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Huematic—An Automated Scorer for the Farnsworth-Munsell 100 Hue Test

A. R. HILL,[1] B. C. REEVES[2] and A. BURGESS[3]
Oxford and Glasgow

Summary
A cheap, portable automated scorer for the Farnsworth-Munsell (FM) 100 hue test has been developed. It consists of a light pen, a series of omni-directional bar-codes attached to the reverse of the FM 100 hue caps and a small micro-computer. The print-out includes patient details, a linear histogram of the partial errors by cap position, indication of the peak error positions for congenital colour vision deficiencies and appropriate statistical analysis of the total error score. All the results are available within four minutes of completing the testing procedure.

Although the Farnsworth-Munsell (FM) 100 hue test was originally designed for use in industrial screening,[1] it has been found to have considerable value in the detection and diagnosis of both congenital colour vision deficiencies and acquired dyschromatopsias.[2] The clinical usefulness of the test was greatly increased by the publication of monocular age-related error score norms[3] and normative data for differences in error score between eyes.[3,4] However, in recent years use of the test appears to have been largely confined to clinical research.[5] The FM 100 hue test is still widely considered to be the best practical clinical test of colour vision, and it is also one of the few tests which are appropriate for investigating acquired dyschromatopsias (*unlike* pseudo-isochromatic tests). Thus the decline in popularity of the test among practicing clinicians is not a reflection of its diagnostic usefulness but rather a consequence of the increased demand for shorter tests with immediately available results. With respect to the first of these two factors, testing both eyes on the FM 100 hue test takes about 20–30 minutes. This may be regarded as longer than desirable, although it should be pointed out that tests of short duration often have poor reliability.[6] But the FM 100 hue test also fails the second requirement, because of the lengthy procedures involved in the scoring and plotting of results; this is particularly the case when there are marked hue discrimination losses and consequent high error scores on the test.

Various attempts have been made to overcome this second failing by automating the scoring and plotting procedures. Many researchers have described computer programmes which perform the necessary arithmetic calculations and which plot the results.[7,8] Although these solutions have reduced the scoring time to some extent, they all require manual keying-in of the raw data which is one of the lengthiest parts of the scoring procedure and one which is prone to transcription errors.

Taylor and Donaldson[9,10] developed an

[1] Principal Optometrist, Oxford Eye Hospital and Honorary Fellow, Nuffield Laboratory of Ophthalmology, University of Oxford, Walton Street, Oxford OX2 6AW.
[2] Visual Science Unit, Radcliffe Infirmary, Woodstock Road, Oxford OX2 6HE.
[3] Glasgow College of Technology, Cowcaddens Road, Glasgow G4 0BA.
Correspondence to: B. C. Reeves, Visual Science Unit, Radcliffe Infirmary, Woodstock Road, Oxford OX2 6HE.

integral system using differentially coded resistors and capacitors to identify each cap. The electronically decoded sequence of caps was then transferred to a microcomputer which calculated the error score for each cap position. These errors were, in turn, used to generate a polar plot, similar to the traditional score chart. This system proved to be of considerable value in a clinical setting where time was at a premium.[11] Minor improvements were made[12] by providing some instrument checks and by making available two scoring options, those of Farnsworth[1] or Kinnear,[13] and the system was made available in 1978 by Osprey Electronics Ltd at a cost of £2,750. However, it met with little success and is no longer available. The high cost, the constraints placed on the test methodology (caps were plugged into position and therefore the subject was not able to slide them to and fro freely) and its sheer bulk were the primary reasons for its unpopularity. A similar system was developed and marketed in France under the name of Chromops in 1982 by Biophysic Medical S.A. It was discontinued in 1985, when its cost was £6,090.

It is clear from the above (a) that there is a need to reduce the time taken to score and plot the results for the FM 100 hue test and (b) that none of the attempts to fulfil this need have so far enjoyed widespread success. Against this background we established the principal aims for an automated scorer. These were that it should be cheap (relative to previous automated scorers), portable, quick and easy to use, and that it should provide output in a form which can be readily interpreted by the clinician.

