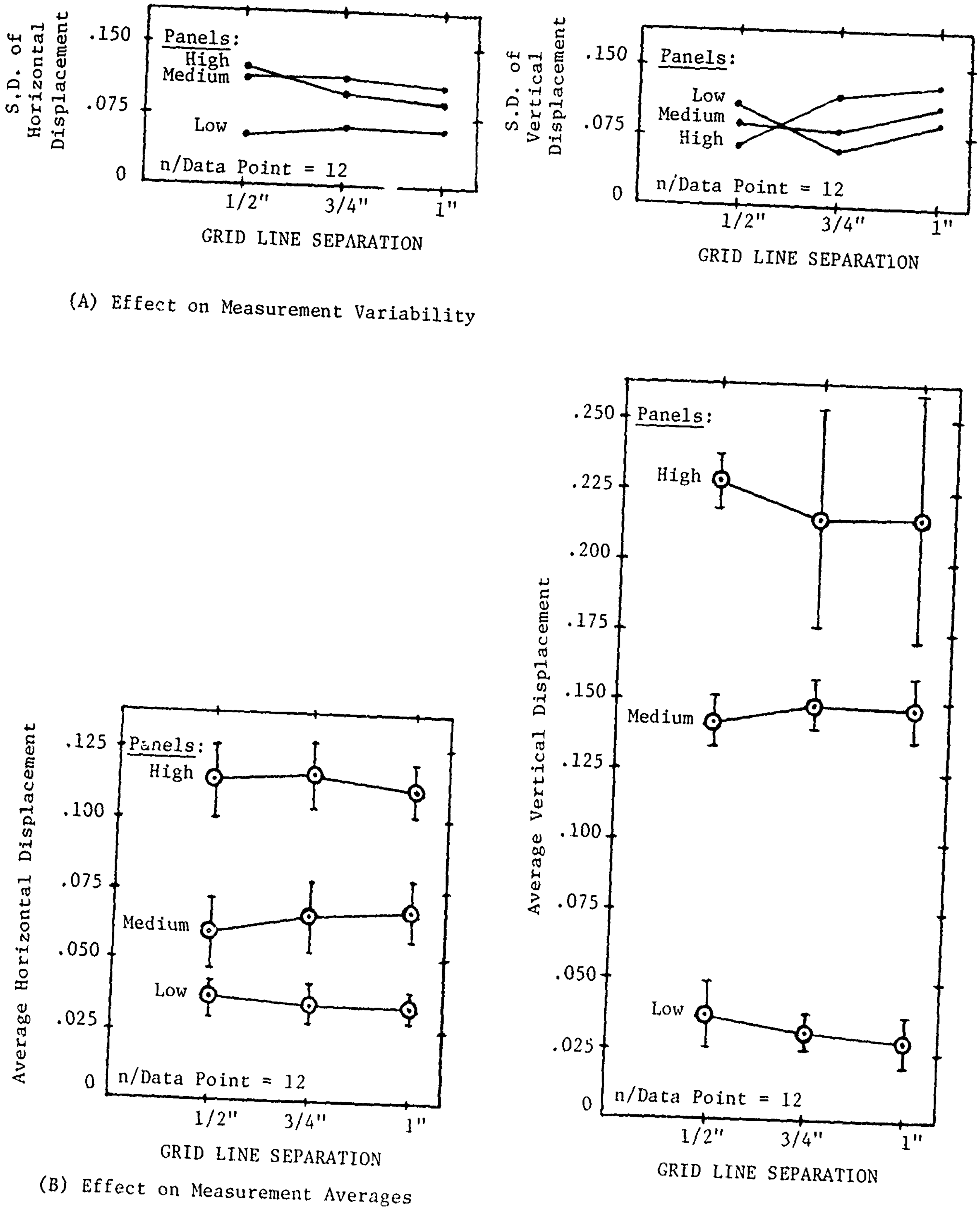


Figure 9. The Effect of Grid Line *Spacing* on Displacement Measurements

TABLE 6

SIGNIFICANT MEANS DIFFERENCES FOR DISPLACEMENT MEASURES

Distortion	Displacement: Horizontal	Displacement: Vertical
Low	(3/4")/1"* = .0350/.0334 = 1.05	(1/2")/(3/4")== .0361/.0302 = 1. (1/2")/1" = .0361/.0275 = 1.31
Medium	1"/(1/2") = .0676/.0595 = 1.14	None
High	None	(1/2")/(1") = .2268/.2145 = 1.06

*(3/4")/1" means the ratio of the averages for the two grid spaces.

