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A COMPUTER-BASED AUTOMATIC METHOD FOR DETERMINING VISUAL ACUITY*

Edward R. F. W. Crossman† and Peter J. Goodeve‡
Department of Industrial Engineering and Operations Research
and
Elwin Marg◈
School of Optometry
University of California, Berkeley, California

ABSTRACT

A computer-based automatic method for clinical visual acuity determinations is described. The procedure employs the staircase method of threshold determination using Landolt C's, and has been tested on 14 subjects representative of normal optometry clinic patients. Though more precise due to small step size, the results show fair agreement with manual determinations performed at the same time using the Snellen chart. The automatic method required more time because (1) subjects used 4 instead of 26 response alternatives, and (2) a mean step size of 1.15:1 instead of 1.5 or 2:1 was used. While most series of repeated automatic determinations were stable, a few subjects showed improvement or deterioration apparently due to practice or fatigue, respectively.

Economic aspects of computer assistance for optometric examinations are briefly discussed and attention is drawn to the potential value of time-sharing and remote operation.

In a previous paper[1], two of the present authors discussed the potential value of computer-based automatic optometry procedures and described a manual simulation of a potentially automatic new method for visual acuity measurement. This was based on continuous adjustment of the size of a test object, the subject being required to report one of four alternative orientations. It was noted that a similar psychophysical procedure had earlier been introduced into clinical audiometry by von Bekesy[2]; Bekesy's method was fully automatic in that it was operated by the subject, and once started it did not require a professional operator. However, results were acquired in graphical form, requiring subsequent human interpretation. Ideally an automatic procedure, either for audiometry or visual acuity determination, would require no human assistance other than that of the subject or patient, and would present results in a form directly useful for clinical diagnosis and recording. The present report describes trials of a

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†Industrial Engineer, Ph.D., Professor of Industrial Engineering.
‡Research Engineer, M.S.
◈Optometrist, Ph.D., Member of Faculty. Fellow, American Academy of Optometry.

visual acuity determination procedure meeting these criteria.

While our earlier method employed a continuously variable test object, the discrete-stimulus principle embodied in the standard Snellen-chart method offers advantages for computer implementation, and has been retained. Discrete stimuli are selected and displayed by means of a program-controlled automatic slide projector developed by modifying a standard commercial product. If discrete stimuli can be presented automatically, it is then necessary to program a procedure yielding rapid and unbiased estimates of the subject's "true" visual acuity. Since visual acuity is essentially the subject's threshold for detection of fine detail, one of the classical psychophysical methods[3] would immediately suggest itself. Either the "method of limits," that of "constant stimuli," or the reaction-time method could be used. However, the "up-and-down" method of Dixon and Mood[4,5] originally devised for sensitivity testing of explosives and other products is faster. It has been used in psychophysics by Cornsweet[6] as the "staircase method," but does not appear to have been employed previously for visual acuity determination by computer.

A still more sophisticated discrete level adaptive method named PEST (Parametric Estimation by Sequential Testing) was recently described by Taylor and Creelman[7] and discussed by Pollack[8]. This has proved effective in auditory research but is considered overly complex without compensating advantages for clinical practice in optometry.

Thus the present paper describes a fully automatic "up-and-down" method for fast routine visual acuity determination implemented on a small digital computer interfaced to a remote-controlled slide projector. In its present form the system achieves a reasonable compromise between the conflicting requirements of simplicity, speed and precision and results obtained in an initial experiment are in reasonably good agreement with Snellen-chart determinations. We have thus been able to demonstrate the feasibility of determining visual acuity by automatic methods, opening the way to possible future development of a fully automatic procedure for clinical refraction. Some of the design tradeoffs and economic considerations governing the adoption of automatic methods are discussed briefly in the light of our experience to date.

PRINCIPLES UNDERLYING THE AUTOMATIC STAIRCASE METHOD

The automatic method is best understood as a development of the conventional non-automatic Snellen-chart procedure for determining visual acuity, which proceeds as follows: The subject or patient is asked to read a semi-random sequence of alphabet letters of a given size (i.e., visual subtense) to the optometrist. The latter mentally notes the correctness of each response and evaluates whether or not the subject appears able to resolve that size of detail. On judging that the subject "Can" or "Cannot" read a particular row, the optometrist calls for the next smaller (or larger) row, and the procedure terminates when the optometrist decides he has found the smallest row that the patient "can" read. Its subtense measures his acuity relative to that of the normal subject, results being normally expressed in the fractional form 20/x, where x is the distance at which the "normal" subject can just read the smallest line that the patient can read at 20 ft distance. If the subject fails to read a certain number of letters on one line, or succeeds in reading some on the next line, a notation may be appended to the fraction indicating slightly less or more acuity than row size would indicate.

