OCCASION

This publication has been made available to the public on the occasion of the 50th anniversary of the United Nations Industrial Development Organisation.

DISCLAIMER

This document has been produced without formal United Nations editing. The designations employed and the presentation of the material in this document do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations Industrial Development Organization (UNIDO) concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries, or its economic system or degree of development. Designations such as "developed", "industrialized" and "developing" are intended for statistical convenience and do not necessarily express a judgment about the stage reached by a particular country or area in the development process. Mention of firm names or commercial products does not constitute an endorsement by UNIDO.

FAIR USE POLICY

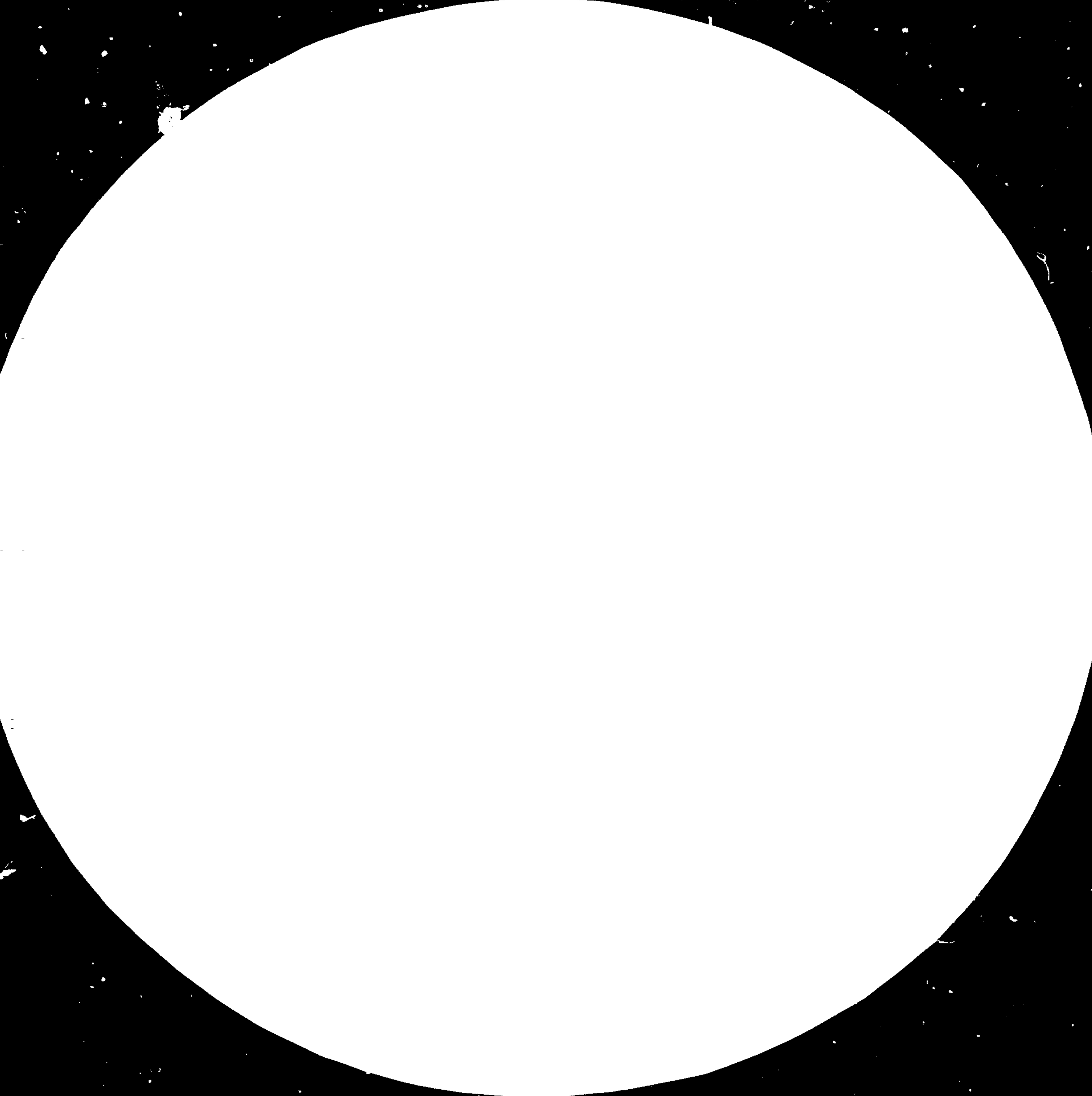
Any part of this publication may be quoted and referenced for educational and research purposes without additional permission from UNIDO. However, those who make use of quoting and referencing this publication are requested to follow the Fair Use Policy of giving due credit to UNIDO.

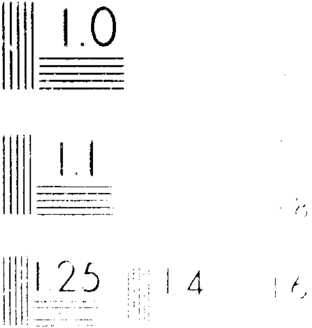
CONTACT

Please contact publications@unido.org for further information concerning UNIDO publications.

For more information about UNIDO, please visit us at www.unido.org

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna International Centre, P.O. Box 300, 1400 Vienna, Austria
Tel: (+43-1) 26026-0 · www.unido.org · unido@unido.org




1.0
1.1
1.8
1.25
1.4
1.6

11856 Restricted

MISSION REPORT

Egypt, 26 October - 24 December
1981

Textile Development Centre
DP/EGY/77/008

by

DR. ROBERT HIRSCHLER
UNIDO Consultant in COLOUR MEASUREMENT

Distribution:

Mr. M. Minke	UNIDO, Vienna
Mr. A. Eraneva	UNIDO, Vienna
Mr. G. Pennacchio /2/	UNDP, Cairo
Dr. R. Nield	TDC, Alexandria
Mr. M. Elaref	TDC, Alexandria
Dr. M. El-Gouroury	Misr Spinning and Weaving Co., Mehalla

TABLE OF CONTENTS

I PURPOSE OF MISSION

1. Conduct a comprehensive course on the theoretical background and practical application of the ACS colour measuring and colorant formulation system installed in MISR MEHALLA, for experts of the dyehouse as well as those appointed by the Textile Development Centre.

2. Instruct experts of MISR MEHALLA in the everyday use of the ACS system, and with their cooperation initiate the regular application of the system within the factory.

3. Assist the experts of MISR MEHALLA in optimizing the dyestuff ranges used in computer colorant formulation.

4. Suggest further applications for the instrument within the factory, e.g. quality control of incoming dyestuffs, quality control of dyed goods, etc.

5. Instruct experts of the Textile Development Centre in the application of the colour measuring instruments available at TDC.

6. Make recommendations for the wider application of instrumental colour measurement in the Egyptian textile industry, primarily that in and around Alexandria and Cairo.

141

II ITINERARY

26 October	Budapest	- Vienna
28 October	Vienna	- Cairo
1 November	Cairo	- Alexandria
28 November	Alexandria	- Mehalla El Kubra
3 December	Mehalla	- Alexandria
18 December	Alexandria	- Cairo
22 December	Cairo	- Vienna
24 December	Vienna	- Budapest

III ACKNOWLEDGEMENTS

The consultant would like to thank first of all those helping him through the first difficult steps of his mission: Mr. L. Leite Recruitment Officer and Ms. J. Tobin Administrative Assistant of Project Personnel Recruitment Section, Ms. A. Zednicek and Ms. J. Guedon of Experts Administration, Mrs. I. Mennel Briefing Co-Ordinator and the Substantive Officer Mr. M. Minke of Agro-Industries Section at UNIDO HQ in Vienna as well as the UNDP Field Office in Cairo , for their help, patience and for understanding all the problems a novice in this field might encounter.

The guidance and advice of Dr. Roy Nield UNIDO Project Manager and Mr. Magdi Elaref Co-Manager are highly appreciated, as are the many useful discussions and consultations with Mr. Derek Wyles, UNIDO Consultant in Dyeing and Finishing. The views and advices given by Dr. Mohamed El-Gouroury, member of the Board of TCF and Chairman of Misr Spinning and Weaving Co. helped a great deal in giving the mission the final shape it took.

It has been a pleasure to work with so helpful and entusiastic colleagues as those at the Textile Development Centre and in Misr Mehalla, especially with Ms. Yusr Allam, Head of Chemical Labs at TDC and Dr. Ahmed Mohamed El Said and Mr. Mamdouh Khalil of Misr Spinning and Weaving.

Special thanks are due to Mr. Abdel Hamid Khairalla, Director Mill Service Department, TDC, whose untiring help in preparing for the courses and seminars, collecting material for the notes, arranging meetings and giving helpful advise in most everything made the consultants work very much easier and his stay in Egypt so much more pleasant.

IV ACTIVITIES

A Textile Consolidation Fund - Textile Development Centre

Most of the consultants activities took place at the TDC in Alexandria. After a brief first meeting with the chemistry staff and a visit to the laboratories a preliminary colour measurement consultancy program and guidelines for the best utilization of existing colour measuring equipment in TDC were prepared /Annex No. 1. /. These two documents, approved by the Project Manager, formed the basis of the consultant's work during his mission.

Instrumentation

There are a number of optical instruments at TDC for the measurement of reflectance or transmittance, notably a HUNTERLAB D 25D2 M/L digital colour difference meter, a HUNTERLAB D 40 reflectometer, a HUNTERLAB D 16 Manual Glossmeter, a SPINLAB Model 280 UV meter, an EEL portable absorbance meter and a BECKMAN AccuLab IR spectrophotometer.

The instruments are several years old, except for the BECKMAN, which is brand new. All are in good working condition. It was agreed that only the utilization of colour measuring instruments /i.e. the D 25 and partly the D 40/ would be discussed, and the other optical instruments measuring attributes not directly related to colour would be disregarded this time.

Discussions

Discussions centred around the following main topics:

- assessment of the repeatability of instruments;
- the CIELAB colour order system and colour space;
- characterization of the behaviour of dyestuffs;
- strength comparison of dyestuffs;

- colour differences, tolerances, pass/fail and colour sorting;
- assessment of the repeatability of dyeing;
- colour calculations.

Practical work

Laboratory exercises and measurements started simultaneously with the discussions. Measurements were made on the D 25 instrument, primarily using the various textile /tow, yarn, fabric/ samples provided by the consultant. Practical exercises for the TDC staff included sample preparation, instrument calibration, determination of repeatability, accuracy and reproducibility; measurement of concentration series and training on the interpretation of data.

The accuracy and the repeatability of the HUNTERLAB D 25 was found to be satisfactory, and it served as a reference instrument in checking similiar colorimeters at IZMADYE and NASR Mehalla mills /see Annex 2. for data/.

Calculations

It became apparent at the very beginning of the practical work, that a programmable pocket calculator was needed to carry out the necessary colour calculations. The consultant selected and purchased for TDC a suitable calculator /a Texas Instrument 58 C/ available locally, wrote the necessary programs, and instructed the staff in using it /see Annex 3./.

Training

The training course and seminars conducted at TDC will be discussed under C.

B VISIT OF TEXTILE MILLS

In order to get acquainted with the status of the application of colour science in some of the important textile dyeing and finishing mills the consultant visited IZMADYE and MISR BEIDA DYERS Co. in Kafr El Dawar, MISR Spinning and Weaving Co. and EL NASR Spinning, Weaving and Finishing Co. in Mehalla El Kubra. He met experts concerned with various aspects of the coloration process, surveyed the colour instruments available in the mills and discussed several aspects of the application of colour measurement in the textile industry as well as various theoretical points.

The visit to MISR Spinning and Weaving Co. was originally supposed to have been much longer, but partly due to the fact, that the ACS computer colour matching system was malfunctioning, and partly due to the increased interest on the part of TDC and several mills in and around Alexandria for a two week training course conveniently held at TDC, the stay was finally reduced to one week.

Detailed desription of the information collected and the conclusions and suggestions made in the mills are to be found in Annex No. 4.

C TRAINING COURSE AND SEMINARS

In addition to the informal discussions and instruction at TDC and in the mills the consultant gave a lo-day training course and three shorter seminars.

The lo-day training course on "Introduction to Colour Measurement in the Textile Industry" was held at the TDC 16-26 November /see Annex 5.1 for Lecture Notes/. It was, as the title suggests a comprehensive course mainly for people from the industry, who are involved in some aspects of colour control in their everyday work, but had so far received no formal training in colour science. There was attendance from MISR Spinning and Weaving Co., EL NASR Spinning, weaving and finishing Co., MISR BEIDA Dyers, MISR RAYON and Polyester, IZMADYE, in addition to several attendants from TDC.

One half-day seminar was given in the MISR mill in Mehalla /"A Brief Survey of Colour Measurement in the Textile Industry" - see Annex 5.2 for the seminar paper/ on 2nd December for people not directly working on the ACS system, but who come across its activities in their work, and should have some general knowledge on the topic.

A special one-day seminar was given on the 14th December in TDC on "The Application of Colour Measurement in Tolerance Specification" /see Annex 5.3 for the seminar paper/. It was requested by several experts in mills that this rather difficult, but very important field of application be discussed in more detail. There was participation from all the mills visited, and the discussion following the presentation of the paper reflected truly how great the interest was for this - as yet not completely solved - problem of applied colour science.

A half-day seminar was also given at the National Research Centre, Dokki, Cairo on the 20th December on "The Application of Colour Measurement in the Textile Industry" for the staff of NRC. There was no special seminar paper, but copies of the previous papers were distributed.

V RECOMMENDATIONS

Based upon consultations with the Project Manager, other experts of the UNIDO team and of the TDC, and members of the Technical Committee the following recommendations could be formulated. /Only those relating to TDC or of a general interest are listed below.. For recommendations relating to one paricular mill only please refer to Annex 4./

1. The program commenced during the consultant's stay should be continued, with special attention given to the repeatability checks of the newly installed dyeing machinery.

2. To make the large amount of colour calculations easier, after adequate practice with the recently purchased TI 58 C calculator it should be up-graded by adding a printer device to it /available locally/, or, preferably it should be changed for a TI 59 C and a printer. The main advantage of the 59 C over the 58 C is its ability /by using magnetic cards/ to store complicated programs - such as the ones listed in Annex No. 3. - permanently. The advantages of a printer device are obvious when large amount of data are to be handled and recorded, as is the case with colour measurement.

3. The purchase of a full computer match prediction system /like the ACS in Mehalla/ for TDC should be considered at a later stage. The best solution would probably be to buy it together with IZMADYE, and use it as a match prediction centre serving the textile industry, primarily in the neighbourhood of Alexandria. Whether to set it up at IZMADYE or at the TDC is a matter for later consideration, but

in the consultant's experience much is to be gained by setting up the centre in a mill, and run it by central staff /in this case that of the TDC/.

4. It is recommended, that some experts from TDC /eventually accompanied by experts from MISR Mehalla/ pay a visit to Hungary where a central colour matching and measuring system has successfully been in operation for over 3 years. The visit can be arranged through any official channel, the program in Hungary will be arranged by the consultant.

5. TDC should continue their cooperation with textile mills interested in the application of colour measurement. They can help in standardizing or checking the existing colour measuring instruments, consulting in the application of the CIELAB system, and also provide the technical literature.

6. Further visit/s/ by a consultant in colour measurement should be planned well in advance /see also point 7. below/. His work should include
   - a training course of 1o-14 days with practical exercises on the special problem of colour tolerances;
   - laboratory training in the selection of optimal dyestuff ranges with and without having recourse to computer match prediction systems;
   - one-day seminar on up-to-date colour instrumentation in the textile industry and criteria of selection;
   - solving special problems in applied colour measurement according to the need of the mills.

7. The consultant has found it most disturbing that much of his time has been taken up by activities which could easily have been performed prior to

commencing his mission had he possessed the necessary information. The preparation and organisation of the training course and the seminars could also have been made more effective had the consultant and his counterpart had the chance to discuss topics, level and interests of audiance etc. in advance.

It is recommended therefore that UNIDO consider the introduction of "two-stage missions" wherever deemed necessary. These would consist of a short or medium term mission /1-2 months/ preceded by a shorter /7-10 days/ preparatory visit. There should be a 1-2 months long interval between the two to allow the consultant to make his preparations at home and his counterpart to do the same at the location of the mission. It is the consultants firm belief that this way the effectivness of the field work could be much improved. /The extra expense of the double air-fare could well be saved by making the mission that many days shorter, the much higher effectivness would surely cover the difference./

ANNEX No. 1.

to Mission Report

EGYPT, 26 October - 24 December 1981

DP/EGY/77/008

by Dr. Robert Hirschler

Textile Development Centre Colour Measurement Consultancy Program and

Guidelines for program for the best utilization of existing colour measuring equipment in TDC.

TDC Colour Measurement Consultancy Program

2-14 November	TDC: Teaching the use of HUNTERLAB instruments, evaluation of their accuracy and repeatability, fields of application (see guidelines) Colour calculations: how to use the pocket-calculator, preparation of written step-by step instructions. Discussion on selected topics. Visits: Mehalla, Isma dyes, Beida dyers.
16-26 November	TDC: course for invited audiance (practical dyers) on the application of colour measurement in the textile industry, including preparation of lecture notes. Discussion with TDC chemists on their progress in using the HUNTERLAB and the calculator.
28 Nov - 10 Dec.	Mehalla, consultation in the every day use of the ACS instrument, advanced course in the theory of computer colorant formulation.
12 Dec - 17 Dec	TDC: evaluation of progress made, discussion of problems as required, preparation of a draft report
19 Dec - 20 Dec.	Visit to NRC Cairo, discussion with Dr. Bendak and colleagues on teaching colour theory and application, also lecture on up-to-date instrumentation or other required topic.

Guidelines for program
for the best utilization of existing colour measuring equipment in TDC

as discussed on the 3rd Novembre 1981 by
Mr. Wyles, Mr. Khairallah, Ms. Allam and dr. Hirschler

The main stages for the instruction of the stuff for using their colour measuring instruments, primarily the HUNTERLAB D25D2M/L digital colour difference meter are suggested as follows.

1./ Assessment of the repeatability of instruments

The repeatability of the instruments should be checked by measuring a number of colored tiles /supplied with the instrument/ and a number of textile samples of different colour, in fabric, but also in yarn and tow form, ten times each, with recalibration of the instruments after each series of measurement /i.e. before starting to measure the same samples again/. The L^{x}, a^{x}, b^{x}, C^{x}_{ab} H^{o}_{ab} values /thereafter CIELAB values/ for each measurement are to be calculated by the formulae given in the Appendix, the average value for the ten measurements and the difference between each measurement value and the respective average value /i.e. the delta CIELAB values/ should be calculated. The averages of these differences indicate then the repeatability, the most easily understandable single figure being the mean of the DE^{x}_{ab} colour differences for each sample between"average colour" /i.e. average L^{x} a^{x} b^{x}/ and individual measurement data. It is to be expected that the average DE^{x}_{ab} values be less, than o.2-o.3, a figure somewhat higher than that quoted for the most up-to-date instruments.

Similar measurements can be carried out on theHUNTERLAB Model D4c reflectometer, but the interpretation for the results must be reduced to comparing the standard deviation for the Y and Z values to those obtained from the D25D2M/L instrument

Other instruments for measuring aspects /or rather attributes/ of appearance are the HUNTERLAB D16 Manual Glossmeter, and the SPINLAB Model 28o U.V. meter, these however are only very vaguely related to colour measurement, and should be treated separately. Optical instruments of other types are also available in TDC, notably the EEL portable colorimeter /it must be emphasized here, that the name is misleading, this instrument does not measure colour, but by using filters of varying maximum wavelength of transmittance and varying band-width, it measures values approximating spectral transmittance in regions of the visible range/,and the latest, not yet unpacked BECKMAN AccuLab infrared spectrophotometer, which measures spectral transmittance in the IR region only. This latter is a very valuable analytical instrument, but, not being related to the measurement of colour, should be discussed at another time.

2./ Characterization of the behaviour of dyestuffs

CIELAB colour space can very conveniently be used for [illegible] ac-terization of the behaviour - as regards build-up prope [illegible] and eventuallly colour - of dyestuffs. As a beginning, the concentration series of vat dyes on cotton yarn brought by dr. Hirschler should be measured on the HUNTERLAB colour difference meter, and graphs showing the lines of increasing concentration for each dyestuff shall be drawn on both $a^{x} - b^{x}$ and $L^{x} - C^{x}_{ab}$ diagrams. The interpretation of these diagrams, the implications of it in the selection of dyestuffs, establishment of colour gamuts etc. will then be discussed.

3./ Strength comparison of dyestuffs

The comparison of the dyeing strength of identical, and in some cases of similar, but not identical, dyestuffs is of major importance in the quality control of dyestuffs as well as in price negotiations with the supplier. The best instrument for that kind of work is the reflectance spectrophotometer, e.g. of the type installed in MISR Mehalla. Some approximations can, however be made on tristimulus instrument of the HUNTER type, and work in this field should be directed to get the maximum result from the equipment available. Approximations will be tried on the basis of tristimulus values /that can be measured on the HUNTERLAB/ for dyed samples of known strength relation. At this stage it is not recommended to use transmittance measurement for the quality control of incoming dyes, but research in this direction - i.e. the relationship between transmittance of the dye liquor and colour of the dyed textile substrate - can be discussed. Here the results shall be compared to the ones calculated on a DATACOLOR system in Hungary as well as to those to be determined in Mehalla on the ACS system.

It must be stressed here, that strength comparison is one of the major, and for the dyer most easily applicable fields of instrumental colour measument, important in terms of economy as well as safety /i.e. reproducibility/ of dyeing in lab or mill.

4./ Colour differences, tolerances, pass/fail and colour sorting

These topics are very closely interrelated, and therefore should be treated together. They comprise the single most problematic, most difficult field in industrial colour measurement. The determination of the limits of tolerance /acceptibility/ is complicated, because these limits depend not only on the end use of the product, but also on the colour itself as well as on the direction of deviation from standard. Here only guidelines can be given, on the state-of-the-art, the two major recent contributions by Marks&Spencers and

J & P Coats, and the very first steps towards research in this field can be discussed.

5./ Repeatability of dyeing

One very important everyday application of colour measurement is the quantification of the repeatability of dyeing, for comparison of the performance of different dyeing machines /be they lab or mill machines/, of various technologies , dyestuffs of dyestuff combinations. This goes along the lines of repeatibility assessment of the measurement itself, repeated dyeings taking the place of repeated measurements /but for the measurement itself making normally 2-3 repeated readings/. These trials are recommended to be run on all the new equipment to be installed in the near future as well.

6./ Timing

An exact schedule for the above program cannot be given yet. It is hoped, that it can be accomplished in six weeks, which should be essential to have an opportunity to discuss all the results. It is suggested, that after a detailed initial discussion on how to go about each problem, measurements and dyeings be started right away, and be continued if possible during dr. Hirschler's not yet exactly known days away in Mehalla and other places.

7./ Equipment

Since the object of these recommendations is first of all to make maximum use of existing eqipment, the program is based on what is already available at TDC. /Recommendations for future development in instrumentation will come later./ It is however absolutely necessary to have a small pocket or desk calculator available, which is capable of handling cube roots, has minimum 3, but preferably more addressable memories, and can be programmed in minimum 7o, but preferably approx. loo-12o steps. In Western Europe such a calculator can be purchased for around 5o-6o $. The everyday use of such a calculator is indispensable in colour measurement, and it is very useful even in the case of having a computerized instrument, such as the ACS 6oo around.

Appendix

/dr. Robert Hirschler/

cc.: Dr. R. Nield
Mr. D. Wyles
Mr. A.H.Khairalla
Ms. Yussr Allam

ANNEX No. 2.

to Mission Report
Egypt, 26 October - 24 December 1981
DP/EGY/77/oo8
by Dr. Robert Hirschler

Accuracy of colour measuring instruments

In order to get some preliminary data on the colour measurment and colour difference measurement accuracy of three instruments in use at three different locations, data were compared from:

HUNTERLAB D 25 D2 M/L	at the	Textile Development Centre
ELREPHO	at	IZMADYE
Toyo Seiki /Hunter type/	at	EL NASR, Mehalla.

The results given in Table 1. show, that there is excellent agreement between the TDC and IZMADYE instruments in colour difference measurement /the average difference between the ΔE^{*}_{ab} values measured on five sample pairs is around o.5 unit, and it is in no case more than o.7/, whereas the agreement between NASR Mehalla and TDC resp. IZMADYE is rather poor /the average differences being 3.3 and 3.4 respectively, with differences as high as 9.1 and 9.8/.

Table 1.

Comparison of the Colour Difference Measurement
Accuracy of Different Instruments

		TDC			Izma			Nasr M.		
Sample pair		Hunter 1	2	Δ	Elrepho 1	2	Δ	Toyo Seiki/Hunter/ 1	2	Δ
1.	L^*	74.2	74.8	-0.6	77.1	78.3	-1.2	76.5	77.8	-1.3
	a^*	-4.8	-3.0	1.8	-4.0	-2.6	1.4	1.2	2.9	-1.7
	b^*	45.8	44.1	1.7	43.8	43.1	0.7	49.2	46.3	2.9
	ΔE^*_{ab}	2.6			1.9			3.6		
2.	L^*	60.6	58.9	1.7	66.0	63.7	2.3	62.3	60.0	2.3
	a^*	30.5	27.5	3.0	22.7	22.0	0.7	43.9	39.4	4.0
	b^*	9.5	8.3	1.2	17.6	14.9	2.7	16.0	14.1	1.9
	ΔE^*_{ab}	3.7			3.8			5.0		
3.	L^*	40.6	38.7	1.9	44.8	42.9	1.9	39.1	35.8	3.3
	a^*	16.2	14.4	1.8	9.7	10.2	-0.5	23.2	26.9	-3.7
	b^*	11.2	8.6	2.6	13.6	10.9	2.7	9.5	3.9	5.6
	ΔE^*_{ab}	3.7			3.3			7.5		
4.	L^*	49.0	42.5	6.5	52.3	46.2	6.1	48.0	40.7	7.3
	a^*	4.5	6.2	-1.7	2.3	3.3	-1.0	11.0	18.0	-7.0
	b^*	23.4	25.5	-2.1	22.3	23.6	-1.3	24.9	12.4	12.5
	ΔE^*_{ab}	7.0			6.3			16.1		
5.	L^*	47.5	47.6	-0.1	49.6	49.8	-0.2	45.9	46.6	-0.7
	a^*	1.8	1.8	0	2.2	2.6	-0.4	7.8	8.5	-0.7
	b^*	6.1	6.1	0	5.8	5.3	0.5	6.8	6.7	0.1
	ΔE^*_{ab}	0.1			0,67			1.0		

Table 2. shows, that even in "absolute" accuracy /which can be defined as the difference between the single measured values rather than between the ΔE values/ the agreement between TDC and IZMADYE is much better than that between NASR Mehalla and the other two. This is rather surprising, because the Hunter type instruments at TDC and NASR Mehalla are very similar in construction, while the ELREPHO instrument at IZMADYE is totally different.

Table 2.

Comparison of the Colour Measurement
Accuracy of Different Instruments

ΔE^*_{ab}

Samples		TDC - Izma	Izma - Nasr Meh.	TDC - Nasr Meh.
1.	a	3.6	7.5	7.3
	b	3.7	6.4	7.0
2.	a	12.5	21.4	15.0
	b	9.8	17.8	13.3
3.	a	8.1	15.2	7.4
	b	6.4	19.4	13.7
4.	a	4.1	10.0	6.7
	b	5.1	19.3	17.7
5.	a	2.2	6.8	6.2
	b	2.5	6.9	6.8
average		5.8	13.1	10.11

ANNEX No. 3.

to Mission Report

Egypt, 26 October - 24 December 1981

DP/EGY/77/008

by Dr. Robert Hirschler

PROGRAMS FOR COLOUR CALCULATIONS

I. To enter CIELAB program into TI 58 C

1. Switch off, then on

2. Press 2nd Fix 9 2 2nd Op 1 7
   The calculator will show 319.19 which means, that you have available 320 program steps and 20 data memories.

3. Press 2nd Fix 2
   This will make the calculator to display only 2 decimals.

4. Press 2nd C P
   This will clear the program

5. Press R S T
   This will send the program to the first step (000).

6. Press L R N
   This will mark the beginning of "learning" for the calculator. The display should show 000 00.

7. Enter program steps one by one by pressing the appropriate button. When finished:

8. Press L R N
   This will mark the end of "learning" for the calculator.

II. Check the program by the following procedure:

9. Press R S T (to send the program to 000)

10. Press L R N
The display will show 000 76 (for the CIELAB PROGRAM).

11. By pressing SST (single step) you can check the code numbers (the two digits on the right hand side) one by one. The three digits on the left hand side show the location (address) where the program is standing at the moment. Please remember: anything you do on the keyboard while the calculator is in the learn (LRN) mode — you see it by the particular display;

xxx xx
address code —

will be taken as program instruction, except

S S T : single step forward
B S T : single step backward

12. Press L R N
When you finished checking the program, this will get the calculator out of the L R N mode.

III. Correcting programs

13. To correct any mistakes in the program, (it can only be done in the L R N mode) step back (by pressing BST the required number of times) until you see a correct code number in the correct address. This means, that in the display the first 3 digits correspond to an address (location) on the program sheet, and the code number on the sheet corresponds to the last 2 digits in the display.

14. Press the button corresponding to the correct instruction (what you see on the display).

15. If you need extra program steps to be inserted (because some steps are missing) press
    <u>2nd</u> Ins
    this will create one space at the next address (and move the rest of the program one step forward). This can be repeated any number of times.

16. If you want to delete instructions, press
    <u>2nd</u> Del
    this will delete the instruction at the next address (and close the gap). This can be repeated any number of times.

17. If you want to change the instruction at the next address, simply press the correct button, the latest instruction always replaces the previous ones.

18. When the program is correct, Press L R N

IV. Final checking of the program

Make sure the calculator is NOT IN THE LRN MODE!

		Display
Press	2nd D'	107.38
Press	RCL 18	94.83
Press	D	118.10
Press	RCL 18	98.04
Enter	44.4	44.4
Press	A	0.77
Enter	47	47
Press	B	0.78
Enter	19.5	19.5
Press	C	74.19
Enter	46	46
Press	2nd A'	0.78
Enter	48	48
Press	2nd B'	0.78
Enter	21	21
Press	2nd C'	- 1.67
Press	RCL 06	74.82
Press	RCL 07	- 2.96
Press	RCL 08	44.13
Press	RCL 09	44.23
Press	RCL 11	0.64
Press	RCL 12	- 1.80
Press	RCL 13	- 1.67
Press	RCL 14	2.54

If you have the correct displays every time, and there is no flashing number (error signal), then the calculator is correctly programmed for the 2° (1931) observer and illuminant C. To calculate CIELAB values follow user's instructions.

CALCULATION OF CIELAB VALUES

(TI 58C, program "X,Y,Z to CIELAB/13.12.1981)

1./ Selecting illuminant and observer

Press D for illuminant C and 2° (1931) observer (TDC)

or Press 2nd D' for ill. D_{65} and 10° (1964) observer (Mehalla)

Please remember, this has only to be done once, the calculator will keep the proper value until you change it.

2./ Calculation of CIELAB values for any sample

1. Enter the value of X
2. Press A
3. Enter the value of Y
4. Press B
5. Enter the value of Z
6. Press C

The display will show the value of L^{*}. To display any of the CIELAB coordinates, press the following buttons:

Press	to display
RCL 01	L^{*}
RCL 02	a^{*}
RCL 03	b^{*}
RCL 04	C^{*}_{ab}
RCL 05	H°_{ab}

3./ Calculation of colour differences in the CIELAB system

First calculate the CIELAB values for the standard, as above:

1. Enter X (st)
2. Press A
3. Enter Y (st)
4. Press B
5. Enter Z (st)
6. Press C

The display will show the value of L^* (st), Then proceed:

7. Enter X (batch)
8. Press 2nd A'
9. Enter Y (batch)
10. Press 2nd B'
11. Enter Z (batch)
12. Press 2nd C'

The display will show the value of ΔH^*_{ab}. The differences between batch and standard (always batch-standard) and the CIELAB values for both are stored in data registers (memories) 00 to 14, and can be displayed by pressing RCL and the appropriate number. These values should be used with two decimal points, the second decimal having neclectable visual significance. Thus:

Press	Display	Press	Display	Press	Display
RCL 01	L^* (st)	RCL 06	L^* (b)	RCL 00	$\Delta(\text{chromaticity})^2$
RCL 02	a^* (st)	RCL 07	a^* (b)	RCL 11	ΔL^*
RCL 03	b^* (st)	RCL 08	b^* (b)	RCL 12	ΔC^*_{ab}
RCL 04	C^*_{ab}(st)	RCL 09	C^*_{ab}(b)	RCL 13	ΔH^*_{ab}
RCL 05	H^o_{ab}(st)	RCL 10	H^o_{ab}(b)	RCL 14	ΔE^*_{ab}

For one standard any number of colour differences with different batches can be calculated, the reentry point is 7. Enter X (batch) and pressing 2nd A', than continue as above. Don't forget to record the necessary values before proceeding with a new batch.

TITLE / TITEL / TITRE: X, Y, Z to CIELAB
PAGE / SEITE / PAGE 1 OF / VON / DE 3
PROGRAMMER / PROGRAMMIERER / PROGRAMMEUR: R. Hirschler
DATE / DATUM / DATE: 13/12/1981

LOC ADR ADR	CODE KODE CODE	KEY TASTE TOUCHE	COMMENTS BEMERKUNGEN COMMENTAIRES	LOC ADR ADR	CODE KODE CODE	KEY TASTE TOUCHE	COMMENTS BEMERKUNGEN COMMENTAIRES				
0	76	2nd Lbl			19	19	M 19	110	95		
1	32	x⇌t	SBR x⇌t	6	91	R/S	X_{st}		42	STO	M 2
2	32	x⇌t		7	76	2nd Lbl			02	2	a*(st)
3	93	.		8	11	A	A		32	x⇌t	
4	00	0			55	÷			43	RCL	
5	00	0		6	43	RCL			03	3	
6	08	8			18	18			22	INV	
7	08	8			95	=			37	2nd P→R	
8	05	5			71	SBR			42	STO	M 5
9	06	6		4	32	x⇌t			05	5	H^{o}_{ab} (st)
10	77	2nd x≥t	!!!		42	STO		120	32	x⇌t	
1	15	E			02	2	$f(X/X_0)$		42	STO	M 4
2	32	x⇌t		7	91	R/S	Y_{st}		04	4	C^{*}_{ab} (st)
3	22	INV		8	76	2nd Lbl			43	RCL	
4	45	y^x		9	12	B	B		01	1	
5	03	3		7 0	55	÷			65	X	
6	95	=		1	01	1			01	1	
7	92	INV SBR		2	00	0			01	1	
8	76	2nd Lbl		3	00	0			06	6	
9	15	E	E	4	95	=			75	−	
20	32	x⇌t		5	71	SBR		130	01	1	
1	65	X		6	32	x⇌t			06	6	
2	07	7		7	42	STO			95	=	
3	93	.		8	01	1	$f(Y/Y_0)$		42	STO	M 1
4	07	7		9	91	R/S	Z_{st}		01	1	L^{*} (st)
5	08	8		8 0	76	2nd Lbl			91	R/S	X_b
6	07	7		1	13	C	C		76	2nd Lbl	
7	85	+		2	55	÷			16	2nd A′	A′
8	93	.		3	43	RCL			55	÷	
9	01	1		4	19	19			43	RCL	
30	03	3		5	95	=		140	18	18	
1	07	7		6	71	SBR			95	=	
2	09	9		7	32	x⇌t			71	SBR	
3	95	=		8	75	−			32	x⇌t	
4	61	GOTO		4	43	RCL			42	STO	
5	00	0		9 0	01	1			07	7	$f(X/X_0)$
6	16	16	END of SBR	1	95	=			91	R/S	Y_b
7	76	2nd Lbl		2	94	+/−			76	2nd Lbl	
8	14	D	D	3	65	X			17	2nd B′	B′
9	09	9	$C - 2^{o}$	4	02	2			55	÷	
40	08	8		5	00	0		150	01	1	
1	93	.		6	00	0			00	0	
2	00	0		7	95	=			00	0	
3	04	4		8	42	STO	M 3		95	=	
4	01	1		9	03	3	b*(st)		71	SBR	
5	42	STO		10 0	43	RCL			32	x⇌t	
5	18	18	M 18	1	02	2			42	STO	
7	01	1	X_o (C)	2	75	−			06	6	$f(Y/Y_0)$
8	01	1		3	43	RCL			91	R/S	Z_b
9	08	8		4	01	1			76	2nd Lbl	
50	93	.		5	95	=					
1	01	1		6	65	X					
2	00	0		7	05	5					
3	02	2		8	00	0					
	42	STO	M 19	9	00	0					

R. Hirschler

SEITE / PAGE / PAGE VON / DE

DATE / DATUM / DATE 13/12/1981

CODING FORM
KODEFORM
FEUILLE DE PROGRAMMATION

(8)

LOC	CODE	KEY	COMMENTS
160	76	2nd [illegible]	C'
	55	÷	
	43	RCL	
	19	19	
	95	=	
	71	SBR	
	32	x⇌t	$f(Z/Z_0)$
	75	−	
	43	RCL	
	06	6	
170	95	=	
	94	+/−	
	65	X	
	02	2	
	00	0	
	00	0	
	95	=	
	42	STO	M 8
	08	8	b^* (b)
	43	RCL	
180	07	7	
	75	−	
	43	RCL	
	06	6	
	95	=	
	65	X	
	05	5	
	00	0	
	00	0	
	95	=	
190	42	STO	M 7
	07	7	a^* (b)
	32	x⇌t	
	43	RCL	
	08	8	
	22	INV	
	37	2nd P→R	M 10
	42	STO	H°_{ab} (b)
	10	10	
	32	x⇌t	
200	42	STO	M 9
	09	9	C^*_{ab} (b)
	75	−	
	43	RCL	
	04	4	
	95	=	M 12
	42	STO	ΔC^*_{ab} (b−st)
	12	12	
	43	RCL	
	06	6	
210	65	X	
	01	1	
	01	1	
	06	6	
	75	−	

LOC ADR ADR	CODE KODE CODE	KEY TASTE TOUCHE	COMMENTS BEMERKUNGEN COMMENTAIRES
	01	1	
	06	6	
	95	=	
	42	STO	M 6
	06	6	L^* (b)
220	75	−	
	43	RCL	
	01	1	
	95	=	
	42	STO	M 11
	11	11	ΔL^* (b−st)
	43	RCL	
	07	7	
	75	−	
	43	RCL	
230	02	2	
	95	=	
	33	x^2	
	85	+	
	53	(	
	43	RCL	
	08	8	
	75	−	
	43	RCL	
	03	3	
240	54	)	
	33	x^2	
	95	=	
	42	STO	M 00
	00	0	$(\Delta$ chroma-
	85	+	ticity$)^2$
	43	RCL	
	11	11	
	33	x^2	
	95	=	
250	34	√	
	42	STO	M 14
	14	14	ΔE^*_{ab}
	43	RCL	
	10	10	
	75	−	
	43	RCL	
	05	5	
	95	=	
	69	2nd OP	
260	10	10	
	65	X	
	53	(	
	43	RCL	
	00	0	
	75	−	
	43	RCL	
	12	12	
	33	x^2	
	54	)	
270	34	√	
	95	=	
	42	STO	M 13
	13	13	ΔH^*_{ab} (b−st)
	91	R/S	
	76	2nd Lbl	
	19	2nd D'	D'
	09	9	D_{65} − 10°
	04	4	
	93	.	
	08	8	
	02	2	
	05	5	
	42	STO	
	18	18	M 18
	01	1	X_0 (D_{65})
	00	0	
	07	7	
	93	.	
	03	3	
	08	8	
	01	1	
	42	STO	M 19
	19	19	Z_0 (D_{65})
	91	R/S	

MERGED CODES / KOMBINATIONS-KODES / TOUCHES COMBINEES

62	72 STO	83 GTO
63	73 RCL	84
64	74 SUM	92 INV SBR

TEXAS INSTRUMENTS

PAGE SEITE PAGE 3 OF VON DE 3

DATE DATUM DATE ____

TI PROGRAMMABLE

PROGRAM RECORD
PROGRAMM-BERICHT
FICHE PROGRAMME

Printer Drucker Imprimante –
Cards Karten Cartes –

• PROGRAMM BESCHREIBUNG • DESCRIPTION DU PROGRAMME

TIONS • BENUTZER INSTRUKTIONEN • MODE D'EMPLOI

	ENTER EINGABE INTRODUIRE	PRESS BEFEHL APPUYER SUR			DISPLAY ANZEIGE AFFICHAGE
	X_{st}		A		$f(X_{st}/X_0)$
	Y_{st}		B		$f(Y_{st}/Y_0)$
	Z_{st}		C		L^* (st)
	X_{batch}	2nd	A′		$f(X_b/X_0)$
	Y_{batch}	2nd	B′		$f(Y_b/Y_0)$
	Z_{batch}	2nd	C′		ΔH^*_{ab} (b-st)

REGISTERS • SPEICHER • REGISTRES MEMOIRE (INV [illegible])

0	$(\Delta \text{Chromaticity})^2$	10	H^o (b)
0	L^* (st)	11	ΔL^* (b-st)
0	a^* (st)	12	ΔC^* (b-st)
0	b^* (st)	13	ΔH^* (b-st)
0	C^* (st)	14	ΔE^*_{ab}
	H^o (st)	5	
0	L^* (batch)	6	
	a^* (batch)	7	
	b^* (batch)	18	X_o
0	C^* (batch)	19	Z_o

LABELS (Op 08)
LABELS (Op 08)
LABELS (Op 08)

INV _ lnx _ CE _ CLR _ x:t _ x² _
√x _ 1/x _ STO _ RCL _ SUM _ yˣ _
EE _ (_) _ ÷ _ GTO _ × _
SBR _ − _ RST _ + _ R/S _ . _
+/− _ = _ [illegible]

3 | 4 | 5 | 6 | 7 | 8 | 9

TITLE / TITEL / TITRE: RGB (to XYZ) to CIELAB
PAGE / SEITE / PAGE 1 OF / VON / DE 3
PROGRAMMER / PROGRAMMIERER / PROGRAMMEUR: dr. Robert HIRSCHLER
DATE / DATUM / DATE: 17/12/1981

TI PROGRAMMABLE
CODING FORM
KODEFORM
FEUILLE DE PROGRAMMATION

LOC ADR ADR	CODE KODE CODE	KEY TASTE TOUCHE	COMMENTS BEMERKUNGEN COMMENTAIRES	LOC ADR ADR	CODE KODE CODE	KEY TASTE TOUCHE	COMMENTS BEMERKUNGEN COMMENTAIRES	LOC ADR ADR	CODE KODE CODE	KEY TASTE TOUCHE	COMMENTS BEMERKUNGEN COMMENTAIRES
0	76	2nd Lbl		5	85	+		110	17	17	
1	32	x⇌t	SBR x⇌t	6	53	(			55	÷	
2	32	x⇌t		7	43	RCL			43	RCL	
3	93	.		8	07	7			19	19	
4	00	0		9	65	X			95	=	
5	00	0		60	93	.			71	SBR	
6	08	8		1	07	7			32	x⇌t	
7	08	8		2	08	8			75	−	
8	06	6		3	02	2			43	RCL	
9	77	2nd x≥t	!!!	4	54	)			01	1	
10	15	E		5	95	=		120	95	=	
1	32	x⇌t		6	92	INV SBR			94	+/−	
2	22	INV		7	91	R/S	← R_X (st)		65	X	
3	45	y^x		8	76	2nd Lbl			02	2	
4	03	3		9	11	A	A		00	0	
5	95	=		70	42	STO			00	0	
6	92	INV SBR		1	07	7			95	=	
7	76	2nd Lbl		2	91	R/S	← R_Y (st)		42	STO	M
8	15	E	E	3	76	2nd Lbl			03	3	L*
9	32	x⇌t		4	12	B	B		43	RCL	
20	65	X		5	42	STO	M 16	130	02	2	
1	07	7		6	16	16	Y (st)		75	−	
2	93	.		7	91	R/S	← R_Z (st)		43	RCL	
3	07	7		8	76	2nd Lbl			01	1	
4	08	8		9	13	C	C		95	=	
5	07	7		80	42	STO			65	X	
6	85	+		1	08	8			05	5	
7	93	.		2	71	SBR			00	0	
8	01	1		3	91	R/S			00	0	
9	03	3		4	42	STO	M 17		95	=	
30	07	7		5	17	17	Z (st)	140	42	STO	M 2
1	09	9		6	71	SBR			02	2	a*
2	95	=		7	43	RCL			32	x⇌t	
3	61	GOTO		8	42	STO	M 15		43	RCL	
4	00	0		9	15	15	X (st)		03	3	
5	16	16	END of SBR	90	55	÷			22	INV	
6	76	2nd Lbl		1	43	RCL			37	2nd P→R	
7	91	R/S		2	18	18			42	STO	M
8	65	X		3	95	=			05	5	h^o_{ab}
9	01	1		4	71	SBR			32	x⇌t	
40	93	.		5	32	x⇌t		150	42	STO	M
1	01	1		6	42	STO			04	4	C^*_{ab}
2	08	8		7	02	2	$f(X/X_0)$		43	RCL	
3	02	2		8	43	RCL			01	1	
4	95	=		9	16	16			65	X	
5	92	INV SBR		100	55	÷			01	1	
6	76	2nd Lbl		1	01	1			01	1	
7	43	RCL		2	00	0			06	6	
8	43	RCL		3	00	0			75	−	
9	08	8		4	95	=			01	1	
50	65	X		5	71	SBR					
1	93	.		6	32	x⇌t					
2	01	1		7	42	STO					
3	09	9		8	01	1	$f(Y/Y_0)$				
4	08	8		9	43	KCL					