Note that three of the five ratios of means are for the low distortion case and that most of the ratios are not large. For three of the five ratios the larger exceeds the smaller by six percent or less. To be on the safe or conservative side, one would select the spacing yielding the largest measured displacement. If this rule is followed, and if one could generalize on the basis of multiple "t" tests, one might prefer 3/4" for horizontal displacement and 1/2" for vertical displacement. The one inch spacing does not appear to be the optimum choice. If only one is to be made, it would be either 1/2" or 3/4" spacing.

Due to the increase in probability of obtaining significant values of "t" with multiple testing, the most appropriate statistical test is analysis of variance. This technique also permits testing of interactions between test conditions. Tables 7 through 10 give the analyses for the four types of measurement for each of three distortion levels. Note in Table 7 that only for high distortion was line width effect on horizontal magnification not significant, with 1/16" yielding a higher distortion measurement than 1/32". No interaction was significant.

In Table 8 on vertical magnification, no line width, line spacing, or interaction was statistically significant. Any width, space or combination of the two was as desirable as any other for measuring vertical magnification.

In Table 9 on horizontal displacement, any width or space or combination of width and space was as desirable as any other. The significant S X O (Space by Observer) interaction means that the effect of spacing varies with the observer: what line spacing is "best" for some observers is not best for others.

In Table 10 on vertical displacement, both width and spacing are statistically significant for low distortion, but neither is significant for medium distortion, and only spacing is significant for high distortion. One of the interactions is statistically significant. The three analyses in Table 10 are in line with the "t" test results. The discussion of Tables 5 and 6 is relevant and the same conclusion is appropriate: avoid one inch spacing, and choose between the 1/2" and 3/4" spacing.

CONCLUSIONS FROM MEASUREMENT DATA ANALYSES

For magnification measurements, it appears that no particular width or spacing or combination is optimum. For horizontal displacement, but not vertical displacement, the choice of width and spacing also appears to make no difference in results. For vertical displacement, the spacing choice is significant for low and high distortion levels, and width for low levels. The one inch spacing yields the lowest values in some cases, and is to be avoided in preference to 1/2" or 3/4". Possibly for low distortion, a line width of 1/16" will yield higher distortion than a line width of 1/32".

In general, it appears that grid line width and grid line spacing have little or no effect on most measurements, however, they do influence vertical displacement.

Table 11 gives the subject's individual written opinions concerning the distortion measurements that they had just accomplished. Subsequent discussions with them allowed the authors to synthesize the following opinion.

TABLE 7

ANALYSES OF VARIANCE FOR HORIZONTAL MAGNIFICATION

A. For the low distortion windscreen

Source	Sum of Squares	df	Mean Square	F
Line Width, W	.000004690	1	.000004690	.228
Line Spacing, S	.00009817	2	.00004909	1.31
Observers, O	.0002592	5	.00005185	
Interactions:				
WxS	.00001350	2	.000006750	.106
WxO	.0001029	5	.00002058	.323
SxO	.0003759	10	.00003759	.590
WxSxO	.0006367	10	.00006307	
Sum		35		

B. For the medium distortion windscreen

Source	Sum of Squares	df	Mean Square	F
Line Width, W	.00009669	1	.00009669	1.90
Line Spacing, S	.0005454	2	.0002727	1.93
Observers, O	.0005565	5	.0001113	
Interactions:				
WxS	.0003112	2	.0001556	.504
WxO	.0002538	5	.00005076	.164
SxO	.001415	10	.0001415	.458
WxSxO	.003089	10	.0003089	
Sum		35		

C. For the high distortion windscreen

Source	Sum of Squares	df	Mean Square	F
Line Width, W	.0001480	1	.0001480	.438
Line Spacing, S	.003252	2	.001626	7.32*
Observers, O	.002874	5	.0005748	
Interactions:				
WxS	.0000325	2	.00001625	.028
WxO	.001689	5	.0003378	.576
SxO	.002222	10	.0002222	.379
WxSxO	.005862	10	.0005862	
Sum		35		

*Statistically significant at the .05 level of significance.