In reading each letter the subject selects one of up to 26 alternatives, or else makes a negative ("don't know") response. The correctness of his 26-choice response is assessed directly by the optometrist who generally appears to encourage guessing in order to avoid underestimating acuity. If the subject guesses, he will be correct by chance only once in 26 times ($p = 0.038$). By inverse probability, a single correct response permits the strong inference that the subject can actually read the letter, there being only 3.8% likelihood that he was unable to read it, yet made a correct guess. If two consecutive correct responses are obtained p nearly equal to $(0.038)^2 = 0.0016$, reducing the likelihood of error to 0.16%[a] Further, assuming a well-motivated subject, a single error permits 96.2% confidence that the subject cannot read the line in question. Thus reading alphabet letters is a fast, accurate method of determining visibility of fine detail.

Our computer-based procedure follows essentially the above sequence, but since verbal responses cannot be interpreted, and we cannot require the patient with poor acuity to operate a 26-key teletype (or other keyboard) accurately, the task must be simplified. A 4-choice Landolt C type of target was adopted, the patient being asked to indicate its orientation by moving a joystick North, South, East or West. With this arrangement, the probability of a guess being correct is 0.25, and five successive correct responses (yielding probability $p = 0.001$) are required to reach the same certainty that the target subject actually can resolve detail of the given size, that we obtain from two correct alphabet letters. A single correct response yields only 75% confidence of readability, and two successive ones are required for 93.8% confidence. Therefore a forced 4-choice procedure is expected, other things being equal, to require about 2½ times as many responses to reach similar confidence levels as with a 26-choice alphabet. Including a "don't know" option theoretically improves the situation more in the former than in the latter case, since in the 4-choice case a single "don't know" response immediately yields perhaps 98-99% confidence that the given size of detail cannot be resolved, and is worth more than two errors. This theoretical advantage was tested by including two alternate procedures, designated Conditions A and B, in the experiment. Condition A provided positive response options only and required guessing if the subject could not discriminate. In Condition B an additional "don't know" button was provided and the subject was asked not to guess.

As mentioned earlier, a random-access slide projector was used to present single targets[b]. This made it feasible to change size at the same time as changing orientation and, as in the "up-and-down" method of Dixon and Mood, the target size was increased after every error (or "don't know" response) and

[a]This argument ignores differences in discriminability of letters. Space does not permit discussion of this apparently minor factor here.

[b]A computer generated CRT display would probably be a feasible alternative.

decreased after every correct response. Due to guessing in Condition A, some 25% of steps are downwards though the subject is actually not able to discriminate the target. This causes appreciable loss of time, but does not affect the final determination, since the computer stores the results of all past trials for use in calculating the final reported value.

As shown earlier the automatic method might be expected to require about twice as much time as the conventional one using the same step sizes as for

TABLE 1
TARGET SIZES USED IN CONVENTIONAL AND AUTOMATIC ACUITY DETERMINATIONS

Automatic		Conventional	
Size (Snellen Scale)	Ratio of Successive Sizes	Size (Snellen Scale)	Ratio of Successive Sizes
20/ 5.0	----	20/ 10.0	----
6.6	1.32	20.0	2.00
8.7	1.32	30.0	1.50
10.7	1.23	40.0	1.33
12.6	1.18	100.0	2.50
15.0	1.19	200.0	2.00
17.3	1.15		
20.0	1.15		
22.6	1.13		
25.6	1.13		
29.0	1.13		
32.3	1.12		
36.3	1.12		
40.6	1.12		
45.6	1.12		
51.6	1.11		
66.7	1.29		
77.3	1.16		
83.3	1.08		
92.3	1.11		
143.2	1.55		
158.2	1.10		

the American Optical Company Snellen chart (Table 1). However, a smaller step size was used to yield greater resolution, the mean ratio being 1.15:1 (see Table 1); there were 22 target sizes in all, covering the acuity range 20/5.0 to 20/158.2. The smaller step size should reduce speed by a further factor of two or three relative to the conventional method. This speed reduction was judged acceptable in a pilot experiment requiring greater than normal precision.