The Huematic

The Huematic prototype (Patent pending, application no. 8628178) uses three components in addition to the standard FM 100 hue boxes and caps. These are:

(i) a series of omni-directional bar-codes (see Figure 1), attached to the bottom of the caps, which act as unique identifiers,
(ii) a standard Hewlett-Packard light-pen to read the bar-codes,
(iii) an Epson HX-20 microcomputer for the analysis and printing of results.

The only other requirement is for slots to be cut in the bottom of the boxes which contain the caps, through which the codes are read (see Figure 2).

The codes are based on one of the internationally accepted bar-code systems, namely: 'Interleaved 2 of 5'. This system is adapted especially for the two digit numbers, one digit being represented by the sequence of black/white transitions and the other by the sequences of white/black transitions. The numbers 1–99 allow all of the 85 caps to be coded uniquely (i.e. no duplication between boxes), with enough spare codes to identify each box as well. The system was chosen because it used the fewest check bits and other sophistications (irrelevant to our application) and could therefore be printed within the smallest space. This was an important requirement since space for the code was restricted to the overall diameter of the FM 100 hue caps. We have incorporated our own checks in the

Fig. 1. *A selection of the omni-directional barcodes on the reverse of the 100 hue caps. The codes are based on the 'Interleaved 2-of-5' system, in which the sequence of black bars encodes the 'tens' digit and the sequence of white bars encodes the 'units' digit.*

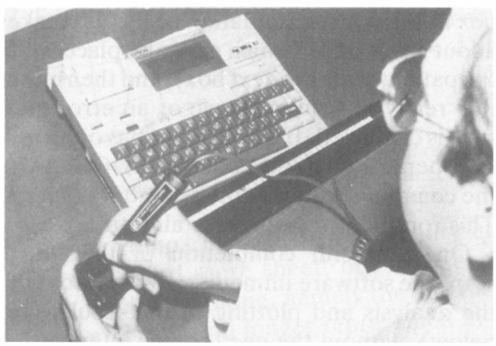


Fig. 2. *The Epson, the barcode wand and one of the 100 hue boxes. The operator is about to read the barcodes (just visible in the photograph), which are scanned by sweeping the wand along the slot in the bottom of the box.*

software to verify the accuracy of the bar-code reading. These are:

(i) to check that all the codes in any one box fall within the range which the software is programmed to expect on reading the 'box identifier' (the code attached to the left-hand anchor),

(ii) to check that the correct number of codes are read for the box being scanned.

(iii) to check that the code on each cap is read identically from edge to centre and from centre to edge. (The software reads a code as the same number, irrespective of the direction of scan. Because of the circular configuration of the omni-directional codes, each one is read twice during scanning, which provides this useful check.)

In each case an appropriate error message is generated if there is a misread.