62 63 64 72 STO 73 RCL 74 SUM

TEXAS INSTRUMENTS

TITLE / TITEL / TITRE [illegible] to (XYZ) to CIELAB PAGE / SEITE / PAGE 2 OF / VON / DE 3

PROGRAMMER / PROGRAMMIERER / PROGRAMMEUR ________ DATE / DATUM / DATE ________

TI PROGRAMMABLE
CODING FORM
KODEFORM
FEUILLE DE PROGRAMMATION

LOC ADR	CODE KODE CODE	KEY TASTE TOUCHE	COMMENTS BEMERKUNGEN COMMENTAIRES
160	[illegible]	×	
1	[illegible]	=	
2	[illegible]	STO	M 1
3	[illegible]	1	L^*(st)
4	[illegible]	R/S	← $R_x(b)$
5	[illegible]	2nd Lbl	
6	[illegible]	2nd A'	A'
7	[illegible]	STO	
8	[illegible]	+	
9	[illegible]	R/S	← $R_y(b)$
170	[illegible]	2nd Lbl	
1	[illegible]	2nd B'	
2	[illegible]	STO	
3	[illegible]	[illegible]	
4	[illegible]	R/S	← $R_z(b)$
5	[illegible]	2nd Lbl	
6	[illegible]	2nd C'	
7	[illegible]	STO	
8	[illegible]	8	
9	[illegible]	SBR	
180	[illegible]	R/S	
1	[illegible]	STO	
2	[illegible]	10	
3	[illegible]	SBR	
4	[illegible]	RCL	
5	[illegible]	÷	
6	[illegible]	RCL	
7	[illegible]	18	
8	[illegible]	−	
9	[illegible]	SBR	
0	[illegible]	x⇌t	
1	[illegible]	STO	
2	[illegible]	+	$f(X/X_0)$
3	[illegible]	RCL	
4	[illegible]	[illegible]	
5	[illegible]	÷	
6	01	1	
7	00	0	
8	00	0	
9	95	=	
20	71	SBR	
1	32	x⇌t	
2	42	STO	
3	06	6	$f(Y/Y_0)$
4	[illegible]	RCL	
5	[illegible]	10	
6	[illegible]	÷	
7	[illegible]	RCL	
8	[illegible]	19	
9	95	=	
21 0	71	SBR	
1	[illegible]	x⇌t	$f(Z/Z_0)$
2	[illegible]	−	
3	[illegible]	RCL	
4	[illegible]	[illegible]	

LOC ADR	CODE KODE CODE	KEY TASTE TOUCHE	COMMENTS BEMERKUNGEN COMMENTAIRES
5	95	=	
6	94	+/-	
7	65	X	
8	02	2	
9	00	0	
220	00	0	
1	95	=	
2	42	STO	M 8
3	08	8	b^* (b)
4	43	RCL	
5	07	7	
6	75	−	
7	43	RCL	
8	06	6	
9	95	=	
230	65	X	
1	05	5	
2	00	0	
3	00	0	
4	95	=	
5	42	STO	M 7
6	07	7	a^* (b)
7	32	x⇌t	
8	43	RCL	
9	08	8	
240	22	INV	
1	37	2nd P→R	M 10
2	42	STO	H^o_{ab} (b)
3	10	10	
4	32	x⇌t	
5	42	STO	M 9
6	09	9	C^*_{ab} (b)
7	75	−	
8	43	RCL	
9	04	4	M 12
250	95	=	ΔC^*_{ab}(b−st)
1	42	STO	
2	12	12	
3	43	RCL	
4	06	6	
5	65	X	
6	01	1	
7	01	1	
8	06	6	
9	75	−	
26 0	01	1	
1	06	6	
2	95	=	
3	42	STO	M 6
4	06	6	L^* (b)
5	75	−	
6	43	RCL	
7	01	1	
8	95	=	
9	42	STO	M 11

LOC ADR	CODE KODE CODE	KEY TASTE TOUCHE	COMMENTS BEMERKUNGEN COMMENTAIRES
270	11	11	ΔL^* (b−st)
	43	RCL	
	07	7	
	75	−	
	43	RCL	
5	02	2	
	95	=	
	33	x^2	
	85	+	
	53	(	
280	43	RCL	
	08	8	
	75	−	
	43	RCL	
	03	3	
5	54	)	
	33	x^2	
	95	=	
	42	STO	M 00
	00	0	$(\Delta$ chromaticity$)^2$
290	85	+	
	43	RCL	
	11	11	
	33	x^2	
	95	=	
29 5	34	$\sqrt{x}$	
	42	STO	M 14
	14	14	ΔE^*_{ab}
	43	RCL	
	10	10	
300	75	−	
	43	RCL	
	05	5	
	95	=	
	69	2nd OP	
5	10	10	
	65	X	
	53	(	
	43	RCL	
	00	0	
310	75	−	
	43	RCL	
	12	12	
	33	x^2	
	54	)	
5	34	$\sqrt{x}$	
	95	=	
	42	STO	M 13
	13	13	ΔH^*_{ab} (b−st)
	91	R/S	

MERGED CODES / KOMBINATIONS-KODES / TOUCHES COMBINEES

62 Pgm Ind	72 STO Ind	83 GTO Ind
63 Exc Ind	73 RCL Ind	84 Op Ind
64 Prd Ind	74 SUM Ind	92 INV SBR

TEXAS INSTRUMENTS

SEITE PAGE 3 VON DE

DATE DATUM DATE —

3 1 9 1 9 Library Module Software-Modul Module enfichable —

PROGRAM RECORD
PROGRAMM-BERICHT
FICHE PROGRAMME

Printer Drucker Imprimante —
Cards Karten Cartes —

PROGRAM DESCRIPTION • PROGRAMM BESCHREIBUNG • DESCRIPTION DU PROGRAMME

USER INSTRUCTIONS • BENUTZER INSTRUKTIONEN • MODE D'EMPLOI

PROCEDURE PROZEDUR PROCEDURE	ENTER EINGABE INTRODUIRE	PRESS BEFEHL APPUYER SUR			DISPLAY ANZEIGE AFFICHAGE
	R X_{st}		A		$f(X_{st}/X_0)$
	R Y_{st}		B		$f(Y_{st}/Y_0)$
	R Z_{st}		C		L^* (st)
	R X_{batch}	2nd	A'		$f(X_b/X_0)$
	R Y_{batch}	2nd	B'		$f(Y_b/Y_0)$
	R Z_{batch}	2nd	C'		ΔH^*_{ab} (b-st)

USER DEFINED KEYS	DATA REGISTERS DATENSPEICHER REGISTRES-MEMOIRE (INV Int)		LABELS (Op 08)
A [illegible] st	0 chromaticity	10 H^o (b)	INV lnx CE CLR x:t x²
B [illegible] st	1 L^* (st)	11 ΔL^* (b-st)	√x 1/x STO RCL SUM yˣ
[illegible] st	2 a^* (st)	12 ΔC^* (b-st)	EE ( ) ÷ GTO ×
[illegible] (2^o) C	3 b^* (st)	13 ΔH^* (b-st)	SBR − RST + R/S .
≤ .008856	4 C^* (st)	14 ΔE^*_{ab}	+/- = CLR INV
[illegible] b	5 H^o (st)	5 X (st)	
[illegible] b	6 L^* (batch)	6 Y (st)	
[illegible] b	7 a^* (batch)	7 Z (st)	
	8 b^* (batch)	18 X_o	
	9 C^* (batch)	9 Z_o	

1	2	3	4	5	6	7	8	9

ANNEX No. 4.

to Mission Report
Egypt, 26 October - 24 December 1981
DP/EGY/77/008
by Dr. Robert Hirschler

VISIT OF TEXTILE MILLS

4.1	MISR Spinning and Weaving Co., Mehalla El Kubra	8 November and also 28 November - 2 December
4.2	IZMADYE Dyestuffs and Chemicals Co., Kafr El Dawar	10 November and also 6-7 December
4.3	MISR Beida Dyers Co.,	12 November
4.4	El NASR Spinning and Weaving and Finishing Co., Mehalla El Kubra	1 December

4.1 MISR Spinning and Weaving Co., Mehalla El Kubra

Purpose of the visit: to instruct the staff in the application of the ACS colour measuring and colorant formulation system, to give detailed information on the theoretical background of its operation and to give general information on the application of such systems in the textile field.

Persons met: Dr. Mohamed E-Gouroury, Chairman of the Board
Mrs. Tomader El-Hawary
Mr. Mamdouh Khalil
Dr. Ahmed Mohamed El Said

Subjects covered: since the measuring instrument itself /the SpectorSensor spectrophotometer/ was out of order, no practical measurements could be done. The computer part, however, was in good working condition, so a very detailed instruction and demonstration could be given on the working principle of the system, with an in-depth interpretation of the input and output data. By the demand of the operators the mathematics of computer colorant formulation was also explained in great detail. A seminar was given on colour measurement /see Annex 5.2 for seminar paper/,and an informal paper on up-to-date colour instrumentation was also presented.

The general problem in the everyday application of the ACS system appears to be the reluctancy of people in the dyehouse in accepting the data given by the computer. This is exactly the same situation as that encountered all over the world where computer colorant formulation systems have been set up, and it can be traced back partly to lack of information - and therefore lack of confidence - on the part of the people who are supposed to use the computed data, and partly to lack of personal incentive. This latter is understandable if we consider the amount of work to be put into changing existing sets of recipes or ranges of dyestuffs for new ones, recommended by the computer.

The staff of MISR Mehalla responsible for operating the ACS system /particularly Mr.Mamdouh Khalil and Dr. Ahmed Mohamed El Said/ are well trained and eminently suitable for their job. They need however the full support of the management in introducing their results into everyday practice. They are able to compute optimized recipes, but these should be asked for by the workshops and used thereafter.

Specific problems identified

The selection of dyestuffs form among the great variety of competitive products is practiced in the form of a "tender", the use of colour measurement in giving an objective figure for comparing competitive products should continue along the lines already started. The problem of "which method of comparison to use" on the ACS system has been solved. The difference between the options available on the ACS system has been clarified by worked examples, and the consultant recommended option M /wavelength of maximum absorbance/ for the comparison of chemically identical dyestuffs, and the application of match prediction /as opposed to the "strength" program/ for all other cases.

The recipe prediction program of the ACS system has been discussed in detail, the algorithm used in the computer program explained on practical examples.

The difference between the CIELAB, HunterLab and FMC II formulae has been discussed. It has been demonstrated that there is no universally applicable "conversion factor" among the different formulae, but there is some similarity in the colour space defined by CIELAB and HunterLab. For university of practice the application of the internationally accepted CIELAB system is strongly recommended.

The question of tolerance limits /the maximum permissible deviation in colour/ has been raised. This question couldn't be answered by giving definite figures, since no universally acceptable limits exist, but an explanation was given on the recommended procedure for setting tolerance limits, and it was later discussed in great detail during the special seminar on tolerances.

Possibilities for cooperation with TDC

1. The TDC staff should be given ample opportunity to study and to work on the ACS system, since they are in an excellent position to give this new tehnique the wide-spread propaganda required for its acceptance by the Egyptian textile industry.
2. The methods for checking the accuracy, repeatability and reproducibility of colour measuring instruments and introduced at TDC should be used for regularly checking the performance of the ACS instrument. The two instruments can be compared to each other as well since TDC has an optional colour difference program on their TI calculator for just that.
3. The repeatability and reproducibility of dyeing techniques and of pieces of laboratory apparatus should be compared by repeated dyeing and measurement on the ACS and/or the HUNTERLAB instrument.
4. Experts from MISR Mehalla should make use of the up-to-date literature on colour measurement available at TDC.

Recommendations

1. Experts operating the ACS system should be given full support from the management in introducing their results in the workshops. The personnel responsible for ordering dyestuffs and deciding on recipes should have direct interest in putting the extra effort required to change the presently used dyestuffs and recipes for the more economical optimized ones.

2. In order to popularize the advantages of the ACS system operating in MISR Mehalla experts from other mills should be invited to have first hand information in its operation, also symposia and other meetings can be organized for participants from all over the industry. In the consultant's view these meeting need more elaborate preparation and very careful selection of the participants so that the "message" should reach the right people.

3. It would be advantageous for experts of the mill to visit textile finishing factories abroad where colour measurement is practiced. A visit to the Colour Measurement and Match Prediction Centre in Hungary would probably prove very fuitful, and the consultant can help in making the arrangements. It is suggested to make it a joint visit with the staff from TDC

4. For strength comparison of chemically identical dyestuffs the M option /Wavelength of maximum absorbance/ of the ACS system should be used, but for dyestuffs which are only similar, but not identical this is not sufficient, here the modified application of the match prediction program is recommended.

Remark

It was rather unfortunate, that the ACS system was partly out of order all through the consultant's stay in Egypt. Since, however, the experts of MISR Mehalla needed no practical training in the operation of the instrument itself, but rather explenation of the theory behind it and interpretation of the input and output data, it is the firm belief of the consultatnt, that no significant loss has occured due to this misfortune.

Follow-up

The staff operating the ACS system should be able to continue the work on their own, with the recommended co-operation with the Textile Development Centre.

4.2 IZMADYE Dyestuffs and Chemicals Co., Kafr El Dawar

Purpose of the visit: to survey the colour measurement facilities at IZMADYE, and comment on their usage.

Persons met: Chemist Lotfi Khattab, General Works Director, Member of the Board
Mr. Abdel Fattah Rezl, Director Techn.Serv.
Dr. Hassan Saaid Mahamoud, Director of Research
Dr. Moustafa Ibrahim Mohamed, Director of Quality Control
Eng. Hussein Abdel Salem, Production Manager

Subjects covered: general information on IZMADYE, the application of colour measuring instruments in general, and steps recommended for IZMADYE in utilizing the instruments for match prediction and quality control.

The general problem in the application of colour measurement at IZMADYE is the same as that encountered elsewhere /e.g. in many dyehouses in Europe and in the USA/ viz. the lack of special training of the staff required to run their instruments efficiently. It was at the same time pointed out, that IZMADYE as a dyestuff manufacturer should be ahead of his customers, just like all the big companies /ICI, Bayer, ACNA etc./ who have played a leading role in developing applied colour science to its present level.

Specific problems identified

Spectromat FS - 3A spectrophotometer /in Research Dept./

At the time of the purchase /1974/ one of the best instruments available, now rather out date. For nearly three years now it has been out of order due to some hardware failure. The method used for "match prediction", utilizing fairly simple mathematics and off-line calculation /on the computer of the university/ is that used in Europe more than a decade ago.

ELREPHO colorimeter /in Quality Control Dept./

A good instrument in its time /the mid-1960's/ by now it is also rather obsolete. It's technical performance however was surprisingly good /see Annes 2, for data/, showing that it is in a good working condition, well standardized and well operated.

The values obtained by the instrument are normally transformed by the Simon-Goodwin graphical method into MacAdam units, and deviations between standard and batch are recorded, but - since the tolerance limits are unknown - no action follows, the pass/fail decision is based on visual estimation.

The graphical method used has been replaced all over the world by the application of the CIELAB system. The RGB instrumental values can easily be converted to CIELAB coordinates, and a special program has been written by the consultant for a TI 58 C calculator doing just that /Annex 3./

Instrumental batch correction

The Production Department would like to have an instrumental method for correcting off-shade batches. The problem was discussed in detail, and the solution based on the existing instruments was outlined. There was unfortunately no possibility in the limited time available to make practical tests of the method, this remains for an eventual follow-up visit.

Beckmann Model 25 UV-vis. spectrophotometer:

seems to be in new condition, a good piece of instrument for solution analysis but unsuitable for colour measurement.

Recommendations made

1. It was emphasized that IZMADYE should be ahead of the industry using his products in the application of up-to-date colour control and formulatin methods, set up as soon as possible their CCM /Computer Colorant Formulation/ system, and offer a match prediction and formula optimization service for their customers. This should improve the marketability of their products, since all major dyestuff manufacturers can - and in fact do - offer such services. This math prediction system could be operated jointly with TDC as explained below.

2. The staff directly involved in colour control work should continue their studies in applied colour science, consult the literature for details and also spend some time in the MISR Mehalla mill studying the ACS system.

3. Pretema AG should be pressed to repair the instrument, at the same time making enquiries about the possibility and eventual cost of up-grading the instrument into a modern match prediction system. Simultaneously other manufacturers of CCM systems /see Annex 6. for names and addresses/ should be contacted for price and technical information.

The selection of the system should be based on price as well as service conditions, with due consideration given to the possibility of cooperation with the ACS system in MISR Mehalla.

4. Even when using the existing instruments /the ELREPHO and the PRETEMA/ the internationally accepted CIELAB system should be used. To perform the necessary calculations a suitable programmable calculator is needed, preferably one similar or identical to that used at TDC /a Texas Instruments 58 C or 59 C/ is recommended. The program for converting the RGB instrumental values to CIELAB coordinates is already available /Annex 3./.

4. Colour tolerances can be set up by one of the methods described in the literature and discussed during the seminar on the topic /Annex 5.3/. It is to be expected however, that the introduction of instrumental methods into mill practice takes several years of systematic work, so a detailed program must be made accordingly.

Possibilities for cooperation with TDC

1. For the present TDC staff are able to help IZMADYE in
   - regularly checking the performance of the ELREPHO instrument,
   - purchasing and programming a calculator for colour work.

2. When the PREMETA /or a new/ match prediction is set up, TDC can join IZMADYE in operating the system. The cooperation here can take several forms, one would be to install the system at IZMADYE and have it run by staff from TDC /a similar joint operation works rather successfully in Hungary/. The advantages for this sort of set-up would be the better physical facilities provided by the mill, and personnal more at home in introducing applied science in other mills provided by TDC.

Follow-up

There are some points, where a follow-up visit by a consultant in colour measurement is recommended:

- initiation of tolerance work, setting up the detailed working program:
- introduction of instrumental methods in the colour correction of off-shade batches:
- eventual selection of a computerized match prediction system and proposing a framework for its operation.

4.3 MISR BEIDA Dyers Co., Kafr El Dawar

Purpose of the visit: to discuss the possibilities of introducing instrumental colour measurement in the mill.

Persons met:	Dr. A.M. El-Borai	Chairman
	Mr. Roshdy Fouad Yassa	Chemist, Director of Planning and Prod.Contr.

Subjects covered: topics of the training course to be organized at TDC, possibilities and necessity of getting familiar with, and introducing in practice a computer match prediction system.

General problems identified: the mill has no colour measuring instrument, therefore no direct experience in instrumental colour control. Being one of the largest dyers in the area the application of up-to-date methods in dyestuff control and recipe prediction is strongly recommended.

Recommendations made:

1. Experts from the mill should begin their education in colour science, a good first step being the lo-day course offered at. TDC.
2. The purchase of a computer colour matching /CCM/ system is recommended only after going through the following preparatory work:
   - thorough education /possibly in the form of a scholarship/ of some experts, preferably textile chemist in the mill in colour science;
   - establishing cooperation with TDC. and MISR Mehalla in the field of colour measurement and match prediction, to give the mill experts possibility to get first hand experience;
   - introducing optimized dyestuff ranges and recipes /calculated on the ACS system in Mehalla/ for one or two of the most important areas at Beida Dyers, and compare their technical and economic performance to those used presently.

Having gone through these steps will the mill get in a position to decide on buying their own CCM system /which could well be justified by the Return on Investment figure alone/, or help in setting up or join in an eventual central match prediction service in or around Alexandria.

Possibilities for cooperation with TDC

The possibilities at present are outlined above, and in the future they depend on the mill's decision about the purchase of an instrument or joining in some project with TDC.

Follow-up

A follow-up visit by a consultant in colour measurement could be useful after the preparatory steps recommended have been made. He could then - based on the data collected by the mill - give advice on future action.

4.4 EL NASR Spinning, Weaving and Finishing Co., Mehalla

Purpose of the visit: to survey the existing colour measurement instrumentation in the mill and comment on their usage.

Persons met:

Mr. Saad Farid	GM Chemical Sectors
Dr. Shawki El Bedewi	Director, Res.Dept.
Mr. Ali Abou Gebba	Research
Mr. Abdel Latif Huseny	Research
Mr. Mohammed Nashaat	Colour Measurement

Subjects covered: colour instrumentation, performance and comparison of instruments, setting up tolerance limits, significance of chromaticity differences, spectral characteristics of light sources.

General problems identified: the laboratory of the mill is fairly well supplied with colour measuring instruments, but they are rather out of date: around 10 years old.

The interpretation of the colour measurement data is not quite clear, this is not unlike the situation in other textile mills all over the world.

Specific problems identified:

Lovibond Tintometer: being a visual instrument it is out of date beyond its age, shouldn't be used in industry.

Toyo Seiki Seisaku Ltd. Colour and Colour Difference Meter

This is a Hunter-type instrument, seemingly in good working condition, but a brief checking of its accuracy /Annex 2./ revealed serious flows. When carefully re-standardized, it could be a useful piece of instrument.

Toyo Seiki /Hunter Type/ Automatic Reflectometer

At the time of the visit out of order. When in good working condition, still usefull, but the accuracy and repeatability should carefully be checked.

The significance of spectral characteristics of light sources was discussed in some detail, with special reference to the measurement and visual assessment of fluorescent materials, e. g. those treated with an optical brightener.

The interpretation of measured values is rather problematic. The superiority of the CIELAB system to the x, y chromaticity coordinates or the X, Y, Z tristimulus values in attaching visual significance to the measured number was pointed out.

Tolerance specification was briefly mentioned, since it was the topic of a one-day seminar, where experts from NASR were to participate.

Recommendations:

1. The Lovi ond Tintometer - being a visual instrument - does not meet today's standards in repeatability and accuracy, and should therefore be used only when there are no stringent requirements in this respect.

2. The Toyo Seiki instruments should be carefully restandardized according to the manufacturers' instructions, and the repeatability and accuracy of the instruments should then be checked. The accuracy compared to a set of colour standards with known coordinates is expected on the average to be better /less/ than $2\Delta E^{*}_{ab}$ units in the CIELAB system, while the repeatability should be better than o.5 units.

3. For all colour calculations the CIELAB system is preferred, the necessary calculations can be performed with suitable pocket calculators. TDS can provide help in selecting and programming one .

4. The mill is in a unique position - being situated in Mehalla - to cooperate with MISR Mehalla in colorant formulation. This can be started immidiately by preparing the necessary calibration dyeings in the laboratories of NASR, and measuring the samples and feeding the data into the ACS system at MISR Mehalla. The purchase of a full match prediction system for NASR is not recommended, but a spectrophotometer- preferably the same ACS SpectraSensor as that in the MISR system - with a smaller computer could well be justified at a later stage.

Cooperation with TDC

TDC can help the mill in standardizing their instruments and also in introducing the CIELAB system, the purchase of a suitable calculator and its programming for colour calculations.

Follow up

A follow-up visit of about one week duration is suggested to help in starting the cooperation with MISR as recommended under point 4.

ANNEX No. 5.

to Mission Report
Egypt, 26 October - 24 December 1981
DP/EGY/77/008
by Dr. Robert Hirschler

Text of Seminars

5.1 Introduction to Colour Measurement in the Textile Industry /Lecture Notes/

5.2 A Brief Survey of Colour Measurement in the Textile Industry /Seminar Paper/

5.3 The Application of Colour Measurement in Tolerance Specification /Seminar Paper/

ANNEX 5.1

LECTURE NOTES

INTRODUCTION TO COLOUR MEASUREMENT IN THE TEXTILE INDUSTRY

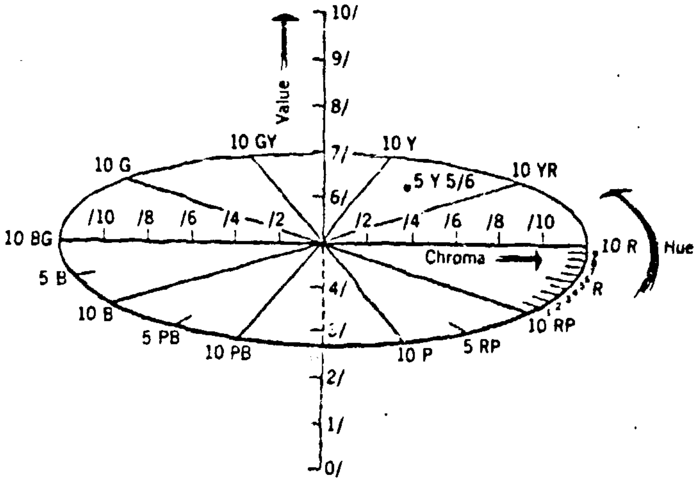
Dr. Robert Hirschler
UNIDO Expert in Colour Measurement

Textile Development Center, Alexandria
16-26 November 1981

Table of Contents

1. The specification of colour, colour order systems

The Munsell System. Perhaps the best known of all color-order systems is the *Munsell System* (Munsell 1929, 1963; Nickerson 1940, Kelly 1943). Based on the guiding principle of equal visual perception of small color differences, the Munsell system is both a collection of samples painted to represent equal intervals of visual perception of color difference between adjacent samples, and a system for describing all possible colors in terms of its three coordinates, *Munsell Hue, Munsell Value,* and *Munsell Chroma.* These coordinates correspond to three variables commonly used to describe color; *hue* is that quality of color which we describe by the words red, yellow, green, blue, etc.; *value* is that quality by which a color can be classified as equivalent in lightness to some member of a series of gray samples ranging from white to black; *chroma* is the quality which describes the degree of difference between a color (which is itself not a white, gray, or black) and a gray of the same value or lightness.



Hue: that quality of color which we describe by the words red, yellow, green, blue, etc.

Value: that quality of color which we describe by the words light, dark, etc., relating the color to a gray of similar lightness.

Chroma: that quality which describes the extent to which a color differs from a gray of the same value.

Figure 1.

In the Munsell color-order system, colors are arranged by *hue* in a hue circle, by *value* or lightness from top to bottom, and by *chroma* or saturation according to distance out from the scale of grays making up the center column.

A typical complete Munsell designation is 5 Y 5/6; the location of this designation is shown in the figure.

The samples of the *Munsell Book of Color* (Munsell 1929) are usually arranged in planes or pages of constant [illegible] each page. samples are arranged by Munsell Value in the vertical direction and by Munsell Chroma in the horizontal direction. A scale of grays, with white at the top and black at the bottom, may be thought of as the "trunk" of the Munsell color "tree," or as the zero-chroma column on each page. Each sample carries a *Munsell Notation* denoting its position; this notation consists of three symbols representing the Munsell Hue, Value, and Chroma in that order. Munsell Hue is expressed by a number and letter combination such as 5 Y or 2 GY where the letters are taken from the ten major hue names (*R*ed, *Y*ellow, *G*reen, *B*lue, *P*urple, and the five adjacent pairs of these, e.g., Green-Yellow) and the numbers run from 1 to 10. Munsell Value and Munsell Chroma are written after the hue designation and are separated by a diagonal line (/).

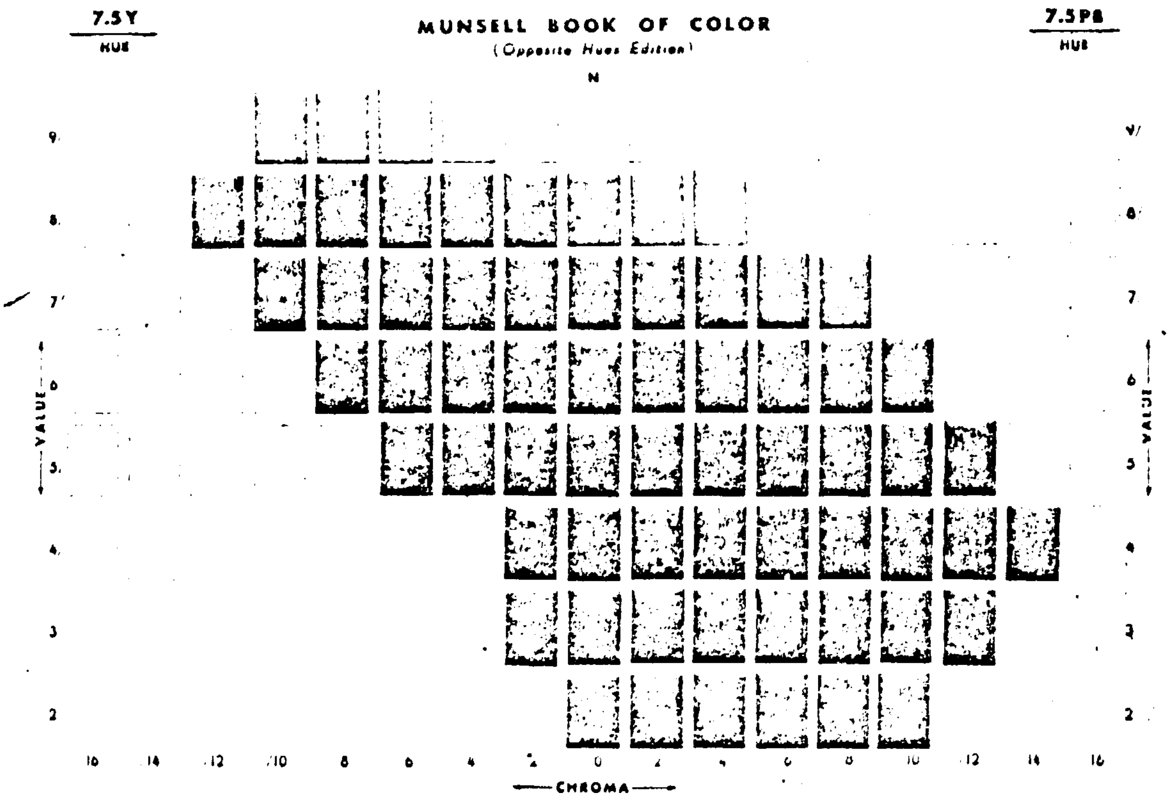


Figure 2. Arrangement of samples in the *Munsell Book of Color*.

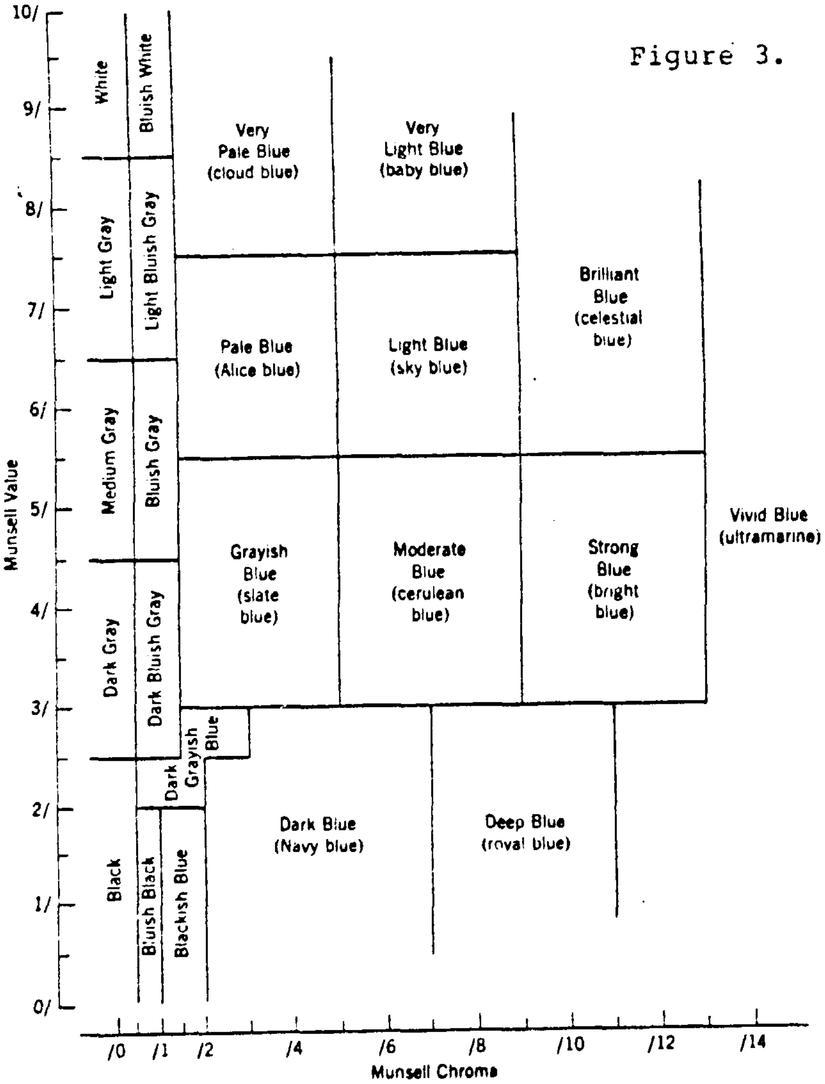
Two outstanding features of the Munsell System contribute to its usefulness and wide acceptance. The first is its conformance to equal visual perception. Within the limits of chroma (6–10) set by the samples of the original *Munsell Book of Color*, there is very little evidence for deviation from equal steps of perception in any of the Munsell coordinates. No other color system is as good in this respect; the Munsell System is the standard to which all other systems are compared.

The second major advantage of the Munsell System is that its notation is not linked to or limited by existing samples. Any conceivable color can be fitted into the system, whether it can be produced with existing colorants or not. In contrast, most collections of physical samples are based on highly colored specimens and could not accommodate a still more highly colored sample if one were found.

The Munsell designations of the original, matte finish, Munsell samples were subsequently adjusted somewhat to correct certain obvious errors in the original spacing. The new designations are known as *Munsell Renotations*, and the revised system as the *Munsell Renotation System* (Newhall 1943). Glossy samples were later painted (Davidson 1957) to whole-number Munsell Renotation designations. The Munsell Renotation System is related to the results of color measurement for all possible colors even though they cannot be produced by existing colorants.

The Munsell System was used as the basis of the ISCC-NBS system for designating color names (Kelly 1955), which was developed as an aid to standardizing the verbal description of color by names (see also C[illegible]oanis 1965). The published method tells how to assign an ISCC-NBS name to a color from its Munsell notation and includes a dictionary of common color names with their ISCC-NBS equivalents. Samples have been painted to represent the center of each region in Munsell color space corresponding to an ISCC-NBS name (Kelly 1958, NBS 1965).

Figure 3.

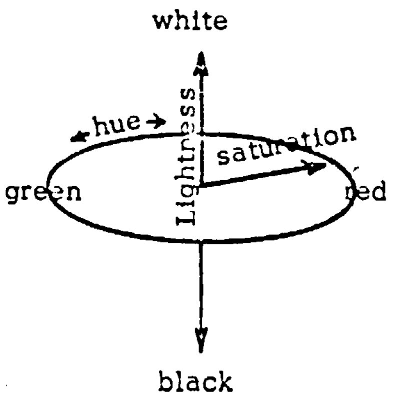
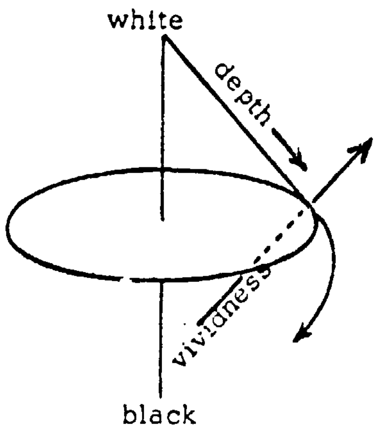
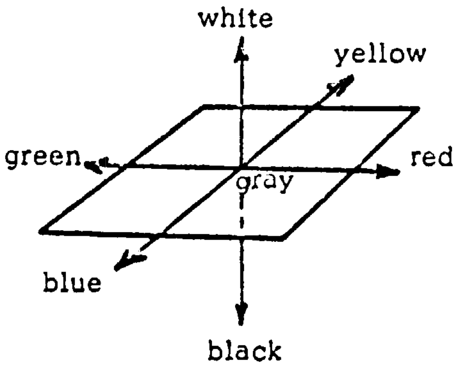


This page from the ISCC-NBS Dictionary of color names (Kelly 1955) shows the ISCC-NBS names assigned to colors with various Munsell Values and Chromas, and Munsell Hues between 0B and 5 PB. We have added some corresponding common names in parentheses.

Other colour systems use other coordinates, and we can mark in colour space the directions corresponding to these, as shown on figure 4. below.

Figure 4.

SYSTEMS OF THREE-DIMENSIONAL COLOR SPACE

SYSTEM USED BY	ARRANGEMENT OF ATTRIBUTES IN COLOR SPACE	TERMS FOR ATTRIBUTES
Designers and colorists in fields such as interior decorating, product packaging. (Munsell)		Hue Chroma (Saturation) Value (Lightness)
Color formulators and color chemists in the creation of colored products such as paints, dyes. (Ostwald)		Hue Depth Brightness (Vividness)
Paper machine foremen or textile bleach plant foremen. (Opponent-colors)		Yellowness-Blueness Redness-Greenness Lightness Whiteness of Whites Blackness of Blacks

2. The description and pratical application of the CIELAB system.

2.1 Colour specification

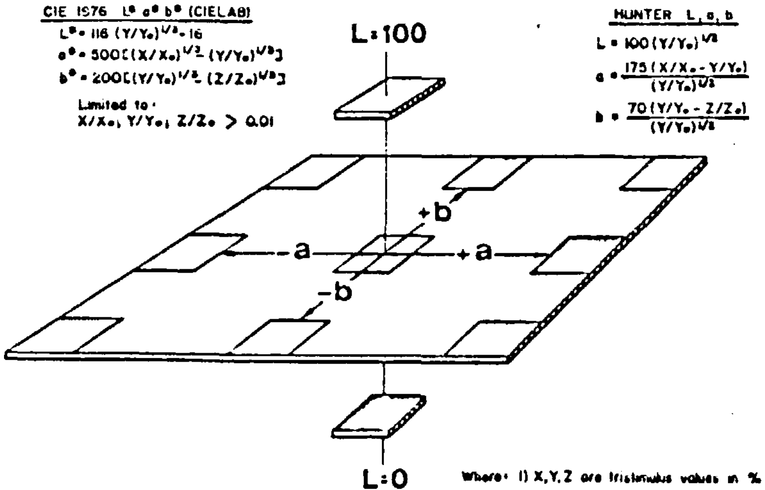
Colour, as we have just seen, can by specified by three attributes. The advantages of measured values as opposed to visually estimated ones are obvious, but naturally we would like to have a set of measured values corresponding to what we see, i.e. to a visually uniform colour system, such as the Munsell system described in the preceding chapter.

In the international system of colorimetry/the CIE system, to be explained in some detail later/ the three numbers used are the X,Y and Z tristimulus values, but these do not correlate well to colour order systems. These quantities can, however, be converted into new ones (called psychometric quantities or terms) which give visually approximately uniform spacing, and are suitable for both quantitiave and qualitative description of colour.

A family of such transformed systems are called the L,a,b scales, the best known examples being the Hunter L,a,b, /Hunterlab/ the Adams-Nickerson L,A,B/ANLAB/ and the most recent CIE L*,a*, b* /CIELAB/ systems. The Hunterlab was the first one of these scales, and had been widely used, particularly in the U.S.A. but other systems have been found with better uniformity. The ANLAB system used to be very popular in Europe, especially in the textile industry, its main disadvantage beeing the somewhat complicated mathematics used in the transformation equations. The CIELAB system is nothing but a very good approximation of ANLAB, with much simpler transformation equations. /These can be found in the Appendix./

ANLAB and CIELAB can thus be treated as very closely related systems, what holds true for one, is valid for the other, the numerical difference between the two scales in generally less than 1-2% relative. Hunterlab on the other hand is only similar in structure to CIELAB (or ANLAB), the two systems cannot be used interchangably.

In all L,a,b systems "L" means the lightness ranging from 0 to 100 (0 for black and 100 for white), "a" the red-green axis (+ for red and - for green) and "b" the yellow-blue axis (+ for yellow and - for blue), as sketched on the figure below



Where: 1) X,Y,Z are tristimulus values in %
2) X_o, Y_o, Z_o are tristimulus values for any illuminant. For CIE Illuminant C, $X_o = 98.041$, $Y_o = 100.000$, $Z_o = 118.103$

Fig. 5 The L,a,b values represent a three-axes opponent-colors scale system, based on the theory that color is perceived by black-white (L), red-green (a) and yellow-blue (b) sensations.

The a-b plane can be considered as a horizontal section of the L,a,b space. On it we can illustrate the chromaticity of colours/which term means a combination of chroma and hue/. The principle Munsell Hues are illustrated on in the a-b plane on Fig 6.

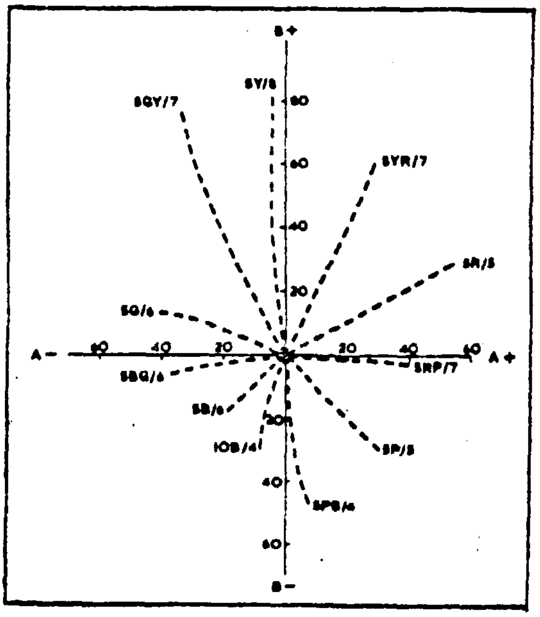


Figure 6– Loci of principal Munsell Hues in AB diagram

The a-b plane of the system thus expresses chromaticity in terms of redness - greenness and yellowness - blueness, but quantities corresponding to Munsell Chroma and Hue (called in the CIELAB system "C^{*}_{ab} metric chroma" and "H^{o}_{ab} metric hue angle") can easily be calculated. The geometrical meaning of these terms is illustrated below, the equations given in the Appendix.

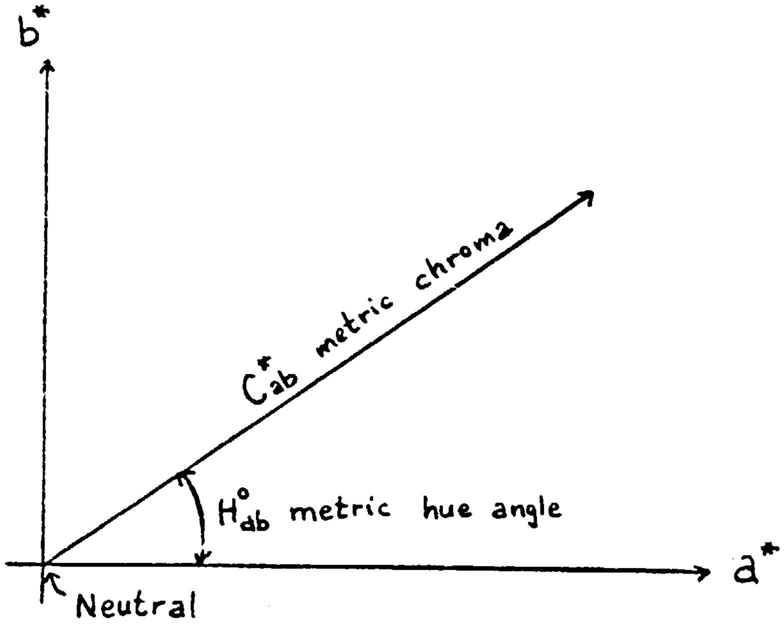


Figure 7 - C^*_{ab} metric chroma and $\overline{H}^{o}_{ab}$ metric hue angle in the a^* - b^* diagram of the CIELAB system.

The similarity between the Munsell and the ANLAB colour spaces is illustrated on Figure 8.