The computer automatically reported the first determination when a target of any single size had been presented five times; it then computed and typed out the acuity. This was done by summarizing the error rates at all target sizes presented and finding the equivalent size for a given "threshold" error rate (37% for Condition A, 50% for Condition B) by interpolation on the resultant psychophysical curve. The result was typed out shortly after the patient's final response, and parameters were then automatically initialized for the next determination.

EQUIPMENT AND PROGRAM

The program was run on a small general purpose computer[c] with 4,096

[c]Digital Equipment Company PDP-8.

12-bit words of core memory and 1.5 μs memory access-time. This actuated a carousel slide-projector[d] containing 80 target slides, by remote control, access-time being about one second. Changeover was initiated immediately after the subject had made his response to the current target and the screen was dark between targets. (See Figs. 1 and 2.)

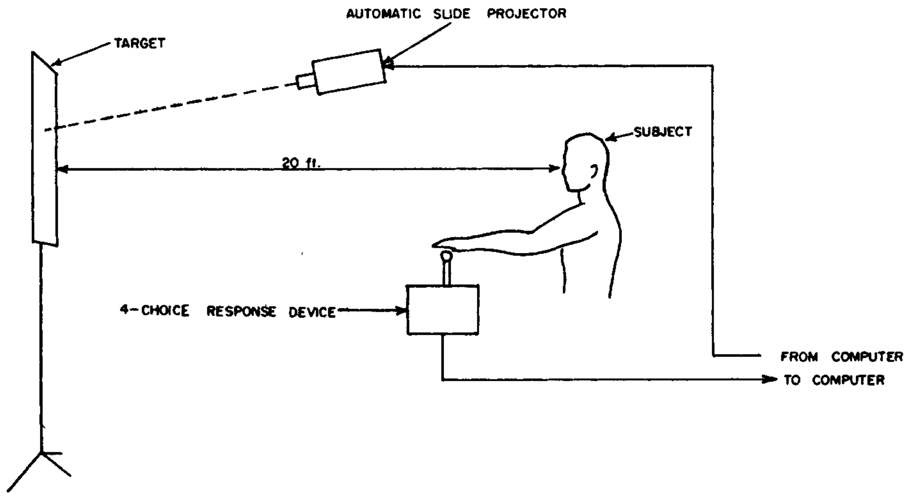

Fig. 1. Geometrical layout for automatic visual acuity determination.

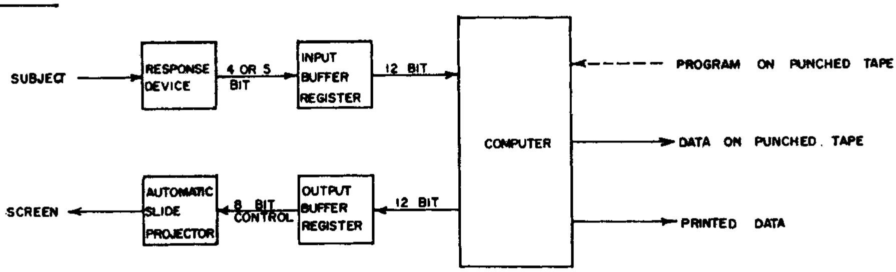

Fig. 2. Schematic arrangement of the automatic system.

The targets[e] (see Table 1) were Landolt C's with black bars forming a surrounding rectangle, projected onto a matte screen at 20 ft distance from the subject. The 20/20 target had a gap size of 1 minarc making it equivalent to a 20/20 Snellen chart C.

The subject's response was recorded by means of a 3″ joystick lightly spring-centered and mechanically constrained to move in one of four directions (Fig. 1). A 1″ movement from center actuated the computer input buffer register, making the occurrence and nature of the response available to the program. In Condition B an extra pushbutton was provided, permitting a "don't know" response.

[d]Kodak Type PR950.

[e]Provided by courtesy of Dr. Lawrence Harwood and Prof. Merton Flom, Optometry School, U.C., Berkeley; these were originally intended for testing amblyopia, and actually represented equal intervals on the Snell-Sterling scale, reduced by a factor of three.