Procedure

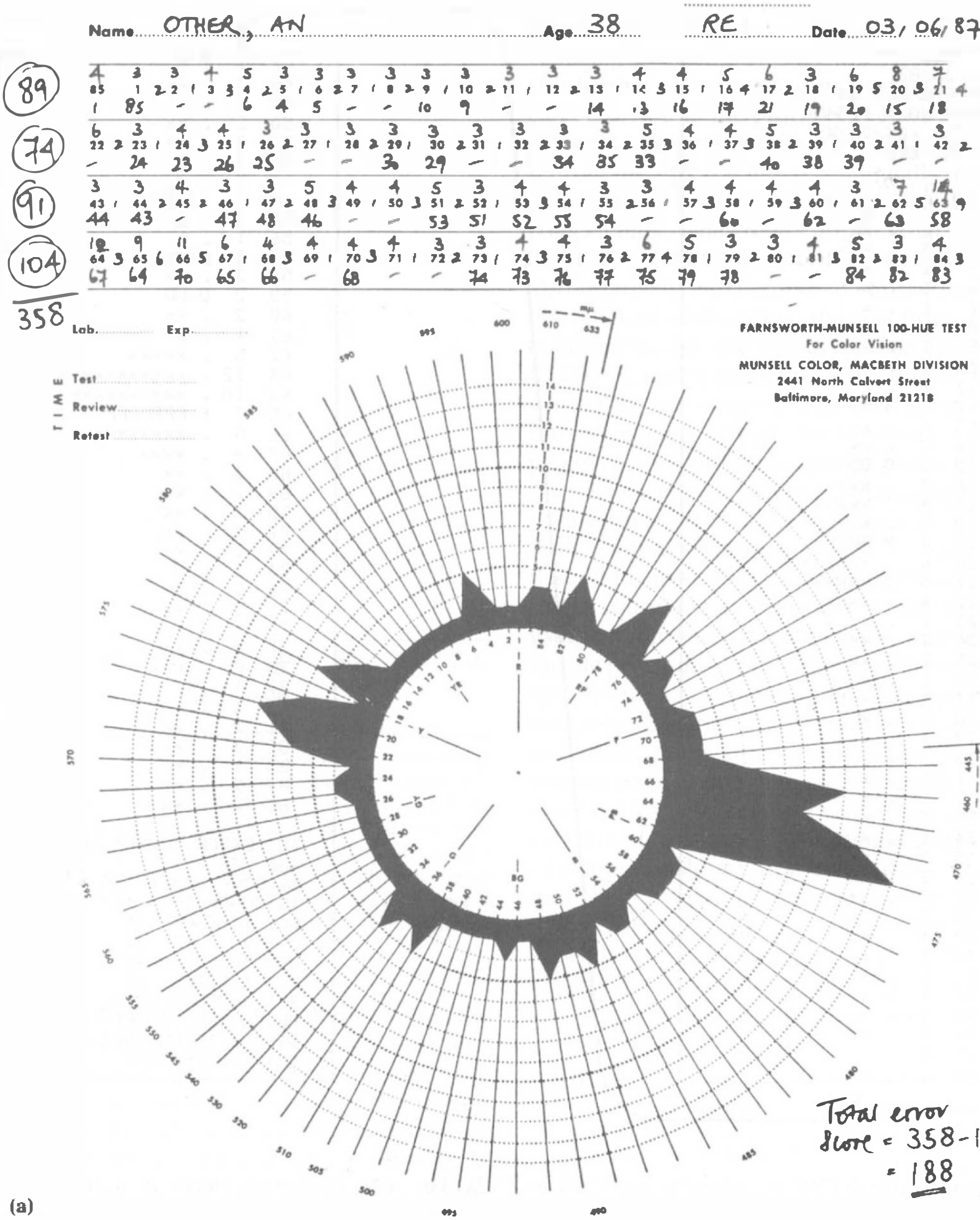
When the Huematic is switched on, it displays a prompt on the liquid crystal screen, requesting the operator for the patient's details, i.e. name (up to 15 alpha-numeric characters), hospital number (a six-figure character field), date of birth (format MM/DD/YY) and eye identifier (R or L). These details are entered via the standard keyboard of the Epson. A message 'ready to scan' is then displayed, and the computer waits for the data from the first box sorted by the patient. To scan, the operator simply presses the switch on the light-pen and sweeps the tip across the codes with gentle pressure, using the slot in the bottom of the box as a guide. Assimilation of the data takes about 30 seconds (which can take place while the patient sorts the next box), and then either the 'ready to scan' message or an error message is displayed. If a read error has occurred, the operator scans the codes again. Otherwise the computer waits for the second set of data. This routine is repeated for all four boxes.

On successful completion of the fourth scan, the software immediately proceeds with the analysis and plotting of the results (see below), without the need of any intervention by the operator. The programme has been designed to use Kinnear's[13] scoring procedure, but the original Farnsworth method[14] could easily be offered as an alternative option. After printing the total error score, the operator is given the option of keying-in the error score for the other eye (if already tested), allowing assessment of the inter-eye difference in score. Finally, an option allowing the operator to proceed to test the next eye, or to finish, is displayed.