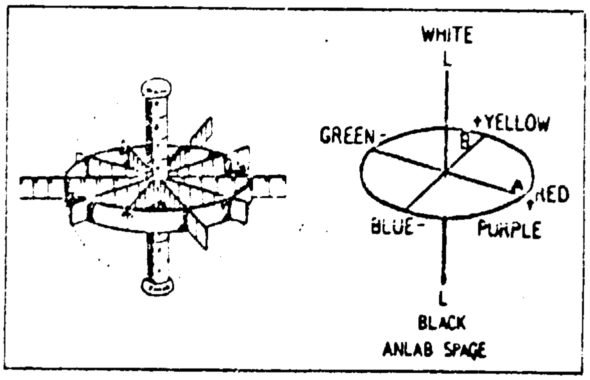


Figure 8 – Left: Munsell space (from 'A Grammar of Color'; New York: Reinhold Publishing Co., 1969). Right: ANLAB space

To summarize: colour can be specified by the perceptually developed Munsell system, or by colour measurement values converted into suitable scales, such as the L,a,b scales. There are several transformation equations given in textbook and papers, but the present internation recommendation is CIE-LAB, and that is the one to be used. Since the majority of publications had been published before 1976, when CIELAB was made the recommended system, much of the discussion below will be given in ANLAB terms, of which CIELAB is a very good approximation.

2.2 The characterization of dyestuffs

The Dyer's Variables

The dyer's variables are 'shade' and strength, the former being divided into two components, hue and brightness. They differ from the three variables of other systems, e.g. Hue, Value and Chroma in the Munsell system, by not being the axes of a colour solid. They cannot be used, therefore, to describe a colour in isolation, only to compare two colours that are themselves similar.

The Variable of Hue

Although this is the simplest of the dyer's variables, it has one or two unusual features. The most interesting is the fact that the dyer rarely needs to use more than one hue term from a total of only four to describe any difference in hue. These four are redder, yellower, greener and bluer, and their interest lies in the fact that there are four of them and not three, as one might have expected from the trichromatic theory of colour vision.

The hues red, yellow, green and blue are known in psychological circles as 'unique' or 'unitary' hues in the sense that it is possible to choose red, yellow, green and blue hues that do not evoke two hue sensations. This cannot be done for other hues; e.g., every orange hue evokes simultaneous sensations of redness and yellowness, every purple, redness and blueness, etc. Twenty-four colourists were asked to select from the Munsell Book of Colour the particular red hue that appeared neither yellowish nor bluish and similarly for yellow, green and blue hues. Their means had ANLAB hue angles of 27, 87, 163 and 254°. It must not be considered a defect of ANLAB colour space that these unique hues do not lie on the *AB* axes. It is a well-established, but at present inexplicable, fact that, if colours of the same saturation are equally spaced visually to form a hue circle, the unique hues do not lie opposite each other .

The only time a dyer invariably finds it necessary to use more than one hue term to describe a perceived colour difference is when he is comparing textiles treated with a fluorescent brightener that imparts a purplish cast to the textile. The dyer is forced to use an unusual term such as 'purpler' or 'violeter' or preferably to use two recognised hue terms together, i.e. 'the treated sample is brighter, redder and bluer than the untreated standard'.

In general, however, when sample–standard pairs are plotted in the *AB* diagram it is invariably found that, if a sample is described as redder, yellower, greener or bluer than the standard, then its hue angle will be nearer 0° (360°), 90° 180° or 270°, respectively.

Although a sample described as, e.g., yellower than standard will be found to have a hue angle nearer to 90° than that of standard, the converse is not always true. A sample of high *L* value with a hue angle of 90° would never be described as yellower than a standard whose hue angle was either 85 or 95°, because all these colours would be described as yellows and one of the hall-marks of the dyer is that he would never describe one yellow as yellower than another. Instead, he would describe the 90° sample as redder than a 95° standard and greener than an 85° standard. Similar considerations apply to red, green and blue colours. This convention is, however, often governed by the commercial name of the dye rather than the appearance. Most colourists would describe batches of C.I. Vat Orange 11 as being redder or greener than standard rather than redder or yellower because most firms sell this dye as - Yellow 3R.

It is, however, desirable to know the zones to which each pair of hue terms applies when the dyer is not aware of the name so as to avoid making wrong deductions from colour-difference measurement.

Consideration of the *AB* diagram of Figure 6 shows how difficult it is to interpret the nature of the hue corresponding to a change in the *A* or *B* components of the total colour difference. Even if only one changes, e.g. the sample has a higher *A* value than the standard, this only implies that the sample is redder than the standard if both are yellows or blues. For other colours, an increase in *A* would imply the following:

greens – vellower
bluish greens – weaker
reds – stronger.

In practice, all three values are likely to have changed and hence the correct interpretation becomes much more difficult.

The Variable of Strength

When the *LAB* values of a series of dyeings of increasing strength are located in ANLAB space, they fall on a smooth curve starting at the position of the undyed substrate – a high *L* value and $A \simeq B \simeq 0$. These curves are best studied by producing three-dimensional models, but the meaning of the dyer's strength variable can be understood by considering first the position of strength lines in the *LC* diagram (Figure 9) and second, in the *AB* diagram (Figure 10), these diagrams referring to dyes of different dyeing and chemical classes.

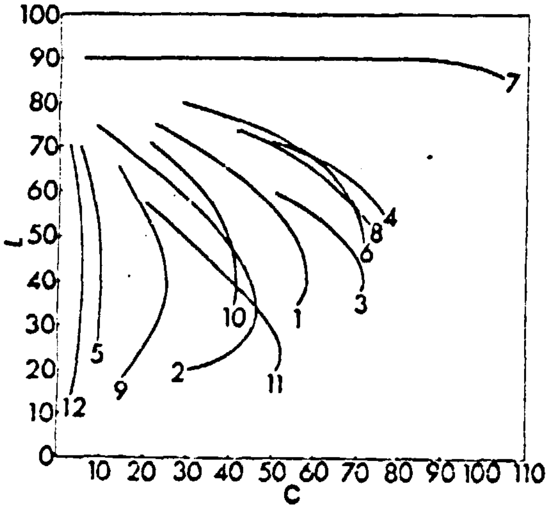


Figure 9 – Strength lines in LC diagram (same dyes as in Figure 10)

1 C.I. Reactive Red 11
2 C.I. Direct Red 1
3 C.I. Acid Red 85
4 C.I. Reactive Orange 13
5 C.I. Vat Brown 49
6 C.I. Disperse Orange 13
7 C.I. Reactive Yellow 86
8 C.I. Reactive Blue 80 and
C.I. Reactive Yellow 86
9 C.I. Acid Green 25:1
10 C.I. Disperse Blue 87
11 C.I. Acid Violet 41
12 C.I. Disperse Blue 35

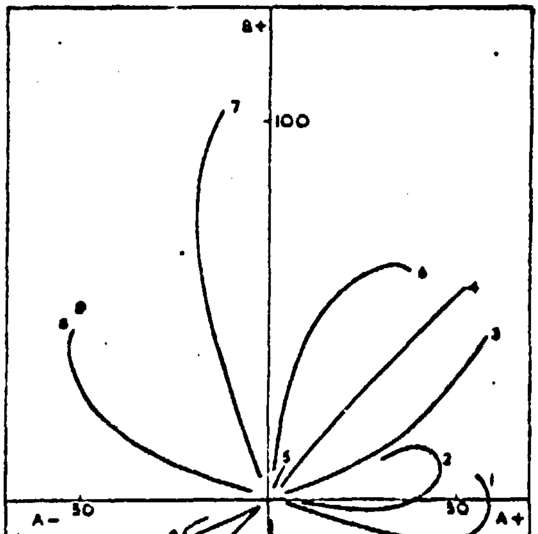


Figure 10 – Strength lines in AB diagram

Figure 9 shows that increasing strength causes mainly an increase in *C* with yellows, and decrease in *L* with navy blues (and equally greys and blacks) and a combination of both with every other colour. In many cases, dyes yield a maximum *C* value well before the fullest depth has been dyed and beyond this point an increase in strength causes a decrease in *C* as well as a continuing decrease in *L*.

Figure 10 shows that in most cases there is a change in hue with increasing strength and the colorimetric evidence for this fact, well known to dyers, does not appear to have been reported before, probably because in all the earlier studies the *x,y* chromaticity diagram was used and colours of constant hue plot as curves in this diagram. In the *AB* diagram, however, they are reasonably straight (Figure 8). It will be noticed that there is a certain symmetry about the lines in Figure 10 which suggests that orange and bluish green dyes build up without change in hue. A similar symmetry has also been observed for paints made from a white pigment with increasing amounts of chromatic pigments.

The Variable of Brightness

The dyer's variable of brightness is most readily described by defining its opposite, dullness; *dullness* is the attribute of perceived colour which increases when increasing amounts of a neutral-grey dye are incorporated in a dyeing of a chromatic dye. The effect on the position of a dyeing in ANLAB space when it was dulled was first studied by plotting the positions of sample–standard pairs which a dyer had assessed as being different in brightness and also by making dyeings of chromatic dyes varying by small amounts of a neutral-grey dye. Although this gave a clear indication of the effect of dullness a much more systematic investigation was made using the mathematics of computer match prediction in reverse. The *XYZ* values of a given percentage of chromatic dye plus increasing amounts of a grey dye were 'back-predicted' and converted to *LAB* values. This technique has the additional advantage of permitting the effect of a theoretically perfect neutral grey dye to be studied, i.e. one whose absorption is independent of wavelength, in the visual part of the spectrum; all real grey dyes depart considerably from perfection.

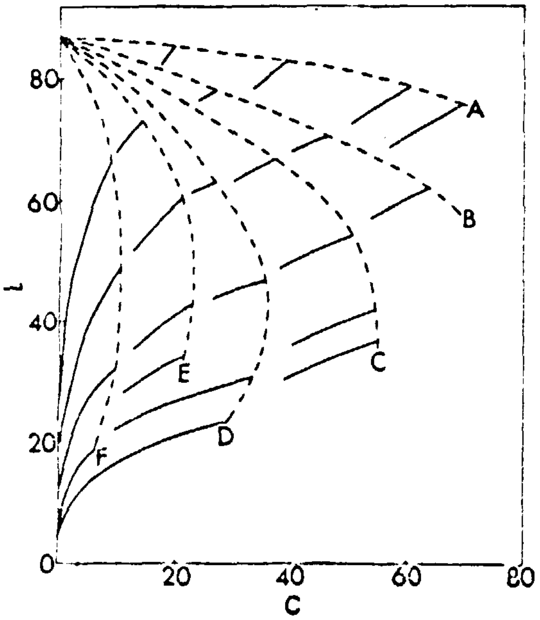
The combined strength and dullness curves for five dyes of different colours are shown in the *LC* diagram Figure 11.

Increasing dullness thus corresponds to a decrease in both lightness and saturation, the ratio between them being primarily dependent on the starting point in the *LC* diagram. It will be noticed, however, that the dullness lines are not in perfect alignment and this arises from the fact that the *LC* lines chosen lie in different hue planes. Within the same hue plane, the dullness lines of the dye of highest lightness must coincide with those of lower lightness because the latter can be matched by mixtures of the dye of highest lightness and a neutral grey. Confirmation that this occurs even when the dye of lower lightness is homogeneous is given in Figure 12; the dullness line of C.I. Reactive Green 5 is thus the dullness–brightness line of C.I. Reactive Green 11.

The addition of a theoretically perfect neutral grey had no effect on the hue angle for any colours except yellows, where a slight increase was observed corresponding to the well-known greening effect of grey dyes when added to yellow dyes. However, the effect was significantly less for the theoretical grey than for real greys, because the colour of all those examined had a blue component, i.e. their hue angles fell between 221 and 305°, between greenish blue and violet.

It is generally accepted that the addition of a neutral grey to a chromatic dye does not increase its strength, so that each solid line of Figure 11 represents the locus of dyeings of the same strength, at least over the range of increasing dullness where visual-strength comparisons would be made which White et al. found to be up to ten times a just-perceptible difference, equivalent to about 1 mm in Figure 11.

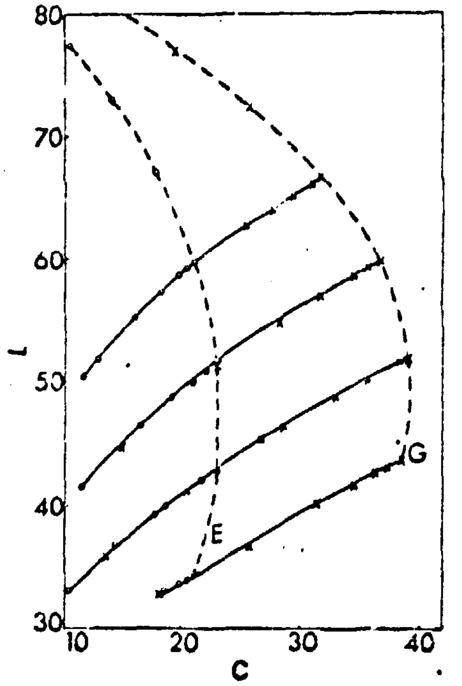
The dullness lines of Figure 11 indicate that increasing dullness corresponds to a decrease in both *L* and *C*. It is therefore obvious that if a dye is perfectly achromatic, i.e. its strength line lies on the *L* axis, the theoretical dullness line must coincide with the line of increasing strength and conversely the theoretical brightness line must coincide with the line of decreasing strength. Theoretically, therefore, a grey cannot be brighter or duller than a neutral grey, and with real homogeneous grey dyes, which are never perfectly achromatic, it is doubtful that the dyer can legitimately use the terms duller and brighter. There is some evidence that blueness in a grey is often described as brightness, but it is hard to justify this practice.



Strength -----   Dullness ——

A C.I. Reactive Yellow 2
B C.I. Reactive Orange 2
C C.I. Reactive Red 3
D C.I. Reactive Violet 1
E C.I. Reactive Green 44
F C.I. Reactive Black 4

Figure 11 Strength and dullness lines in LC diagram



Strength -----   Dullness ——

E C.I. Reactive Green 11
G C.I. Reactive Green 5

Figure 12 – Strength and dullness lines in LC diagram at constant hue

2.3 Dyestuff selection

In the CIELAB/or ANLAB/ system not only single dyestuffs in various strengths can be illustrated, but combinations of various dyestuffs also. Since a two-dimensional graph is easier to comprehend, than a three-dimensional model, for this purpose horizontal cross-sections of LAB space (i.e A-B planes/ are generally used. The third parameter /lightness, or-in the ICI system, what they call the ICI Colour Map - depth/ is fixed at a constant level, and in this case "brightness" and "chroma" have the same meaning.

Shade Gamuts

The colour of any two-dye mixture is represented by the locus joining the positions of the two dyes. These loci are generally curved, especially in the case of yellow-blue combinations. The gamut of colours obtainable with a three-dye mixture is represented by all those colours enclosed within the triangle that is formed by the three loci joining the three dyes taken in pairs, as can be seen on Fig 13.

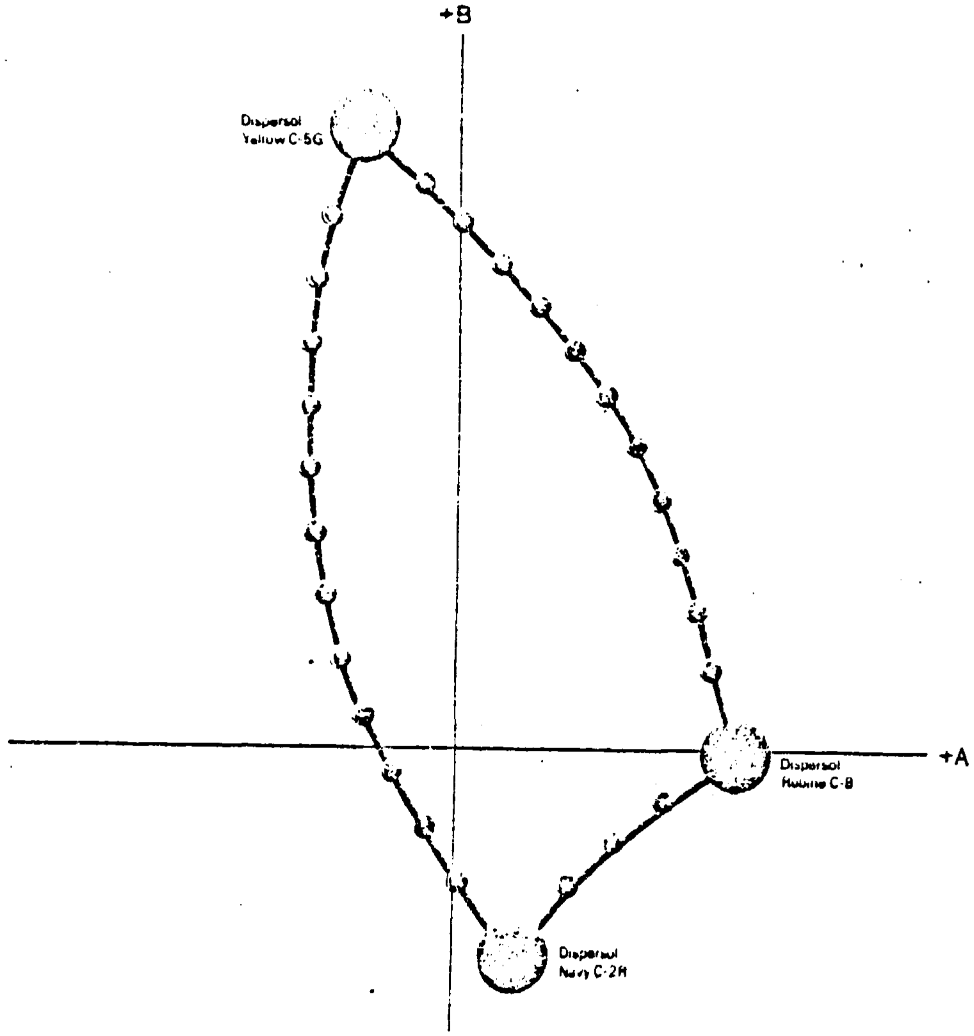


Figure 13 - Colour points of three disperse dyestuffs and their binary mixtures in the A-B diagram.

If we add a fourth dyestuff to the range, the colour gamut will be enlarged as shown on Fig 14.

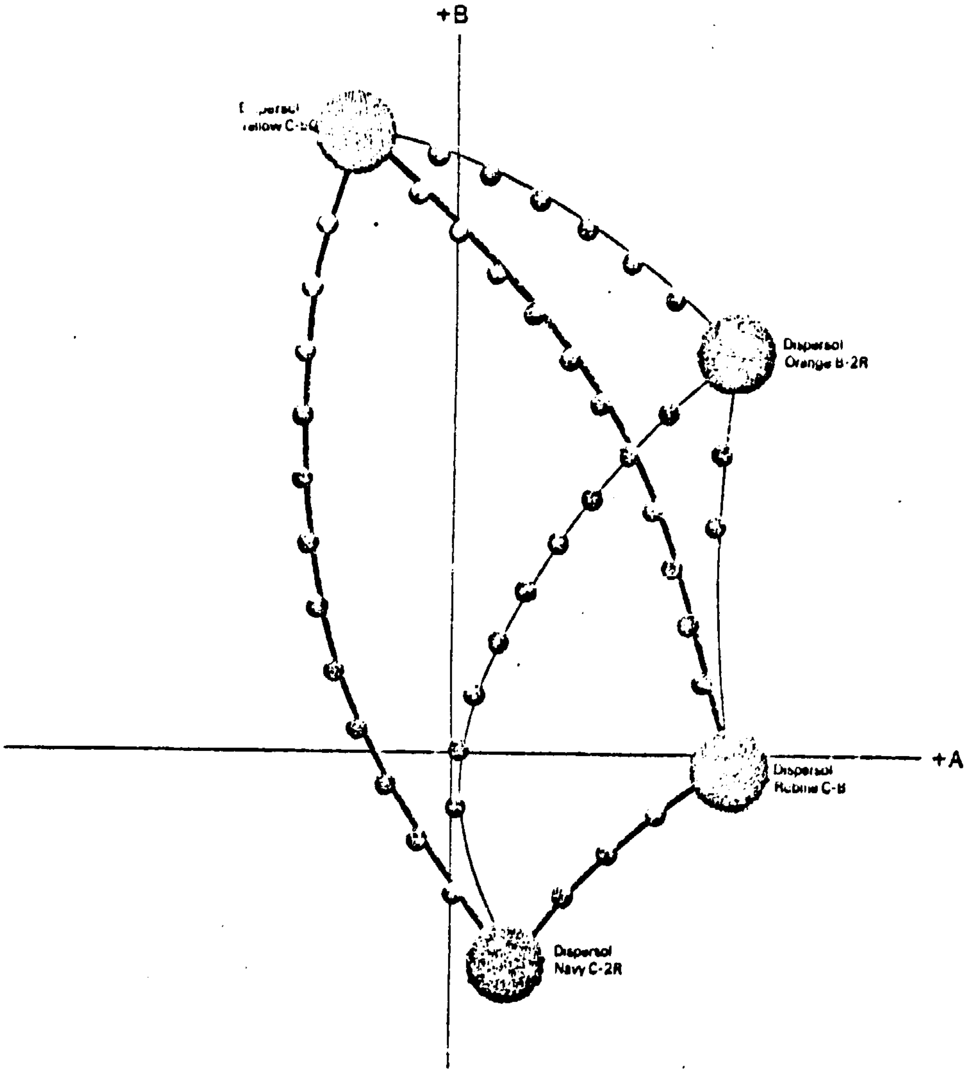


Figure 14 - A fourth dyestuff added to the gamut illustrated on Fig. 13.

By adding other dyestuffs to the range, we can cover larger and larger areas in the A-B diagram. ICI Ltd. uses this approach in illustrating the colour gamut obtainable at a given depth L, using various dyestuff ranges. A typical example for Procion MX (reactive) dyes is shown on Fig. 15.

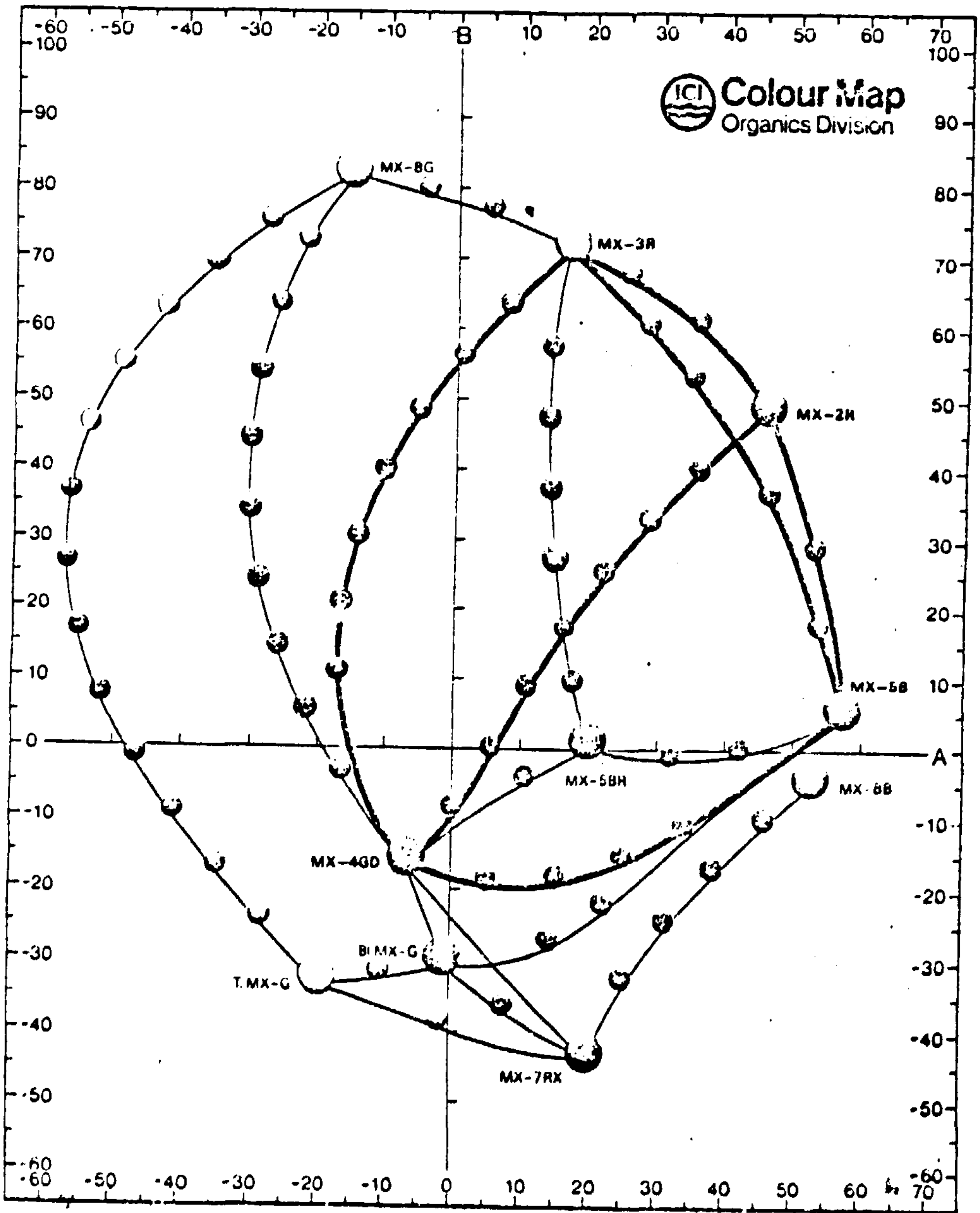
Figure 15

Map 1 Procion MX Dyes

A short range of economical and compatible dyes with good fastness

Procion Yellow	MX-3R
Procion Orange	MX-2R
Procion Red	MX-5B
Procion Blue	MX-4GD

Procion Yellow	MX-8G
Procion Blue	MX-G
Procion Blue	MX-7RX
Procion Turquoise	MX-G
Procion Brown	MX-5BR
Procion Red	MX-8B



7

Significance of Shade Gamuts

The position in the map of any dye will lie inside the colour gamut area of some three-dye combinations and outside the gamut of others.

If it falls *inside* the colour gamut of a rationalized dye selection, its inclusion then depends on other justifications: cost, fastness properties or dyeing properties.

If it falls *outside* the colour gamut its inclusion can be justified on the grounds of the additional colour gamut obtainable. It would, however, only replace completely one of the original dyes if

1 its colour gamut includes all the colours obtainable

and

2 it is preferred on cost or technical grounds.

If two dyes are justifiably included for the coverage of similar colour areas, one will be considered as the first choice and the other used only for the specific colours necessitating its use.

Where three dyes giving primary colours are used to produce a wide shade gamut, and where browns and drabs are of particular importance, it is often convenient to break this large area up by introducing a brown or by forming a colour gamut using three dull shades, *e.g.* a red brown, a yellow brown and an olive drab or grey as "internal" primaries.

This approach is common practice with vat dyes and improves shade reproducibility by reducing the importance of weighing errors, etc. This is the principle adopted in "Matched Pair" system recommended for dyeing polyester/cellulose blends.

A good example of this approach is afforded by an examination of the cost of producing green dyeings on polyester fibre, using different disperse blue dyes with a common greenish-yellow dye. The results described below were obtained to establish the technico-commercial position of Dispersol Green C–6B (C.I. Disperse Green 9), at the time this dye was being added to the range, but they make the general point about the brightness/cost relationship as well as some specific points about this particular dye.

The approach adopted was to produce a family of mid-green dyeings, all at the same depth and all at the same hue angle, with a common yellow dye (Dispersol Yellow C–5G) and a number of different "blue" dyes including Dispersol Green C–6B. The position of each green dyeing is shown in the Colour Map in Figure 16. The brightness of the green dyeing produced depends on the greenness and brightness of the blue dye used, and is indicated by the radial distance (C) from the neutral point.

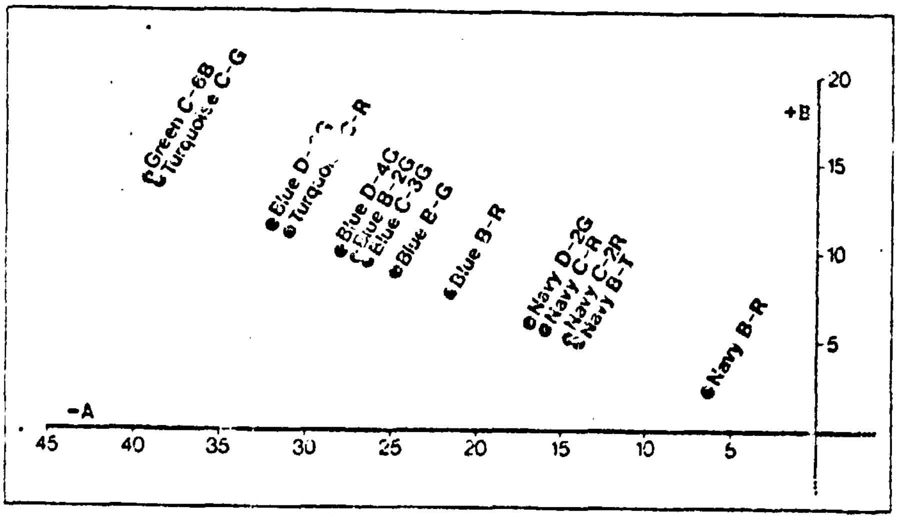


Figure 16 – ICI Colour Map: Equal hue green dyeings on texturized polyester fabric at 1/1 Control Depth (using the Dispersol "blue" dyes shown with Dispersol Yellow C–5G)

Control Depth: a given depth of dyeings, which is the same for a wide range of hues, and defined by ICI Ltd. by colorimetric methods. These Control Depth values should correspond to the internationally used ISO Standard Depth values, although there is no strict correlation between the two sets.

Control Price: the cost of the amount of dyestuffs necessary to achieve a given Control Depth.

The 1/1 Control Price of each green dyeing can be calculated (using UK list prices for the dyes concerned); these Control Prices are plotted in Figure 11 against the measured brightness (C) of the dyeings. It is clear that for the established blue dyes there is a relationship between the cost of producing a green dyeing and its brightness, the cost increasing slightly with brightness in the duller greens and then quite sharply as the limiting brightness from existing dyes is approached. The position of Dispersol Green C–6B in Figure 11 demonstrates that

(a) this dye produces a green dyeing which is marginally brighter than the brightest green obtainable with existing Dispersol dyes, but at much lower cost.

(b) in spite of its outstanding economy for the production of bright greens, the dye is not a sensible choice on cost grounds for the production of dull greens, or as a general purpose blue for use in ternary recipes, since other blue dyes are available which are cheaper still for these purposes.

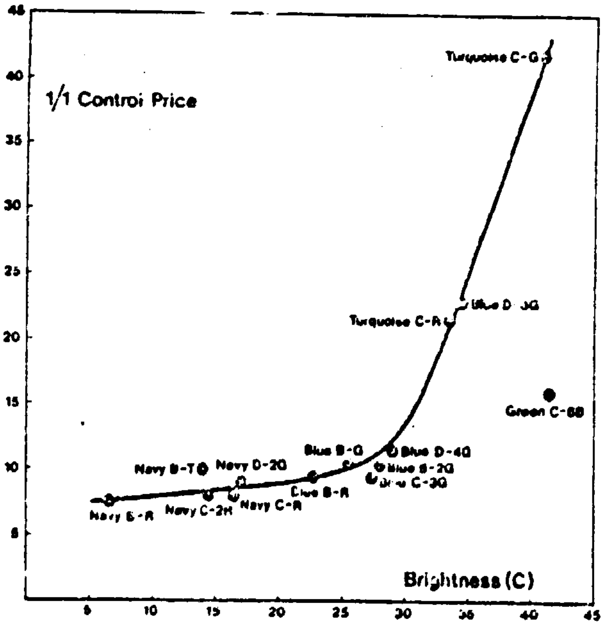


Figure 11 – Cost/brightness relationship for green dyeings on texturized polyester fabric at 1/1 Control Depth (using the Dispersol "blue" dyes shown with Dispersol Yellow C–5G)

For the production of bright greenish-blue and bright green dyeings on polyester, the optimum use of Dispersol Turquoise C–G, Turquoise C–R (C.I. Disperse Blue 165) and Green C–6B can be demonstrated by the Colour Map of Figure 18, with the 1/1 Control Price of each dye added. For all bright green dyeings to the yellow side of Dispersol Green C–6B, the use of this dye with a suitable greenish-yellow (Dispersol Yellow C–5G is again used in the illustration) will clearly be the cheapest combination. For the brightest colours between Dispersol Green C–6B and Dispersol Turquoise C–G, the use of these two dyes as a binary combination will be much cheaper than shading Dispersol Turquoise C–G with a small amount of a greenish-yellow. Finally, for slightly duller colours in this greenish-blue area, the use of Dispersol Turquoise C–R with Dispersol Green C–6B will offer additional economy.

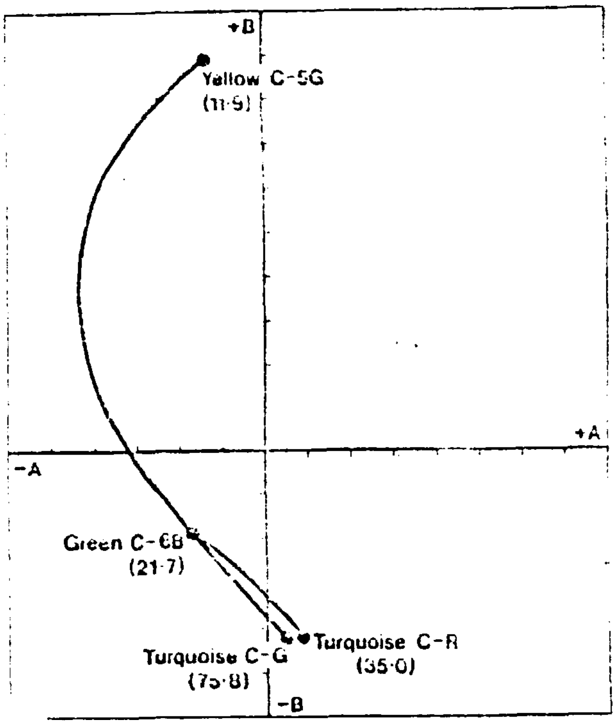


Figure 18 – ICI Colour Map: Dispersol dyes on texturized polyester fabric at 1/1 Control Depth

USE OF THE TECHNIQUE TO SELECT DYES TO STOCK FOR A PARTICULAR OUTLET SEGMENT

All of the foregoing examples are comparatively simple ones, chosen to illustrate particular features of this technique. By an extension of these processes, however, it is possible to use the method to make an optimum selection of dyes to stock to meet all requirements for a particular outlet segment. This may be done for the dyes of a single supplier, by first listing all the dyes on his range which have suitable application and fastness properties for the outlet in question. These can be plotted in a Colour Map, and the Control Price of each tabulated. It is then possible to make a selection on cost-effectiveness grounds of the most suitable dyes to cover different colour areas, and to eliminate a number of dyes which give no additional gamut coverage to justify their higher cost. In some instances, of course, the decisions involved are not completely clear cut. For example, a bright greenish-yellow dye will give a large extension of gamut compared with a reddish-yellow dye as the yellow component of a trichromatic combination. If it also has a lower Control Price, it is clearly the preferred product on a cost-effectiveness basis. If, however, it has a higher Control Price, there is a judgement to be made about this additional cost in relation to the convenience of using one dye for all purposes in place of two dyes. The method will not make this judgement, but it will provide quantitative data on costs and gamut coverage which are a valuable aid in making this type of decision.

The technique, of course, is equally applicable to dyes from all sources, provided the necessary dyeings and measurements are made to characterize these products.

2.3 Colour differences

CIELAB or ANLAB space is widely used for colour specification, i.e. for marking the location of colours in colour space. Another important application of colour measurement is the quantitative description of the difference between two colours. The distance in colour space between two colours is generally known as the colour difference, and in the CIELAB system it is designated ΔE^*_{ab}.

For several decades the major aim of research work in colour science was the development of a "visually uniform colour space", in which equal distances in any part of colour space meant equal perceived difference. Inspite of the tremendous effort put into research, there is still no "perfect" system, the presently recommended colour difference formula - that associated with CIELAB space - is just one of the good approximations.

Colour differences in the CIELAB system can be calculated from ΔL^*, Δa^* and Δb^* values (see Appendix), but a much more useful splitting of ΔE^*_{ab} is that into differences in metric lightness (ΔL^*), chroma ΔC^*ab and hue (ΔH^*_{ab}). The formulae for calculating these quantities are given in the Appendix, and their geometrical meaning is illustrated on Fig. 19.

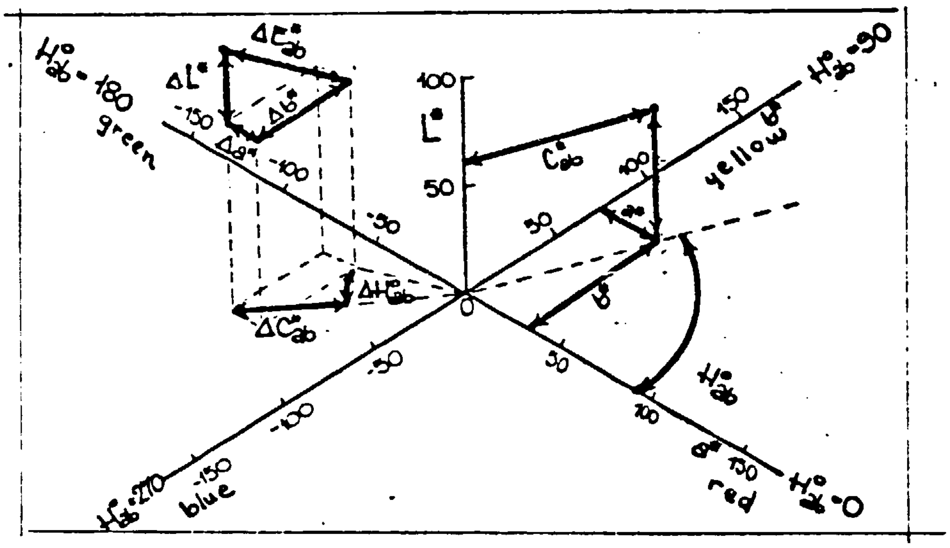


Figure 19. The geometrical representation of colour differences in CIELAB space

ΔE^{*}_{ab} : total colour difference

Δa^{*} : redness - greenness difference

Δb^{*} : yellowness - blueness difference

ΔL^{*} : Metric lightness difference

ΔC^{*}_{ab} : metric chroma difference

ΔH^{o}_{ab} : metric hue angle difference

ΔH^{*}_{ab} : metric hue difference (not shown on diagramm).

The terms illustrated in Fig 19 need no explanation, except for ΔH^*_{ab}, which has no exact geometrical meaning, and is therefore not illustrated in the diagram. The reason for this lies in the nature of colour space given in polar coordinates, i.e. in terms of metric lightness, chroma and hue. Lightness (L^*) and chroma (C^*_{ab}) are distances in vertical resp. radial direction, whereas hue is given as H^o_{ab} metric hue angle. It is very difficult to assign visual meaning to ΔH^o_{ab} metric hue angle differences, since it depends on the chroma of the two colours as well. The Colorimetry Committee of the CIE has therefore decided to recommend a new term for hue difference: ΔH^*_{ab}, which - together with the lightness and chroma differences - would give the total colour difference as the square root of the sum of squares:

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta C^*_{ab}) + (\Delta H^*_{ab})^2}$$

This could only be achieved by defining ΔH^*_{ab} according to the following equation:

$$\Delta H^*_{ab} = \sqrt{(\Delta E^*_{ab})^2 - (\Delta L^*)^2 - (\Delta C^*_{ab})^2}$$

This definition has the advantage of simplicity in calculation and visual (perceptual) interpretation,, but has the disadvantage of having no clear geometrical meaning. It also follows from the definition, that ΔH^*_{ab} is always positive, and can give no indication as to the direction of hue difference. Most up-to-date instruments calculate ΔH^*_{ab} so that an arbitrary sign is assigned to hue change, e.g. "-" for clockwise and "+" for anticlockwise.

It is very simple to interpret hue differences (as well as brightness - dullness differences for equal lightness) on an a^* - b^* diagram, as shown in Fig. 20.

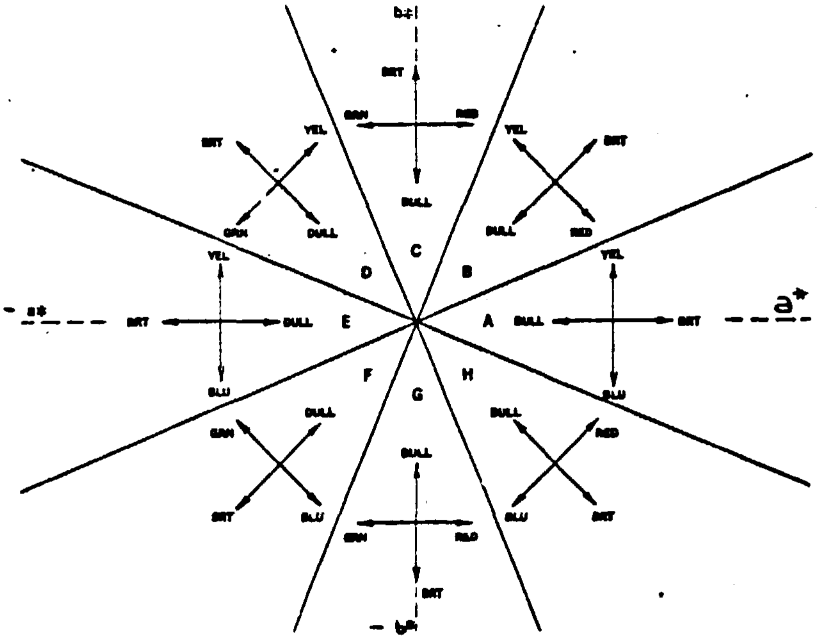


Fig. 20. Co-ordinates of CIELAB color space as sectioned in the hue angle sort program.

2.4 Evaluation of the parameters influencing the colour of dyed and printed textiles

A very important field of application for colour measurement is the quantitative indication of the change in colour due to some change in processing parameters. In the most detailed paper published so far on the subject SUMNER describes the effect of dyehouse variables on the reproduction of dyeings.

The treatment used is best illustrated by taking as an example the effect of salt concentration in the dyeing of Procion H dyes. The values of ΔE for the different salt concentrations, obtained from the ANLAB treatment, were plotted against their respective salt concentrations (Figure 21) the control (80 g l^{-1}) being taken as zero. Clearly, negative values of ΔE are impossible but for convenience those values for dyeings carried out at concentrations in excess of control were assumed to be negative. This enabled a continuous curve to be drawn through zero. By drawing a tangent to the curve at this point, the gradient of the tangent becomes an adequate measure of the rate of change of ΔE for small changes in the concentration of salt above and below 80 g l^{-1}, and hence the effect of such small changes can be evaluated. By taking care when drawing the curves it was found that an adequately high degree of reproducibility could be achieved. The results obtained by applying this treatment to all the variables for the different dye mixtures are shown in Tables 1 and 2. The figures in these tables refer to a change of 10% from the control conditions, a figure chosen because it represented in many cases the maximum variation from the control for which the tangent gave adequate accuracy. Clearly, for changes of less than ± 10%, the figures in the tables need only be multiplied by the appropriate fraction.

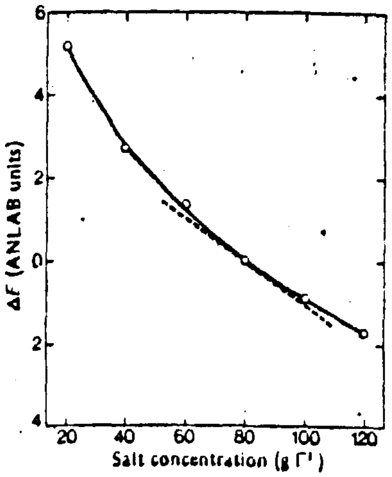


Figure 21– Interpretation of ANLAB data (Effect of salt concentration on Procion H dyes, Mixture 1)

EFFECT OF CHANGES IN DYEBATH CONDITIONS

For the reactive dyes (Table 1) the figures show a marked degree of consistency irrespective of the class of dye or of the particular mixture of dyes.

Because of the consistency of the results from mixture to mixture it is possible to use average values to illustrate the importance of the different variables. This is done in Figures 22 and 23, where the average effect of a ± 10% change in each variable is presented in histogram form.

It can be seen that, for the reactive dyes (Figure 22), the important variables observed as a result of this work are temperature after the addition of alkali, cloth weight and the various weights of dye. It must be remembered that these effects relate to the dyeing conditions used and the particular dyes studied. For example, if the quantity of salt used as control had been drastically reduced, changes in salt concentration could have assumed greater importance or, if the dyes had been much slower dyeing, then the effect of time could similarly have been increased.