The program[f] employed approximately 500 machine instructions and a flow chart is given in Fig. 3. Computations were performed in binary arithmetic and results were punched on paper tape and/or printed on a teletypewriter. Subsequent analysis of the data was performed on the same machine using a Fortran system.

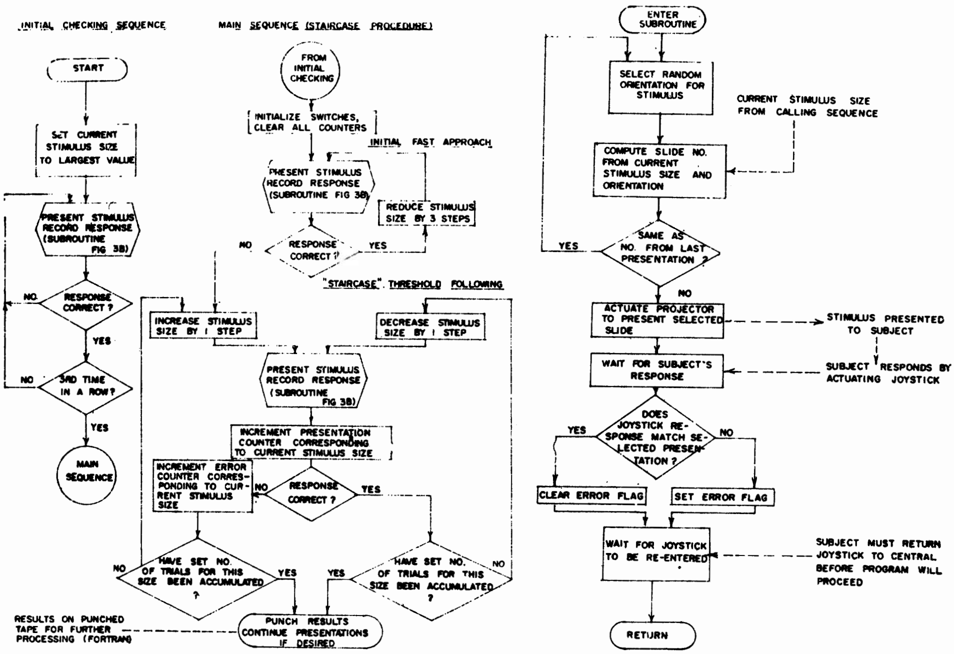

Fig. 3. Flow diagram of acuity determination program (mode B). A. (Left) Initial checking and main sequence. B. (Right) Stimulus presentation and response recording subroutine.

EXPERIMENTAL DESIGN AND PROCEDURE

Fourteen student subjects were used, the later ones being selected for poor uncorrected acuity. While this group, having a mean age of 21 years, good intelligence and being apparently free from pathology, was certainly not a random sample from the total population of potential optometric patients, it was representative in that none of the subjects were experienced in computer usage, optometry, or psychophysics. None of the subjects experienced difficulty in performing the required task and all gave satisfactory results.

In routine clinical use a single determination would be performed for each eye, but for the present purpose we made several successive determinations to assess reliability, and to compare Conditions A and B. Successive conditions were prepared manually by the experimenter.

Subjects were tested singly; they sat in a standard position in an open laboratory, with a screen at 20 ft distance, and with the joystick placed for convenient manipulation by their dominant hand. Their visual acuities were first determined by the conventional method with and without eyeglasses (if

[f] The symbolic code is available from the authors.

any), using an American Optical Company Snellen chart (#194) at 20 feet with about 10 ft-candles of illumination[g].

After brief instruction and demonstration of the automatic system, the program was set running and the experimenter made no further intervention. The automatic procedure had three phases, each being a series of target presentations in random orientation. It began by checking that the subject was able to see and respond correctly to the largest target, by continually presenting it until he made three successive correct responses. The successful completion of the initial check phase initiated a rapid approach to an approximate threshold value by a series of presentations each three steps smaller than the last (size reduced by a factor of 3 x 1.15); this rapid reduction in target size was maintained as long as the subject responded correctly; at his first error, the size was increased by one step and the third phase was entered. From this point on, a correct response always resulted in selection of a target one size smaller for the next presentation, an incorrect one (or "don't know" in Condition B) in a target one size larger. When the number of presentations of any single target size reached a limit value held in the program, the procedure was interrupted and the accumulated data punched out; the limit began at five and was increased by five after data punching; the third phase was then resumed and continued until the new limit was reached, a cycle which could be continued as many times as desired.