Patient Record Chart

A sample print-out is shown in Figure 3, together with an example of the conventional scoring sheet. The Huematic print-out starts with the date of the test, patient details and identification of the eye tested. This information is followed by a linear bar chart showing the individual errors for each cap position. On each row the cap position is printed first, followed by a number denoting the error score for the position, a dot or a letter if the position corresponds to one of the primary error axes for congenital colour vision deficiencies (T, S, D, or P for tritan, scotopic, deutan or protan error axes respectively) and a histogram bar representing graphically the number of errors by crosses, T, S, D or Ps. In some cases the maximum number of errors in some of the positions can be so large that the bar would extend beyond the edge of the paper if one cross represented each error. Therefore, when the maximum cap error exceeds 14 the Huematic prints only one cross for every two errors, thereby maintaining the profile of the bar chart for easy visualisation and error axis interpretation.

The patient's age is calculated from the date of birth entered at the start of the test and the internal calendar of the Huematic. The computer is programmed with age norms, in the form of two fifth order polynomials, for one-tailed 95 per cent and 99 per cent confidence limits respectively (see Figure 4), derived from the results of Verriest *et al.*[3] Below the bar chart the total error score, with the relevant confidence limits for the patient's age, and the partial scores for each box are printed. The computer then automatically compares the total error score with both confidence limits, and prints a statement giving the result of a one-tailed statistical test of the hypothesis that the total error score is abnormally high. If the fellow eye score is then entered by the operator, a one-tailed test of the hypothesis that



(a)

Fig. 3. *(a) The traditional 'polar' plot of the 100 hue results and (b) a sample Huematic patient record sheet. The same data, suggestive of a protonomalous loss of colour discrimination, are plotted in both cases.*

the inter-eye difference is abnormally high is also carried out, using inter-eye norms of Verriest *et al.*,[3] and the result printed. The printing of the bar chart and the data analysis takes less than four minutes, a considerable improvement over the *twenty to thirty* minutes usually required for scoring the test manually.

Comparing the Huematic print-out with the standard score sheet, one difference is particularly striking, namely the fact that the cap errors are no longer represented in a 'colour circle'. At first sight, this may seem a serious disadvantage, since the 85 colours which constitute the FM 100 hue test are distributed

```
06/03/87
NAME=OTHER AN
HOSP.NO. = 123456
D.O.B. =04/23/49
RIGHT EYE

1   1  T T
2   1  . x
3   2  . xx
4   3  . xxx
5   1  . x
6   1  . x
7   1  . x
8   1  . x
9   1  . x
10  1  . x
11  1  . x
12  1  S S
13  1  . x
14  2  . xx
15  2  D DD
16  3  . xxx
17  4  . xxxx
18  1  . x
19  4  P PPPP
20  6  . xxxxxx
21  5  . xxxxx
22  4  . xxxx
23  1  . x
24  2  . xx
25  2  . xx
26  1  . x
27  1  . x
28  1  . x
29  1  . x
30  1  . x
31  1  . x
32  1  . x
33  1  . x
34  1  . x
35  3  . xxx
36  2  . xx
37  2  . xx
38  3  . xxx
39  1  . x
40  1  . x
41  1  . x
42  1  . x
43  1  . x
44  1  . x
45  2  . xx
46  1  . x
```

```
47  1  T T
48  3  . xxx
49  2  . xx
50  2  . xx
51  3  . xxx
52  1  . x
53  2  . xx
54  2  S SS
55  1  . x
56  1  . x
57  2  . xx
58  2  . xx
59  2  D DD
60  2  . xx
61  1  . x
62  5  . xxxxx
63  12 . xxxxxxxxxxxx
64  10 . xxxxxxxxxx
65  7  P PPPPPPP
66  9  . xxxxxxxxx
67  4  . xxxx
68  2  . xx
69  2  . xx
70  2  . xx
71  2  . xx
72  1  . x
73  1  . x
74  2  . xx
75  2  . xx
76  1  . x
77  4  . xxxx
78  3  . xxx
79  1  . x
80  1  . x
81  2  . xx
82  3  . xxx
83  1  . x
84  2  . xx
85  2  . xx

TOT.ERROR SCORE= 188
AGE  38
5% CONF.LIM. = 135
1% CONF.LIM. = 169
BOX 1 SCORE= 45
BOX 2 SCORE= 32
BOX 3 SCORE= 49
BOX 4 SCORE= 62
RES.ABNORMAL,P<1%
FELLOW EYE SCORE= 236
DIFF.BETWEEN EYES
NOT SIGNIFICANT
```

(b)

systematically in CIE xy colour space. Consequently, an operator experienced in colorimetry and used to relating test results to colour space may feel that the presentation of cap error scores in a linear bar chart removes an important frame of reference. Several points can be made in response to this potential criticism:

(1) It is not easy to compare the FM 100 hue colour circle with the CIE colour diagram since the former is rotated by about 120° with respect to the latter.