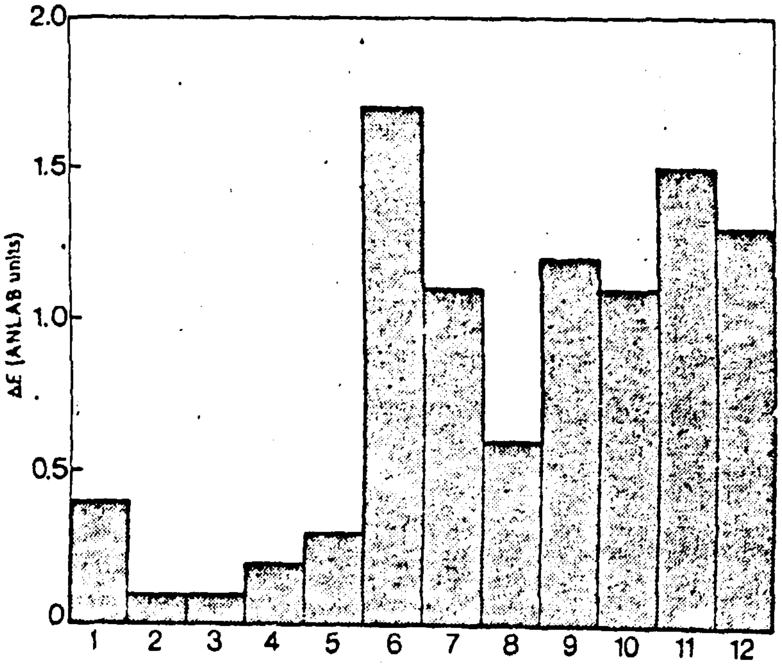


Figure 22 – Average effect of 10% variations in dyebath conditions for reactive dyes (For key to numbers see Table)

TABLE 1

Reactive Dyes – Comparison of the Effect on Tertiary Dye Mixtures of 10% Variations in Dyebath Conditions

The figures refer to total colour change, i.e. ΔE in ANLAB units

Dye Mixture		Variable											
		NaCl concn	Na_2CO_3 concn	Time before addition of alkali	Time after addition of alkali	Temperature before addition of alkali	Temperature after addition of alkali	Wt of cloth	Vol. of dyebath	Dye concn All	Dye concn Yellow only	Dye concn Red only	Dye concn Blue only
Procion MX	Mixture 1	0.4	0.1	0.1	0.1	0.7		1.2	0.8	1.1	1.2	1.5	1.4
Procion MX	Mixture 2	0.5	0.1	0.1	0.3	0.9		0.9	0.8	1.5	0.7	1.6	1.2
Procion H	Mixture 1	0.5	0.1	0	0.3	0.4	2.0	1.1	0.6	1.1	1.0	1.2	1.1
Procion H	Mixture 2	0.5	0.2	0.1	0.3	0.5	2.7	1.1	0.7	1.2	1.2	1.5	0.9
Procion H–E	Mixture 1	0.2	0.2	0.1	0.2	0.1	0.9	1.1	0.3	1.2	1.1	1.4	1.4
Procion H–E	Mixture 2	0.3	0.1	0.1	0.1	0.1	1.1	1.2	0.4	1.2	1.2	1.4	1.4
Procion H–E	Mixture 3	0.3	0.1	0.1	0.1	0.2	0.9	1.2	0.4	1.0	1.3	1.6	1.3
Average ΔE		0.4	0.1	0.1	0.2	0.3*	1.7*	1.1	0.6	1.2	1.1	1.5	1.3
Key for Figures 22 & 24		1	2	3	4	5	6	7	8	9	10	11	12

*Omitting Procion MX Mixtures 1 and 2

The effects of the dyeing method and the dyes used also apply to the disperse dyes (Fig. 23) where again the important variables from this work are temperature, cloth weight and the various dye weights.

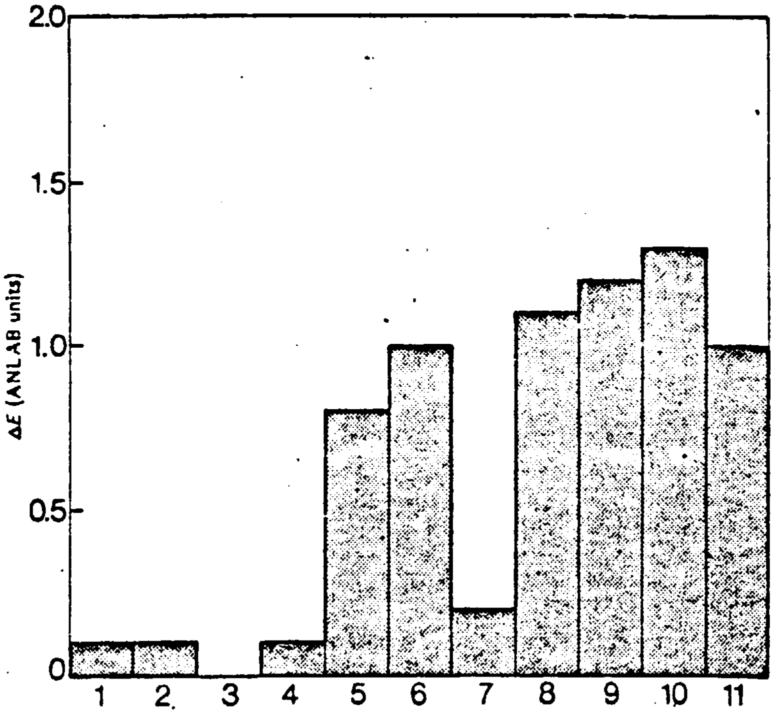


Figure 23 – Average effect of 10% variations in dyebath conditions for disperse dyes (For key to numbers see Table 2)

TABLE 2

Disperse Dyes – Comparison of the Effect on Tertiary Dye Mixtures of 10% Variations in Dyebath Conditions

The figures refer to total colour change, i.e. ΔE ANLAB units

Dye mixture	Variable										
	Acetic acid (80%) concn	Matexil DA–AC concn	Silcolapse 5001 concn	Time	Temp.	Wt of cloth	Vol.of dyebath	Dye concn All	Dye concn Yellow only	Dye concn Red only	Dye concn Blue only
Dispersol dye Mixture 1	0	0.1	0	0.1	1.0	1.0	0.3	1.1	1.4	1.4	1.0
Dispersol dye Mixture 2	0.1	0	0	0.1	0.5	0.9	0.1	1.0	1.1	1.2	1.0
Dispersol dye Mixture 3	0.1	0.1	0	0.1	0.8	1.2	0.1	1.2	1.1	1.3	1.1
Average ΔE	0.1	0.1	0	0.1	0.8	1.0	0.2	1.1	1.2	1.3	1.0
Key for Figure 23	1	2	3	4	5	6	7	8	9	10	11

It is apparent that the average colour difference associated with a ± 10% change in these major variables is approximately 1.0–1.3 ANLAB units. In order to estimate this result, the variables were taken one at a time, but obviously, in practice, it is possible for more than one variable to be in error, indeed it is very possible that they could all be in error at the same time. Unfortunately from the point of view of simplicity, it is not possible to add together the ΔE values shown in these figures since ΔE possesses no directional properties. If the additive effect of a number of variables is required, it is necessary to split ΔE down into its components of *ΔHue*, *ΔStrength* and *ΔBrightness*, all of which are directional. The calculation of the effect of small changes in the variables on the values of these latter three parameters is carried out in precisely the same way as for ΔE (Fig. 21). As an example, the results of such a computation for a ± 10% increase in each application variable is shown in Figure 24 for Procion MX dyes (Mixture 1).

These results show that if all the variables are increased by 10% then the total effect is not the sum of the respective ΔE values since there are compensating factors in that the changes are not all in the same direction. Although not strictly true on the basis of colour physics, it is now possible to obtain a reasonable estimate of the additive effect of variables if it is assumed that a reduction of 10% would produce a similar change in the opposite direction and that there is little or no interaction between variables. Confirmation of this was obtained by carrying out a number of dyeings where two or three variables were changed simultaneously. Comparison of the measured colour differences of these dyeings from control showed a reasonable agreement with the arithmetic sum of the variables taken one at a time. Clearly it is possible, therefore, to get a reasonable approximation of the effect of any combination of the application variables, but for the purposes of the moment only the maximum effects of ± 2% and ± 10% changes have been evaluated, i.e. the unfortunate dyeing when all the errors combine in the same direction.

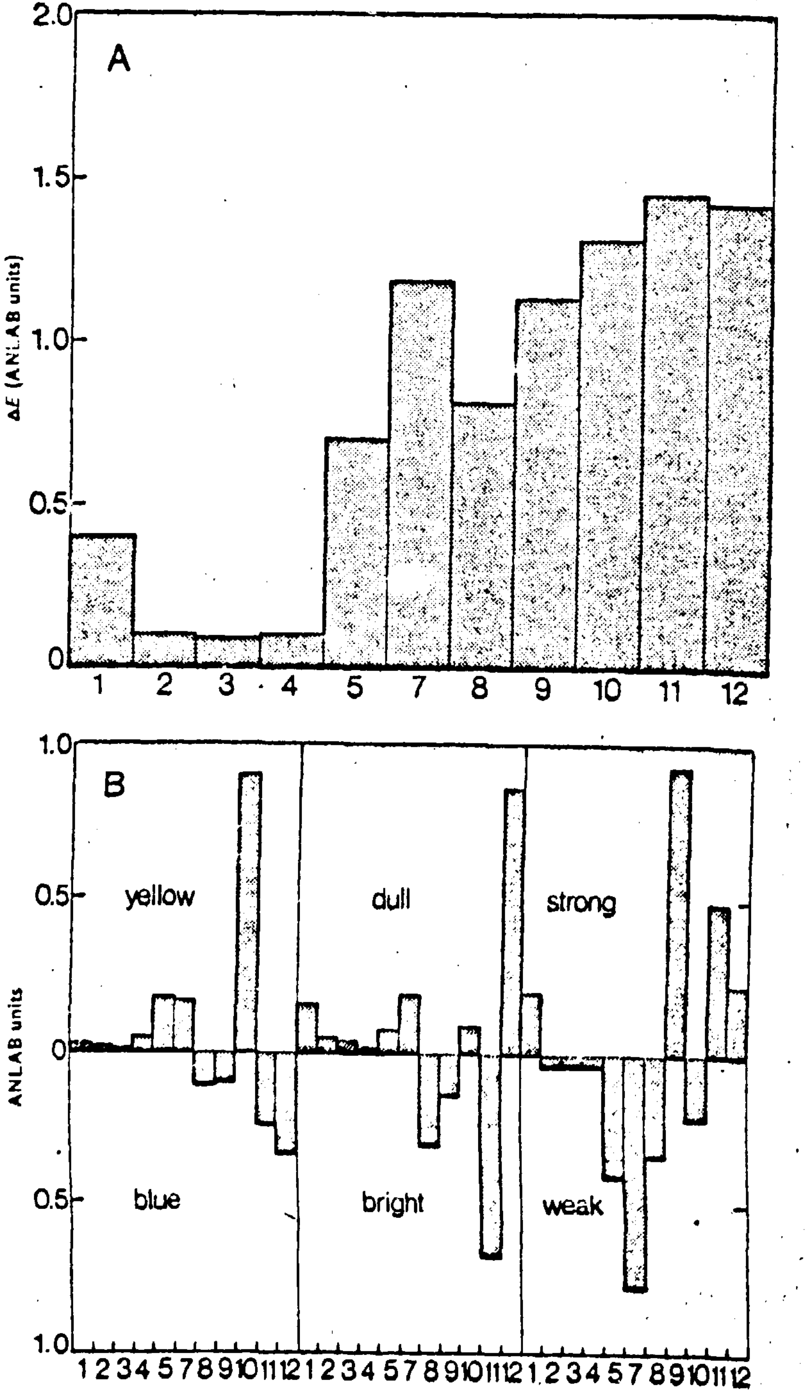


Figure 24– Effect of 10% variations in dyebath conditions for Procion MX dyes, Mixture 1.
A – ΔE (Total change); B – ΔHue, ΔStrength, Δ Brightness (For key to numbers see Table 1

The differences from target which would be obtained are shown in Table 3. Although the chances of the particular combination of variations occurring to produce this maximum result are remote, nevertheless the result is interesting in that commercial selection of dyes for selling has produced colours which have an amazingly similar 'robustness' to change in dyebath conditions.

TABLE 3

'Robustness' of Tertiary Mixtures of Dyes (calculated)

Dyeing mixture		Maximum possible colour change (ANLAB units) occurring as a result of varying dyeing conditions by: ± 10%	± 2%
(A) Reactive dyes			
Procion MX	Mixture 1	5.1	1.0
Procion MX	Mixture 2	5.2	1.0
Procion H–E	Mixture 3	5.4	1.1
Procion H–E	Mixture 1	5.7	1.1
Procion H–E	Mixture 2	6.2	1.2
Procion H	Mixture 1	6.2	1.2
Procion H	Mixture 2	7.7	1.5
(B) Disperse dyes			
Dispersol	Mixture 2	3.5	0.7
Dispersol	Mixture 1	4.7	0.9
Dispersol	Mixture 3	5.2	1.0

N.B. This is the worst possible result, only observed when all the variables change in a completely additive fashion

So far only the calculated effects of various percentage changes have been considered. It is interesting to note the practical effects which are obtained. Taking a tertiary mixture of disperse dyes (Mixture 1) on Crimplene, a series of dyeings were prepared in which the three dye variables were all changed by ± 10% in various combinations. After dyeing, the patterns were measured spectrophotometrically and the various values of ΔE from the control were computed. A description of the mixtures and the ΔE values are shown in Table 4. It can be seen that the average effect produced was 1.8 ANLAB units and, since all the dyebaths used to produce these dyeings were substantially exhausted at the end of the dyeing sequence, this variation can be associated with a change in dye-on-fibre of approx. ± 10% for each of the dyes in the mixture.

TABLE 4

The Measured Effects of varying the Individual Dye Concentrations, in Disperse Mixture 1, in Full Permutation by ± 10% and ± 2.5% (Figures in Brackets). Quoted as Total Colour Difference from Control (ΔE ANLAB units)

Recipe change			ΔE	Recipe change			ΔE	Recipe change			ΔE
Y	R	B		Y	R	B		Y	R	B	
0	0	0	control	0	-	+	1.4 (0.4)	-	-	0	1.2 (0.3)
+	0	0	1.4 (0.3)	0	-	-	1.5 (0.8)	+	+	+	1.1 (0.3)
-	0	0	1.4 (0.3)	+	0	+	1.2 (0.4)	+	+	-	2.2 (0.6)
0	+	0	1.4 (0.3)	+	0	-	1.8 (0.4)	+	-	+	2.0 (0.6)
0	-	0	1.4 (0.4)	-	0	+	2.2 (0.6)	-	+	+	3.1 (0.7)
0	0	+	1.0 (0.3)	-	0	-	1.7 (0.4)	-	-	-	1.1 (0.3)
0	0	-	1.0 (0.3)	+	+	0	1.6 (0.4)	-	-	+	1.7 (0.4)
0	+	+	2.0 (0.3)	+	-	0	1.9 (0.5)	-	+	-	3.0 (0.8)
0	+	-	2.3 (0.6)	-	+	0	3.1 (0.7)	+	-	-	2.5 (0.7)

Average difference = 1.8 ANLAB units (0.5 ANLAB units)

Y = Dispersol Yellow B–A
R = Dispersol Red B–3B
B = Dispersol Blue B–2G

0 = as recipe
+ = recipe + 10% (+ 2.5%)
- = recipe – 10% (– 2.5%)

ROBERTS has investigated the effect of some process parameters in the preparation stage on the final colour of the fabric. He has found that the heat treatment (e.g. during drying, singeing etc.) of sized cotton yarns has significant effect on the colour in the case of starch-based sizing agents. The effect depends both on the time and the temperature of the heat-treatment, as shown on Fig. 25.

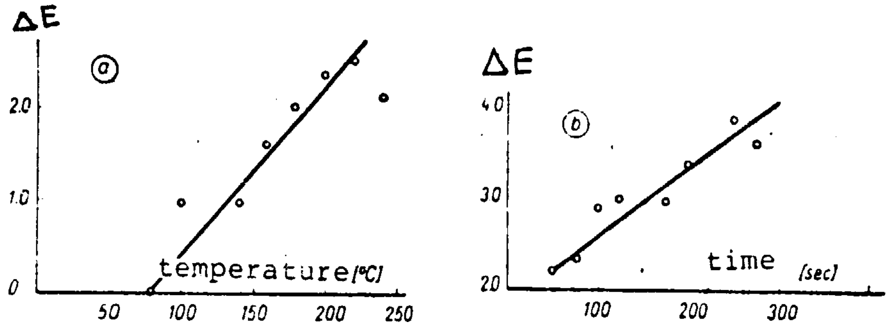


Fig. 25. The effect of heat treatment following sizing on the colour of cotton fabrics.
ΔE total colour difference in ANLAB units between untreated and treated samples dyed together with reactive dyes.

a) Effect of temperature of heat treatment for 50 sec.

b) Effect of time of heat treatment at 160°C.

It is well known, that the temperature of heat-setting has significant effect on the dye-uptake of polyester fibres during subsequent dyeing. Fig. 26. shows the effect for polyester sewing thread (staple yarn), and Fig. 27, illustrates the same for polyester fabrics.

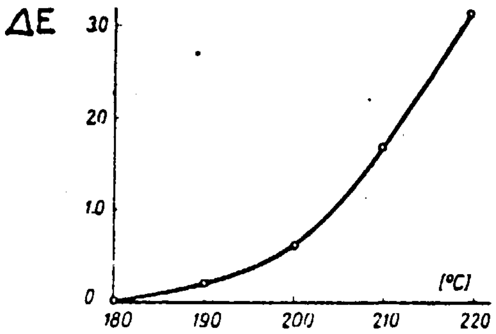


Fig. 26. The effect of heat-setting temperature (^{o}C) on the dyeing properties of polyester sewing thread. ΔE total colour difference in ANLAB units between control and treated samples.

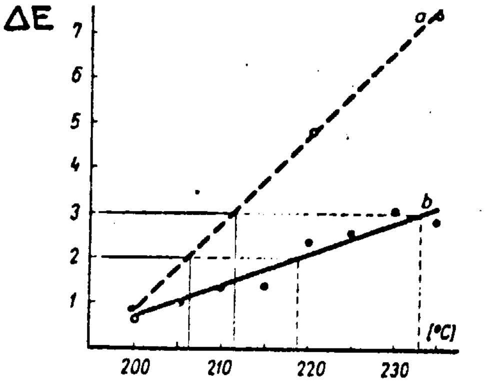


Fig. 27. The effect of heat-setting temperature (^{o}C) on the dyeing properties of woven polyester fabrics (filament warp, staple weft).
ΔE total colour difference in ANLAB units between control and treated samples.

a) samples dyed separately, under identical conditions.

b) samples dyed competitively in the same bath.

On the problem of the color-change during finishing

Textile finishing operations have the general purpose of making textiles saleable and or improving the wearing properties and the ease of care of clothing produced with them. One of these types of finishes is high-grade finishing, with which easier care of the textile is achieved.

It is just the classical high-grade finishing processes for crease-resistant or easy-care finishing which causes, on dyed goods, more or less great color changes, which in practice are known under the term "shade change during finishing." The task of the colorist is to control the turnout of the dyeing in the dyehouse so that after the finishing, the fabric can be considered to be in conformity with the dyeing sample. Here, the colorist has several possible approaches; those described in the following are used with special frequency:

a) Estimation of the shade change in finishing:
The dyer estimates the shade change during finishing and dyes to a dye turnout which he assumes will be corrected, in magnitude and direction, by the estimated shade change in finishing which he anticipates. This procedure is the simplest, but also the most hazardous method. It presupposes long years of experience.

b) Estimation of the shade change during finishing in combination with a laboratory control finishing:
The dyer estimates, as in (a), the shade change during finishing and dyes to a corrected dye turnout. In contrast to (a), however, he controls the dyeing taking into account the shade change during finishing, by inspecting after the finishing to discover if an acceptable conformity with the dye sample has actually been attained. This inspection takes place in the following way: the dyer takes a sample from his dye bath and finishes it in the rapid process in the laboratory, according to the finishing recipe which will also be used for the dye batch. If the color agreement is acceptable, the dye batch is finished; if not, a correction takes place in the dyehouse.

c) Comprehension of the shade change during finishing with the aid of a dyehouse sample corrected for shade change during finishing (determination of a theoretical change):
The dyer has, for each color to be finished, kept back from each dye batch a dyehouse sample which, according to his experience to date, takes the shade change during finishing optimally into account. This sample serves as the dye sample. If an acceptable color agreement between such a dyehouse sample and a dye batch has been achieved, then he assumes that after the finishing of the batch, an acceptable color conformity to the dye pattern will result. The shade change during finishing which contains the color interval dyehouse pattern-dye pattern, is designated an ideal change which is to be completed with the dye batch.

The success of the three methods and the control of the shade change during finishing depend on various factors:

— color conceptualization of the colorist: for method (a) and (b) the colorist dyes to a dye turnout for which there is no direct sample. The subjectivity of the color conceptualization of the colorist thus significantly determines the result.

— matchability (reproducibility) of the shade change during finishing in the plant; each prior taking into account of the shade change during finishing — by whatever means — remains without success if the shade change during finishing in the plant is not reliably controlled and is there subject to uncontrollable changes.

— matchability (reproducibility) of the shade change during finishing in the laboratory: the success of a prior taking into account of the shade change during finishing by means of a laboratory control finishing is also dependent upon how reliably the shade change during finishing can be controlled in the laboratory. Variations in the change here are added to those in the plant, so that, on the whole, the turnout of the finished batch is not under control.

— transferability between laboratory and plant finishing: This transferability must be generally guaranteed for all measures where the shade change during finishing is to be designed to be more reliable with the aid of a laboratory finishing. Otherwise, the turnout in the plant will be different from that in the laboratory, so that conclusions from the laboratory turnout about the plant turnout are not allowable and will lead to erroneous results.

2. Statement of the problem

From the discussion thus far, it appears, that in controlling the shade change during finishing from a technical process standpoint, its matchability (reproducibility) plays a special role. For this reason, we studied how reliably the shade change during finishing can be matched, on the one hand, in the plant, and, on the other hand, in the laboratory, with repeated finishings of articles of the same color. The reproducibility of the shade change during finishing was characterized by statistical characteristic magnitudes. The visual perceptability and the acceptability of the change differences which appear during repetition of finishing were not interpreted here; rather, the evaluation was limited to statistical working out of the data.

The reproducibility of the shade change during finishing is characterized by the mean value $\overline{x}$ of the shade change during finishing from the shade changes of the individual repeated batches (plant finishing) or repated finishings (laboratory finishing), and by the mean value confidence interval q (95% statistical certainty).

Reproducibility of the shade change during finishing in the plant

The reproducibility of the color change during finishing in the plant can be demonstrated with the aid of a viscose finishing. Figure 28 demonstrates the contribution of the lightness change (ΔL, chroma change (ΔC), and hue change (ΔH), to the color change during finishing, as well as the total color change (ΔE). The change values are shown in "column form"; to the left, the theoretical change, in the center, the individual changes of the repeated batches, and to the right, the mean change $\overline{x}$ from the individual changes of the repeated batches with the indicated confidence interval q.

We can see that the changes during finishing of the 6 repeated batches, scatter more or less in magnitude and direction. The lightness change and the total color change are especially affected; the chroma change is less so, and the hue change is only slightly affected. The scattering of the change during finishing is reflected in the size of the confidence interval.

A color change during finishing which is very different in direction for the repeated batches is only explainable in the cases where — as here for the hue -- one only records a minimal change, and the finishing has thus practically no influence; color intervals which are very little different from zero, can also very easily undergo a change in sign with very low scatterings. In this example, however, the relationships are completely different for the lightness and chroma change. The color differences are — especially for the lightness -- greater and nevertheless scatter markedly in direction, and of necessity this also has an effect on the total color change (ΔE). In the example described, then, the color change during finishing can be only poorly controlled with regard to lightness and chroma of the dyeing.

The unsatisfactory reproducibility of the color change during finishing also appears from a comparison of size and direction of the theoretical change with the size and direction of the change of the individual repeated batches. With the theoretical change, a color shift toward lighter, less saturated and bluer color is provided. As we can see, this change of direction was reproduced in the three individual components lightness, chroma, and hue only for a single batch (Nr. 5). As far as the magnitude of the change during finishing is concerned, only the chroma and hue change of this batch corresponds approximately to the size of the theoretical change. In the lightness, the change, with respect to size, is above the value of the theoretical change.

No other repeated batches exhibit change identical with that of the theoretical one.

The batches Nr. 4 and Nr. 6, with an approximately equally large total color difference (ΔE = 0.8 AN) indeed, as desired, are lighter because of the finishing, but, varying from the envisioned goal, are more saturated, and somewhat redder. This shows that the total color difference ΔE is not sufficient by itself for the characterization of the color change during finishing, but a separation into the individual differences for the lightness (ΔL), the chroma (ΔC), and the hue (ΔH) is necessary.

The reproducibility of the color change during finishing in the plant finishing is illustrated further in Figure 29. Here the mean values and confidence intervals of the color change during finishing are indicated which were obtained in the finishing of viscose-substantively dyed in the color grey, steel blue, brown, dark brown, and then shaded—with triple repetition. Here also, from the large confidence intervals it appears that the color change during finishing in practice--at leas for the textile material viscose and the finishing process used here-- can scatter relatively greatly.

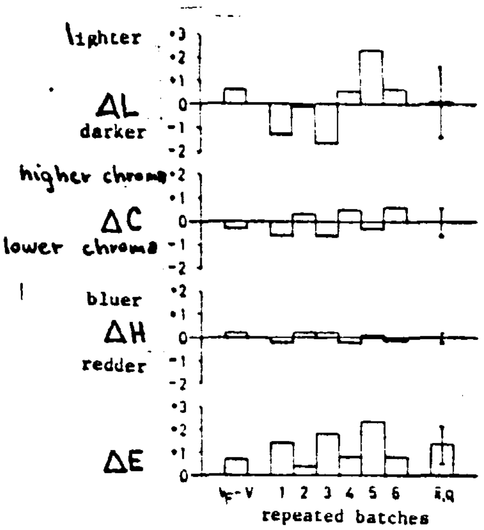


Figure 28. Plant finishing of viscose, shade change during finishing of a color (anthracite) in brightness, saturation and hue for 6 repeated batches in comparison to the theoretical shade change of the dyehouse sample (V_F) → dye sample (V).
ANLAB units

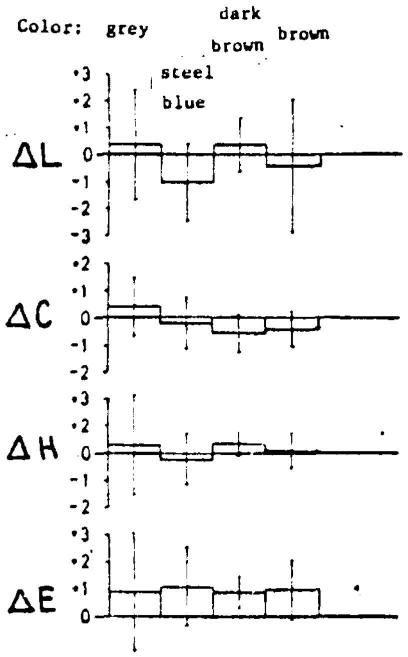


Figure 29 Plant finishing of viscose. Mean value x and confidence interval q of the shade changes during finishing of 4 colors in brightness, saturation and hue for 3 repeated batches.
ANLAB units

Causes of the uncertain reproducibility of the color change during finishing and conclusions for practice

If one proceeded from the thesis, that the color change during finishing is an indicator for the accuracy of the process guidance, then we must ask what process magnitude in particular can influence it. In the framework of this study this question cannot be exhaustively answered, however. Accordingly, we shall only note a few observations.

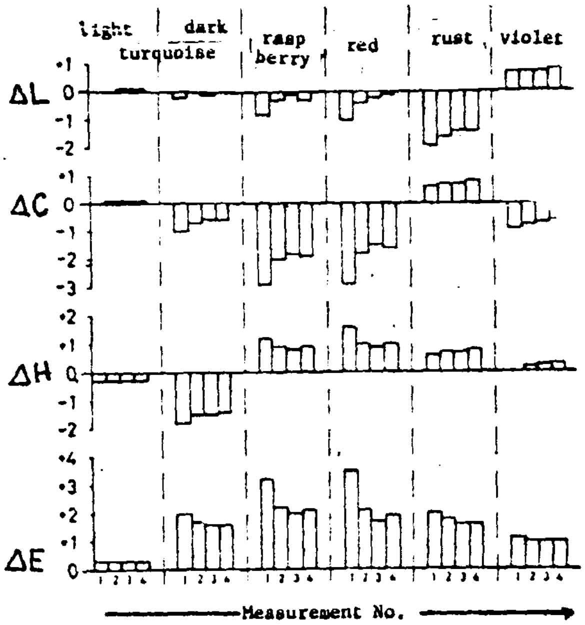
The causes for the uncertainties could, on the one hand, be of a technical nature: even for the exact laboratory finishing, it is, e.g., not possible for batches of different color (for the same dye class and method of dyeing), and even for the same batches, to reproduce the liquor absorption exactly. Thus it appears that the liquor absorption of a textile material dyed with dyes of a dye class, even with identic. roller pressure on the padding machine, can differ significantly from color to color.

If one considers that the liquor absorption determines the chemical absorption or coating decisively, then it is understandable that scatterings appear in the color change during finishing. A further—coloristic—cause of the uncertain reproducibility of the color change during finishing is given by thermochromy. By this we understand the reversible change of dyes and colors during heating. The "hot" form of dyes is, under certain circumstances so long-lived that days and hours after the heat treatment is finished, e.g., condensation in the finishing, the color can still change. We observed this case in the finishing of several cotton dyeings (Figure 30).

Cotton, reactively dyed in the colors bright turquoise, dark turquoise, raspberry, red, rust, and violet, was finished, and after condensation measured after 3 hours, 24 hours, 3 days and 10 days; and the total color change (ΔE) the lightness change (ΔL), the **chroma** change (ΔC) and the hue change (ΔH) was calculated. As Figure 30 shows, for the colors bright turquoise, and violet, thermochromy can be excluded. The other colors, above all the colors raspberry and red, change during storage for up to 24 hours, and thereafter the dye turnout remains unchanged to a very great extent.

In practice, thermochromy means that a sample taken directly after finishing, under certain circumstances does not always represent the same dye turnout which is recorded in the final inspection in the plant or by the customer. In the extreme case, this can mean that a finished batch in evaluation directly after the end of the condensation stage exhibits a good agreement with the specimen, but that during storage, a color adjusts which can no longer be considered in conformity with the sample.

Liquor absorption and thermochromy are variables which can influence the color change during finishing uncontrollably in the plant and laboratory. Accordingly, they must be controlled or inspected. The color changes which occur for susceptible colors during storage in the first period after condensation can be taken into account by empirical values if, e.g., directly after a control finishing in the laboratory, one tests whether the dye turnout of the dye batch sufficiently takes into account the color change during finishing. Colorimetry can be of assistance here, since with it, in analogy to Figure 30, one can estimate what components of the color (lightness, **chroma** or hue) are to be given special attention.



No. 1 after 3 hours
No. 2 after 24 hours
No. 3 after 3 days
No. 4 after 10 days

Figure 30. Laboratory finishing of cotton. Influence of thermochromy on the turnout of the dye.

3. The problems of tolerance specification

If the color tolerances are based on a study of the probable variations in color arising from the manufacturing process, the tolerances for each new color have to be individually studied, and it does not matter much what coordinate system is used to express them, so long as it is defined in terms of a CIE standard system.

But, if the color tolerances are set purely on the basis of the acceptability (or objectionableness) of the variations, from the standard or on the basis of the perceptibility of such variations, a coordinate system yielding nearly uniform color scales, such as the Munsell renotation system has an advantage. If perceptibility of the variations is the sole basis, the advantage is obvious. The color tolerances may be stated directly in terms of size of color difference by means of those equations. In such a case no special study of tolerances for each new color need be made. All that is required is a specification of the standard color and the number of units of color difference to be tolerated.

If the color tolerance is to be set on the basis of the acceptability of the color variations from standard, it is still advantageous to use a coordinate system yielding nearly uniform color scales. Noticeability of the variations is a very helpful place to start an analysis of the acceptability of color variations. In writing color tolerances for textiles, it has usually been found that a close hue match is imperative, but larger tolerances may be allowed for variations in lightness and chroma. Hue variations often carry the meaning that a wrong dye has been used. A considerable lightness difference even though easily seen is not objected to by the ultimate consumer because she sees similar differences all the time caused by uneven illumination. A chroma difference, even though detectable, is not as objectionable as a hue difference because it indicates only that too much or too little dye as been used. This is not so bad as using the wrong dye; it fails to give the impression that a gross mistake has been made. Also two colors of the same hue that are perceptibly different in lightness and saturation still harmonize, but a perceptible though small hue difference produces an unpleasant effect.

The difference between the acceptability and the perceptibility of a color difference is of considerable importance and care must be taken to distinguish between the two in industrial applications. Of course, occasions do arise when only "perfect" matches are acceptable; on such occasions the nonacceptability of a color difference becomes synonymous with the perceptibility of that difference. Frequently, however, industrial applications call for an estimate of the acceptability of a color difference. Such an estimate cannot be made by any of those color-difference formulas which we have discussed above and which are intended to predict the perceptibility of color differences. Thus, it should not come as a surprise that color-difference formulas fail to predict accurately the acceptability of a color difference.

Nevertheless, as pointed out above, a color-difference formula can be used to advantage to describe established magnitudes of acceptability in given directions away from standard. Figure 31 is a sketch to illustrate the idea.

We have plotted a portion of the ($L^*a^*b^*$)-space in two cross sections. The upper-left part of Fig. 31 shows a plane of constant lightness (L^*) and the lower-right part shows a plane of constant hue ($b^* = ma^*$ with m = constant). Both planes pass through the point $L_{(Std)}^*$, $a_{(Std)}^*$, $b_{(Std)}^*$ of the standard color, and the point representing the achromatic color (gray) of the same lightness as the standard. Colors which differ from standard by one just perceptible difference (1 j.p.d.) lie on a sphere in ($L^*a^*b^*$)-space with its center at the standard (Std). This sphere is represented by a circle of unit radius in our plane of constant lightness and a similar circle in our plane of constant hue. Colors which differ from standard by two just perceptible differences (2 j.p.d.) lie on a sphere of twice the radius of the first sphere, and in our plane cross sections this sphere is shown by the circles of twice unit radius. We can continue this and can readily imagine a series of concentric spheres of increasing size representing larger multiples of just perceptible color differences.

A typical example of a gamut of colors with *acceptable* differences from standard is illustrated by the hatched areas in Fig. 31. Let us assume that our experience has shown that a particular fabric is usually accepted as "commercial match" to the given standard when the hue difference between fabric and standard did not exceed 1 j.p.d., the chroma difference did not exceed 2 j.p.d., and the lightness difference did not exceed 3 j.p.d. This empirical information can be converted into a color gamut of ellipsoidal shape which contains all colors that would be judged as acceptable duplicates of the standard. The cross sections of this gamut in the planes of constant lightness and of constant hue are the ellipses as shown in Fig. 31.

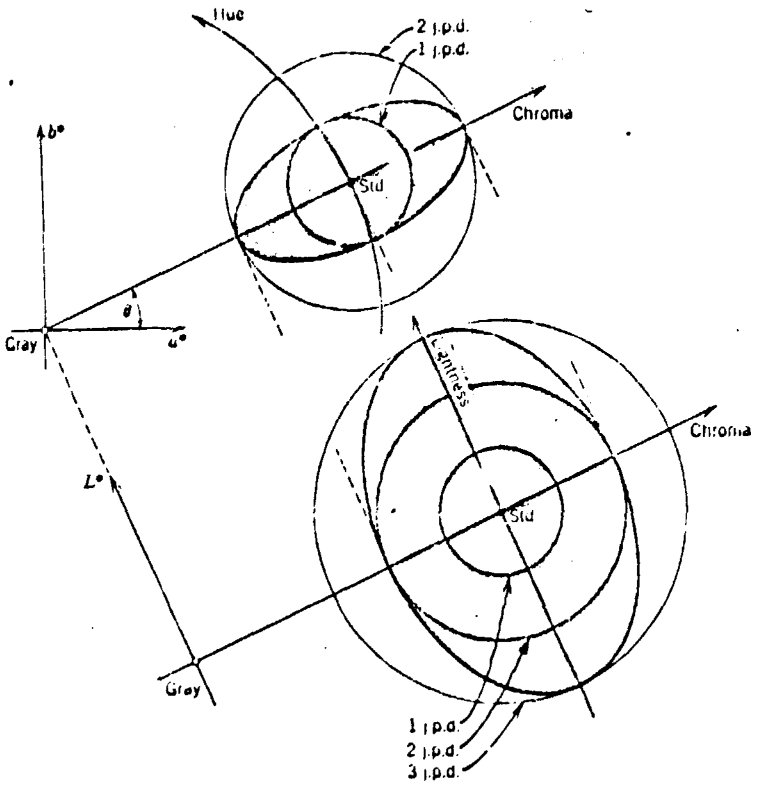


Figure 31. Cross-sections through ($L^*a^*b^*$)-color space. (Upper-left) plane of constant lightness L^*; (lower-right) plane of constant hue (θ). Concentric circles around standard color (Std) are loci of constant perceptibility (1 j.p.d. (just perceptible difference), 2 j.p.d., 3 j.p.d.). Concentric ellipses (hatched) are cross sections of acceptability ellipsoid.

The main problem of tolerance specification is of course the determination of the tolerance limits. In the example above we assumed to have limits of 1, 2 and 3 just perceptible difference units in hue, chroma and lightness respectively. Generally these limits are determined by statistical analysis of a large number of samples around each colour standard, some of which have been accepted as "good commercial matches", others rejected. (To establish the limits we need both accepted and rejected samples.) In some cases "limit samples" are available around the standard as shown in Fig. 32, these only have to be measured to get the instrumental limit values.

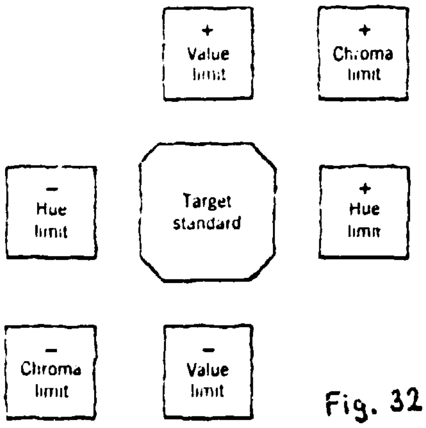


Fig. 32.

In this arrangement, the eye is presented with six standardized color differences (between the target standard and each limit standard). The difference between sample and target standard can be compared with one or more of these.

4.3. Necessary, superfluous, successful, and unsuccessful dye corrections

The colorist has the task of monitoring the course of production, but is also responsible to a great extent for the quality of the finished goods. This is especially true with reference to the agreement between a sample and a correspondingly produced dye batch. One of the chief tasks of the colorist, accordingly, is to decide, in the matching-off, whether a batch agrees in color with a sample to the extent that it can be accepted, i.e., that it can be released for delivery or finishing. In other words: the colorist has to answer the question: is sufficient sample conformity between the dye sample of the batch and the reference sample achieved or not?

For the last color correction, with regard to the matching off limit, in principle, the following four cases are to be differentiated [5]:

Case I: The color interval of the M1 sample from the reference sample lies outside the matching of limit for the accepted sample M2. By means of the correction, the color interval to the reference sample is reduced to the extent that the resulting sample M2 lies within this limit.

Direction of correction: outside - inside

Characterization of the color correction: necessary and successful.

Case II: The color interval of the M1 sample from the reference sample lies within the matching off limit for the accepted samples 2 and after correction, as a sample M2, remains within this limit.

Correction direction: inside - inside

Characterization of the color correction: superfluous, but no deterioration with respect to the matching off limit.

Case III: The color interval of the M1 sample from the reference sample lies outside the matching off limit for the accepted sample M2 and remains, after correction, as sample M2, outside this limit.

Correction direction: ouside - outside

Characterization of the color correction: necessary, but not successful.

Case IV: The color interval of the sample M1 from the reference sample lies within the matching off limit for the accepted sample M2. [illegible] ause of the correction, the color interval [illegible] ases so much that the resulting sample M2 [illegible] utside of this limit.

rrection direction: inside - outside

aracterization of the color correction: [illegible] uous and, in addition, deteriorates the sa [illegible] e with respect to the matching off limit.

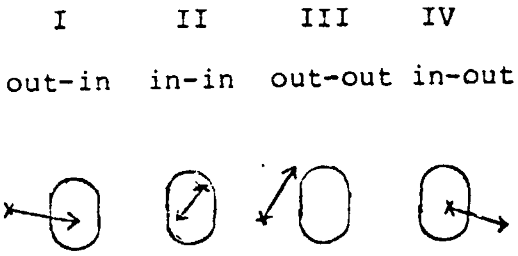


Figure 33. The four cases of last correction:

I: necessary and successful
II. unnecessary, no harm done
III: necessary, unsuccessful
IV: unnecessary, harmful

Table 5. Articles used in the dyehouses investigated

Article	Substrate (fiber type)	Processing form	Finishing data
A	viscose	lining material	subst. dyes pad-jig dyeing
B	cupram-monium rayon	lining material	subst. dyes pad-jig dyeing
C	2 1/2 acetate	lining material	dispersion dyes jigger-dyeing
D	viscose/ polyamide	lining material	subst., dispers., acid dyes, jigger dyeing
E	text. polyester	outer material	dispers. dyes, winch, HT-winch, jet dyeing
F	wool	outer material	acid, MK-dye, winch, beam dyeing

With the aid of the article specific matching off limits given in Table 6, we now determined how frequently, in the matching off of individual articles A-F, the possible four individual cases or correction directions are represented. The results are to be found in Table 7.

The values of case I show the percentages of the unaccepted samples M1 for which a correction was necessary, and for which this correction has led to the desired results. These values are a criterion for the success of the last correction step. The great differences among the articles are worthy of note: the most favorable findings were for article E, with 58.8%.

The values for case II show the percent of the unaccepted M1 samples which did not have to be corrected, but whose color interval from the reference sample (V-M2) after the correction fortunately remained within the matching off limit.

The values for case III informs us of the percent of the unacceptable M1 samples for which a correction was necessary, but was not successful.

The values of case IV show the percent of the unaccepted M1 samples for which a correction was not necessary and in which the color intervals to the reference sample (V-M2) were so deteriorated by the correction that they are greater than the matching off limit.

If one forms a ratio of the necessary and successful corrections (values of case I) to all the necessary corrections (cases I and III), then one obtains the "chances of success" for the last dye correction steps undertaken for articles A-F:

Article A:	83.4%
Article B:	47.5%
Article C:	80.0%
Article D:	71.3%
Article E:	87.0%
Article F:	55.5%
across all Articles A-F;	73.9%

The "chance of success" is dependent on the quality of the matching off, but also on the constancy of the color process guidance. Let us consider the differences among the individual articles. On the average, the chance is quite high that in the last correction - where it was necessary - one will get within the matching off limit. This means that the goal-orientation of the corrections is good. As the following shows, however, very often there is a defective recognition of whether the last correction is necessary at all.

Erroneous judgments in the sense of the open question posed in the heading are the following decisions:

Table 6. Matching off limits (computational) of the color intervals V-M2 for a tolerance probability of 90%.

article	matching off limit V-M2
A	0,80
B	1,02
C	1,53
D	1,56
E	1,08
F	1,24
across all articles A-F	1,18

Table 7. Percentage frequency (%) of the 4 possible correction directions.

Article	Case outside-inside	inside-inside	outside-outside	inside-outside
A	26,7	64,0	5,3	4,0
B	9,5	77,9	10,5	2,1
C	33,9	52,5	8,5	5,1
D	12,2	78,0	4,9	4,9
E	58,8	32,4	8,8	–
F	15,6	71,9	12,5	–
across all articles A-F	23,5	65,2	8,3	3,0

a) the colorist does not recognize that the M1 sample refused has, with respect to the reference sample, a color interval V-M1 which is already smaller than the matching off limit. Thus, samples are corrected which already lie "inside". The number of these erroneous decisions is given from the numerical sum of cases II and IV. These corrections were superfluous, i.e., an unnecessary correction expenditure was made. On the average of all articles A-F, 68.2% of such corrections were calculated. This value corresponds approximately to the value of 71% which results graphically in Figures 5 and 6. The highest value in Table 3 is shown by article D, with 82.9%; the lowest value is article E, with 32.4%.

b) The colorist does not recognize the lack of success of the last correction carried out and accepts a coloration whose color interval to the reference sample V-M2 is greater than the matching off limit. The colorist releases colorations which are not "inside" but "outside". In the studies, the number of these erroneous decisions is given by the addition of the numerical values for cases III and IV. Here we are dealing with a falsely accepted M2 sample which can give rise to complaints. On an average, of all articles A-F, a value of 8.3% results.