TABLE 8

ANALYSES OF VARIANCE FOR VERTICAL MAGNIFICATION

A. For the low distortion windscreen

Source	*Sum of Squares*	*df*	*Mean Square*	*F*
Line Width, W	.0001247	1	.0001247	3.10
Line Spacing, S	.00005489	2	.00002745	.507
Observers, O	.0004325	5	.00008649	
Interactions:				
WxS	.0001291	2	.00006453	.553
WxO	.0002012	5	.00004024	.345
SxO	.0005418	10	.00005418	.464
WxSxO	.001168	10	.0001168	
Sum		35		

B. For the medium distortion windscreen

Source	*Sum of Squares*	*df*	*Mean Square*	*F*
Line Width, W	.00008100	1	.00008100	1.50
Line Spacing, S	.0003262	2	.0001631	.973
Observers, O	.0004842	5	.00009684	
Interactions:				
WxS	.0001074	2	.00005370	.164
WxO	.0002694	5	.00005388	.165
SxO	.001676	10	.0001676	.513
WxSxO	.003266	10	.0003266	
Sum		35		

C. For the high distortion windscreen

Source	*Sum of Squares*	*df*	*Mean Square*	*F*
Line Width, W	.00003403	1	.00003403	.845
Line Spacing, S	.0003927	2	.0001963	.912
Observers, O	.002974	5	.0005948	
Interactions:				
WxS	.0001864	2	.00009320	.214
WxO	.0002014	5	.00004028	.092
SxO	.002153	10	.0002153	.494
WxSxO	.004356	10	.0004356	
Sum		35		

Note: None of the widths, spacing or interactions in the above tables are statistically significant.

TABLE 9

ANALYSES OF VARIANCE FOR HORIZONTAL DISPLACEMENT

A. For the low distortion windscreen

Source	Sum of Squares	df	Mean Square	F
Line Width, W	.00005878	1	.00005878	2.72
Line Spacing, S	.00005406	2	.00002703	.373
Observers, O	.0004606	5	.00009211	
Interactions:				
WxS	.00003905	2	.00001953	.193
WxO	.00010788	5	.00002158	.214
SxO	.0007253	10	.00007253	.718
WxSxO	.001010	10	.0001010	
Sum		35		

B. For the Medium distoration windscreen

Source	Sum of Squares	df	Mean Square	F
Line Width, W	.00005378	1	.00005378	.689
Line Spacing, S	.0004254	2	.0002127	.985
Observers, O	.001422	5	.0002844	
Interactions:				
WxS	.0001560	2	.00007803	.021
WxO	.001080	5	.0002160	.593
SxO	.0007309	10	.00007309	.201
WxSxO	.003645	10	.0003645	
Sum		35		

C. With a high distortion windscreen

Source	Sum of Squares		Mean Square	F
Line Width, W	.00006400	1	.00006400	.113
Line Spacing, S	.0002345	2	.0001172	.001
Observers, O	.002537	5	.0005075	
Interactions				
WxS	.0009532	2	.0004766	2.22
WxO	.002841	5	.0005681	2.64
SxO	1.4063	10	.14063	2.55**
WxSxO	.002148	10	.0002148	
Sum		35		

**Statistically significant at the .01 level of significance

TABLE 10

ANALYSES OF VARIANCE FOR VERTICAL DISPLACEMENT

A. For the low distoration windscreen

Source	Sum of Squares	df	Mean Square	F
Line Width, W	.00711	1	.000711	9.82*
Line Spacing, S	.0004611	2	.0002305	16.6***
Observers, O	.0007279	5	.0001456	
Interactions:				
WxS	.0005900	2	.0002950	.329
WxO	.0003622	5	.00007244	.020
SxO	.0001393	10	.00001393	.078
WxSxO	.001793	10	.0001793	
Sum		35		

B. For the Medium Distortion Windscreen

Source	Sum of Squares	df	Mean Square	F
Line Width, W	.0003674	1	.0003674	3.84
Line Spacing, S	.0002904	2	.0001452	3.61
Observers, O	.001464	5	.0002928	
Interactions:				
WxS	.0001391	2	.00006955	.427
WxO	.0004789	5	.00009578	.588
SxO	.004024	10	.00004024	.247
WxSxO	.001629	10	.0001629	
Sum		35		

C. For the High Distoration Windscreen

Source	Sum of Squares	df	Mean Square	F
Line Width, W	.0006502	1	.0006502	3.97
Line Spacing, S	.001258	2	.0006292	5.12*
Observers, O	.0004945	5	.00009889	
Interactions:				
WxS	.0006847	2	.0003423	.936
WxO	.0008189	5	.0001638	.448
SxO	.001223	10	.0001230	.336
WxSxO	.003659	10	.0003659	
Sum		35		

*, **, ***statistically significant at the .05, .01, and .001 levels, respectively.