(2) The FM 100 hue circle is actually an ellipse around the central white point in the CIE xy diagram, not a circle.

(3) Relating the FM 100 hue results to the CIE xy colour diagram is only important in so far as one needs to know where the primary error axes for the congenital colour vision deficiencies lie, since these are orthogonal to the appropriate iso-confusion lines. Because these error axes are specifically marked on the Huematic print-out and not on the traditional polar-

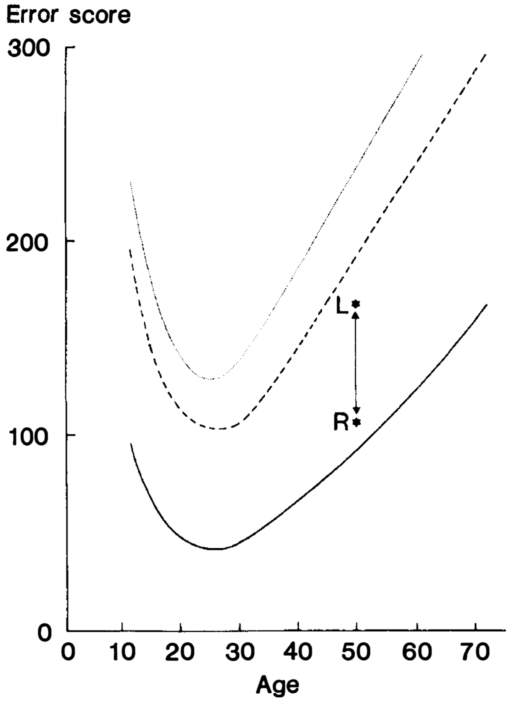


Fig. 4. *Graph showing mean 100 hue error score (——), and one-tailed 95 per cent (––––) and 99 per cent (·······) confidence limits as a function of age. The functions are described by fifth order polynomials, fitted to the data of Verriest* et al.[3] *R and L denote right and left eye scores which are both clinically normal ($p>0.05$) with respect to the age norms, but which demonstrate an abnormally large inter-eye difference in score ($p<0.05$, one-tailed test), which may be of clinical significance.*

plot score sheet, one might argue that the Huematic fulfils this requirement *better.*

Ophthalmological and optometric colleagues, asked to comment on the linear presentation of results, said that they foresaw no problems in interpreting the print-out. In other respects, all the information represented on the traditional score sheet also appears on the Huematic print-out with the added advantage that it is printed automatically, thereby eliminating transcription and other errors.

Discussion

It is important to realise that the Huematic, as reported here, is only a prototype, and one might expect a production model to incorporate changes, perhaps substituting a dedicated micro-chip for the Epson, thereby reducing the computation and printing time still further. Yet, even in its current form, it can be seen that the prototype offers a practical and convenient solution to the problem of scoring the FM 100 hue test manually. It consists almost entirely of commercially available components, the only non-standard item being the omni-directional bar-codes. It is also relatively inexpensive, compared to previous automated scorers; the cost price of the components for the prototype was less than £1,000. Another attraction is its compactness, which places no constraint on the versatility of the original test; in fact, the Epson used in the prototype runs off rechargeable batteries and thus does not even require a mains supply.

The advantages of the Huematic go further than simple automation of scoring. As described above, the current software performs routine statistical tests on the results, using established normative data, thus avoiding the possibility of mistakes and the need for the operator to have some knowledge of statistics. Computerising the data from the test offers many other possibilities, such as making comparisons between a patient's total error scores on successive visits[14] and the calculation of 'axis ratios' to highlight congenital or acquired colour vision deficiencies that fall into well-documented categories. In all of these cases, it is the gathering of normative data that is the limiting factor, since it would be simple to incorporate all of these options into a new version of the software.

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