RESULTS AND ANALYSIS

First Automatically Determined Acuity vs. Snellen (Manual) Acuity

Table 2 presents the acuity values obtained by the automatic procedure on its first run for a given subject with left and/or right eye. Due to the statistical design of the study, not all the possible determinations were made on each subject, and these results are presented to give the reader a general idea of the agreement between manual and automatic rsults, rathr than formally to establish the validity of the latter. It will be noted that the automatically-determined acuities were generally better than those measured manually. The difference is largely explained by the smaller step size used in the automatic method (see Table 1; ½ to ⅓ that of the Snellen chart). Other possible factors are the nature of the Landolt C targets and the greater contrast obtained by projection. Aside from this constant difference the manual and automatic results were in good agreement, though further research will be required to establish full confidence in the latter.

It will also be noted that the automatic determinations yield more significant figures than the manual ones. This was due to the interpolation algorithm used to compute final values from stored data, and represents a genuine gain in precision. The manual procedure could of course be modified to match this at a cost in speed and simplicity.

Stability of Automatically Determined Acuity Under Sequential Testing

Some sequences of results obtained from successive automatic determinations on selected subjects are graphed in Fig. 4. While most subjects yielded

[g]The experimenter (PG) had had relatively little experience with this method and the results may not have obtained the full performance of which subjects were capable.

TABLE 2

COMPARISON OF ACUITIES DETERMINED BY CONVENTIONAL AND AUTOMATIC METHODS

Subject No.	Correction	Eye	Conventional (Snellen) Acuity (Denominator)	Automatic Acuity (1st Value)	Condition	No. of Presentations	No. of Targets
1	No	Both	20	12.3	B	9	3
	No	R	20+4	13.0	B	9	3
	No	L	20+4	14.1	B	10	3
3	No	R	100+1	69.3	A	18	5
	No	L	40+3	13.8	A	12	5
4	No	R	200/100†	73.5	A	16	7
	Yes	L	20−4	18.5	A	13	5
5	No	R	20	12.2	A	15	4
	No	L	20+2	16.4	A	14	7
6	No	R	20+5	16.5	A	14	5
	No	L	20+4	14.1	A	14	5
7	No	R	20−5	32.6	A	10	3
	No	L	40−1	39.7	A	9	3
8	No	R	20+3	12.8	A	16	6
	No	L	20+1	12.2	A	9	3
10	No	R	30−1	30.5	B	13	5
	No	L	30−2	23.1	B	11	4
11	No	R	200	82.0	A	12	4
	No	L	100	109.0	A	11	4
12	No	R	20+6	9.4	B	11	4
	No	L	40−1	41.0	A	17	6
13	No	R	100−1	77.7	A	11	4
	No	L	100+3	49.5	A	12	4
14	No	R	200	47.8‡	A	24	9

†Obtained by "squinting."
‡Off scale of automatic system in subsequent trials.

stable series of values, certain individuals (e.g., #12, left eye) showed improvement with practice, and others (e.g., #10, right eye) showed a decrement, perhaps due to fatigue or loss of motivation. These fluctuations did not exceed a 2:1 ratio. It will probably be desirable to modify the automatic procedure for optimum stability over a wide range of types of subject, and in particular it seems necessary to detect and offset initial lack of skill at manipulating the response stick, perhaps by a brief period of practice before the determination proper. The optometrist seems to recognize the unskilled patient by hesitation or verbally-expressed uncertainty and presumably helps him by special instruction. An automatic system cannot do this directly, but could perhaps use reaction time[h], or inconsistency of errors as cues to give additional initial practice trials.

The performance decrement observed in a few cases and attributed to fatigue should cause no problems in clinical use, as the single determination normally required should not last long enough (25-50 responses) to cause fatigue.

Forced vs. Unforced Choice

The availability of a "don't know" response option did not affect the measured acuity (Table 3). However, as predicted theoretically and shown in Table 2, the average number of presentations was significantly less in the

[h]The time between the initial presentation of the visual acuity test object and the joystick response of the patient.