The results show the great uncertainty with which color intervals are evaluated in visual matching off. Of the corrections carried out on the whole, on the average, across articles A-F, only about one quarter (exactly: 23.5%, Table 3) are both necessary and successful; only about a third (exactly: 31.8%) of all last feed additions are necessary at all, and about two thirds are superfluous. In the article-specific evaluation, the balance for some articles (e.g., article E) is clearly more favorable, but significantly poorer results are also recorded (e.g., article D). Also with reference to the "chances of success" for the last color correction, article E turns out to be the most favorable.

Since the evaluations were made on colorations of low saturation and weak metamery, these resulting differences between the individual articles cannot be caused by saturation and metamery influences. Causally, they are rather attributable to the specific differences in the individual articles with respect to substrate, processing form or application, and finishing, as well as personal matching off quality.

The pronounced weakness in separating sharpness between the yes/no decisions in "unacceptable-acceptable" is responsible for the large number of erroneous judgments. It is, viewed economically, a serious disadvantage. If one uses, for each correction alone, 45 minutes of machine occupancy, with all the personnel and energy costs, then the extent of the reserves in the dyeing mill for coat reduction and production increase is demonstrated.

The surprisingly high number of incorrectly judged M1 samples can be explained by the fact that the visual matching off does not have a temporally constant matching off limit. The acceptability criteria for sample M1 are obviously significantly more vigorous than for the M2 samples. The longer the dye process lasts, the greater are the [illegible] with respect to color conformity. [illegible] for this can be: pressure of time, [illegible] of production capacity and dye [illegible] well [illegible] of [illegible] quality [illegible] [illegible] [illegible]

Colour sorting (shade sorting)

[illegible] two or three years, the concept of color or shade sorting has found renewed interest.
Most color sorting uses the 555-box method. The concept is based on subdivision of a three-dimensional color space into equally-sized "boxes" surrounding a standard color. Each box is assigned a three-digit code corresponding to its distance from the standard along three chosen axes. The box containing the standard is designated 555 with other boxes ranging from 111 to 999. Several co-ordinate systems such as Hunter, L,a,b and CIE 1978 $L^*a^*b^*$ are in wide use.

When several samples are to be compared, each piece is measured and its co-ordinates are calculated. The piece is then assigned the code of the box in which those co-ordinates fall. Generally all pieces falling within a box are acceptably close in color for shipping or cutting together even though all may be noticeably different from standard. Although the concept may sound involved, in practice modern instruments reduce the task to placing a sample for measurement and reading the code determined.

While developing programs to meet the needs of customers in this area, it was realized that the concept could be made applicable to monitoring color quality even when sorting is not required. The result was the SORT program which combines the spectrophotometric determination of color codes with the ability of the color system to store many of these codes and analyze variance from lot-to-lot for any given product.

In using the SORT program, the user identifies and positions samples for measurement. The spectrophotometer transmits the color measurement directly to the computer where the three-digit code is calculated. The system files the color code with the lot identification.

Periodically the user may obtain analyses of color codes in files. For any product produced, a history of color by lot is available. In addition, the system will report the total number of 555's, 655's, 565's, etc. produced in a specified time period. Ideally, of course, all lots would be 555 since that is the color of the standard. Since they are not, however, the distribution of color codes describes the consistency of color produced.

A graphical frequency distribution of color codes is provided by the system to show color uniformity for any product. Table 8 shows a typical distribution for a well controlled process and good dye formulation. Table 9 gives data which should alert production management to poor color control for the product.

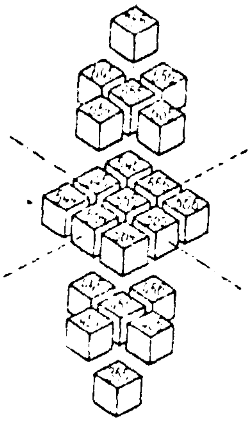


Figure 34. "Boxes" in CIELAB or other similar colour space used in colour sorting. Colours in any one box make one set, which contains all colours within tolerance for the central colour of this box.

Table 8—Color Distribution for Well Controlled Process

SORT Code	Frequency	
865	1	.•
765	3	.•••
665	9	.•••••••••
655	15	.•••••••••••••••
555	18	.••••••••••••••••••
455	14	.••••••••••••••
445	6	.••••••
345	1	.•

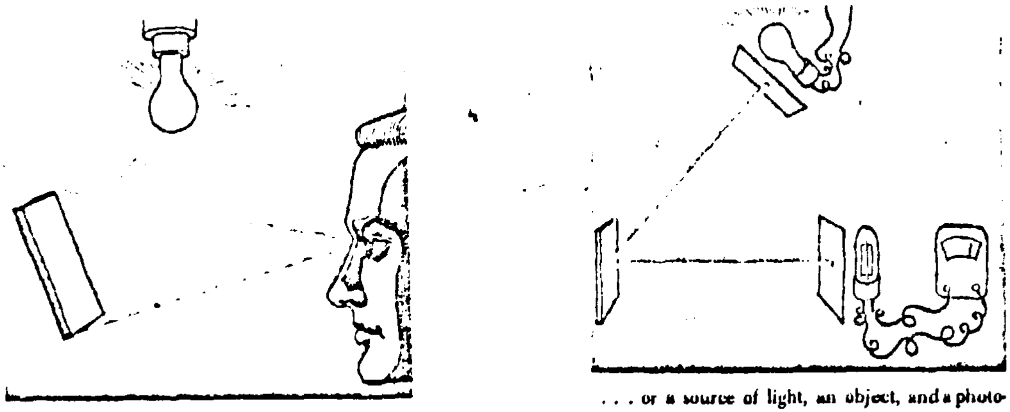
Table 9—Color Distribution for Poorly Controlled Process

SORT Code	Frequency	
874	1	.•
875	1	.•
865	2	.••
766	1	.•
756	3	.•••
665	5	.•••••
655	3	.•••
565	4	.••••
555	7	.•••••••
545	5	.•••••
554	7	.•••••••
455	5	.•••••
445	4	.••••
444	1	.•
345	3	.•••
344	1	.1

4. Light and matter

4.1 Physics and psychophysics of colour: the CIE system

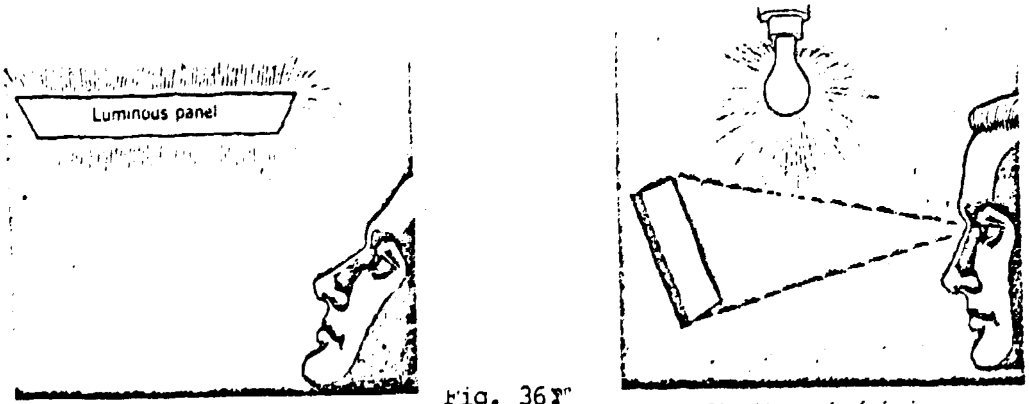
> From the purely physical point of view, the production of color requires three things: a source of light, an object which it illuminates, and the eye and brain to perceive the color. Alternatively, the eye may be replaced by a photosensitive detector and auxiliary equipment which approximate its action in detecting light. While a light source may be seen directly as having color without illuminating anything but the eye (the *illuminant mode* of viewing; see Evans 1948, Judd 1961), we always refer to seeing a material sample illuminated by a light source (the *object mode* of viewing) unless we specify otherwise.



A source of light, an object, and the eye and brain . . .

Fig. 35.

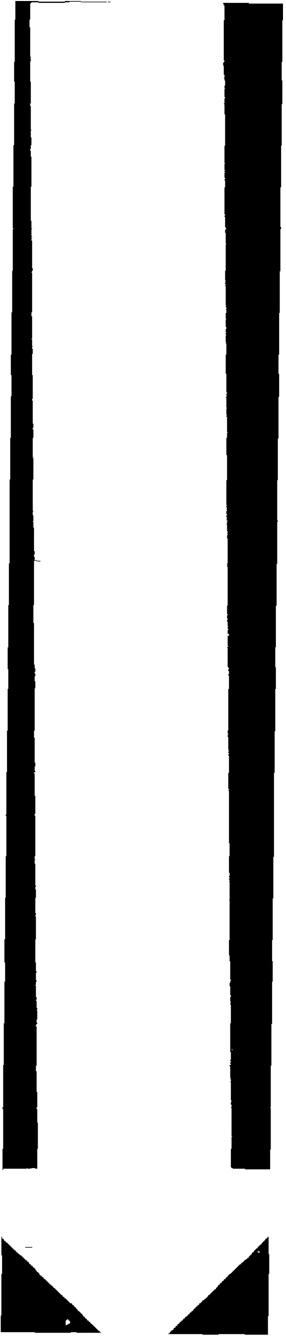
. . . or a source of light, an object, and a photoelectric detector, and meter.

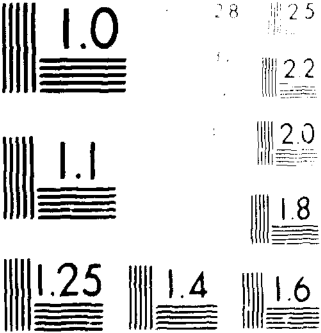


The illuminant mode of viewing.

Fig. 36

The object mode of viewing.




1.0
2.8
2.5
2.2
2.0
1.1
1.8
1.25
1.4
1.6

Sources of Light

Visible light is a form of energy, part of the family which includes radio waves and x-rays, as well as ultraviolet and infrared light. Light can be described by its *wavelength*, for which the *millimicron* (mμ) or *nanometer* (nm) is a convenient unit of length. One nm is 1/1,000,000 millimeter.

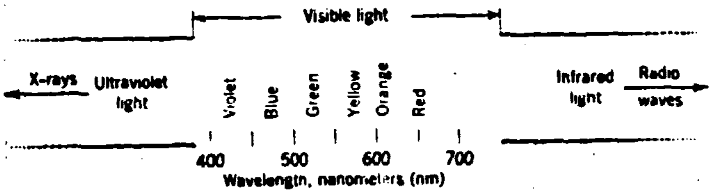


Figure 37. **The visible spectrum and its relation to other kinds of radiation.**

The relation of visible light to the other members of its family is shown in figure 37. The relative insensitivity of the eye limits the visible part of the spectrum to a very narrow band of wavelengths between about 380 and 750 nm. The hue *we recognize as blue lies below about 480 nm; green, roughly* between 480 and 560; yellow, between 560 and 590; orange between 590 and 630; and red at wavelengths longer than 630 nm.

Many of the objects we think of as sources of light emit light which is white or nearly white—the sun, hot metals like the filaments of light bulbs, and fluorescent lamps, among others. Sir Isaac Newton showed many years ago (Newton 1730), by using a prism to disperse light into a spectrum, that white light is made up of all the visible wavelengths.

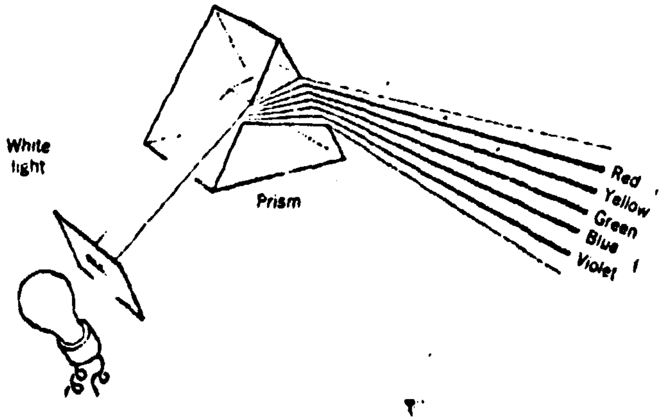


Figure 38. **Dispersing white light into a spectrum.**

The light from any source can be described in terms of the relative energy (or amount of light) emitted at each wavelength. Plotting this energy against the wavelength gives the *spectral energy distribution curve* for the light source.

Here we must point out a distinction, in CIE terminology, between a source and an illuminant. A *source* is a real physical light which can be turned on and off and used in real color-matching experiments. A, B, and C are sources, although B and C are very seldom used in this way. The spectral energy distribution of a *source* is determined by experiment, . An *illuminant*, on the other hand, is defined by a spectral energy distribution, and it may or may not be possible to make a *source* representing it. CIE Illuminant D_{6500} is an illuminant by definition, representing average natural daylight, but there are artificial sources available duplicating D_{6500} closely (McLaren 1965). A source can be used as an illuminant, as are A, B, and C for calculating tristimulus values from spectrophotometric data, and in such cases it is correct to speak of Illuminants A, B, and C.

Source: A physically realizable light, whose spectral energy distribution can be experimentally determined. When the determination is made and specified, the source becomes a *standard source.*

Illuminant: A light defined by a spectral energy distribution, which may or may not be physically realizable as a *source.* If it is made available in physical form, it becomes a *standard source.*

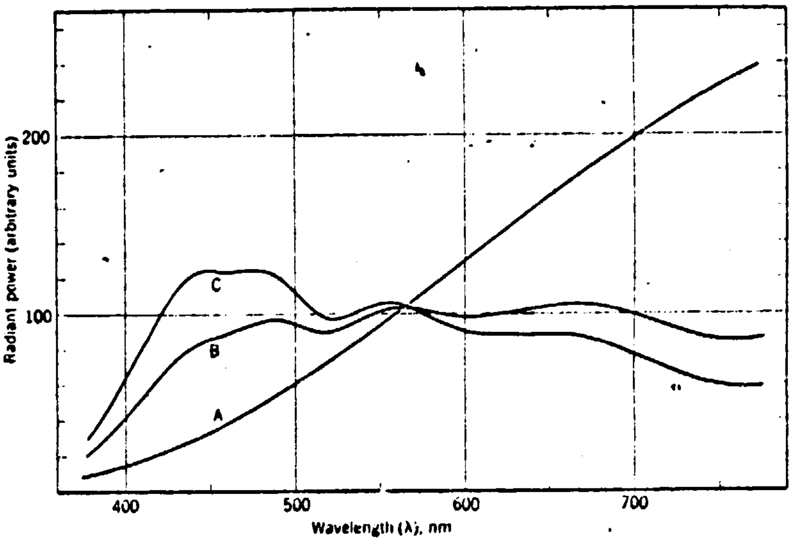


Figure 39 Relative spectral power distributions of CIE standard illuminants A, B, C.

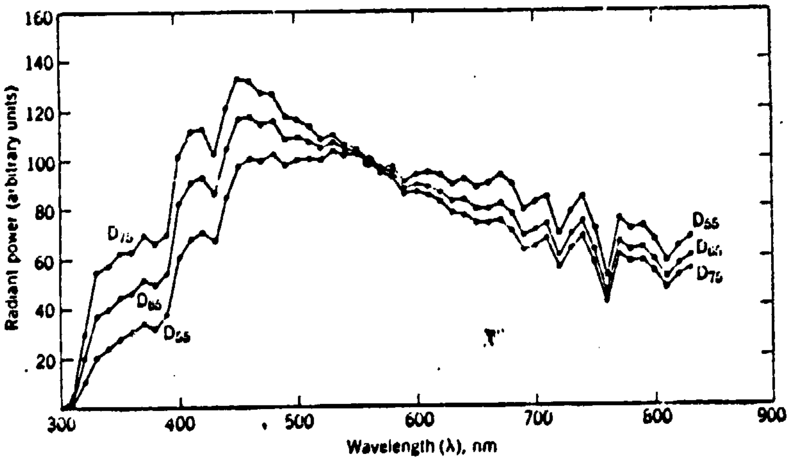


Figure 40 Relative spectral power distributions of CIE standard illuminants D_{55}, D_{65}, D_{75}.

How Materials Modify Light

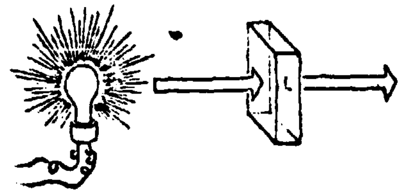
When light strikes an object, one or more things pertinent to color can happen:

1. Transmission. The light can go through essentially unchanged. It is said to be *transmitted* through the material, which is described as *transparent.* If the material is colorless, all the light is transmitted except for a small amount which is reflected from the two surfaces of the object.

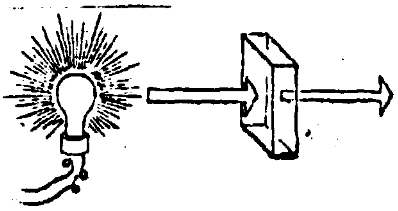
2. Absorption. In addition to being transmitted, light may be *absorbed*, or lost as visible light. (If a very large amount of light is absorbed, we can sense that at least part of it is converted into heat.) If the material absorbs part of the light, it appears colored but is still transparent; if all the light is absorbed, the material is black and is said to be *opaque.*

3. Scattering. Finally, light may be *scattered* when it passes through matter. It may be reflected, partly in one direction and partly in another, until ultimately some light travels in many different directions. The effects of light scattering are both common and important, accounting for the blue color of the sky and the white colors of clouds, smokes, and most white pigments.

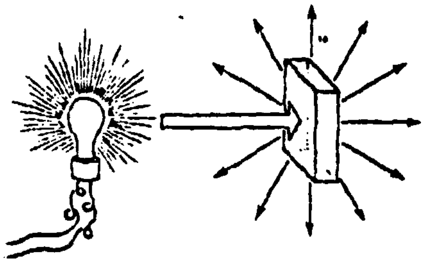
If only part of the light passing through a material is scattered, and part is transmitted, the material is said to be *translucent;* if the scattering is so intense that no light passes through the material (some absorption must be present, too), it is said to be *opaque.* The color of the material depends on the amount and kind of absorption present: If there is no absorption, a scattering material looks white; otherwise, colored.



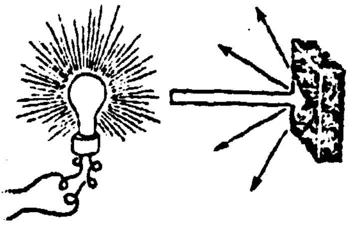
The transmission of light through a transparent object.



The absorption of light by a transparent, colored object.



The scattering of light by a turbid or translucent material. In such a material, some light is transmitted and some is reflected by scattering.



In an opaque material, no light is transmitted, but some is reflected by scattering.

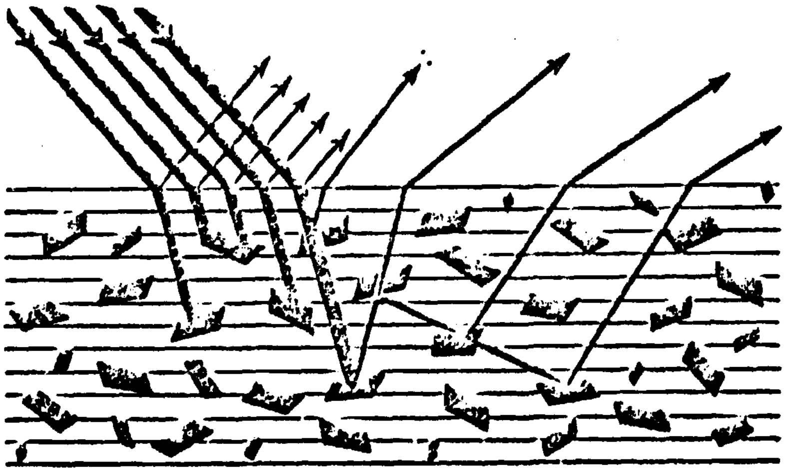
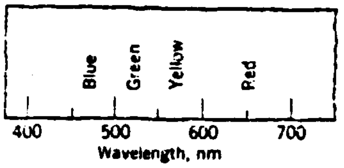


Figure 41, The absorption, scattering, and reflection of light in a layer of pigment

The Spectral Characteristics of Materials. From the standpoint of color, the effect of an object on light can be described by its *spectral transmittance* or *reflectance curve* (for transparent or opaque materials, respectively; both are needed for translucent objects). These curves show the fraction of the light at each wavelength transmitted by or reflected from the material, describing it just as the spectral energy distribution curve describes a source of light. The spectral reflectance curves of several opaque colored materials are shown on Fig. 42. By comparing these figures with the hue names of the colors of the spectrum, and noting that colored materials always reflect light of their own color and (except yellow) absorb other hues, one can readily develop the ability to recognize colors in a general way from their spectral reflectance or transmittance curves.



Hue names of the spectrum colors. Purple, a color which does not appear in the spectrum, is a mixture of blue or violet with red.

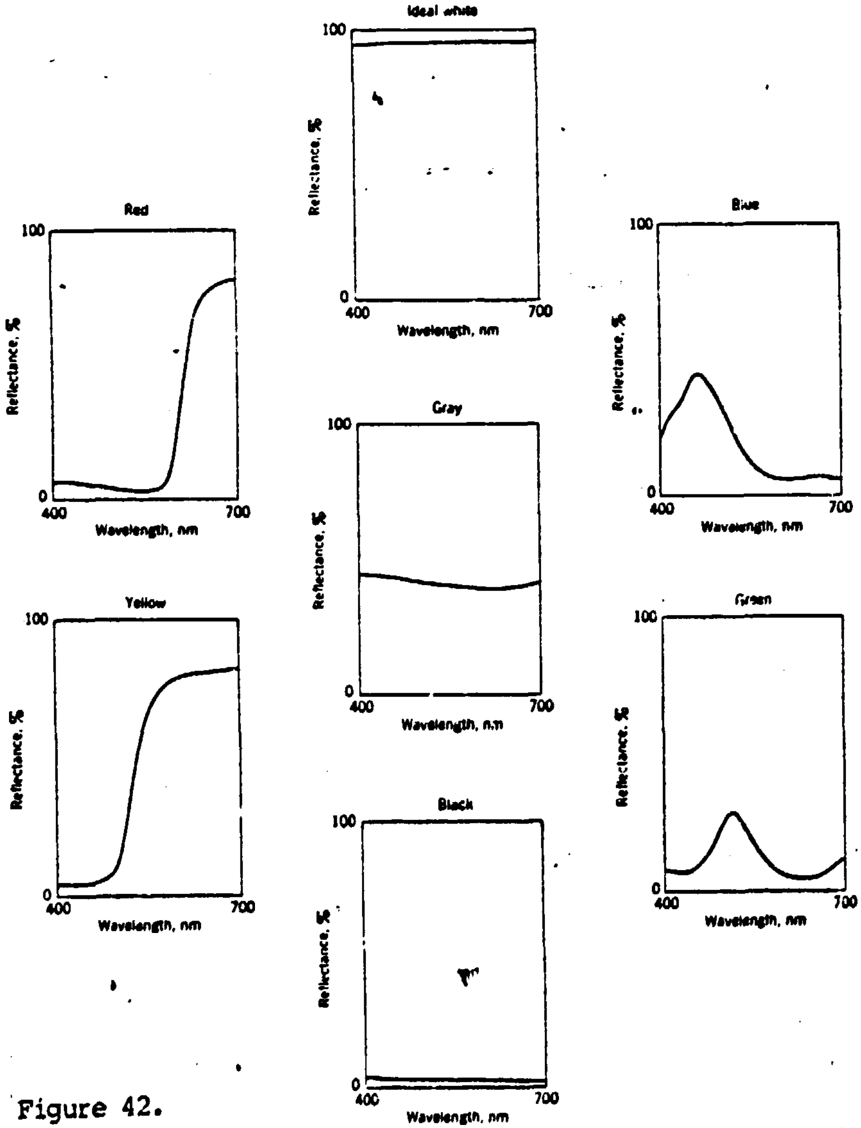


Figure 42.

The spectral reflectance curves of several opaque colored materials, with their color names (Kelly 1955, 1959). We designate reflectance as *R*, but other authors (especially European) may use the symbol *ρ*.

Spectrophotometry

Spectrophotometry, the measurement of the spectral reflectance or transmittance curves of materials, has many uses besides color measurement. We shall describe only spectrophotometry in the visible region of the spectrum, which we saw on page 4 to be between about 380 and 750 nm, as carried out on instruments especially designed or adapted for color measurement.

Source of Spectrum. The white light from the source in a spectrophotometer, often a tungsten filament bulb, is spread out into a spectrum by means of a prism or a diffraction grating. A slit is used to select a small portion of the spectrum to illuminate the sample. This portion may be between a few tenths and 10 nm wide, depending on the instrument. The wavelength of the light passing through the slit is varied, either manually or by automatic scanning, to cover the entire visible spectrum.

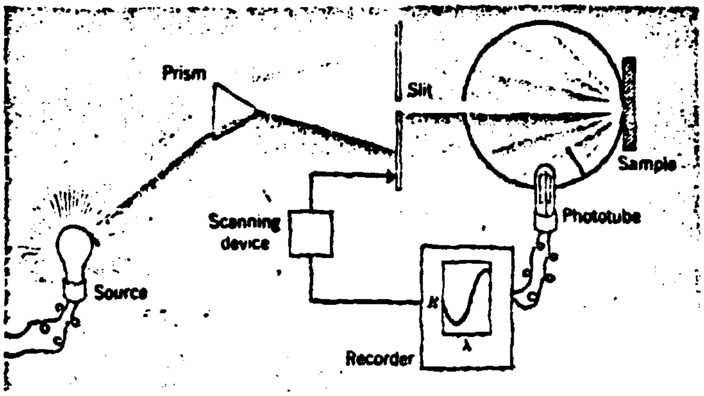


Figure 43.

In a spectrophotometer, light is dispersed into a spectrum, made approximately monochromatic by means of a slit, and used to illuminate the sample (in this sketch, using integrating-sphere geometry). The reflectance of the sample is plotted against the wavelength of the light to give the sample's *spectrophotometric* (or spectral reflectance) curve.

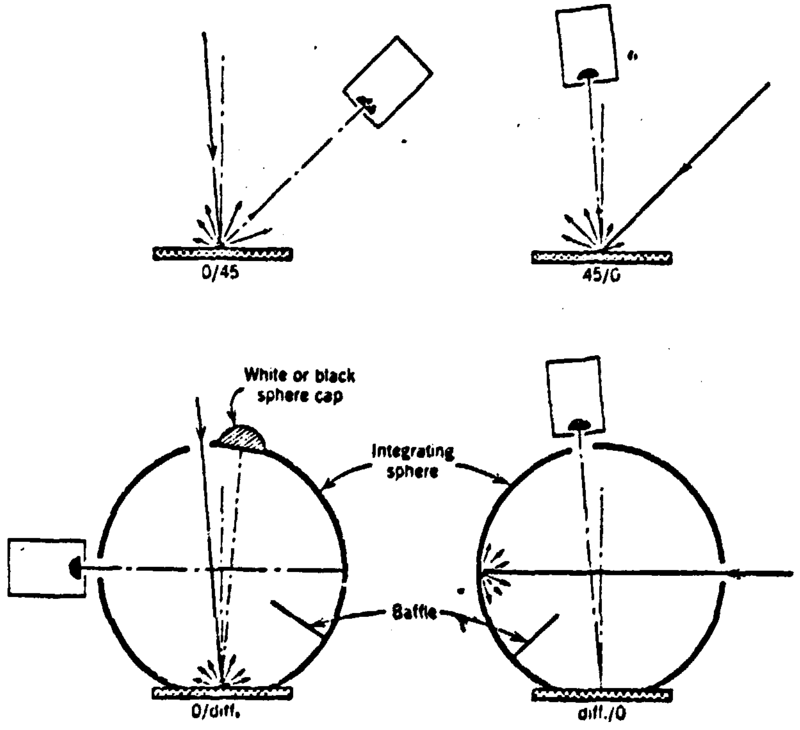


Figure 44. Schematic diagram showing the four CIE standard illuminating and viewing geometries for reflectance-factor measurements.

The CIE standard observer and tristimulus values

The CIE system of colour measurement is based on the experiment, in which light from a test lamp shines on a white screen and is viewed by an observer. A nearby part of the screen is illuminated by light from one or more of three lamps, equipped to give light of three widely different colours, say red [Ⓡ], green [Ⓖ], and blue [Ⓑ]. The arrangement is illustrated in Figure 45.

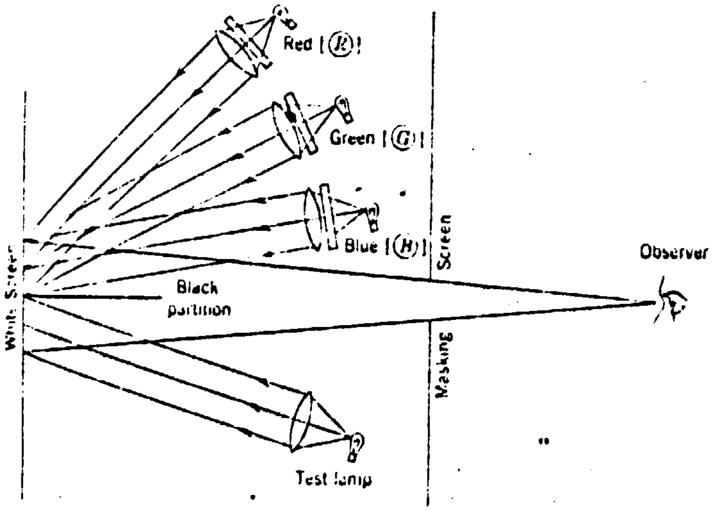


Figure 45. An arrangement producing a large number of colours by mixing the light from three different coloured lamps.

For convenience, we may refer to these as primary lights. By adjusting the intensities of these lights, the observer can make their combined colour on the screen match that of the test lamp. The purpose of the experiment if this:

Colors can be specified in terms of the three numbers representing the amounts of the three primary lights added together to make the match; thus the term "additive colour matching" is used. For example, a dull greenish-blue test light might be matched by 10 parts of [Ⓡ], 40 parts of [Ⓖ], and 50 parts of [Ⓑ].

The amounts of the three primaries, which are the three numbers describing the test colour, are called the "tristimulus values" of that colour. If we call the amount of the red primary Ⓡ, the amount of the green Ⓖ, and the amount of the blue Ⓑ, the dull greenish-blue test light can be described by writing down

Ⓡ = 10, Ⓖ = 40, and Ⓑ = 50.

If the colours of the three primary lights are quite different, a wide variety of test colours can be matched in this way. It was found experimentally however, that in no case can all possible test colours be matched with combinations of any one set of primaries, even if the spectrum colours are used as primaries. Thus a bright yellow test light cannot be matched by any combination of red and green.

This problem can be overcome in several ways. The method used by CIE is the use of unreal or imaginary primary lights, chosen so that their mixtures do match all possible real colours.

It should be emphasized that, despite the use of the imaginary primaries designated X, Y and Z tristimulus values, the CIE system, is very real indeed, for the amounts of these primaries needed to "match" - that is to specify - any colour can be calculated easily.

The first step to do is the measurement of the tristimulus values for the spectrum colours, that is the amounts of the X (red), Y (green) and Z (blue) primaries needed to match the colour of monochromatic light, taken from 400 to 700 nm at very narrow intervals. If the energy is the same all through the spectrum, we speak about "an equal energy spectrum", and the amounts of X,Y and Z for monochromatic lights of equal energy are designated $\bar{x}$, $\bar{y}$ and $\bar{z}$ respectively, and are called "spectral tristimulus values". We can imagine this experiment by substituting lamps putting out momochromatic light (we can call them "spectrum lamps") for the test lamp on figure 45.

We can plot the spectral tristimulus values as a function of wavelength, and get the curves describing the colour matching properties of the average human eye, these curves, or rather the data they are derived from give the definition of the <u>CIE standard observer</u>.

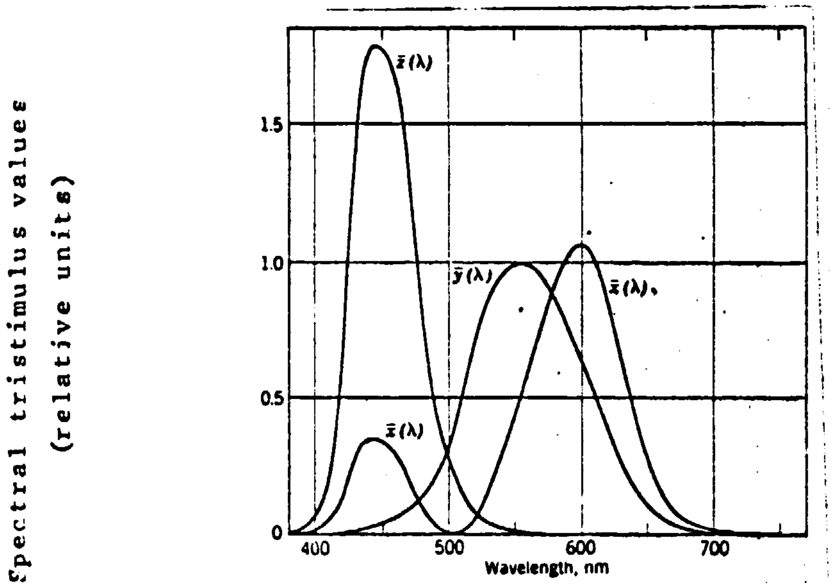
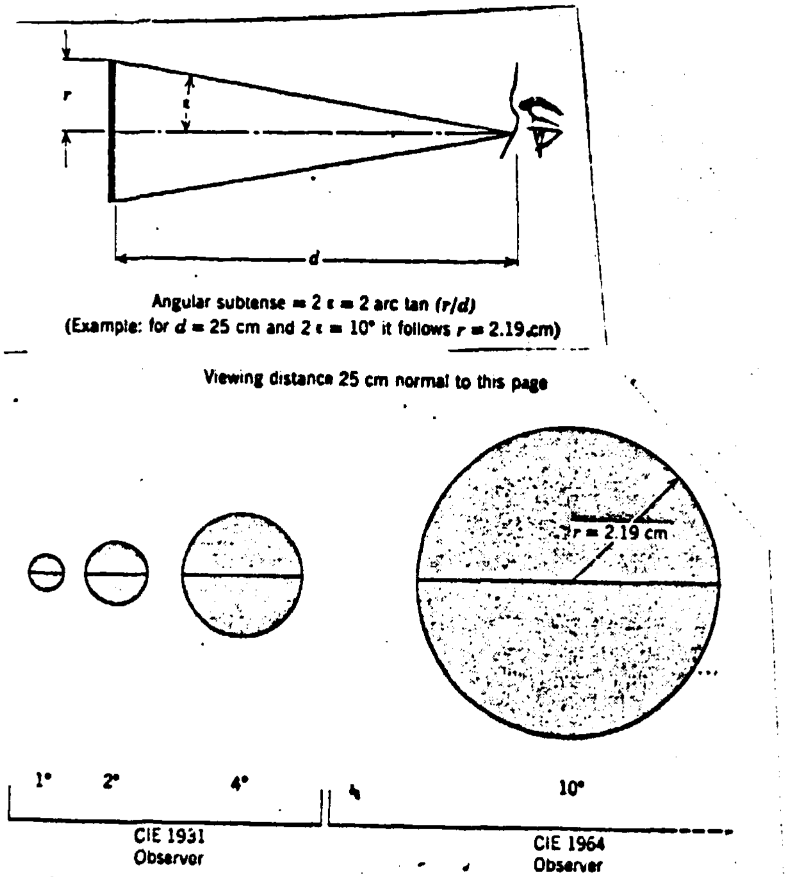


Figure 46. The CIE standard observer
Spectral tristimulus values for the equal energy spectrum

Due to the structure of the human eye, the colour vision properties depend to a certain extend on the angle of viewing (the angular subtense). When it is less than 4°, light falls only on the very centre of the retina (which is the detector part in our eyes). This central part - called the fovea - has colour vision properties, that are different from other areas of the retina. The experiments by which the spectral tristimulus values have been determined had made the measurements at an angular subtense of 2°, therefore the system adopted by the CIE in 1931 is valid only for fields of view not more than 4°. This is the CIE 1931 (2°) standard observer.



Angular subtense = 2 ε = 2 arc tan (r/d)
(Example: for d = 25 cm and 2 ε = 10° it follows r = 2.19 cm)

Viewing distance 25 cm normal to this page

Figure 47 Bipartite visual fields of different angular subtense. When viewed normally at a distance of 25 cm (≈ 10 inches) the fields subtend at the observer's eye 1, 2, 4, and 10 degrees. The derivation of angular subtense is indicated at the top of the figure.

For practical purposes viewing conditions corresponding to the 2^{o} observer are rather inadequate, and in 1964 the CIE defined a standard observer for 10^{o} viewing, called the CIE 1964 (10^{o}) standard observer. When we give the tristumulus values we must specify wether it is the 2^{o} (X,Y,Z) or the 10^{o} (X_{10}, Y_{10}, Z_{10}) system. The difference between the spestral tristimulus values for the two viewing conditions are illustrated on Fig. 48.

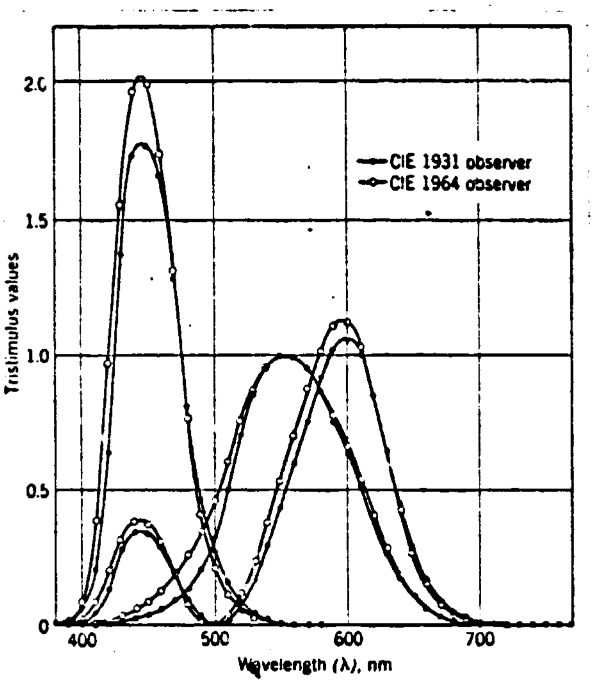


Figure 48. Spectral tristimulus values (relative units) for the 2° (1931) and the 10° (1964) standard observer.

The spectral tristimulus values refer to the equal energy spectrum. The relative amounts are so adjusted, that when we add them up for the whole visible range (380-780 nm) they give 100 for X, Y and Z. If we have a light source, which emits light not of equal energy (which is the case for all practical light sources) we can still calculate the tristimulus values, but we have to multiply the $\bar{x}$, $\bar{y}$, $\bar{z}$ values with the relative energy distribution values at each wavelength.

So for every wavelength we have $S \cdot \bar{x}$, $S \cdot \bar{y}$ and $S \cdot \bar{z}$ instead of just $\bar{x}$, $\bar{y}$ and $\bar{z}$, and it means, that for light sources other than equal energy the tristimulus values will be different. They are, however so adjusted, that for Y we always get 100. Thus the tristimulus values of illuminants A and D_{65} for the 2° and 10° observer respectively are the following:

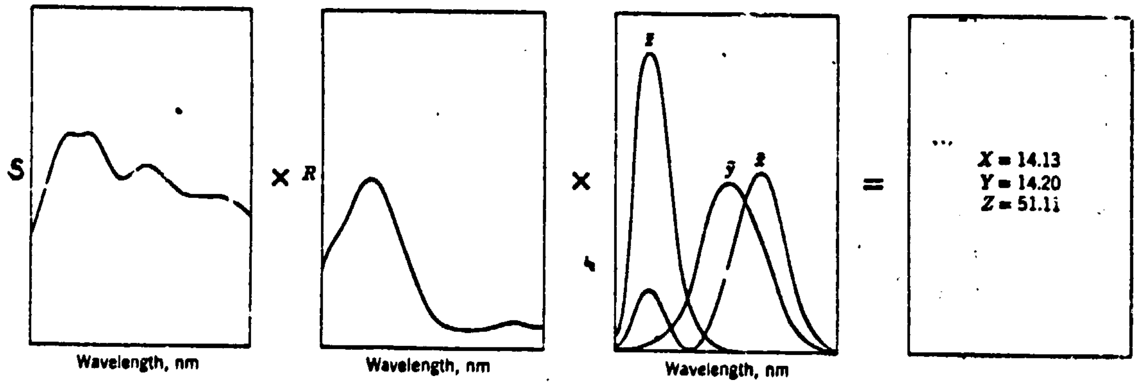
Illuminant	X	Y	Z	X_{10}	Y_{10}	Z_{10}
A	109.8	100.0	35.5	111.2	100.0	35.2
D_{65}	95.1	100.0	108.8	94.8	100.0	107.4

Tristimulus values for coloured objects

The calculation of the tristimulus values for any coloured object (which is in practice the most important case) follows very similar lines. The only difference is that when we calculate the tristimulus values for light sources, we assume a perfect white surface, where its light is reflected from. If we now put a surface with reflecting properties characterized by R spectral reflectance factor, the amount of light reaching the observer will at any wavelength be R times the amount reflected from the perfect white (this comes from the definition of R itself). Thus at every wavelength we get from the sample with a reflectance R and illuminated by a source with an energy distribution S radiation corresponding to $S \cdot R$. This will modify the spectral tristimulus values, and we get at every wavelength $S \cdot R \cdot \bar{x}$, $S \cdot R \cdot \bar{y}$ and $S \cdot R \cdot \bar{z}$. If we add up all these value for the entire visible range, we get for the tristimulus values

$$X = \sum S \cdot R \cdot \bar{x}$$
$$Y = \sum S \cdot R \cdot \bar{y}$$
$$Z = \sum S \cdot R \cdot \bar{z}$$

This process can be illustrated as shown on figure 49.



CIE Standard Source

Object

CIE Color-matching functions for the equal-energy spectrum

CIE Tristimulus values

The CIE tristimulus values X, Y, and Z of a color are obtained by multiplying together the relative energy S of a CIE standard light source, the reflectance R (or the transmittance) of the object, and the tristimulus values of the equal-energy spectrum colors $\bar{x}$, $\bar{y}$, and $\bar{z}$. The products are summed up for all the wavelengths in the visible spectrum to give the tristimulus values, as indicated in the diagram.

Wavelength, nm	R, %	$S_c\bar{x}$	$S_cR\bar{x}$	$S_c\bar{y}$	$S_cR\bar{y}$	$S_c\bar{z}$	$S_cR\bar{z}$
400	23.3	0.00170	0.04	0.00004	0	0.00807	0.19
420	33.0	0.02474	0.82	0.00073	0.02	0.11889	3.93
440	41.7	0.07944	3.31	0.00524	0.22	0.39846	16.62
460	50.0	0.06719	3.36	0.01387	0.69	0.38569	19.29
480	47.2	0.02222	1.05	0.03234	1.53	0.18908	8.93
500	36.5	0.00104	0.04	0.06797	2.48	0.05724	2.09
520	24.0	0.01151	0.27	0.12914	3.10	0.01423	0.34
540	13.5	0.05560	0.75	0.18285	2.47	0.00390	0.05
560	7.9	0.11751	0.93	0.19668	1.55	0.00078	0.01
580	6.0	0.16822	1.01	0.15972	0.96	0.00032	0
600	5.5	0.17885	0.99	0.10624	0.58	0.00014	0
620	6.0	0.14130	0.85	0.06301	0.38	0.00004	0
640	7.2	0.07381	0.53	0.02884	0.21	0	0
660	8.2	0.02720	0.22	0.01007	0.08	0	0
680	7.4	0.00737	0.05	0.00268	0.02	0	0
700	7.0	0.00164	0.01	0.00058	0	0	0
			Sum = X = 14.23		Sum = Y = 14.29		Sum = Z = 51.45

How to calculate tristimulus values from spectral distribution data. The products of the spectral energy distribution of the illuminant, S, and the tristimulus values of the spectrum, $\bar{x}$, $\bar{y}$, and $\bar{z}$, are tabulated in many books (Judd 1952, 1963; OSA 1953; Hardy 1936; Mackinney 1962, etc.) as they are here for CIE Illuminant C. Such tabulations must be adjusted so that the sum of $S\bar{y}$ = 1.000 in order for the tristimulus values to be correct.