The most difficult panel to use was the 1/2 x 1/2 inch grid with the broad, 1/16-inch lines. In the magnification measurements, these wide lines made interpolating the "squares-per-inch" numbers particularly difficult. Measuring displacement was more difficult with the higher distortion levels because of the larger number of lines that had to be counted at the point of maximum displacement. The greatest fatigue was reported when using the 1/2" x 1/2" x 1/16" grid.

Opinions were divided on the 3/4 and one inch grids. However, the thinner lines were clearly preferred. The one inch grid was felt to be too "coarse" for making displacement measurements, but it was the unanimous favorite for ease of making magnification measurements.

Considering both magnification and displacement grading, the unanimous choice was the 3/4" x 3/4" x 1/32" grid. The measurement data do not statistically support this choice. However, the subjects expressed the opinion that a thin-lined grid with an angular spacing of about 3.7 x 3.7 milliradians represents the best choice for the range of variables tested in the study.

TABLE 11

SPACING AND WIDTH PREFERENCES

Subject	*Comments*
1.	The 1" grid spacing is too large for quickly finding and measuring areas with maximum displacement. 1/2" or 3/4" is preferable. I like 3/4" better than 1/2". I prefer the narrow (1/32") line width.
2.	My preference is 3/4" grid and 1/32" width. The least liked was the 1/2" grid of either line width. The 3/4" grid seemed to give better accuracy compared to the 1" grid, but was still easy to read.
3.	I preferred narrow lines – easier to measure. The 1/2" grid was very difficult to use with lensing and displacement grade – a matter of counting lines. The 1" grid seemed too coarse for displacement grade, but made locating maximum lensing areas easier. Overall, I preferred the 3/4" x 1/32" grid as a compromise between the dense lines of the 1/2" grid and the coarse 1" grid.
4.	Grid sizes 1" and 3/4" are the ones easy to work with, even though on the 1" it seems that you miss most of the deviations. I like the narrow grid line.
5.	I like the 1" grid and the thin line. The small 1/2" squares are too tedious to work with· hard on your eyes, easier to loose your place in counting squares. The 3/4" not as bad as the 1/2". Worst was the 1/2" with a broad grid line.
6.	The first choice of grid size would be 3/4" (spacing) by 1/32" (width). Second choice would be 1" by 1/32". For me these are the best to work with.

DISCUSSION AND CONCLUSIONS

The measurement data and the observer preference data both indicate that the one inch spacing should be avoided. While the measurement data indicate that either 1/2" or 3/4" spacing is equally desirable, observers did not like the 1/2" spacing. It follows that 3/4" should be the recommended grid square size. There is some indication, from the low distortion panel measurements only, that the 1/16" line width will possibly yield higher vertical displacement, but the possibility is not high. It should be kept in mind that the low distortion panel was of excellent optical quality and that neither magnification measurements nor horizontal displacement were influenced by line width. The recommended line width, then, should be that preferred by the observers, namely the narrow line. The first conclusion of the study is that neither line width nor line spacing appreciably influence measurement data acquired using the measurement methods of the present study. The second conclusion is that the 3/4" spacing and the 1/32" line width are preferred by observers and should receive serious consideration in any effort directed at standardizing the line width and spacing of gridboards.

APPENDIX

INSTRUCTIONS TO TEST SUBJECTS

1. Technique for measuring the lens factor and displacement grade of transparencies from photographs.

   A. Equipment

   Measurements will be made at a drafting table using a drafting machine. Equipment will include:

   1. A drafting machine securely fastened to a drafting table.
   2. A ruler with a scale accurately divided into hundredths of an inch.
   3. A 45°-45° or 30°-60° drafting triangle with a leg at least 8 inches long.
   4. A pair of precision bow dividers, such as used in a drafting set, with opening of the points adjusted by a rotating screw operated by turning a knurled ring or wheel.
   5. A large diameter (3"-5") low power commercial illuminated magnifier supported on a long flexible arm which is fastened to the drafting table.
   6. A roll of 1/2" or 1" wide drafting tape.
   7. Pencil and scratch paper.
   8. A strong low glare illumination source.
   9. A supply of data recording forms made especially for the present investigation.

   NOTE

   For the purposes of this study each photograph will be completed before going on to the next one. The photographs will be evaluated in numerical order, according to a number written in the upper right hand corner of each print.