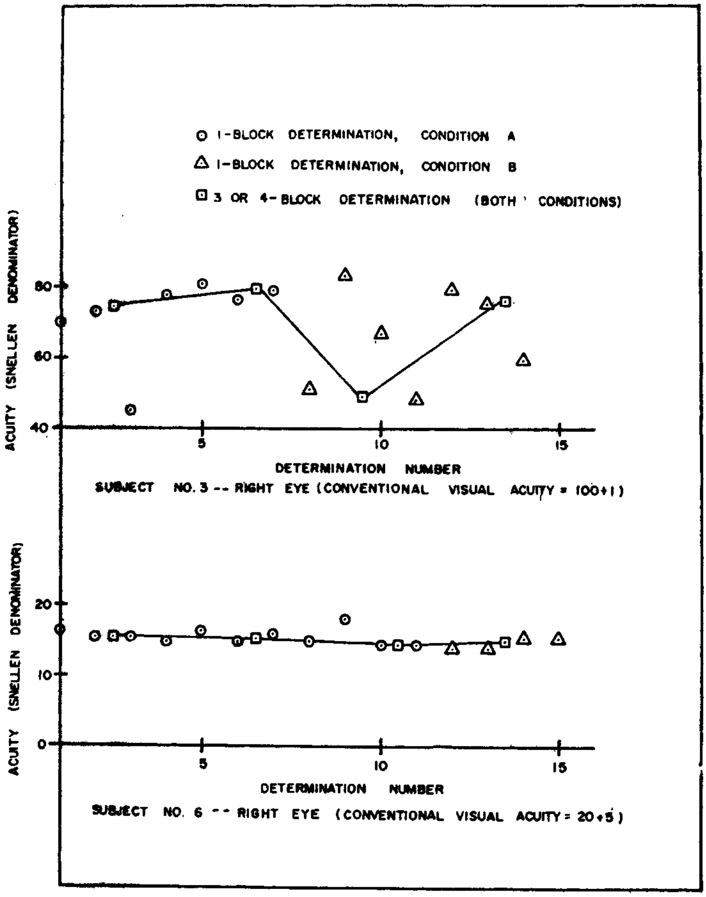

Fig. 4A. Sequences of automatic visual acuity determinations obtained from typical subjects under conditions A and B. Subjects numbers 3 and 6.

B Condition. We conclude that the "don't know" response option should be retained.

Relative Speed

The approximate duration of the automatic procedure may be obtained from the number of presentations listed in Table 2, each taking between 1½ and 5 seconds. Stopwatch times were also taken in a number of sample cases (Table 4). Times on the order of 2 minutes were normal for a single first determination.

CONCLUSIONS FROM THE EXPERIMENT

The experiment appears to demonstrate the feasibility of automatic visual acuity determinations, and to show fair *prima facie* agreement with results obtained by the conventional method. The automatic technique used was somewhat primitive and considerable improvements in efficiency, precision and reliability can be foreseen; but even in its present form it offers a satisfactory substitute for the manual method. The addition of an auditory channel, such as a computer-actuated tape recorder, to provide initial instructions, select the eye