The chromaticity diagram

If any one of the tristimulus values can be said to be the most important, it is Y, for this coordinate is the *luminance** or intensity of the matching light, equal to the ***luminous transmittance*** or ***luminous reflectance*** of the object. It is usual to describe the *chromaticity* of the object, that is, the qualities of its color other than luminance (such as hue and chroma) by ratios of the tristimulus values to their sum. These ratios are known as the *chromaticity coordinates, x, y,* and *z.* Since the sum of the chromaticity coordinates is 1, they provide only two of the three coordinates needed to describe the color. One of the tristimulus values, usually Y, must also be specified.

Color as described in the CIE system can be plotted on a *chromaticity diagram,* usually a plot of the chromaticity coordinates *x* and *y*. Perhaps the most familiar feature of the chromaticity diagram is the horseshoe-shaped ***spectrum locus,*** the line connecting the points representing the chromaticities of the spectrum colors. The chromaticities of blackbody sources, as well as of CIE standard Sources A, B, and C, are also shown in the figure on this page. Locations corresponding to common color names are indicated in the similar diagram on page 57.

$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

$$z = \frac{Z}{X + Y + Z}$$

These equations define the CIE *chromaticity coordinates x, y,* and *z.*

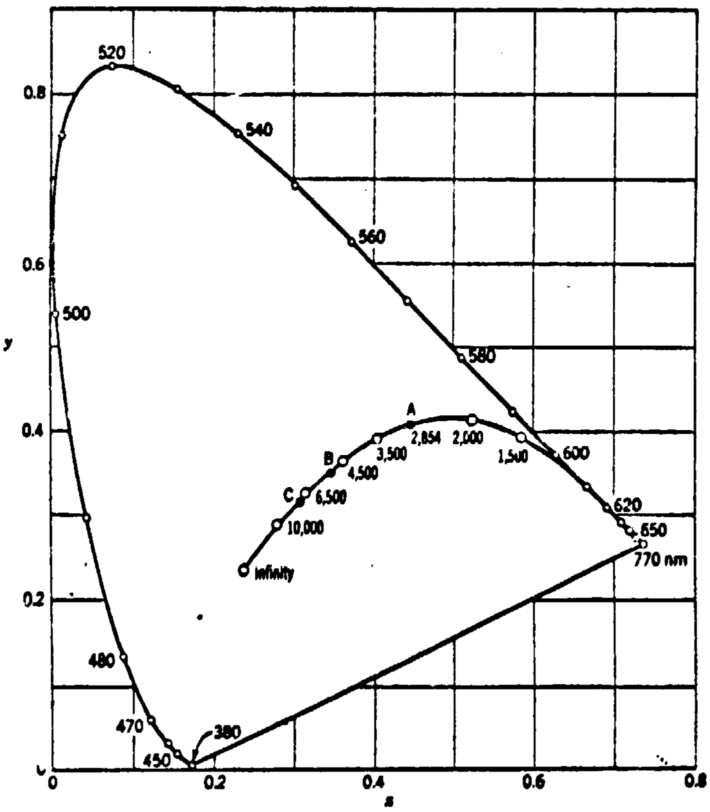


Figure 50.

This is the famous CIE 1931 chromaticity diagram, showing the horseshoe-shaped spectrum locus with the spectrum colors identified by their wavelengths, the locus of blackbody light sources identified by their color temperatures in K, and the locations of the CIE standard Sources A, B, and C.

*If we convert the Y tristimulus value in the L^* value of the CIELAB system, we get metric lightness, which is the psychometric equivalent of luminannce factor.

It is important to note that the CIE system is not associated with any particular set of physical samples. Only incidentally have sets of samples been produced to illustrate the system. Nor is the system based on steps of equal visual perception in any sense, although many modifications of the CIE system have been proposed as approaches to equal perception.

An alternative set of chromaticity coordinates, ***dominant wavelength*** and ***purity***, correlate more nearly with the visual aspects of hue and chroma, although their steps and spacing are not visually uniform. The dominant wavelength of a color is the wavelength of the spectrum color whose chromaticity is on the same straight line as the sample point and the illuminant point. Purity is the distance from illuminant to sample divided by that from illuminant to spectrum locus.

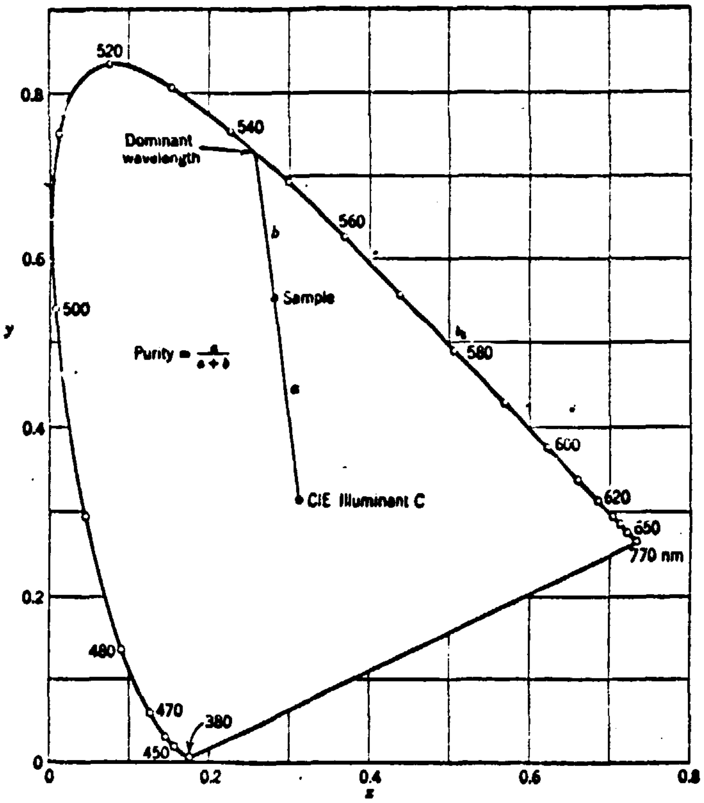


Figure 51.

The definitions of dominant wavelength and purity are shown on this CIE chromaticity diagram.

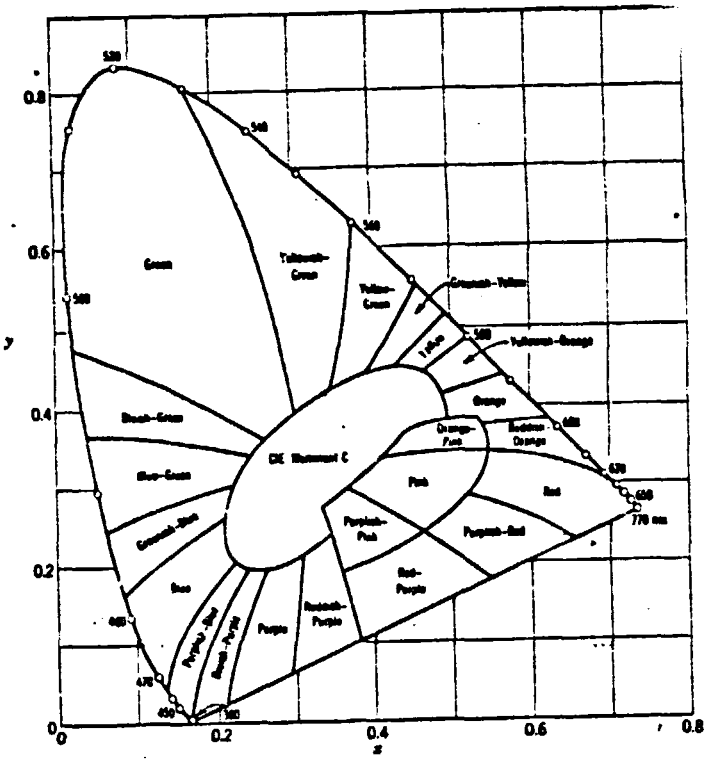


Figure 52. The names of various colours shown on the CIE 1931 chromaticity diagram

It is very important to note, that the chromaticity coordinates and diagram - derived from the tristimulus values - refer always to either the 2° or the 10° observer, there is som[illegible]rence between the two, as shown on figure 53.

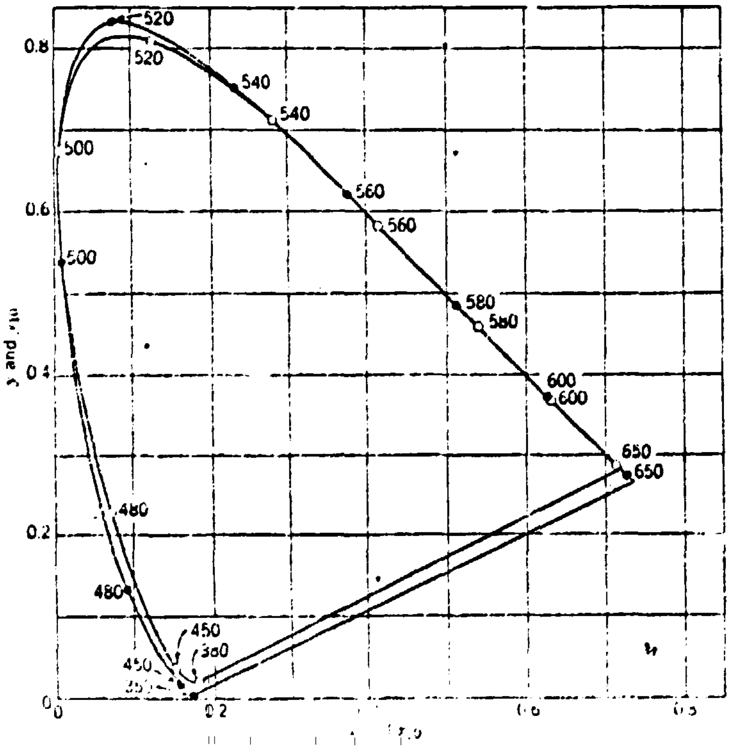


Figure 53.

The CIE 1964 (x_{10}, y_{10}) chromaticity diagram (o) as compared to the CIE 1931 (x, y) chromaticity diagram (●).

Metamerism

Metamerism is a term used to describe the phenomenon of two objects having the same apparent color under one set of observation conditions and differing apparent colors under another set of conditions.

Two colors look identical to the standard observer for a given illuminant if they have the same tristimulus values. It is possible that two objects with different reflectance factor curves have identical tristimulus values for a given illuminant. This is illustrated in Figure 3-11. The two reflectance factor curves in this figure have identical tristimulus values for the 2° observer and illuminant *C*. In daylight they will appear to have the same color to most observers. In tungsten light and certain other light sources, they will be a mismatch because they do not have identical tristimulus values under these conditions anymore.

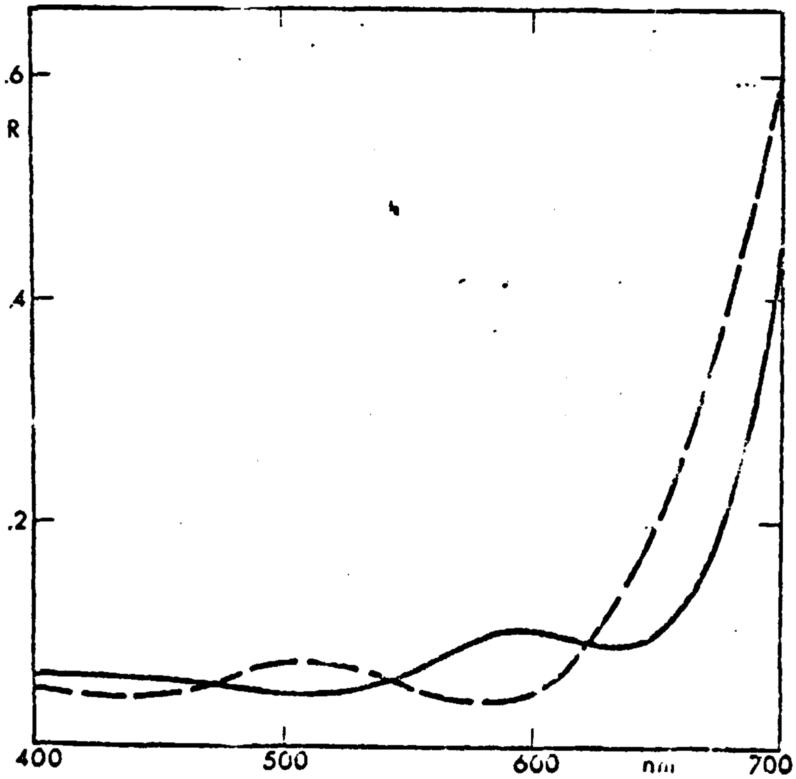


Figure 3-11. Reflectance factor curves of two metameric dyeings with identical tristimulus values for standard light source *C*.

The physiological reason for metamerism is related to the three sensory processes responsible for color perception. The three processes are sensitive only to the product of energy distribution and reflectance factor in three broad areas of the spectrum and not to specific spectral differences. A positive difference between two reflectance factor curves in one area can be compensated for by a negative difference in an adjacent area with a resulting identical response of the sensory receptor to both stimuli.

In daily routine colorant formulation metamerism is a very common difficulty. The fundamental problem is the inability to match the reflectance factor curve of the standard exactly, because different colorants and/or a different substrate are being used. The term "nonmetameric" is used for matches with identical reflectance factor curves. Very often a complete curve match is impossible and the problem is reduced to finding the least metameric match possible with the colorants available.

The most commonly known types of metamerism are illuminant metamerism, observer metamerism, geometric metamerism, and various combinations of these. Illuminant metamerism is the most important one in daily routine. It is of considerable economic importance where two differently manufactured parts of a piece of merchandise have to match under all lighting conditions. It is important to realize that it is possible for two objects to have the same color under two different light sources and still appear to be a mismatch under a third light source.

Observer metamerism deals with the fact that a real human observer has generally somewhat different color matching functions from those that define the two standard observers. A match calculated to be a perfect one for a standard observer may, therefore, actually look like a mismatch to a real observer.

In practical situations observer metamerism can be the cause for arguments between colorists or buyer and seller, where one party perceives the standard and sample to be a match and the other party, characterized by different color matching functions, perceives a mismatch.

Metamerism is probably best described in terms of the color difference exhibited by the metameric pair under a given set of conditions. Such a color difference is, however, only meaningful for a set of samples which match (zero color difference) under another set of conditions.

The calculation of the degree of metamerism (we call it index of metamerism, and designate it MI) is best shown by an example. We have two samples, 1 and 2, with the following tristimulus values (notice, that the tristimulus values for the same sample are different when either the illuminant, or the observer (or both) change:

Sample	Illuminant D_{65}						Illuminant A		
	X_{10}	Y_{10}	Z_{10}	X	Y	Z	X	Y	Z
1	42.20	33.08	14.62	42.49	33.00	15.09	59.43	40.25	4.95
2	41.99	32.76	13.82	42.49	33.00	15.09	60.01	40.23	5.35

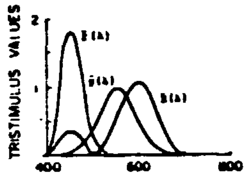
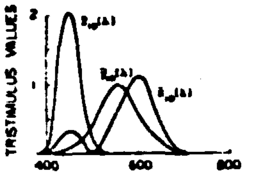
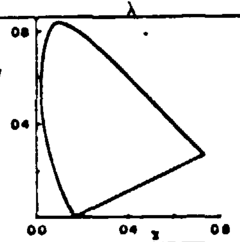
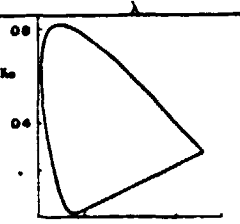
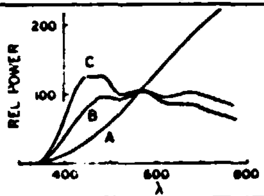
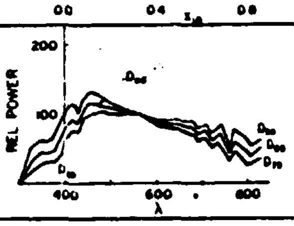
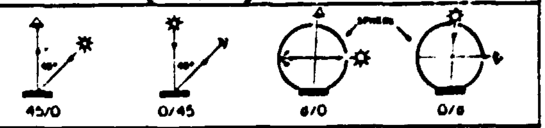
$MI_{2° \to 10°} = 1.9$

MATCH

$\Delta E = MI_{D_{65} \to A} = 2.5$

We can summarize the basics of the CIE system by help of the following table. Notice, that the reflectance factor is designated $\beta(\lambda)$ or $\rho(\lambda)$, and that in the official recommendation there is a constant (k) incorporated in the definition equations for the tristimulus values, so that the value of Y for the perfect white will be 100 for every illuminant and both observers.

CIE STANDARDS OF BASIC COLORIMETRY

OBSERVERS		...
CHROMATICITY DIAGRAMS		
ILLUMINANTS S(λ)		
SOURCES	"A", "B", "C"	"D" NOT AVAILABLE
MEASUREMENT OF REFLECTANCE FACTOR $\beta(\lambda)$, $\rho(\lambda)$	RELATIVE TO PERFECT REFLECTING DIFFUSER $[\beta(\lambda)=\rho(\lambda)=1]$	
ILLUMINATING AND VIEWING CONDITIONS		
TRISTIMULUS VALUES	$X = k\sum\beta(\lambda)S(\lambda)\bar{x}(\lambda)$ $Y = k\sum\beta(\lambda)S(\lambda)\bar{y}(\lambda)$ $Z = k\sum\beta(\lambda)S(\lambda)\bar{z}(\lambda)$ $k = 100/\sum S(\lambda)\bar{y}(\lambda)$	$X_{10} = k_{10}\sum\beta(\lambda)S(\lambda)\bar{x}_{10}(\lambda)$ $Y_{10} = k_{10}\sum\beta(\lambda)S(\lambda)\bar{y}_{10}(\lambda)$ $Z_{10} = k_{10}\sum\beta(\lambda)S(\lambda)\bar{z}_{10}(\lambda)$ $k_{10} = 100\sum S(\lambda)\bar{y}_{10}(\lambda)$
CHROMACITY COORDINATES	$x = X/(X+Y+Z)$ $y = Y/(X+Y+Z)$	$x_{10} = X_{10}/(X_{10}+Y_{10}+Z_{10})$ $y_{10} = Y_{10}/(X_{10}+Y_{10}+Z_{10})$

In colour measurement and specification we can distinguish the following four steps:

Measurement of $S(\lambda)$ and $R(\lambda)$ physical

Measurement or calculation of

X, Y, Z tristimulus values

x, y chromaticity coordinates

λ_d, p_e, Y dominant wavelength, excitation purity and luminance (lightness) factor psychophysical

Measurement or calculation of

$L^*, a^*, b^*, C^*_{ab}, H^o_{ab}$ CIELAB coordinates psychometric

Visual estimation of

H V/C Munsell coordinates perceptual

Thus: $S(\lambda), R(\lambda)$. What we measure

$\bar{x}, \bar{y}, \bar{z}$ λ_d, Y, p_e is connected to how we specify colour by three additive primaries,

H^o_{ab}, L^*, C^*_{ab} then it is modified to describe it in a visually (approximately) uniform manner, to approximate

H V / C what we see.

4.2 Reflectance and dyestuff concentration

The fact that a systematic relationship exists between spectral reflectance and dyestuff concentration is shown in Fig. 55 with the example of a blue dyestuff dyed in several concentrations. The reflectance R in % is measured as a function of the wavelength.

Such a curve is plotted automatically in approximately one minute on a recording spectrophotometer. The reflectance, as measured on the undyed textile, is designated with 0%. It can be seen in Fig. 55 that the reflectance in the yellow and red area of the spectrum is reduced strongly with increasing concentration. It is much smaller than in the blue part of the spectrum. The reflected light is primarily blue and for this reason, the dyeing has a bright blue appearance. Corresponding facts are true for the red and yellow dyes shown in Fig. 56 and 57, whereby it should be added that in Fig. 57, the high reflectance in the areas green, yellow and red produces in the eye by additive mixing the impression of yellow. Characteristically, in each case the high reflectance of the undyed substrate is changed only slightly in those areas of the spectrum which have the same colour as indicated by the name of the dyestuff. The reflectance is primarily reduced in the complimentary area of the spectrum.

If one has a dyeing of unknown concentration of the blue dyestuff in Fig. 55 it can be determined by direct comparison of its reflectance curve with the set of curves in that illustration. The measurement of the total reflectance curve is not necessary in this case. It is sufficient to measure it at one wavelength. The wavelength best suited for this purpose is one near the absorption maximum —for the blue, this is around 600 nm—because the individual curves are most distinctly separated in this area and deviate most strongly from the curve of the textile substrate.

The comparison of a measured reflectance value with those of known dyeings is simplified and more accurate if the reflectance at the chosen wavelength is plotted as a function of reflectance (Fig. 58). To contain a large range of values with equal accuracy, the diagram is best plotted in logarithmic scale for both axes. The accuracy of the curve obtained by connecting the plotted points depends on the number of dyeings prepared and measured.

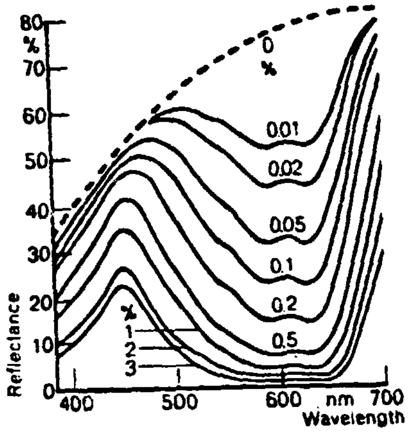


Fig. 55 Reflectance curves of the concentration series of a blue dyestuff

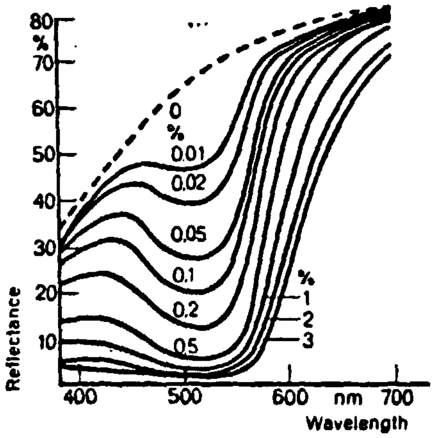


Fig. 56 Reflectance curves of the concentration series of a red dyestuff

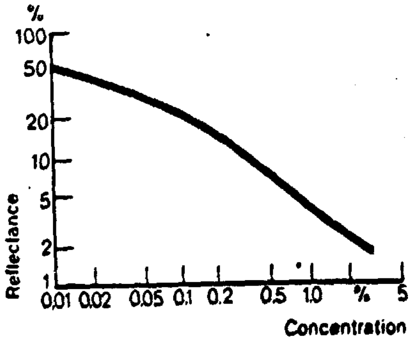


Fig. 58 Reflectance of the blue dyeing of Fig. 55 at 600 nm as a function of the concentration (both axes plotted logarithmically)

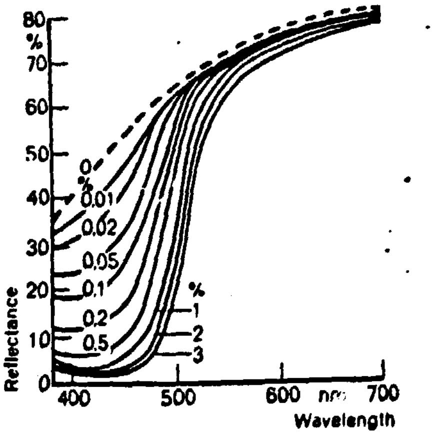


Fig. 57 Reflectance curves of the concentration series of a yellow dyestuff

The concentration of a dyeing could be deduced from its reflectance in a simple manner and without the necessity of preparing several calibration dyeings, if the same mathematically describable relationship between concentration c and reflectance R could be found to hold true for all wavelengths and all dyestuffs, e.g.

$$A \cdot c = F(R) \qquad (5)$$

where A is a constant depending on dyestuff, wavelength, substrate and dyeing conditions. F (R) is always the same function of R. Such a function can be determined on an empirical or a theoretical basis.

The most commonly used function f (R) is the one developed theoretically by Kubelka and Munk. In their theory, the optical properties of a sample are described by two values. K is a measure of the light absorption and S is a measure of the light scattering. On textiles, K is determined primarily by the dyestuffs and S only by the substrate. At the wavelength λ Kubelka and Munk calculated the following relationship for the reflectance R of a thick, opaque sample with the constants K and S:

$$\frac{K}{S} = \frac{(1-R)^2}{2R} \qquad (5)$$

In this equation R is used as a ratio, e.g. 28% reflectance as 0.28. According to Beer's law, the absorption constant K is empirically nearly proportional to the concentration c for the dyestuff. By using this and including the scattering constant which is, as mentioned before, independent of the dyestuff concentration in the proportionality constant A, the following is obtained:

$$A \cdot c = \frac{(1-R)^2}{2R} \qquad (6)$$

where A is a constant to be determined empirically which depends upon the factors discussed before, but not on the concentration. From a measurement of R on a calibration dyeing of known concentration, A can be determined and when A is known, the dyestuff concentration of any unknown dyeing of the same dyestuff can be determined. Conversely, the colorant strength of a dyeing of the same dyestuff with unknown strength can be established by dyeing it in a known concentration and determining A. The ratio of the A values of the standard and the sample is equal to the relative strength of the sample.

A relationship according to equation (6) would only be found if the textile substrate, on which the dyeing is made, would not have an absorption of its own and if its reflectance curve would be at R = 100%. In reality every textile substrate has an absorption K_t which is added to the absorption K_f of the dyestuff. According to equation (5), the reflectance is determined by the sum of both:

$$\frac{K_f + K_t}{S} = \frac{(1-R)^2}{2R} \qquad (7)$$

If Beer's law is introduced again for K_f and the reflectance of the substrate is considered with:

$$\frac{K_t}{S} = \frac{(1-R_t)^2}{2R_t}$$

instead of equation (6), the following equation is obtained:

$$A \cdot c = \frac{(1-R)^2}{2R} - \frac{(1-R_t)^2}{2R_t} \qquad (8)$$

We are next considering qualitatively the combination of two dyestuffs on the basis of reflectance curves (Fig. 59) by looking at the formation of a green dyeing by e.g. mixing 1% blue and 1% yellow. In the red spectral area, only the blue dyestuff is absorbing. The green combination made from 1% blue and 1% yellow has to have the same reflectance in the red spectral area as that of the 1% blue dyeing alone. On the other hand, in the blue spectral area the curve of the green dyeing has to be close to that of the 1% yellow dyeing, since the blue dyestuff absorbs very little there. In the green spectral area, both blue and yellow absorb to some degree and the green combination has to absorb considerably more than either of the single dyestuffs. The reflectance curve of the combination is correspondingly below the curve of each single dyestuff.

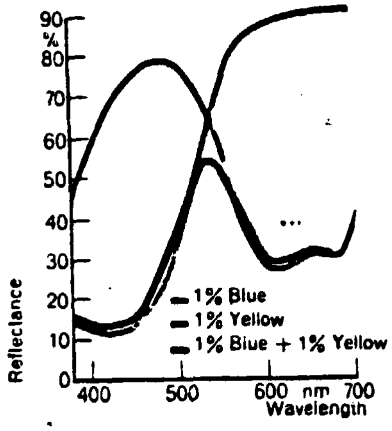


Fig. 59 Reflectance curves of dyeings of a blue and a yellow dyestuff and their mixture. (This actually measured green dyeing is a little weaker than expected by theory.)

To express these considerations quantitatively and at the same time for three dyestuffs a, b and c, we start from equation (5):

$$\frac{K}{S} = F(R). \qquad (5)$$

This equation holds true for the combination dyeing as well. K, however, is no longer the constant of absorption of a single dyestuff, but that of the combination, which consists additively of the absorption constants of the individual dyestuffs and of the textile substrate ($K = K_a + K_b + K_c + K_t$).

$$\frac{K}{S} = \frac{K_a + K_b + K_c + K_t}{S} = F(R) \qquad (14)$$

By assuming again proportionality between the constants of absorption and the dyestuff concentrations and including S, which depends only on the textile substrate, in the proportionality constant, we obtain:

$$A \cdot c_a + B \cdot c_b + C \cdot c_c + F(R_t) = F(R) \qquad (15)$$

The constants A, B and C are obtained from this equation by measuring the spectral reflectance of primary dyeings of the individual dyestuffs. In equation (15) e.g. c_b and c_c are to be set equal to zero for the primary dyeing of dyestuff a, so that A can be determined as the only unknown. With the same equation the reflectance curve of a dyeing with known concentrations can be calculated in advance. From the reflectance curve the tristimulus values X, Y, Z can be computed.

Calculation of formulas

While in the previous chapter the dyestuff concentrations were assumed to be known and from them the reflectance curve and the tristimulus values were calculated, the target of computer dyestuff formulation is just the reverse. The calculation determines the dyestuff concentrations necessary to prepare a dyeing which has the same colour i.e. the same tristimulus values as the standard.

From all possible methods, those methods which rely on electronic data processing equipment for the computation have found especially widespread practical application today. The following presentation of computer dyestuff formulation is, therefore, restricted to those methods.

Working procedure

In advance of a more detailed description of the necessary individual steps, the total procedure for the calculation of a formula to match a standard is illustrated in form of a table below, whereby the required steps in the computer method are compared to those in the conventional method without colour measurement.

With computer	Conventional
Preparative work:	
Preparation of primary dyeings Measurement and storage of primary data	Colouristic experience
Matching of a standard:	
Measurement of standard	Visual observation of standard
Dyestuff selection	Dyestuff selection
Data input Calculation Output of results	Estimation of concentrations based on formula collection and/or experience
Dyeing of calculated formula	Trial dyeing
Measurement of dyeing	Visual comparison
Correction calculation	Estimation of correction
Dyeing of corrected formula	Dyeing

Preparative work

Preparation of primary dyeings of individual dyes.

Computer dyestuff formulation is based on the determination of dyestuff constants by measurement of primary dyeings of individual dyestuffs. The dyeing conditions used in preparing these primary dyeings should be as close as possible to the conditions which will exist when the match is being dyed. No other factor is as important as this one. The closer these conditions agree, the better the results of computer colour matching will be.

This is also important if the actual calculations are not done on a company-owned computer, but e.g. at a dyestuff supplier. An indiscriminate use of primary dyeings from a dyestuff company for computer dyestuff formulation in a textile plant leads mostly to disappointing results. For the same reason, it is of little value to use the reflectance curves of dyestuffs, available from most dyestuff companies, as primary data.

If the Kubelka-Munk law would be followed strictly, a single dyeing of each dyestuff in a medium concentration would be sufficient. Due to smaller or larger deviations from the theory, it is useful to dye the dyestuffs in several concentrations. In many cases, satisfactory results are obtained with the following four concentrations: 0.1, 0.5, 2.0 and 4.0% but, depending on the colorant strength, other concentrations can be used.

Measurement and storage of dyestuff data. The reflectance curves of the primary dyeings have to be measured with a spectrophotometer or an abridged spectrophotometer. Depending on the degree of automation, the reflectance values are either printed, punched, directly fed into the computer or read off the instrument and jotted down. 16 readings of R values at 20 nm intervals from 400–700 nm are sufficient. If less than 16 points are used, the accuracy is reduced considerably. The increase in accuracy when measuring more than 16 points usually bears no relationship to the increase in work and computer memory and to the errors from other sources. In the choice of instruments, it has to be considered that the measuring geometry for the measurement of the primary dyeings and later of the standards and strike dyeings should agree as closely as possible.

The measured reflectance values have to be stored in the computer in a suitable manner. Depending on the computer and the program, the storage is accomplished in different ways.

Frequently, the values are punched into cards manually, but it is also possible to punch the values automatically into tape or cards, from which they are fed into the computer. A program subroutine calculates the F (R) values, subtracts the substrate absorption and divides the resulting values by the concentration. The data is then stored on magnetic disks, tape or punched cards.

For the individual formula calculation, depending on the program, smaller or larger groups of the stored dyestuffs are read into core.

The primary dyeings have to be prepared, measured and stored only once. The more they are used later, the less weighty is the considerable work necessary in the beginning. In any case, since the success of computer dyestuff formulation depends markedly on the quality of this initial work, every possible care should be used.

Matching of a standard

Measurement of the standard. The influence of a measuring error is less disturbing if the instrument used for the measurement of the standards agrees closely with the one used for measuring the primary dyeings. On the other hand, since dyeings of calculated formulas deviate usually quite noticeably from the standard for several reasons, small measuring errors are not decisive in the result of the first dyeing and can usually be tolerated.

Depending on the computer and the program, the 16 reflectance values, the tristimulus values X, Y, Z or the filter values R_x, R_y, R_z are measured and fed into the computer.

Dyestuff Selection. The dyestuffs to be used in the match depend on the fastness requirements, the dyeing behaviour in the used equipment, on the substrate, the costs, the availability and finally on the possibility of obtaining the desired shade with them. This requires so many compromises, which are different in each case, that up to now, no program is available which considers all these factors efficiently. The knowledge and experience of a good colourist are, therefore, especially valuable in the dyestuff selection.

After the colourist has reduced the suitable dyestuffs, based on the above constraints, to a number of from 10 to 15, it is possible to have the computer calculate automatically e.g. all possible three colour combinations. Since 10 dyestuffs lead to 120 and 15 dyestuffs to more than 450 possible combinations, considerable computation time is required. Abbreviated approximations are therefore frequently used to preselect suitable combinations, whereby it must be investigated if in this manner suitable combinations are not dropped prematurely. The program finally sorts all calculated combinations and prints only the best formulas, based on price or degree of metamerism.

Data input. The following information has to be fed into the computer:

Reflectance values of standard
Dyes to [illegible]
Textile su[illegible] to be used

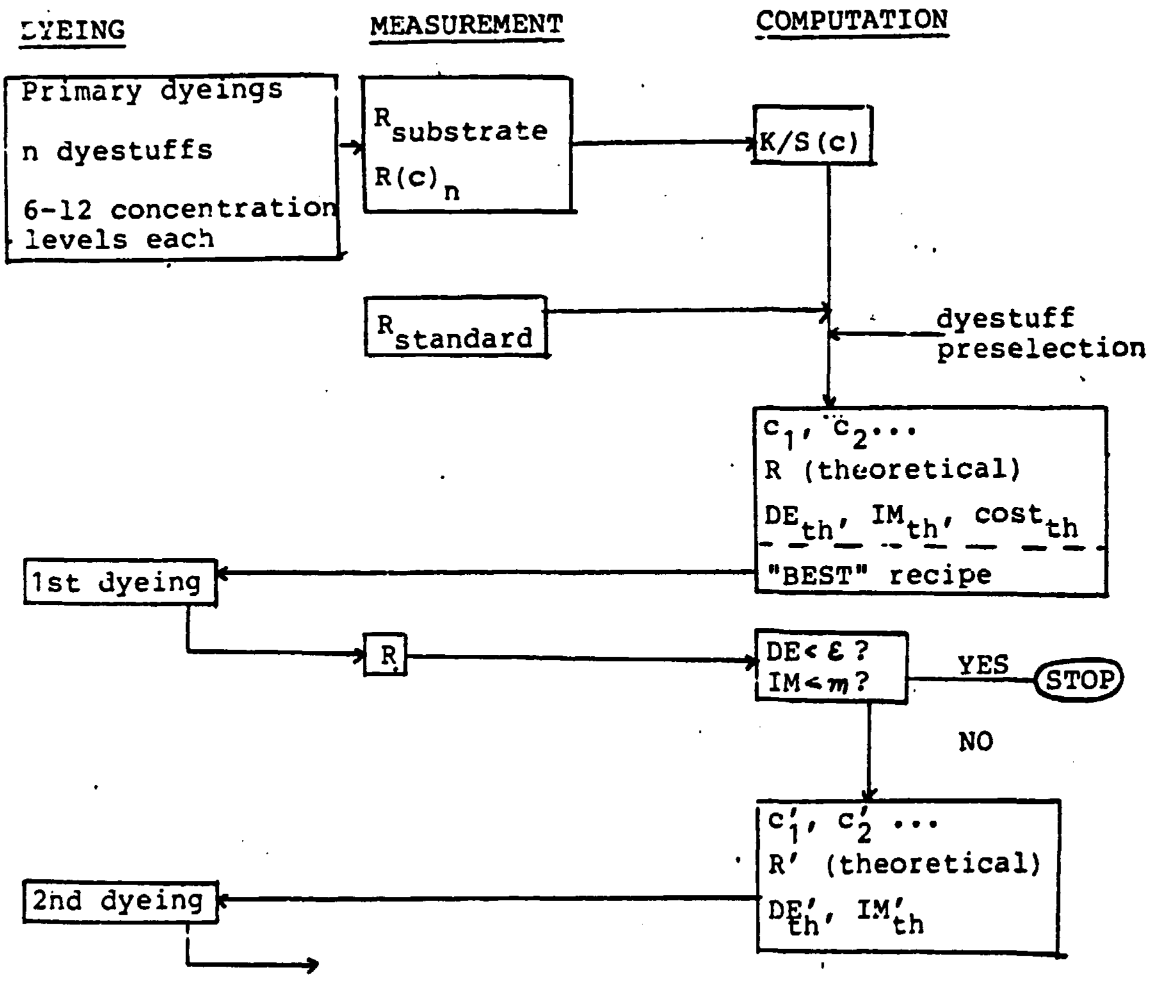
The result o[illegible]ng depends on the substrate in different w[illegible]: on the affinity of the dyestuffs to the f[illegible] (different exhaust and penetration), on the [illegible] scattering properties of the fibres (fine fibres require a larger amount of dyestuff for the same depth than coarse fibres; a velvet requires less dyestuff than a flat fabric), and finally on the absorption of the fibres (their whiteness). Only the last influence can be considered easily in computer dyestuff formulation by using, in addition to the dyestuff data, also the F (R) values of the substrate treated in a blind bath. The other two can only be considered via the primary dyestuff data—in the most favourable case with a factor independent of wavelength and concentration.

The dyestuffs to be used are normally identified by a number. The computer program limits the maximum number of dyestuffs to be considered for the match. If the program takes care of the dyestuff selection automatically, 8–10 dyestuffs or more can be choosen. If the program is not capable of automatic dyestuff selection normally three dyestuffs are used, since the colour space is three dimensional. To reduce metamerism, sometimes a fourth dyestuff is added. If in special cases only one or two dyestuffs are necessary, the computer will print out the other concentrations as zero, but for the calculation three dyestuffs are necessary.

Formula calculation. The calculating sequence in the computer depends, of course, fully on the program in use, which can consider all special requirements. The basic scheme most commonly used is approximately as follows: With an approximative method, the dyestuff concentrations of an initial solution are determined based on the reflectance values, or the tristimulus values of the standard.

This calculating procedure is completely automatic, the user is only interested in the final result. Basically, the calculation can be considered to be an imitation of the visual method with estimation of the formula, dyeing, visual comparison, estimation of correction etc. whereby the dyeing as well as the other steps have been replaced by very rapid computation.

The main stages of computer colorant formulation can be illustrated by the following chart:



Explanation of Computer Printout

In printout the boldface portion indicates operator input. The lines are not normally numbered. This was done for ease of identification.

Line 1. The operator asks the computer to run the match program (MAT I). The computer prints the version number of the program and asks for the user number. The user number, which is supplied by the operator, lets the computer know which set of correction factors to apply to any reflectance data which is inputed to the computer. These factors can represent calibration corrections for more than one spectrophotometer. They can also represent a variety of calibration conditions for the same instrument; i.e., standard reflectance measuring conditions, small area viewing, transmission calibration, etc

Line 2. The operator types in the name of the color to be matched. This is for record keeping purposes only.

Line 3. The operator lets the computer know if the reflectance or transmission measurements of the sample to be matched are coming directly from the spectrophotometer (S), from a file (F) or typed in from the keyboard (K).

Line 4. The operator chooses how many dyes or pigments he would like to see in each formula (3), the total number of colorants to be considered (6) and the identification number (position in a file) of the substrate to be printed (9).

Line 5. This is the name of the file in which the dyes are stored.

Line 6. The six identification numbers (position in the file) of the dyes to be considered for the match.

Line 7. Daylight tolerance (FMCII) limit.

Line 8. Amount of print paste to be made—grams, pounds, etc.

Line 9. The operator has the option to have the computer print out all of the formulas which match within the tolerance (Line 7) or to sort the formulas to the five best (least metameric) and five lowest cost.

Line 10. This line starts the output of the formulas computed. The colorants are identified for each formula. The percentage formula as well as the amount needed to make up 175 units are given. The predicted color difference in daylight (DEC), tungsten (DEA) and fluorescent light (DEF) are given. The cost of the formula is also computed in whatever units desired. In Printout , the best formula was the last one printed. If the operator had chosen to sort the formulas (for least metameric) the last formula would have been printed out first.

Computer Printout (ACS system)

```
1 - R MAT I
    MAT I VER 002-1023
    USER #* 1
2 -> NAME OF TARGET* PE 2246 - RUST
3 -TARGET %R'S* K
    25.019.114.812.311.311.011.713.115.418.326.735.847.062.376.584.4

4 ->-> CLRNT./COMB., FIELD SIZE, & SUB. ID#* 3,6,9
5 -FILE NAME* POLYE
6 -ID"'S OF COLRNT.* 1,2,4,5,6,7

7 ->>> DEC TOL.*1.
8 -BATCH WEIGHT* 175.
9 -SORT OUTPUT / *N

    08-MAY-79
      PE 2246 - RUST              EXTENDER 2018

10- COLORANT                      %        AMOUNT   DEC    DEA    DEF    COST
    1 YELLOW 306               4.2100     7.3674
    4 RED 105                 14.1763    24.8084
    6 GS BLUE 524              5.0970     8.9197
      CLEAR                   76.5158   133.9044    0.4    5.1   13.9   130.33

    1 YELLOW 306               4.8581     8.5017
    4 RED 105                 11.3866    19.9265
    7 RS BLUE 603              3.1409     5.4966
      CLEAR                   80.6144   141.0751    0.1    2.8    5.8    97.88

    1 YELLOW 306               5.2292     9.1511
    5 BS RED 607              19.8615    34.7577
    6 GS BLUE 524              3.2595     5.7042
      CLEAR                   71.6497   125.3870    0.2    2.8   12.1   110.85

    1 YELLOW 306               5.5617     9.7330
    5 BS RED 607              16.8580    29.5014
    7 RS BLUE 606              2.3497     4.1120
      CLEAR                   75.2306   131.6535    0.2    7.3    6.1    91.00

    2 ORANGE 204               7.2196    12.6344
    4 RED 105                 10.9583    19.1770
    6 GS BLUE 524              5.7823    10.1190
      CLEAR                   76.0398   133.0696    0.4    9.5   10.5   113.83

    2 ORANGE 204               7.9059    13,8353
    4 RED 105                  6.9019    12.0783
    7 RS BLUE 603              3.5020     6.1285
      CLEAR                   81.6902   142.9579    0.1    2.3    1.3    70.01

    2 ORANGE 204               7.9211    13.8619
    5 BS RED 607              13.9364    24.3888
    6 GS BLUE 524              4.2562     7.4483
      CLEAR                   73.8863   129.3010    0.3    5.0    7.8    91.34

    2 ORANGE 204               8.2813    14.4922
    5 BS RED 607              11.4544    20.0452
    7 RS BLUE 603              3.0162     5.2783
      CLEAR                   77.2482   135.1843    0.0    0.0    0.0    68.79
```

5./ The measurement of colour

We have seen on p. 47. how spectrophotometers work: they measure the amount of light reflected by a coloured sample compared to that reflected by the perfect diffuser /ideal white/. The X, Y, Z tristimulus values /and from these the L^*, a^*, b^*, C^*_{ab}, H^o_{ab} CIELAB values/ can be calculated for any illuminant and either of the two standard observers by the formulae on p. 55. and the Appendix resp.

There is another way to get the tristimulus values, and that is the use of special instruments called tristimulus colorimeters, or just colorimeters. These should not be confused with the simple instruments used in laboratories for the measurement of the transmission of solutions; although these latter are often /wrongly/ called "colorimeters"; they are, in fact, abridged spectrophotometers or absorpion-meters. The working principle of a tristimulus colorimeter is illustrated in Figure 6o.