2. **Measuring the Calibration Photographs**

   A. Six of the twenty-four prints will not have a distorting transparency placed in the field-of-view. They may be readily identified by the fourth line of the ID board, which will read, "WS CALIBRATION." (Also, there is no outline of a transparency present.)

   B. It will be necessary only to measure the grid squares per inch in the horizontal and vertical directions on these six prints. The procedure is as follows.

   C. Tape the print down in a convenient position on the drafting table. Set the tips of the dividers to exactly one inch (1.000"), using the precision ruler. Mentally dividing the grid board image into equal quadrants, count the number of horizontal and vertical grid squares per inch in each quadrant. Interpolate to the nearest 10th of a square. Record these numbers (such as 15.9) in the appropriate block on the Data Recording Form.

   D. There is no requirement to measure the displacement grade of these calibration prints.

3. **Measuring Horizontal and Vertical Displacement Grade of the Distortion Photographs**

   A. The remaining eighteen prints consist of combinations of three distorting transparencies, three grid sizes, and two line widths. The horizontal reference of the drafting machine must be accurately paralleled to the undistorted horizontal lines of these distortion photographs. For the 12 x 12-inch flat plate, use one of the grid board lines showing over the top of the plate. For the two F-111 windscreens, use one of the longest grid board lines showing underneath the foreward arch of the part in the lower left hand corner of the print. In either case, rotate the print under the horizontal reference of the drafting machine until you are positive the undistorted grid lines are parallel to the machine. Carefully tape the print down by its four corners and recheck the parallelism.

B. **Measuring Vertical Displacement of the Horizontal Lines**
Beginning at the top (or bottom) of the photograph, move the horizontal reference down (or up) until it is just tangent to the highest (or lowest) point of a particular horizontal line. Follow this line to the left and right of this point and mentally note how much it deviates from the reference. Use the grid board's divisions as a rough unit of measure. Scan the entire photograph in this measure, noting those lines for which the deviation is close to the maximum encountered. Now go back and make accurate measurements on the handful of candidate lines. For each of these lines, carefully position the drafting machine at the point of tangency so that when a tip of the dividers is positioned vertically at this point, it rests firmly against the reference and *bisects* the line. Follow the line to its point of maximum deviation and make a horizontal scratch on the print, using the reference to guide a tip of the dividers. Move the reference out of the way and adjust the dividers to exactly span the maximum vertical distance between the scratch and the *middle* of the candidate line. Place the dividers on a precision ruler, divided in hundredths of an inch, read and record the distance to the nearest estimated (interpolated) thousandth of an inch. Do this for each of the candidate lines. Once the line with the maximum deviation is determined, mark one of the ends of the line with a small arrow, using a tip of the dividers again, and record the displacement in decimal format on the form. Be sure to use the illuminated magnifier for all accurate measurements.

C. **Measuring Horizontal Displacement of the Vertical Lines**
Without removing the photograph or adjusting the drafting machine's horizontal reference, use a 45°-45° or a 30°-60° drafting triangle to provide the vertical reference and repeat the above procedure.

4. **Measuring the Horizontal and Vertical Magnification of the Distortion Photographs**
A. The drafting machine will not be required for these measurements, but it will be convenient to keep the print taped to the drafting table. Locate the Data Recording Form corresponding to the same grid size and line width as that of the print you are presently evaluating. Double check this! Note the average horizontal grid squares per inch you had calculated earlier on the calibration print. Setting the dividers to exactly one inch as before, you are to find a distorted area on this print that is *maximally different* in its horizontal grid squares per inch measurement from that of the average measurement taken from the corresponding calibration print. For example, let 16.0 be the average. On the present print you measure, 16.1, 15.8, 15.1, 16.3, and 15.9. The maximally different measure is 15.1 rather than 16.3 because 15.1 is almost twice as far from the average as is 16.3. Check as many distorted areas as you feel is necessary. Be sure to use the illuminated magnifier. Frequently check the spacing of the divider points, as it is quite easy to inadvertantly "adjust" them during this procedure. Record the maximally different number on the form and, using a divider point, draw a narrow ellipse about the line segment on which the measurement was made.

B. Repeat this procedure for the vertical lines.

NOTE

Feel free to make marks and notes on these prints as may help you save time and increase your accuracy. Only be sure that the lines you used for calculating the recorded magnification and displacement grade are clearly indicated on the print.

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