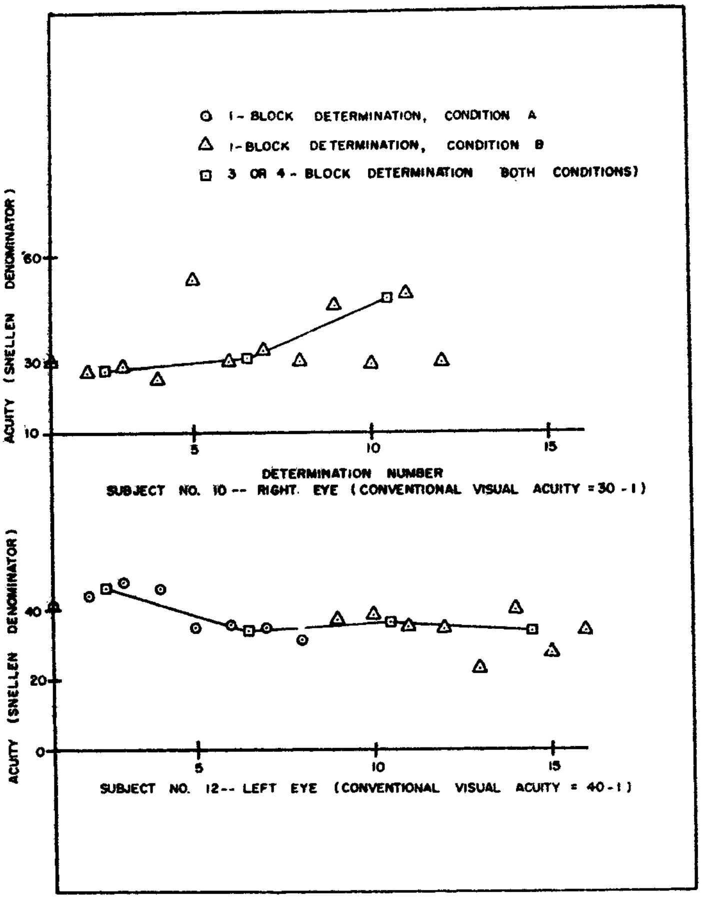

Fig. 4B. Sequences of automatic visual acuity determinations obtained from typical subjects under conditions A and B. Subjects numbers 10 and 12.

being examined, call for use or non-use of eyeglasses, and tell the patient when the session ends, would render the system entirely independent of expert assistance. This would permit unattended operation, for instance in mass screening procedures such as multiphasic physical examinations and driver fitness tests.

ECONOMIC CONSIDERATIONS

Demonstrating the technical feasibility of a procedure does not, of course, establish an economic case for its adoption in professional and clinical practice. This requires that benefits must clearly outweigh costs. Thus it seems likely that investment in even a small automatic system, such as that described, costing on the order of $10,000[1] could be justified only where large numbers of acuity determinations were performed, as in vision testing for motor vehicle operators or for armed services medical examinations. In clinical optometry it would save only a very few minutes of professional time per patient. However, coupled with an automatic case history taker and means of performing subjective refractions and generating prescriptions, the economic outlook would be very much more

[1]At 1968 prices.

TABLE 3

COMPARISON OF AUTOMATICALLY DETERMINED VISUAL ACUITIES OBTAINED ON FIRST TRIAL WITH AND WITHOUT A "DON'T KNOW" RESPONSE OPTION

Subject No.	Eye	Condition A (Mean of 4 Trials)	Condition B (Mean of 1st 4 Trials)	Difference	Percent of A Value
3	R	66.7	62.5	−4.2	− 6.2
	L	25.0	23.3	−1.7	− 6.8
4	R	82.1	76.0	−6.1	− 7.4
	L	20.2	23.8	+3.6	+17.8
5	R	12.0	12.9	+0.9	+ 7.5
	L	15.2	11.8	−3.4	−22.4
6	R	15.7	14.8	−0.9	− 5.7
	L	15.5	14.3	−1.2	− 7.7
7	R	28.1	29.7	+1.6	+ 5.7
	L	41.1	36.9	−4.2	−10.2
8	R	11.5	11.7	+0.2	+ 1.7
	L	11.3	11.8	+0.5	+ 4.4
12	L	44.8	36.2	−8.6	−19.1
13	R	78.9	82.9	+4.0	+ 5.1
	L	66.1	71.5	+5.4	+ 8.2
			Mean Difference (A − B)		− 2.34

TABLE 4

TIME REQUIRED TO COMPLETE AUTOMATIC DETERMINATIONS OF VISUAL ACUITY

Subject	Eye	Condition	Time to Complete 3 Automatic Determinations
7	R	A	4.57 min
	L	A	6.00
	R	B	3.36
	L	B	7.25
9	R	A	3.90
	L	A	2.80
	R	B	3.30
	L	B	2.60

positive due to increased time savings. Capital investment in computer hardware would then probably look attractive. Both of these are currently under development in our laboratory and show distinct promise. Time-sharing the services of the computer to operate two or more examination stations simultaneously is also feasible with the type of equipment described here, and would further improve the cost-benefit ratio.

As an alternative to direct purchase of a small computer, buying time on a large machine may also be considered. Since the necessary control signals and voice instructions can readily be transmitted over normal telephone channels, there is no reason in principle why the examination should not be controlled by a larger remote machine. This suggests that a central optometric utility could provide the necessary service on a per-hour rental basis, requiring the optometrist or clinic to install only a moderate amount of peripheral equipment and obtaining service as and when required.

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