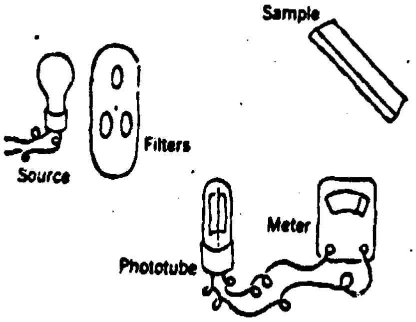
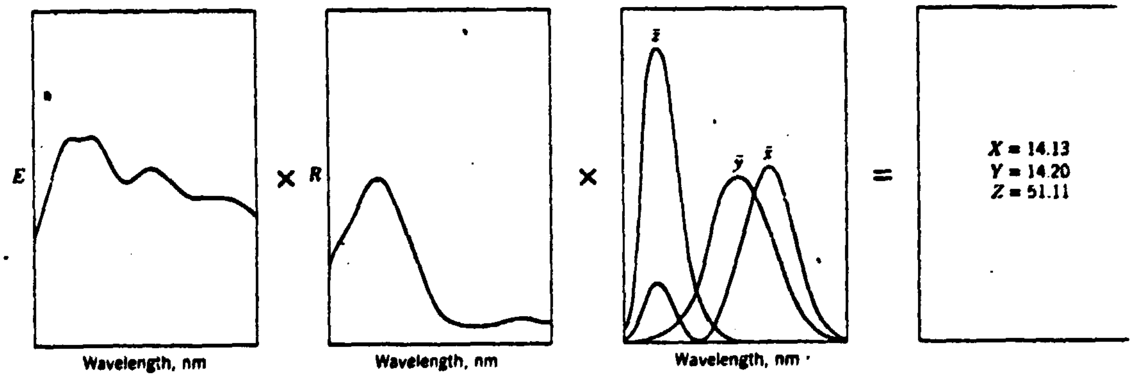


Figure 6o. In a colorimeter, light from a source passes through colored filters onto the sample. The reflectance of the sample is measured as it is illuminated, in turn, by the light passing through each filter.

Source-Detector Response. In Chapter 4.1 we saw that the tristimulus values of a sample, that set of three numbers re- senting its color, can be obtained by combining the samp- ectral reflectance curve with the spectral energy distribu- one of the standard CIE light sources and the response of CIE standard observe. in the form of the tristimulus values of the spectrum colors. If we wish to duplicate this same process in an instrument, we must make provision for adjusting the combined response of the source and detector used to equal that of the combination of one of the CIE standard sources (usually Source C, daylight) and the tristimulus values of the spectrum ,. It is usual for this purpose to use glass filters somewhere in the light beams in the instrument (whether before or after the sample makes little difference except for fluorescent materials, which should be illuminated directly by the source selected). The degree to which the instrument readings approximate the true CIE tristimulus values of samples depends on how well these curves are duplicated.

The curves to be duplicated are shown in the figures on page 68, with the actual response curves of a widely used set of filters (Hunter 1958b). One source of difficulty in duplicating the curves lies in the presence of two peaks in the curve for the *X* tristimulus value. In some instruments (Glasser 1952, 1955) the small *X* peak is taken to be identical in shape to the Z curve, but not as high. This procedure has limited accuracy, however and other instruments use a separate filter to obtain this part of the *X* curve.



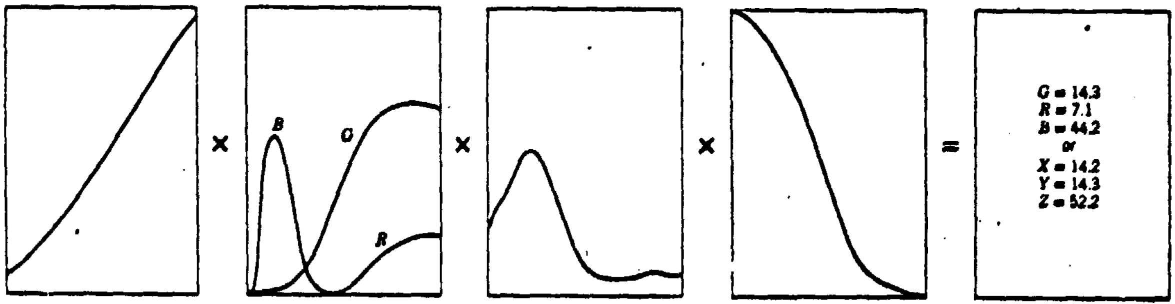
CIE Standard Source

Object

CIE Color-matching functions for the equal-energy spectrum

CIE Tristimulus values

Fig. C1 **A reminder of the way in which the CIE tristimulus values are obtained.**



Source

Filters

Sample

Detector

Colorimeter Readings or Tristimulus Values

Fig. C2.

In *colorimetry*, the tristimulus values or numbers closely related to them are obtained from measurements with the instrument's response (light source times filter times detector) adjusted to that required by the CIE system and sketched in the figure just preceding this one. It is important to note, that it is difficult to do this with absolute accuracy.

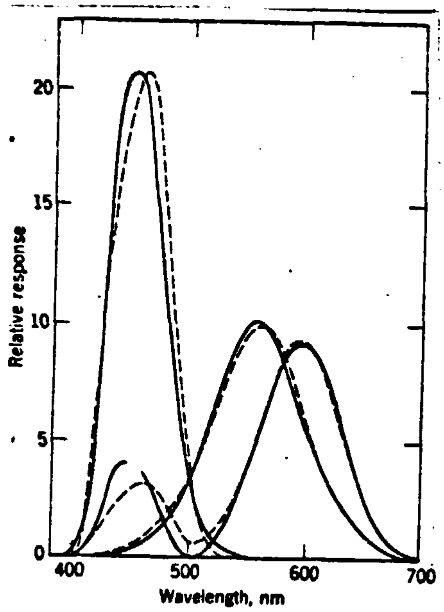


Figure 63.

In this Figure, the solid curves are the CIE color-matching functions $\bar{x}$, $\bar{y}$, and $\bar{z}$. The dashed curves show the extent to which they can be duplicated in colorimeters

One problem associated with tristimulus colorimeters is their limited accuracy, as shown in Figure 63. The other main disadvantage - as compared to the spectrophotometer - is the fact, that any one set of /3 or 4/ filters enables the measurement of the tristimulus values for one illuminant and one observer only. There are some - very few - tristimulus instruments with more than one set of filters, but it is rather complicated to work with these. The spectrophotometer as we have seen, measures the reflectance curve of the sample, and from the data of one measurement tristimulus values for any illuminant and observer can be computed.

Trends in colour instrumentation for the industry

Colour measurement, as we now know it, had its beginning in the late 1920's, when Professor Hardy of M.I.T. designed his classical instrument, later to be known as the General Electric Hardy spectrophotometer.

The original model, the "stovepipe" /Fig. 64/ was later replaced by the "new model" G.E. /Hardy/ Recording Spectrophotometer /Fig.65/ ', that has for decades been considered the referee instrument in colour measurement.

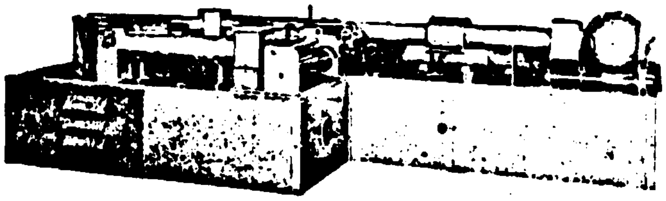


Figure 64.

The original model /the "stovepipe"/ General Electric spectrophotometer

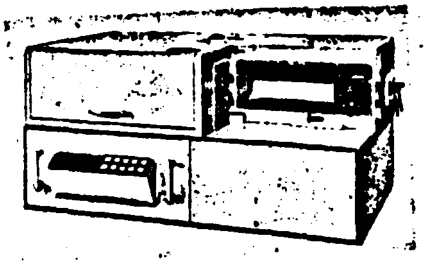
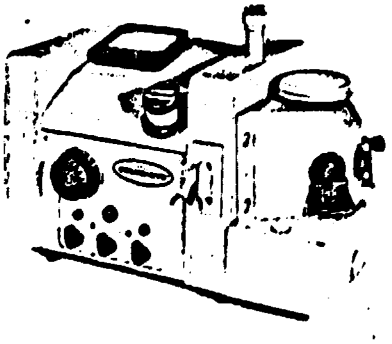


Figure 65.

The new model GE recording spectrophotometer

The first tristimulus colorimeters were introduced in the 1940's, thone of the most famous models was the IDL Color-Eye /Figure 66./

Figure 66.



The IDL Model D-1 Color-Eye.

In spite of 35 years of development however, Professor Billmeyer, a well known authoritiy in colour instrumentation wrote the following in a publication of his in 1965:

> "It is clear, that even under the best conditions, the precision and accuracy of industrial color measurement is currently barely adequate to meet the demands placed on it."

What exactly was wrong with colour measurement in the 1960's?

PROBLEMS 1960	SPECTROPHOTOMETER	COLORIMETER
MEASUREMENT	SLOW /1-2 min/	SLOW /1-2 min/
CALCULATION of DE	MANUAL	MANUAL
CALIBRATION	MANUAL	MANUAL
PRECISION and ACCURACY	BARELY ADEQUATE	BARELY ADEQUATE
DETECTION of METAMERISM	YES	NO
PRICE	HIGH /c. $ 20.000/	LOW /c. $ 2.000/

The 1970's are considered the age of the computer. Well, the digital revolution hit the colour measuring instruments as well, and ten years ago the first computer driven, fully automatic spectrophotometer, the KCS 40 /Fig. 67/ was put on the market by the Kollmorgen Corp. A long line of similarly built instruments followed, each using 16-33 separate interference filters instead of a prism or a grating monochromator. The most recent examples of this type of abridged spectrophotometers are the FS-4 of Pretema /Fig. 68/ and the RFC 16 of OPTON These instruments are much faster, than the older types of instrument, the typical measuring time beeing around 45-60 seconds for the older models, and around 20 seconds for the FS-4 or RFC 16.

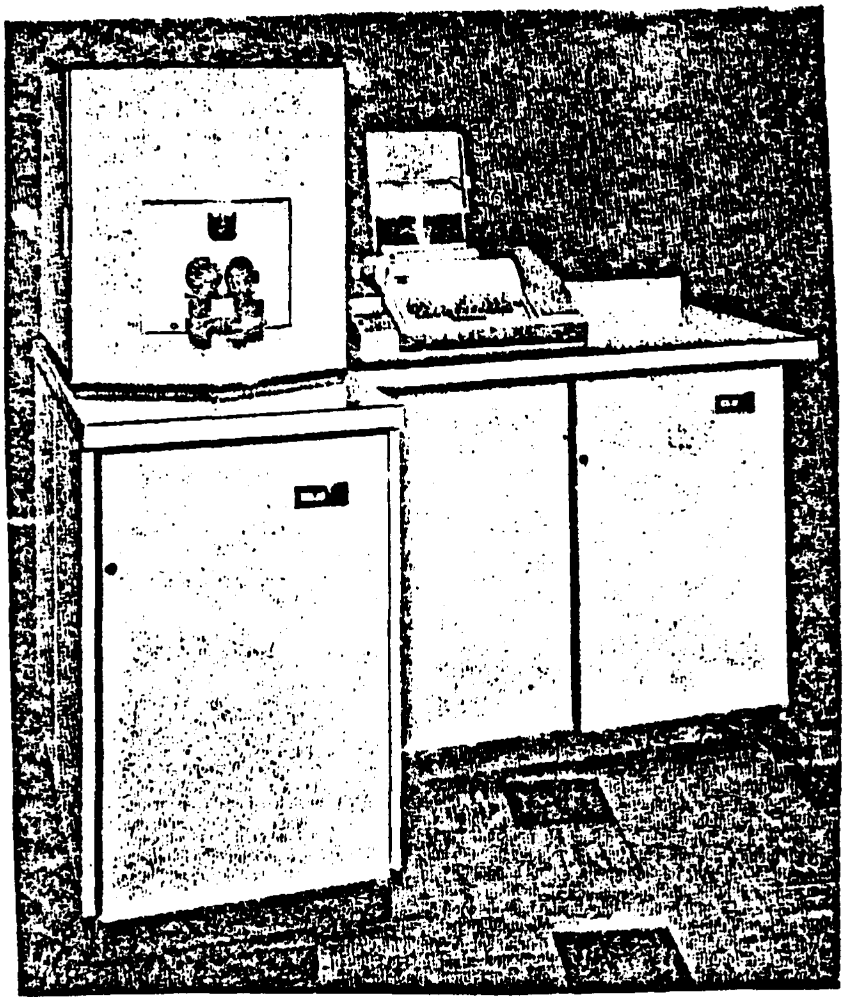


Figure 67.
The first fully automatic, computer-controlled spectrophotometer, the KCS 4o by Kollmorgen

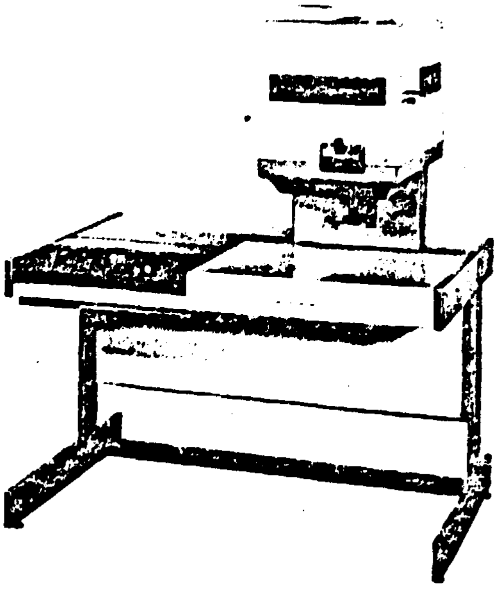


Figure 68.
The latest model of the Pretema 35-filter spectrophotometer - the FS-4

In the early 197o's yet another novelty appeared on the market, the DATACOLOR 71oo spectrophotometer. The most interesting feature of this instrument can be seen in Figure 69: this was the first spectrophotometer to use a continuous interference filter wedge instead of separate filters.

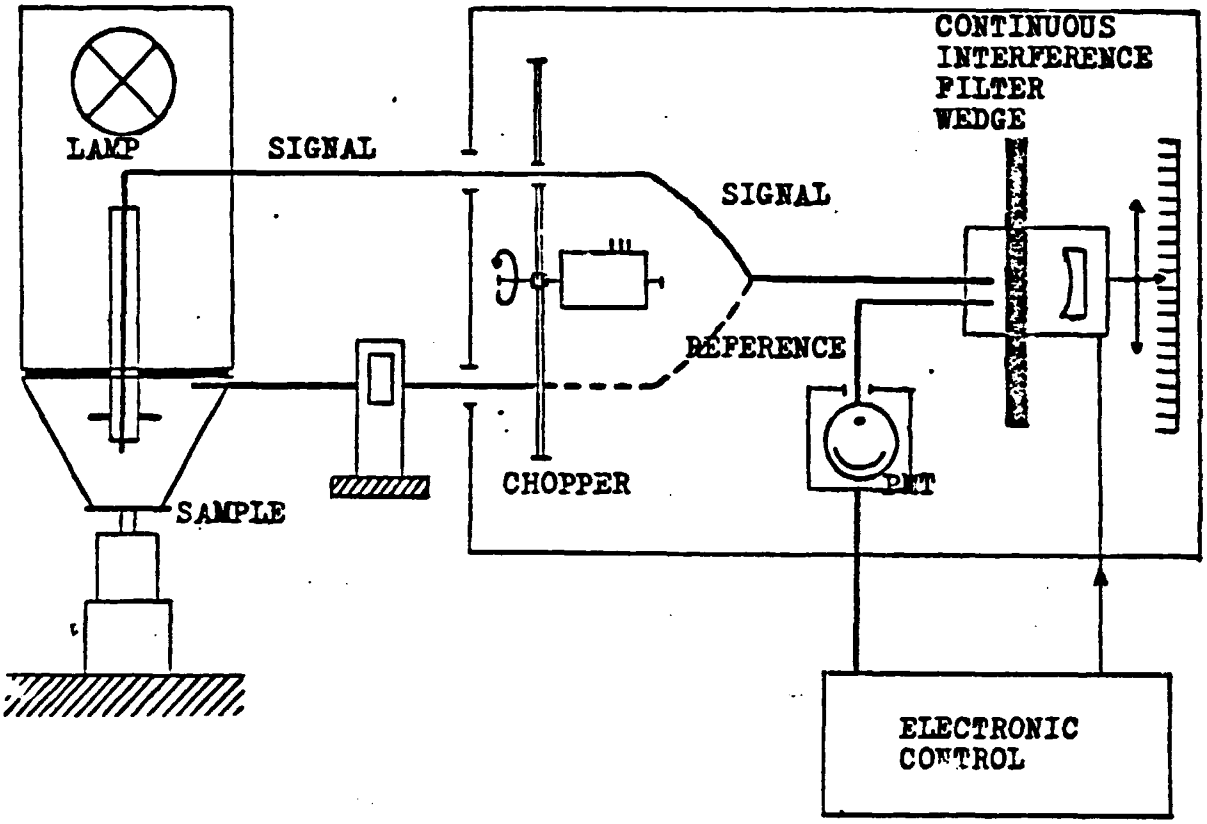


Figure 69. Block diagram of the DATACOLOR spectrophotometer

The advantages over the conventional abridged /separate filter/ spectrophotometer are obvious: faster measurement on the one hand, and the possibility of reading spectral data every 1o or even every 5 nm if required. The scanning time for 16 points is 17 sec.

In 1977 several new instruments working by similar principles have been marketed. HunterLab developed their first spectrophotometer /prior to that time they had manufactured only tristimulus colorimeters/, the D54P-5 /Figure 7o/.

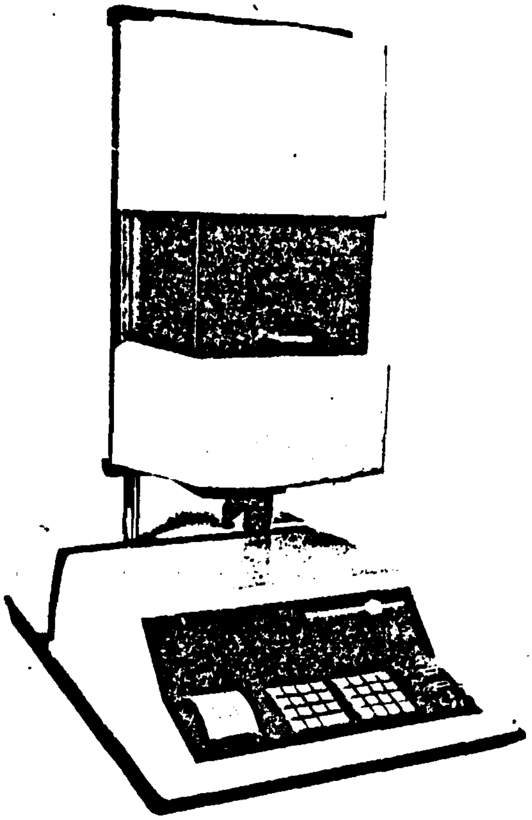


Figure 7o.

The HunterLab D54P-5 spectrophotometer with the sensor mounted over the data processor unit

This instrument uses a rotating continuous filter, the measuring time is 7 sec. The same optical head is used in a more elaborate computer set-up by Applied Color Systems in their SpectroSensor, used in the computer match prediction system in MISR Mehalla . Similar rotating filter is used in the Color Analyser of IBM, who were the first to develop a spectrophotometer with o/45° illuminating/viewing geometry. DATACOLOR have also improved their instrument, the 3o8o is similar to the original design, but it is smaller, cheaper and faster /scanning time c. 6 sec./

The most innovative instrument of the new generation is perhaps the MS 2ooo of Kollmorgen which is marketed in Europe under the name Micromatch by Instrumental Colour Systems of GB /Fig. 71 /, with their own software.

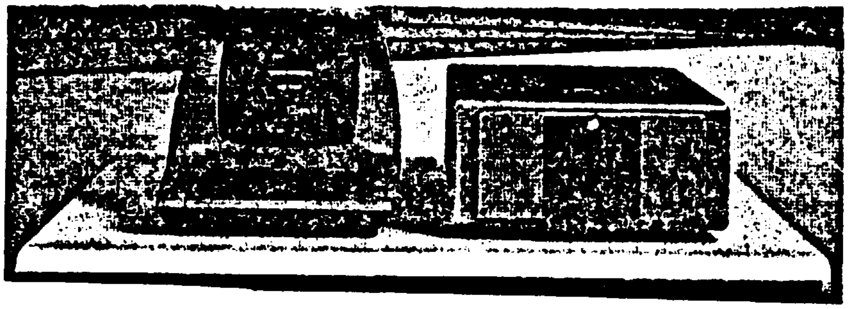


Figure 71. The Micromatch spectrophotometer of ICS

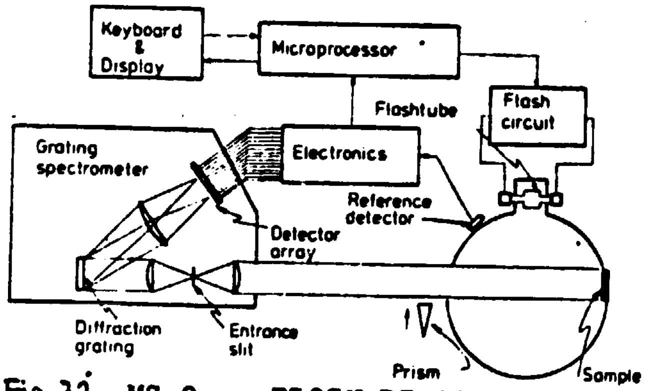


Fig. 72 MS 2ooo BLOCK DIAGRAM

The block diagram /Fig. 72 /shows the optical arrangement. The sample is illuminated by polychromatic light, and the reflected ligth is dispersed by a grating monochromator. There is an arrey of 17 silicone diodes for the simultaneous detection of 17 separate signals - each from a narrow spectral band. The simulaneous detection makes it possible to use a pulsed Xenon lamp -a flash - as the light source. There is also a cheaper version of this instrument with the same optics, but simplified electronics, it is sold as a "spectral tristimulus instrument", the MC lolo.

There is one member of the new generation, which is built along the classical lines.

The DIANO MatchScan is a true spectrophotometer ./Fig. 73/ with dual beam reversible optics, a grating monochromator driven by a step motor, with full electronic control. The scanning time is below lo sec for 16 points, and below 12 sec for 32 points.

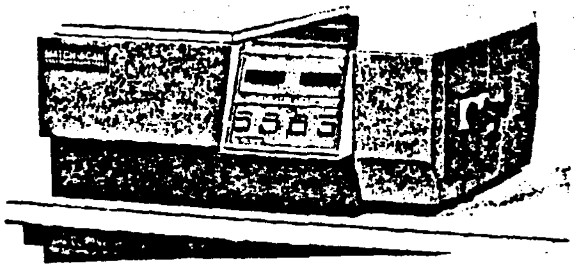


Figure 73. DIANO MatchScan

The traditional tristimulus instruments were first equipped with some calculating facilities, than also controlled, calibrated and driven by microprocessors or desk-top calculators.

There are also special signal processors for colour calculations, such as the D25-9 used by HunterLab in their systems :

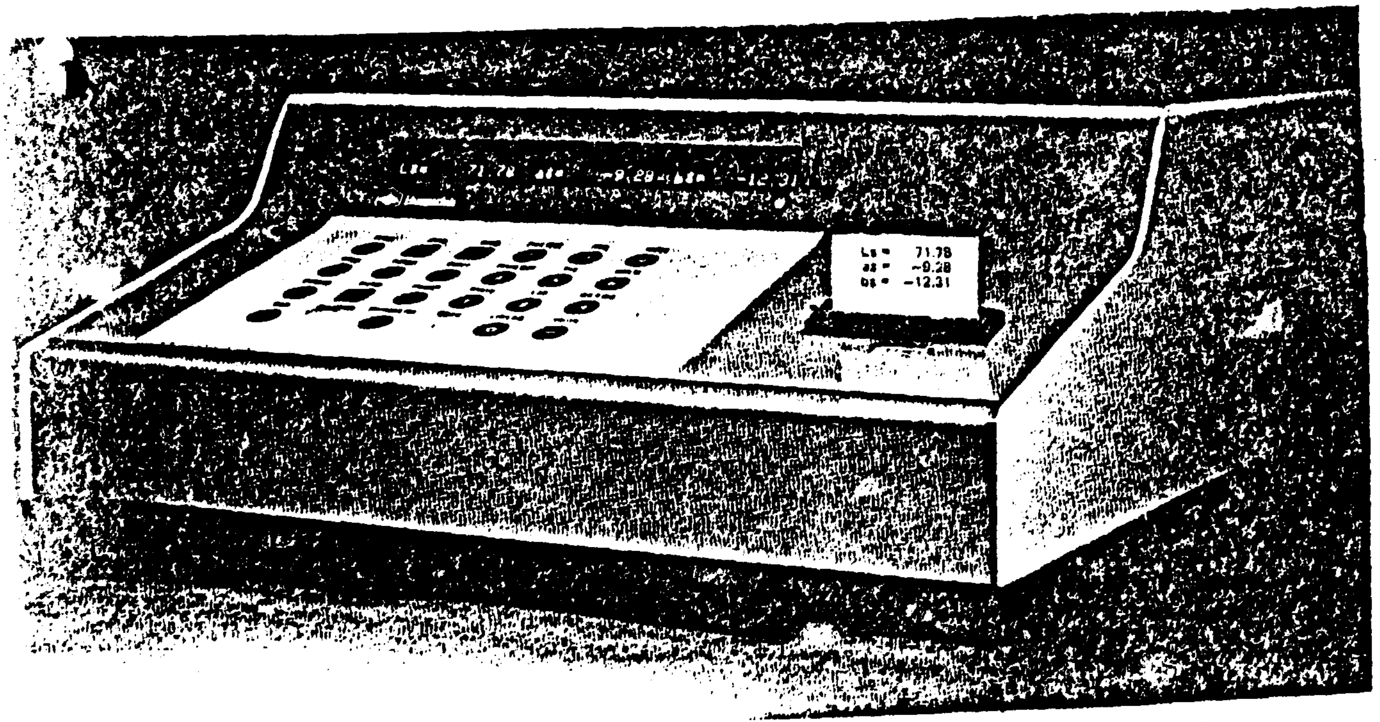


Figure 74. Signal processor for HunterLab colorimeters

Well, did the instrument manufacturers succeed in solving the problems of the 60's?

SOLUTIONS 1980	SPECTROPHOTOMETER	COLORIMETER
MEASUREMENT	FAST /4-10 sec/	FAST /6-12 sec/
CALCULATION of DE	AUTOMATIC	AUTOMATIC
CALIBRATION	AUTOMATIC	AUTOMATIC
PRECISION and ACCURACY	EXCELLENT	EXCELLENT FAIR
DETECTION of METAMERISM	YES	YES?
PRICE	MEDIUM /$ 15.000 - 20.000/	MEDIUM /$ 10.000 - 15.000/

Yes, indeed, as it can be seen in the table above, the speed of the measurement makes it possible to measure the more problematic samples several times, whereas by electronic control, automatic calibration and improved components of the hardware fully satisfactory accuracy and precision is achieved. Interestingly, the price of the spectrophotometer went down, while that of the tristimulus instruments increased, and it seems that the latter will eventually be replaced by that new generation of instruments, the fast, accurate, electronically controlled, fully automatic spectrophotometer.

Last year at a colour measurement symposium in Charlotte, N.C. Max Saltzman another leading expert remarked:

"We have instruments that are far better than the samples we prepare for measurements"

Selecting surface-colour measuring instruments and monitoring their performance

As a result of the widespread and increasing use of colour-measuring instruments in recent years it has been considered by the Colour Measurement Committee that some guidance to members either using or contemplating the purchase of such equipment is desirable. Given below, therefore, is an outline of the principles to be followed in the evaluation of prospective colour-measuring instruments, and a summary of the factors which should be considered in relation to monitoring the performance of such instruments once purchased.

Instruments for measuring surface colour are broadly divided into three main types:

(a) reflectance spectrophotometers which employ prisms or gratings to disperse the incident or reflected light into its spectral components.

(b) abridged spectrophotometers which employ narrow-band filters or filter wedges to disperse the incident or reflected light into its spectral components.

(c) tristimulus colorimeters which employ filters coupled to light detecting devices and mechanical and/or electrical circuitry to produce directly the tristimulus values X, Y, Z of the CIE system or some other numerical specification such as CIELAB L^*, a^*, b^* colour co-ordinates.

The absolute accuracy of the spectrophotometer and abridged spectrophotometer is usually higher than that of the tristimulus colorimeter. On the other hand, for colour-difference work, the tristimulus colorimeter is often adequate, being cheaper, usually quicker and simpler to operate and control, and having good repeatability.

The choice of spectrophotometer or colorimeter is dictated by the use for which the instrument is intended. The disappointments in the performance achieved in colour measurement are frequently due to failure to evaluate requirements fully and to ensure that these can be achieved by the chosen measuring instruments. To obtain the required absorption coefficients for computer match prediction, and to deal with metamerism, reflectance measurements at a minimum of 16 wavelengths are required. This requires a spectrophotometer or abridged spectrophotometer. However, if the main requirement is shade passing and sorting of non-metameric patterns, then the simplicity of the tristimulus colorimeter becomes attractive.

The main requirements of a good colour-measuring instrument are:

(a) High absolute accuracy.

(b) Good repeatability.

(c) Good between-instrument reproducibility.

(d) Ease of operation.

Also of importance, but not always catered for even in modern instruments, is capability of measuring fluorescent samples correctly. Instruments which irradiate the specimen with polychromatic light should be checked to ensure that heating up of the specimen during measurement does not cause changes in its reflectance. Finally, the prospective purchaser should ensure that, if small specimens have to be measured, the instrument can be fitted with an aperture which is small enough yet still retains adequate accuracy and repeatability; some check should also be made concerning the availability of after-sales service.

The following tests can be used as the basis for selection and monitoring of colour measuring instruments:

ABSOLUTE ACCURACY

Absolute accuracy is best ascertained by measuring the standard ceramic tiles produced for instrumental calibration by the British Ceramic Research Association [1–8]. The calibration sets consist of a series of 12 tiles, 10 cm X 10 cm, which have been specially selected and match within certain published tolerances the colour co-ordinates of an original master set measured at the National Physical Laboratory. The colours are:

Light Grey
Medium Grey
Dark Grey
Maroon
Pink
Brown
Yellow
Light Green
Dark Green
Green Blue
Medium Blue
Dark Blue

The sets of tiles are obtainable in two forms: (a) uncalibrated, but supplied with colorimetric data relating to the NPL master measurements; (b) standard, specially calibrated at NPL. The calibrated sets are intended for use in those areas of work where the highest degree of accuracy is required.

To determine the order of the absolute accuracy of the instrument under test, it is recommended that an NPL calibrated set of ceramic tiles be measured in series at least five times, removing the tiles between each measurement, and the resulting colour co-ordinates averaged. The difference between the averaged colour co-ordinates and the NPL master values can then be determined, either in terms of ΔX, ΔY, ΔZ, or preferably in the more visually meaningful CIELAB terms ΔL^*, Δa^*, Δb^*, ΔE.

For between-instrument comparisons, the use of an uncalibrated set of ceramic tiles is considered adequate. The BCRA indicate that even with the most variable tile, 95% are expected to be within 1.2 CIELAB units of the master tile. Such tests for comparing instruments for absolute accuracy are especially valuable when a colour-measuring instrument is being assessed as a possible replacement for, or supplement to an existing instrument.

The detection of systematic deviations between the values obtained with a particular instrument and the target values measured on the organization's master instrument is easier if the tristimulus or L^*, a^*, b^* values from the test instrument are plotted against the master instrument values. Linear paper should be used for L^*, a^*, b^* plots, but if tristimulus values are being plotted small instrumental deviations have a proportionally greater effect on low values and this is illustrated better if the plot is done on log-log paper. Such plots sometimes reveal faults in the zero or 100% setting of the instrument, or interfering effects such as stray light, specular component treatment etc.

MEASUREMENT OF MATERIALS OF SPECIFIC INTEREST TO THE USER

While the ceramic tiles provide an excellent set of standards for comparing instruments, and for daily calibration checks, they may not expose measurement problems which may be encountered when materials with different surface textures, such as textiles, are being handled. For this reason, in the evaluation of an instrument it is necessary for samples of the type likely to be measured on the instrument to be assessed in a similar way to that described above for the ceramic tiles. Examples covering the range of surface textures likely to be encountered in practice should be selected.

The method suggested is to take at least 10 pairs of samples, distributed evenly over the colour gamut, and measure these pairs at least five times, removing the samples from the instrument after each measurement. From these measurements, the repeatability of measurement of single samples and of measurement of colour differences on the materials in which the user is interested can be determined. Repeatability of measurement of single samples can be expressed in relation to the averaged CIELAB L^*, a^*, b^* values of the sample, as mean values of ΔL^*, Δa^*, Δb^*, ΔE.

The effect of sample orientation on colour measurement can easily be determined by measuring the colour co-ordinates of the samples of the different types of surfaces likely to be encountered at different orientations, increasing in steps of 45 degrees until a full circle has been completed. To simulate the effect of slight positioning errors, the effect on measurement of 5 degree variation in sample presentation should also be determined. The orientation effects can be expressed in terms of ΔL^*, Δa^*, Δb^*, ΔE with respect to the zero degree position.

In the case of measuring instruments with integrating spheres, measurement with and without the specular (gloss) component included can be carried out at several sample orientations to evaluate the effectiveness of the device for excluding the specular component.

FLUORESCENT SAMPLES

Where it is required to measure accurately the colour of fluorescent samples, such as certain textile substrates and dyes, care should be taken that the instrument under evaluation can adequately deal with these samples. This means that the specimen must be irradiated with a source resembling Ill.D65 as closely as possible, both in the visible and u.v. regions, since, unlike the reflectance factors in the case of non-fluorescent specimens, the spectral radiance factors are dependent on the source used.

It is also important that fluorescent samples should be illuminated directly with white light so that the fluorescence can be correctly stimulated.

PRESENTATION OF DATA

In evaluating a colour-measuring instrument, consideration should also be given to the form in which the measurement data are presented. It is desirable that some form of computing device be fitted to spectrophotometers to convert the reflectance measurements into visually-meangingful terms if required, e.g. into *XYZ* values or into CIELAB colour co-ordinates. Modern spectrophotometers usually have such equipment incorporated for automatic machine calibration and drift control purpose.

In the case of tristimulus colorimeters, consideration should be given to the type of data required for rapid and meaningful interpretation of colour-difference attributes, e.g. ΔL^*, Δa^*, Δb^*; ΔLightness, ΔMetric Chroma, ΔHue; ΔHue, ΔBrightness, ΔStrength, etc.

DAILY CALIBRATION AND SETTING-UP PROCEDURES

For day-to-day calibration of colour-measuring instruments it is normally sufficient to set up the instrument to a standard white tile and black tile, (alternatively a light trap in the form of a black velvet-lined box is often used in place of a black tile). In some of the more sophisticated instruments with computer calibration systems, these measurements are used to compensate for instrument drift. After calibration, the black and white tiles should be measured repeatedly until the expected consistency of readings is obtained, indicating that the instrument is adequately warmed up and stable.

To guard against the effects of short-term instrument drift during colour-difference measurement of several samples against one standard, the standard should be remeasured at intervals throughout the run.

SHORT-TERM REPEATABILITY

The BCRA ceramic tiles can be used to assess short-term stability of colour-measuring instruments. It is necessary to know this in order to determine how often instrument calibration procedures must be carried out. Repeat measurements of the tiles are made at short intervals during the period of interest. The differences between each of the individual measurements and the average of these measurements should be calculated and the average difference expressed in CIELAB terms ΔL^*, Δa^*, Δb^*, ΔE. The time between the repeat measurements can be varied, depending on whether the test is designed to check short-term or medium-term repeatability.

LONG-TERM REPEATABILITY

The BCRA tiles are invaluable for determining the long-term stability of colour-measuring instruments. Regular measurement of a set of ceramic tiles is essential and will enable virtually all instrument faults to be detected. However, careful inspection of the results is required. Slight, but significant changes in the measurements made with an instrument may enable a developing fault to be detected at an early stage.

One of the simplest methods of plotting data in order to check for significant changes is to plot the *XYZ* or CIELAB $L^*a^*b^*$ values of each tile *versus* time on a Cu-Sam chart [9,10]. In this form of chart the difference between the current measured value and the first measured value is added to the value of the previously plotted point, and the resulting value plotted. When good repeatability is being achieved the result is a line showing a constant slope. Any significant change in instrument performance is indicated by a change in slope of the plot. The technique makes it easier to detect significant changes in performance which might otherwise be obscured by the normal insignificant and acceptable random variation which occurs in day-to-day measurement.

General References

11. Coates, Day, Durrans, Rigg, ibid., 87 (1971) 379.
12. Coates, Provost, Rigg, Ibid., 88 (1972) 151.
13. Alder, ibid., 95 (1979) 61.
14. Jaeckel, ibid., 92 (1976) 353.
15. Johnston, J. Col. & App, 1, No. 2 (Sept 1971) 27.
16. Billmeyer, Cambell, Marcus, Applied Optics, 13 (1974) 1510.
17. Billmeyer, Marcus, Ibid., 13 (1974) 1519.
18. Billmeyer, ibid., 8 (1969) 775.
19. Marcus, Col. Res. & Appn, 3 (1978) 29.

6. References

Billmeyer, F.W. - Saltzman, M: Principles of Colour Technology , John Wiley & Sons., 1966.

Cooper, A.C. - Mclaren, K: The ANLAB Colour System and the Dyer's Variables of 'Shade' and Strength. J. Soc. Dyers and Colourists 89, 41 (1973).

Derbyshire, A.N. - Marshall, V.1: Value Analysis of Dyes - A New Method Based on Colour Measurement . J. Soc. Dyers and Colourists 96, 166 (1980).

Summer, H.H.: Random Errors in Dyeing - The Relative Importance of Dyehouse Variables in the Reproduction of Dyeings. J. Soc. Dyers and Colourists 92, 84 (1976).

Roberts, J.G. - Corless, M.G. - Walton, P.F.: Causes of colour differences in dyed textiles. Paper presented at the 1973 Annual Conference of the Textile Institute.

Rieker, J. - Troska, D: How can shade change during finishing be controlled in the Dyehouse and in the laboratory ? Melliand Textilberichte 58, 1023 (1977).

Rieter, J. - Rohner, E. - Troska, D.: How many mistakes are made in the final dyeing correction by visual colour matching?. Melliand Textilberichte 57, 994 (1976)

Berger, A. - Brockes, A.: Colour Measurement in the Textile Industry. Bayer Farben Revue Special Edition No. 3/1 (1971).

Recommended reading:

F. W. Billmeyer and M. Saltzman: The Principles of Color Technology. Second edition
A Wiley - Interscience publication, John Wiley and Sons Ltd., New York, Chichester, Brisbane, Toronto. 1981.
£ 20 (UK) or $ 39.95 (USA).

This is a very highly recommended book, covering all major aspects of colour science in a clear, simple manner. It gives the best introduction to the subject, with a bibliography of all important American and European text-books, and papers on a wide range of subject.

D. B. Judd and G. Wyszecki: Color in Business, Science and Industry.
John Wiley and Sons, New York/London, 1975.
Price: approx. $40.00 (USA).

This is an advanced treatment of colour science, with much more mathematical detail than "Principles" by Billmeyer and Saltzman. It is, however, the other most important textbook, for those who wish to get deeper insight into theory it is a must.

R. G. Kuehni: Computer Colorant Formulation Lexington Books, D. C. Heath & Co., Lexington, Mass./Toronto/London, 1975.
Price: Approx $ 20.00 (USA).

This rather brief book (120 p.p.) is the only one published so far on this very important topic. It is mixture of theory and practice, the author couldn't really make up his mind about the readership he wrote if for. Still, for those involved in computer colour matching it is useful.

APPENDIX

Formulae for calculating CIELAB coordinates from tristimulus values X, Y, Z

Designations

L^{*} : psychometric lightness

a^{*} : red-green axis

b^{*} : yellow-blue axis

C^{*}_{ab} : psychometric chroma

H^{o}_{ab} : " hue angle

DL^{*}, DC^{*}_{ab}, DH^{*}_{ab} : differences in respective quantities

DE^{*}_{ab}: total colour difference in CIELAB units

X, Y, Z : CIE tristimulus values

X_o, Y_o, Z_o : CIE tristimulus values for absolute white, for the 1931 CIE 2° Standard Observer and Illuminant C the respective values are $X_o = 98.041$; $Y_o = 100.000$; $Z_o = 118.103$

Formulae

$$L^{*} = 116(Y/Y_o)^{1/3} - 16 \quad \text{if} \quad Y/Y_o > 0.008856$$

$$= 903.29\ Y/Y_o \quad \text{if} \quad Y/Y_o \leq 0.008856$$

$$a^{*} = 500\left[(X/X_o)^{1/3} - (Y/Y_o)^{1/3}\right] \quad \text{if} \quad X/X_o > 0.008856$$

$$= 3893.5\ (X/X_o - Y/Y_o) \quad \text{if} \quad X/X_o \leq 0.008856$$

$$b^{*} = 200\left[(Y/Y_o)^{1/3} - (Z/Z_o)^{1/3}\right] \quad \text{if} \quad Z/Z_o > 0.008856$$

$$= 1557.4\ (Y/Y_o - Z/Z_o) \quad \text{if} \quad Z/Z_0 \leq 0.008856$$

$$C^{*}_{ab} = \left[(a^{*})^{2} + (b^{*})^{2}\right]^{1/2}$$

$$H^{o}_{ab} = \text{arc tan}\,(b^{*}/a^{*})$$

$$DL^{*} = L^{*}_{1} - L^{*}_{2}$$

$$DC^{*}_{ab} = C^{*}_{ab,1} - C^{*}_{ab,2}$$

$$DH^{*}_{ab} = \left[DE^{*2}_{ab} - DL^{*2} - DC^{*2}_{ab}\right]^{1/2}$$

$$DE^{*}_{ab} = \left[DL^{*2} + Da^{*2} + Db^{*2}\right]^{1/2} = \left[DL^{*2} + DC^{*2}_{ab} + DH^{*2}_{ab}\right]^{1/2}$$

ANNEX 5.2

TEXTILE CONSOLIDATION FUND
TEXTILE DEVELOPMENT CENTRE
UNIDO PROJECT DP/EGY/77/008

Seminar

A Brief Survey of Colour Measurement in the Textile Industry

By

Dr. Robert Hirschler
UNIDO Expert in Colour Measurement

2nd December 1981

at

MISR Spinning & Weaving
Mehalla El Kubra.

Colour is part of our daily life. Man has always been fascinated by and attracted to colour, and the wish to measure - to put numbers on - colour is as old as scientific thinking itself.

Many of the objects we think of as sources of light emit light which is white or nearly white - the sun, hot metals like the filaments of light bulbs, and fluorescent lamps, among others. Sir Isaac Newton was the first to show many-many years ago by using a prism to disperse light into a spectrum, that white light is made up of all the visible wavelengths.

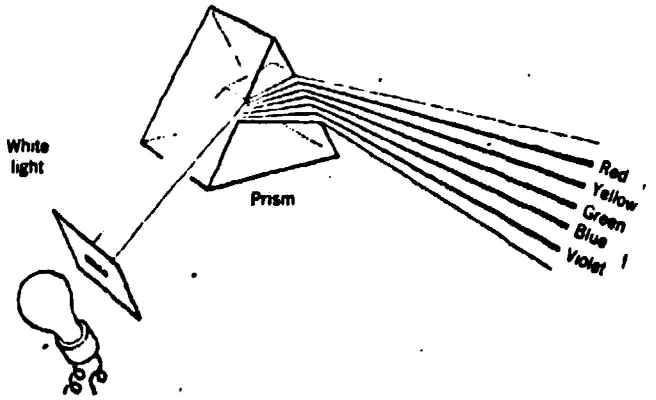


Figure 1 Dispersing white light into a spectrum

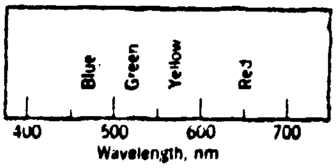
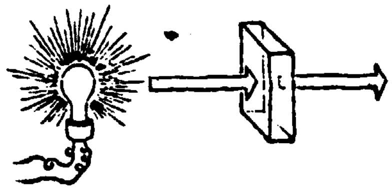


Figure 2 Hue names of the spectrum colours.

How Materials Modify Light

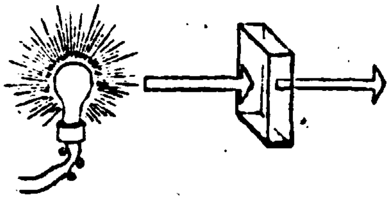
When light strikes an object, one or more things pertinent to color can happen:

1. Transmission. The light can go through essentially unchanged. It is said to be *transmitted* through the material, which is described as *transparent.* If the material is colorless, all the light is transmitted except for a small amount which is reflected from the two surfaces of the object.



The transmission of light through a transparent object.

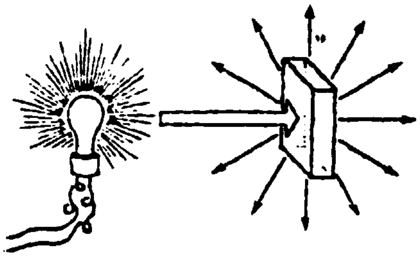
2. Absorption. In addition to being transmitted, light may be *absorbed,* or lost as visible light. (If a very large amount of light is absorbed, we can sense that at least part of it is converted into heat.) If the material absorbs part of the light, it appears colored but is still transparent; if all the light is absorbed, the material is black and is said to be *opaque.*



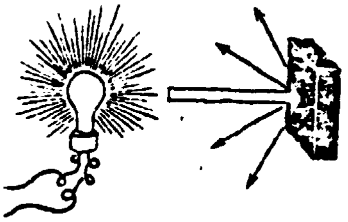
The absorption of light by a transparent, colored object.

3. Scattering. Finally, light may be *scattered* when it passes through matter. It may be reflected, partly in one direction and partly in another, until ultimately some light travels in many different directions. The effects of light scattering are both common and important, accounting for the blue color of the sky and the white colors of clouds, smokes, and most white pigments.

If only part of the light passing through a material is scattered, and part is transmitted, the material is said to be *translucent;* if the scattering is so intense that no light passes through the material (some absorption must be present, too), it is said to be *opaque.* The color of the material depends on the amount and kind of absorption present: If there is no absorption, a scattering material looks white; otherwise, colored.



The scattering of light by a turbid or translucent material. In such a material, some light is transmitted and some is reflected by scattering.



In an opaque material, no light is transmitted, but some is reflected by scattering.

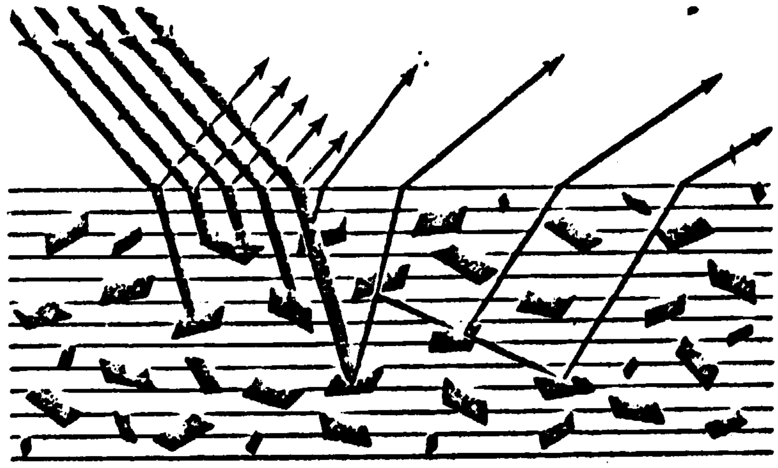


Figure 3 The absorption, scattering, and reflection of light in a layer of pigment

The spectral characteristics of materials

The amount of absorption due to the coloured material can be calculated from the amount reflected or transmitted by the object. The spectral reflectance shows the fraction of the light at each wavelength reflected from the material. Reflectance curves characteristic of different colours are shown in Figure 4, while the principles of measuring reflectance by a spectrophotometer are illustrated in Figure 5.

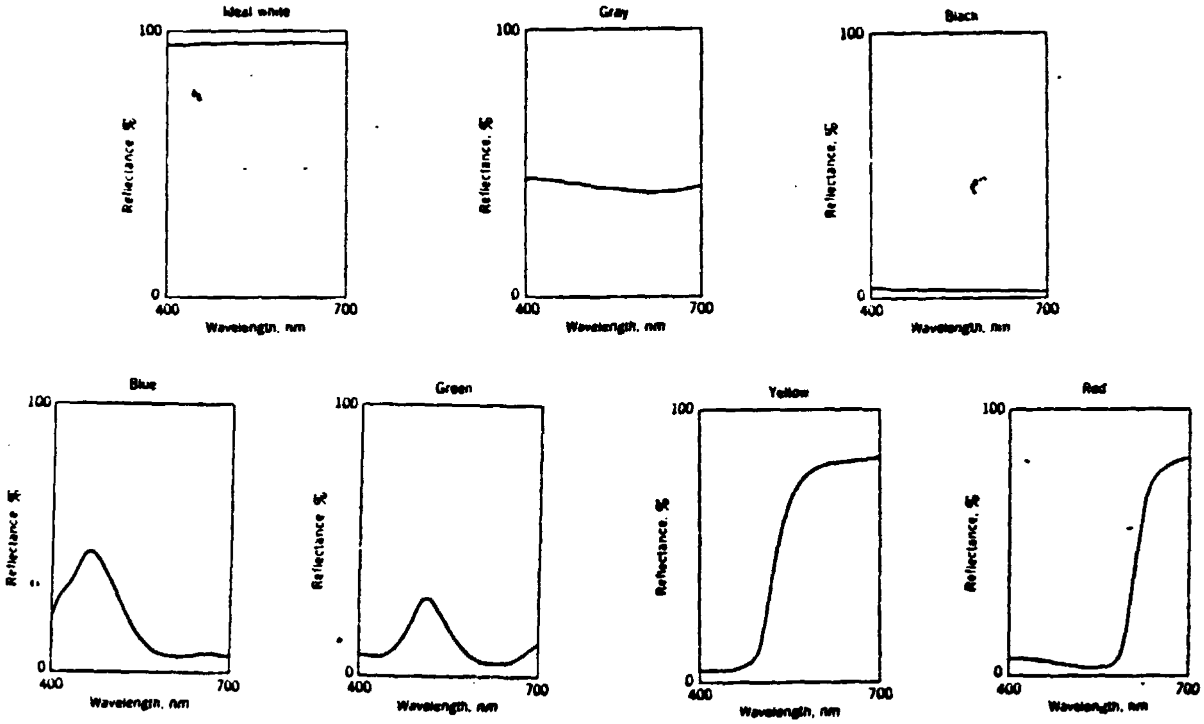


Figure 4   Characteristic reflectance curves of achromatic (neutral) and chromatic colours

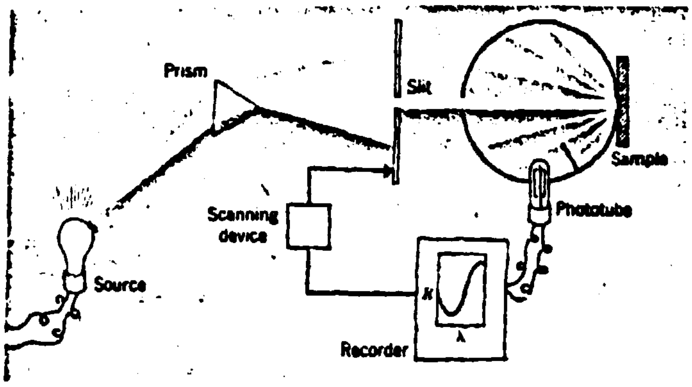


Figure 5

In a spectrophotometer, light is dispersed into a spectrum, made approximately monochromatic by means of a slit, and used to illuminate the sample (in this sketch, using integrating-sphere geometry). The reflectance of the sample is plotted against the wavelength of the light to give the sample's *spectrophotometric* (or spectral reflectance) curve.

The specification of colour

The spectral reflectance curve describes exactly the physical stimulus reaching our eyes, but doesn't give us indication on the colour sensation itself. Colour - as we see it - can be specified by three numbers. In the most widely used colour order system - the MUNSELL system - these numbers are called Munsell Hue, Munsell Value and Munsell Chroma. The meaning of these terms as well as the structure of the Munsell system is given in Figure 5 below.

Hue:	that quality of color which we describe by the words red, yellow, green, blue, etc.
Value:	that quality of color which we describe by the words light, dark, etc., relating the color to a gray of similar lightness.
Chroma:	that quality which describes the extent to which a color differs from a gray of the same value.

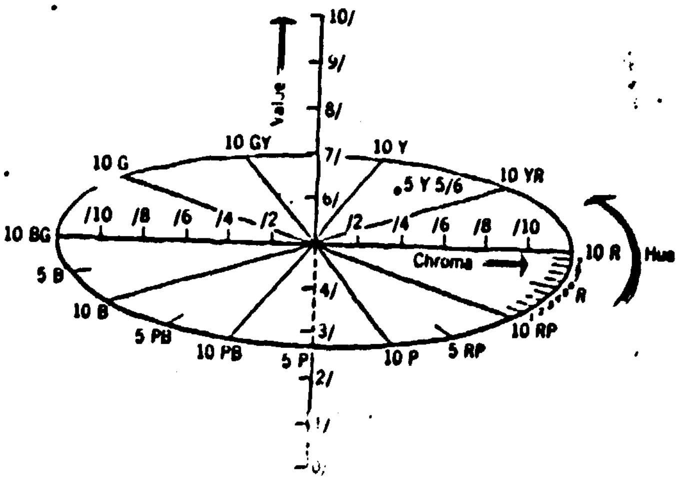


Figure 5

In the Munsell color-order system, colors are arranged by *hue* in a hue circle, by *value* or lightness from top to bottom, and by *chroma* or saturation according to distance out from the scale of grays making up the center column.

The CIE system of colour measurement

The link between the physical aspects of colour (the spectral reflectance curves) and colour order systems describing what we see is provided by the CIE (Commission Internationale de l'Eclairage - International Committee on Illumination) system of colour measurement. This is based on the empirical fact that any colour, irrespective of its spectral characteristics can be matched by a suitable mixture of 3 primary colours, e.g. red, green and blue. This phenomenon is the basis of the colour television, where all colours that we see are produced by the mixed light from the red, green and blue phosphors on the screen.

In the CIE system the primaries are called the X (red), Y (green) and Z (blue) tristimulus values.

The tristimulus values can be calculated from the spectral reflectance data, combining them with data characterizing the light source and the colour vision of the human eye. (These latter can be taken from tables compiled and standardized by the CIE.)

The Y tristimulus value indicates the lightness of the sample, but it is very difficult to give visually easily understandable meaning to X and Z. Therefore it is more common to specify colours by their lightness (Y), and the two chromaticity coordinates x and y, which are derived from X, Y and Z by

$$x = \frac{X}{X + Y + Z} \quad \text{and} \quad y = \frac{Y}{X + Y + Z}$$

If we plot y vs x in a rectangular coordinate diagram we get the famous CIE chromaticity diagram illustrated in Figure 6. Spectrum colours lay on the horseshoe-shaped curve known as the spectrum locus, and all realizable colours (which of course are mixtures of spectrum colours) are located within the boundaries of the spectrum colours. Purples, which are missing from the spectrum itself, are located on the straight line connecting the points of spectrum blue and red.

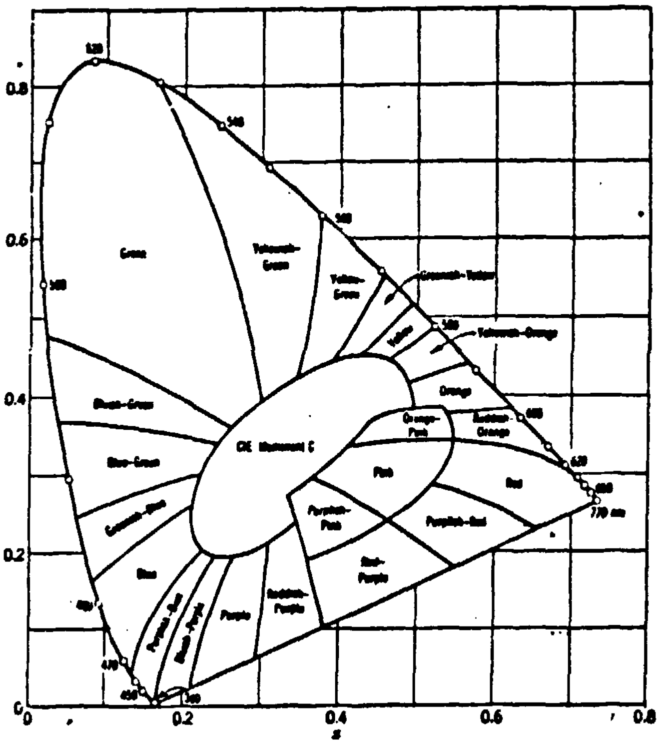


Figure 6 The names of various colours shown in the CIE·1931 chromaticity diagram

Unfortunately this diagram is not perceptually uniform, that is the same distance in the various parts of the diagram is seen as a smaller or greater colour difference, depending on where we are in colour space. There were several attempts to transform the X,Y Z system into one with new coordinates, that will conform better with what we see. Some years ago more than 30 different "colour difference formulae" were used, and to achieve uniformity of practice, the CIE recommended 2 for use in various industries. In the textile industry the CIE 1976 $L^* a^* b^*$ (CIELAB in short) is widely used today. The structure and the spacing of the CIELAB system is very similar to that of the Munsell system, and it makes the CIELAB system very useful in describing colour and colour differences.

Application of the CIELAB system in the textile industry

1./ Colour specification

Colours can be specified in the CIELAB system by either the $L^* a^* b^*$ coordinates, or by the metric lightness (L^*) metric chroma (C^*_{ab}) and metric hue (H^o_{ab}) coordinates, which correspond very well to the same terms in the Munsell system.

2./ The characterization of dyestuffs

Dyestuffs can be characterized in the CIELAB system by plotting the colour points of dyeings in a^*-b^* and L^*-C^*_{ab} diagrams. "Strength lines" are the lines connecting the colour points of increasing concentrations of the same dye, as in Fig. 7.

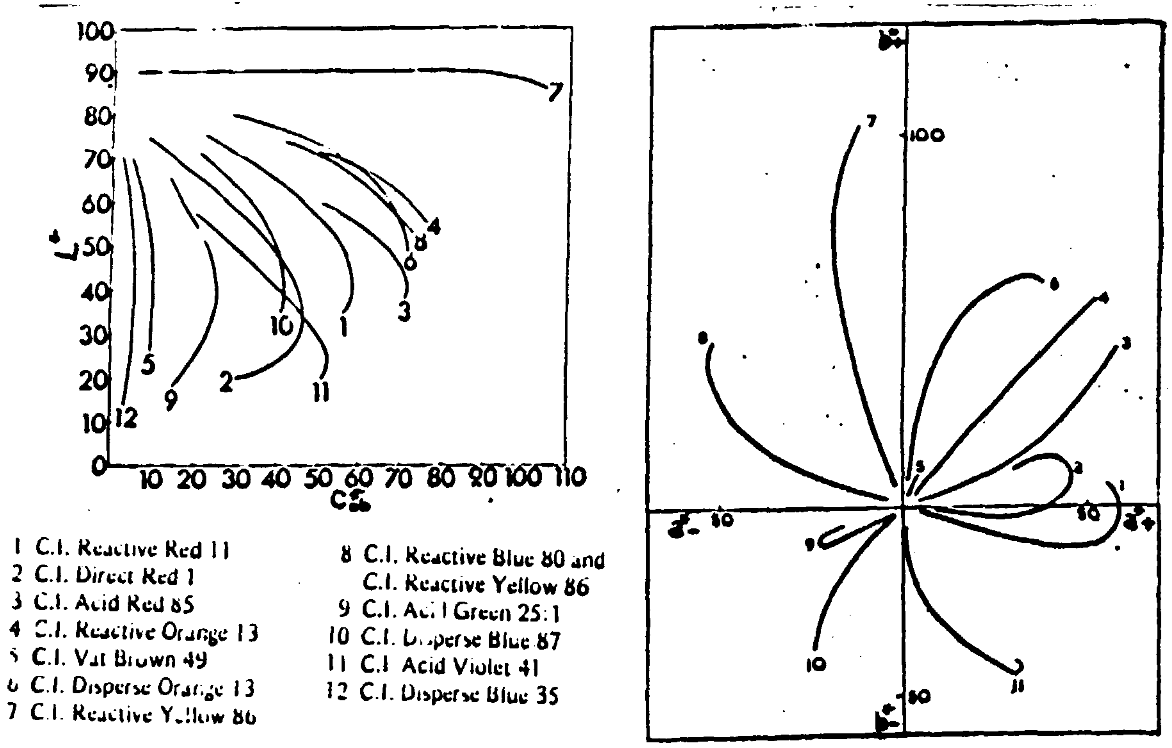


Figure 7 Strength lines for 12 different dyes in an a^* - b^* (right) and an L^* - C^*_{ab} diagram. The concentrations increase from the middle outward and from top to bottom respectively.

Mixtures of colorants can also be illustrated in an a^* - b^* plot, and that can give great help in dyestuff selection.

3./ Colour difference measurement

Colour difference measurement can be used to describe the effect of technological or process parameters on the final colour. This technique was used successfully to describe the effect (in visual terms) of random variations in the most important process variables in dyeing, as shown in Figure 8.

- NaCl concentration (1)
- Na_2CO_3 conc. (2)
- time before addition of alkali (3)
- time after addition of alkali (4)
- temperature before addition of alkali (5)
- temperature after addition of alkali (6)
- weight of cloth (7)
- volume of dyebath (8)
- dye conc. all (9)
- dye conc. yellow (10)
- dye conc. red (11)
- dye conc. blue (12)

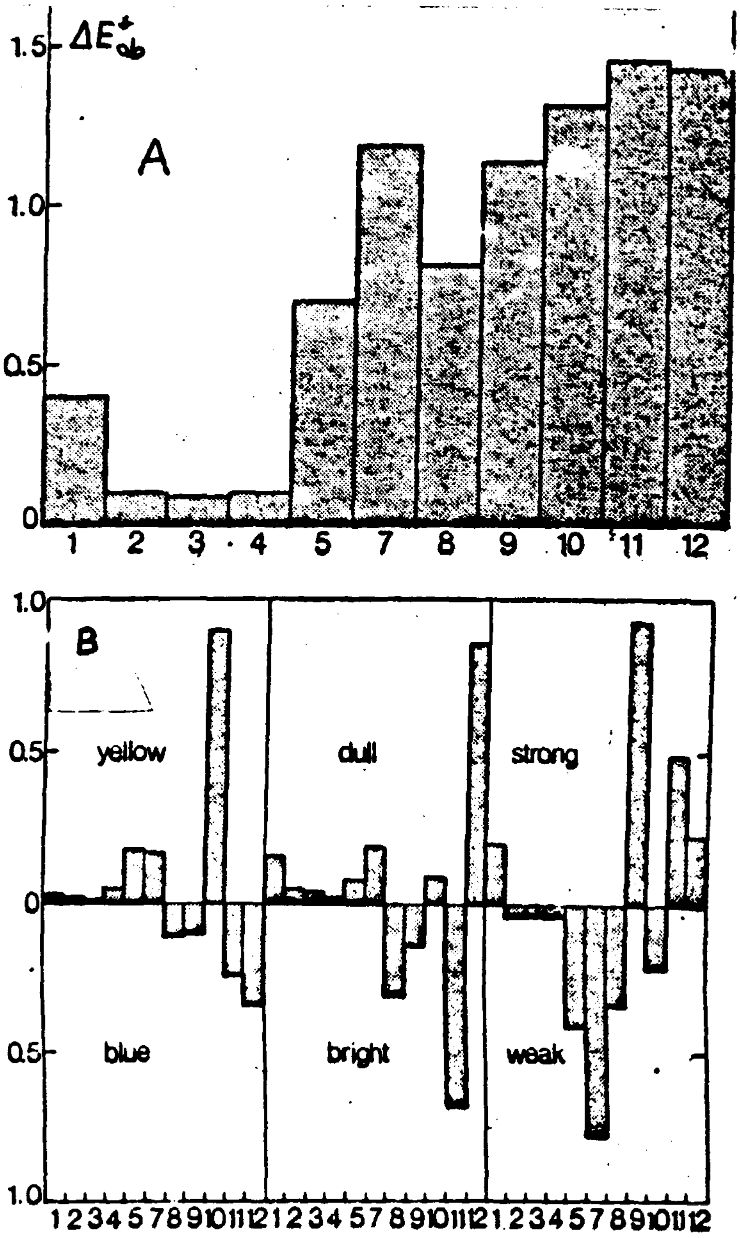


Figure 8 Effect of 10 % variation in dyebath conditions for reactive dyes on cotton. A: total colour change, B: change in hue, strength and brightness.

Colour change due to heat treatment following the sizing of cotton yarns, and the effect of heat setting on the final colour of polyester have also been measured.

The colour change due to resin finishing can only be described quantitatively by the help of colour difference measurement, whereby the thermochromic behaviour of certain dyestuffs could also be characterized.

4./ Tolerance specification

One of the most difficult problems in dyeing - and also in colour measurement-is to decide whether a sample is acceptable or not, is it inside or outside the tolerance limits as compared to the standard. It is clear, that single number colour differences cannot describe the tolerances, since the limits in various directions in colour space are not necessarily equal, as illustrated in Figure 9.

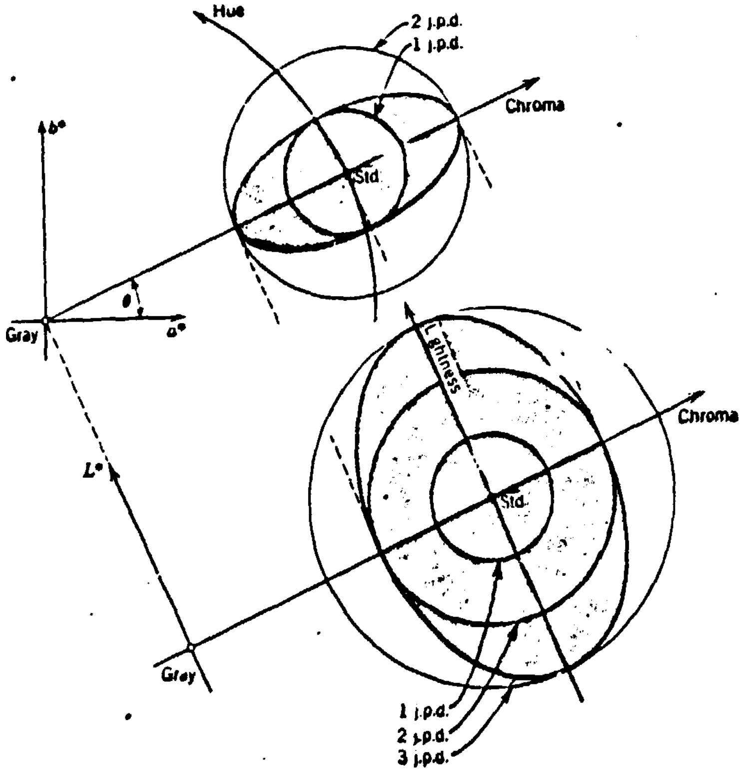


Figure 9 Cross sections through ($L^*a^*b^*$)-color space. (Upper-left) plane of constant lightness L^*; (lower-right) plane of constant hue (θ). Concentric circles around standard color (Std) are loci of constant perceptibility (1 j.p.d. (just perceptible difference), 2 j.p.d., 3 j.p.d.). Concentric ellipses (hatched) are cross sections of acceptability ellipsoid.

It is very difficult, and takes a long time and lot of work to determine the tolerance limits for instrumental specification, but once we have these; the answer to that difficult question "is this sample pass or fail" can be read off the colour measuring instrument in a matter of seconds.

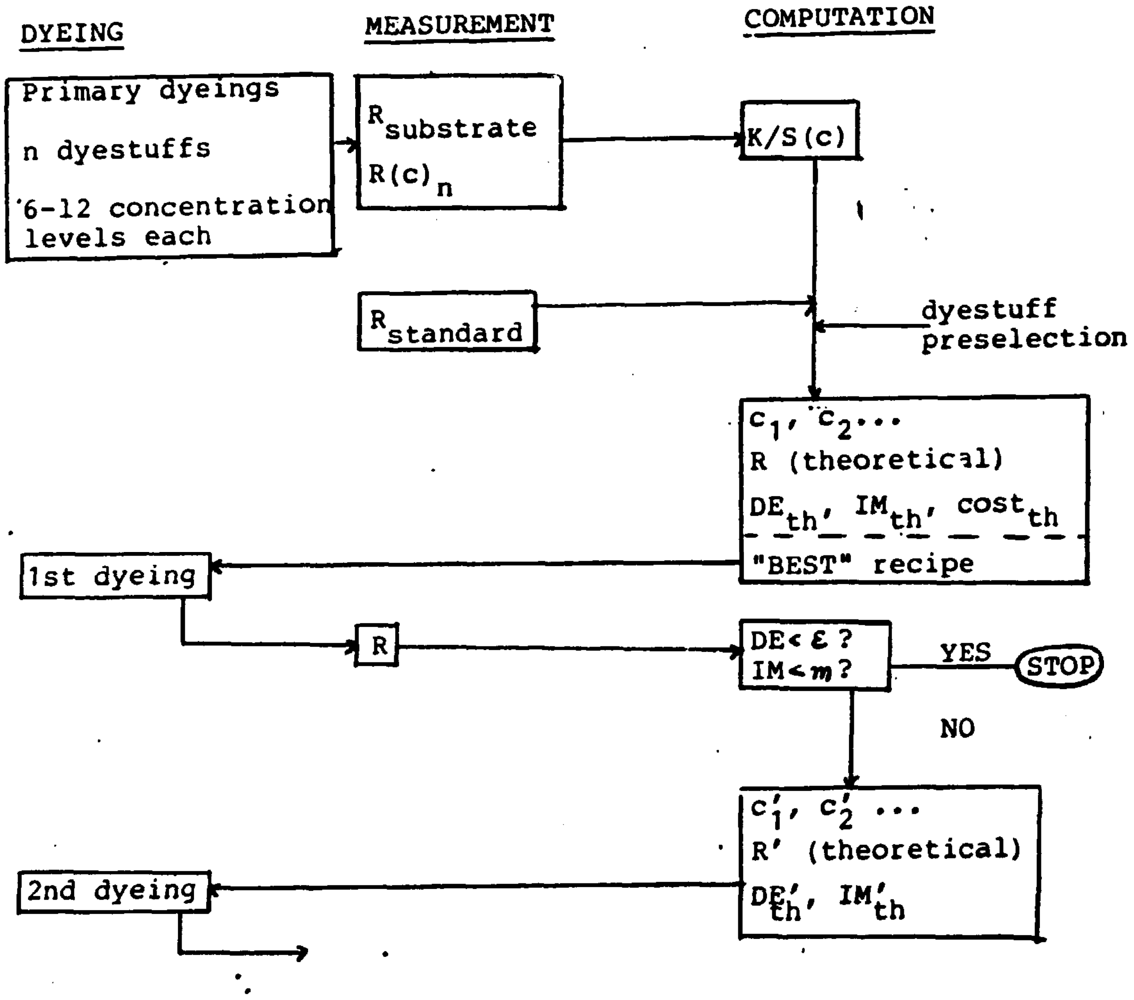
5. Colour sorting

Another very useful application of instrumental colour specification is colour (or shade) sorting. Here the samples from different lots that are supposed to be of the same colour are sorted into "boxes", within which every sample is considered to be within tolerance as compared to the central sample for that particular box. This technique is particularly useful for sorting into uniform lots prior to cutting and making-up, but it can also be used for statistical analysis of the production itself.

Computer colorant formulation (match prediction)

The most spectacular use of colour measurement is the calculation of dyeing recipes, known as "computer colour matching" (CCM) or "computerized colorant formulation" (CCF). Here a computer is 'taught' the behaviour of dyestuffs by preparing a number of calibration dyeings and measuring them on a spectrophotometer. Then the necessary amounts of dyestuffs to match the colour of any standard are calculated automatically for all possible combinations of the colorants given to the computer. The predicted recipe can be checked in the laboratory, and corrected if necessary. The greatest advantage of CCM as compared to conventional colour matching is that it is possible to compute several hundred alternative recipes in a matter of minutes, and select the "best" recipe according to price, goodness of match (colour difference) under daylight and/or artificial light.

The main stages of computer colorant formulation can be illustrated by the following chart:



Explanation of Computer Printout

In printout   the boldface portion indicates operator input. The lines are *not normally numbered. This was done* for ease of identification.

Line 1. The operator asks the computer to run the match program (MAT 1). The computer prints the version number of the program and asks for the user number. The user number, which is supplied by the operator, lets the computer know which set of correction factors to apply to any reflectance data which is inputed to the computer. These factors can represent calibration corrections for more than one spectrophotometer. They can also represent a variety of calibration conditions for the same instrument; i.e., standard reflectance measuring conditions, small [illegible] viewing, transmission calibration, etc.

Line 2. The operator types in the name of the color to be matched. This is for record keeping purposes only.

Line 3. The operator lets the computer know if the reflectance or transmission measurements of the sample to be matched are coming directly from the spectrophotometer (S), from a file (F) or typed in from the keyboard (K).

Line 4. The operator chooses how many dyes or pigments he would like to see in each formula (3), the total number of colorants to be considered (6) and the identification number (position in a file) of the substrate to be printed (9).

Line 5. This is the name of the file in which the dyes are stored.

Line 6. The six identification numbers (position in the file) of the dyes to be considered for the match.

Line 7. Daylight tolerance (FMCII) limit.

Line 8. Amount of print paste to be made—grams, pounds, etc.

Line 9. The operator has the option to have the computer print out all of the formulas which match within the tolerance (Line 7) or to sort the formulas to the five best (least metameric) and five lowest cost.

Line 10. *This line* starts the output of the formulas computed. The colorants are identified for each formula. The percentage formula as well as the amount needed to make up 175 units are given. *The predicted color difference* in daylight (DEC), tungsten (DEA) and fluorescent light (DEF) are given. The cost of the formula is also computed in whatever units desired. In Printout   , the best formula was the last one printed. If the operator had chosen to sort the formulas (for least metameric) the last formula would have been printed out first.

Computer Printout (ACS system)[1]

```
1 - R MAT 1
   MAT 1 VER 002-1023
   USER #* 1
2 -> NAME OF TARGET* PE 2246 - RUST
3 -TARGET %R'S* K
   25.019.114.812.311.311.011.713.115.418.326.735.847.062.376.584.4

4 ->-> CLRNT./COMB., FIELD SIZE, & SUB. ID#* 3,6,9
5 -FILE NAME* POLYE
6 -ID''S OF COLRNT.* 1,2,4,5,6,7

7 ->>> DEC TOL.*1.
8 -BATCH WEIGHT* 175.
9 -SORT OUTPUT / *N

   08-MAY-79
     PE 2246 - RUST            EXTENDER 2018

10- COLORANT                   %       AMOUNT    DEC     DEA     DEF     COST
   1 YELLOW 306            4.2100     7.3674
   4 RED 105              14.1763    24.8084
   6 GS BLUE 524           5.0970     8.9197
      CLEAR               76.516    133.9044     0.4     5.1     13.9   130.33

   1 YELLOW 306            4.8581     8.5017
   4 RED 105              11.3066    19.9265
   7 RS BLUE 603           3.1409     5.4966
      CLEAR               80.6144   141.0751     0.1     2.8      5.8    97.88

   1 YELLOW 306            5.2292     9.1511
   5 BS RED 607           19.8615    34..577
   6 GS BLUE 524           3.2595     5.7042
      CLEAR               71.6497   125.3870     0.2     2.8     12.1   110.85

   1 YELLOW 306            5.5617     9.7330
   5 BS RED 607           16.8580    29.5014
   7 RS BLUE 606           2.3497     4.1120
      CLEAR               75.2306   131.6535     0.2     7.3      6.1    91.00

   2 ORANGE 204            7.2196    12.6344
   4 RED 105              10.9583    19.1770
   6 GS BLUE 524           5.7823    10.1190
      CLEAR               76.0398   133.0696     0.4     9.5     10.5   113.83

   2 ORANGE 204            7.9059    13,8353
   4 RED 105               6.9019    12.0783
   7 RS BLUE 603           3.5020     6.1285
      CLEAR               81.6902   142.9579     0.1     2.3      1.3    70.01

   2 ORANGE 204            7.9211    13.8619
   5 BS RED 607           13.9364    24.3888
   6 GS BLUE 524           4.2562     7.4483
      CLEAR               73.8863   129.3010     0.3     5.0      7.8    91.34

   2 ORANGE 204            8.2613    14.4922
   5 BS RED 607           11.4544    20.0452
   7 RS BLUE 603           3.0162     5.2783
      CLEAR               77.2482   135.1843     0.0     0.0      0.0    68.79
```

[illegible]

Textile Consolidation Fund
Textile Development Centre

The Application of Colour Measurement in Tolerance Specification

by Dr. Robert Hirschler
UNIDO Expert in Colour Measurement

14 December 1981
Alexandria

1./ Colour difference specification

Any colour can be specified by three numbers: we can say that our colour vision is three-dimensional. In the most widely used colour order system (the MUNSELL system) these three quantities are called hue, value and chroma, and they can be considered the three axis of colour space. One of the main advantages of the MUNSELL system is its perceptual uniformity: the same difference in the coordinates (the same number of hue, value or chroma steps) have the same perceptual significance in any part of the MUNSELL colour space.

The MUNSELL system was developed on perceptual basis, but we like to measure quantities by instruments, and that is true for colour as well. There is an international system of colour measurement, which specifies colour by three easiliy measurable quantities: the X, Y, Z tristimulus values of the CIE system. These are usually converted into chromaticity coordinates, which can be more easily illustrated on a plane diagram, this is the famous CIE chromaticity diagram. The chromaticity coordinates x and y are calculated by the equations

$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z} .$$

The chromaticity diagram gives only approximate indication of the spacing of colours, it is not perceptually uniform. This means, that equal distances on the x, y diagram do not represent colour differences which are seen as equal. This drawback of the CIE system is not a fault of the system itself, it is inherent in the way we see colours. To illustrate the visual non-uniformity of the chromaticity diagram we can plot the coordinates of MUNSELL colours of equal lightness as in Figure 1.

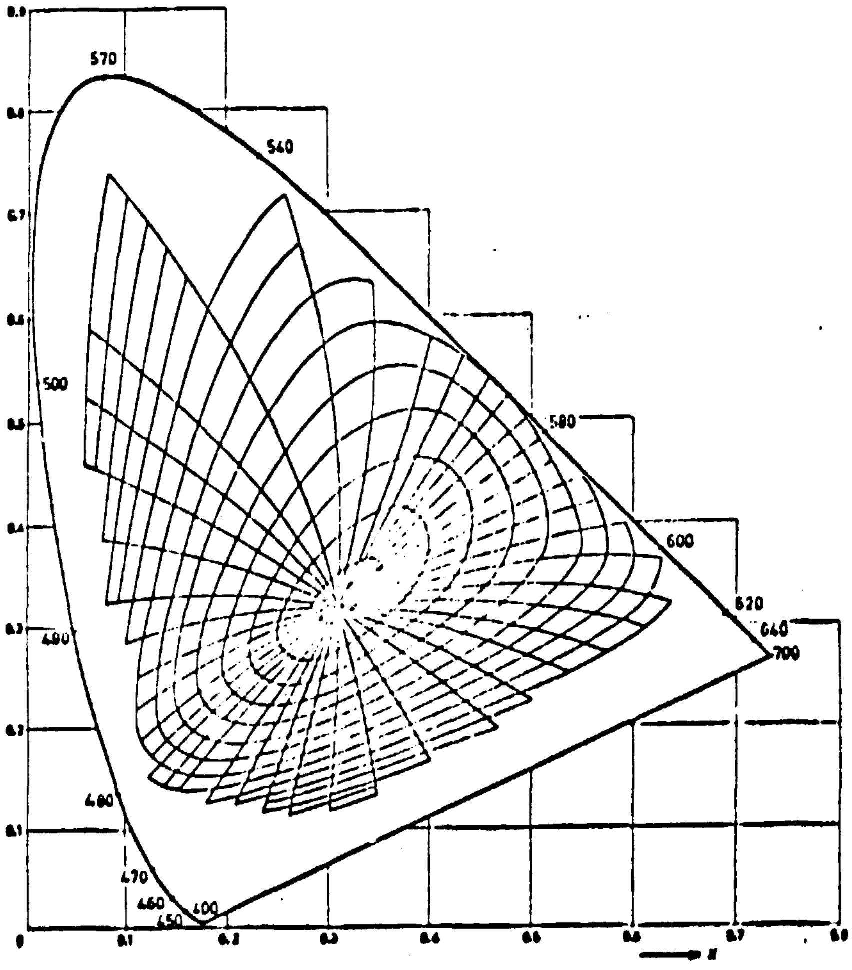


Figure 1. Colours of equal MUNSELL value (5) plotted on the CIE 1931 chromaticity diagram.

the x, y diagram were perceptually uniform, the equal chroma contours (which look in Figure 1 like distorted ellipses) would plot in concentric circles, and the constant hue line (which for most hues form strongly curved lines) would be straight.

MacAdam has run a very detailed investigation to analyse the colour difference perception properties of the human eye. He plotted around 25 colour centres the uncertainty of colour discrimination, which can be regarded a very good measure of colour difference perception. When he connected the points around the centres which his observer regarded as equal distances, he got ellipses, like the one illustrated in Figure 2.

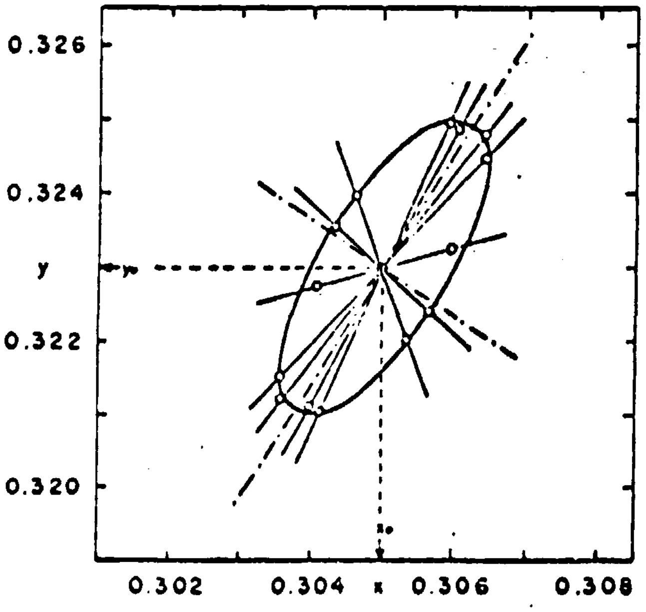


Figure 2. Points in the CIE 1931 chromaticity diagram, which the observer has seen as equidistant from the centre.

If the x, y diagram were perceptually uniform, these points would plot as circles around the centre. The other - maybe even more serious - problem that can be deduced from MacAdam's data is the different sizes of the discrimination ellipses as illustrated in the well known figure (Figure 3).

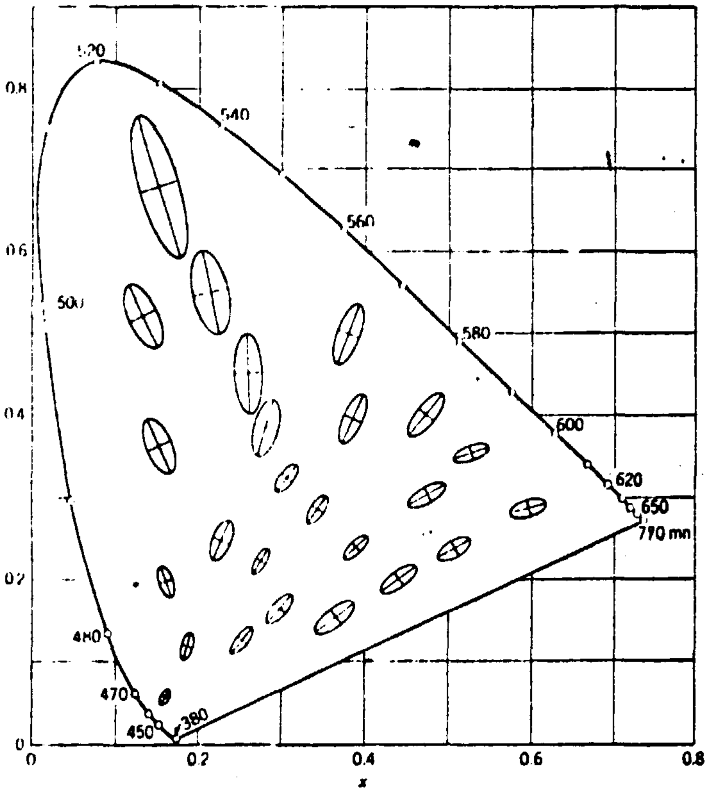


Figure 3. The famous MacAdam ellipses in the chromaticity diagram. They should plot as circles of equal size in a perceptually uniform system.

From MacAdam's data several colour difference equations have been derived. The purpose of these equations is the transformation of the CIE X,Y,Z or x,y,Y system in such a way, that the new system be perceptually uniform.

himself suggested the following colour difference

$$DE\ (\text{MacAdam}) = \left[g_{11}Dx^2 + 2g_{12}DxDy + g_{22}Dy^2 + GDY^2\right]^{1/2} \qquad (1)$$

where g_{11}, $2g_{12}$, and g_{22} are constants whose value depends on x and y, and G and K are constants whose value depend on Y. (In this formula as in all the following ones through this paper D designates (colour) difference, usually designated Δ.

In the late 195o's Simon and Goodwin developed a graphical method for the fast calculation of Eqn. (1). This method has been used quite widely, but today it is considered obsolete. Figure 4. illustrates the basic principle.

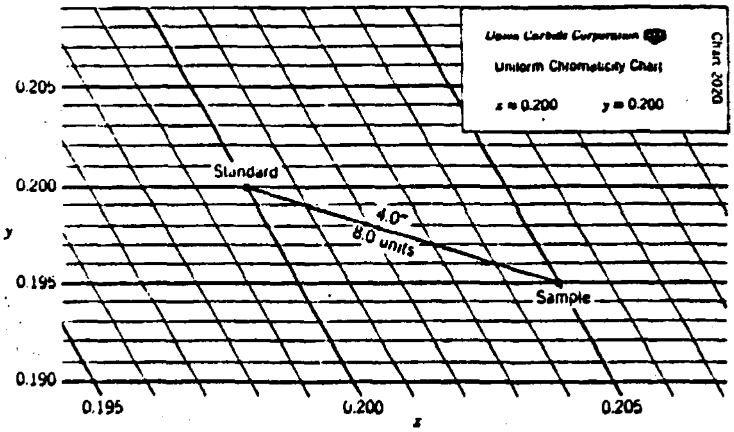


Figure 4/a

A section of a Simon-Goodwin color-difference chart, illustrating the calculation of the MacAdam color difference between a standard with $x = 0.200$, $y = 0.200$, $Y = 29.0\%$, and a sample with $x = 0.205$, $y = 0.195$, and $Y = 25.0\%$.

This chart, drawn according to the values of g_{11}, $2g_{12}$, and g_{22}, for *x near 0.200 and y near 0.200*, is used to find the "uncorrected" chromaticity difference between sample and standard. On the original chart, where ½ in. = 1 MacAdam unit, this difference was 8.0 MacAdam units for the test *calculation. . . .*

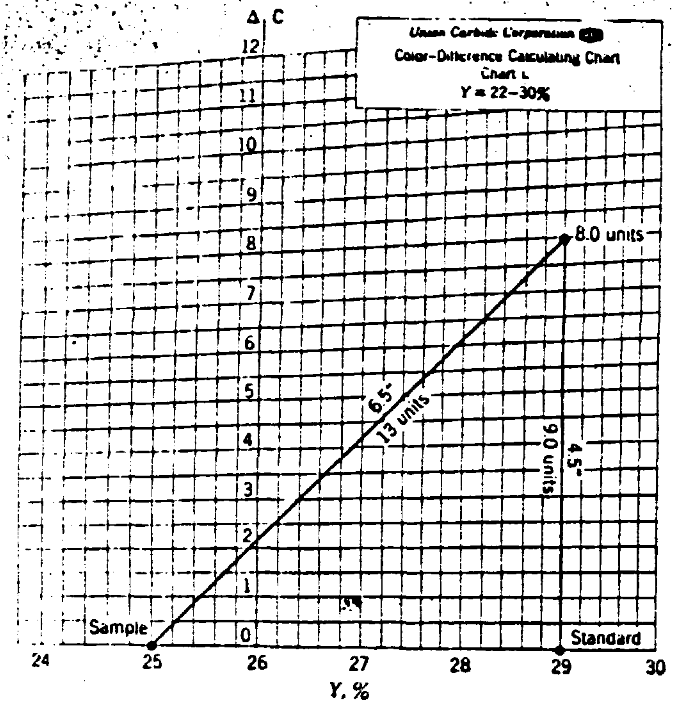


Figure 4/b

. . . The "uncorrected" chromaticity difference ΔC is now measured off at the lightness (Y) level of the *standard* on this chart. The "corrected" chromaticity difference is the distance between this point and the base line, here 9.0 MacAdam units. The total color difference is the slant distance shown, or 13 MacAdam units. (To clarify the test calculation, a rather large color difference was chosen. Note also that in the original Simon-Goodwin charts, Y is expressed as a decimal fraction—*for example, 0.25 and 0.29*—rather than in per cent as is our convention.)

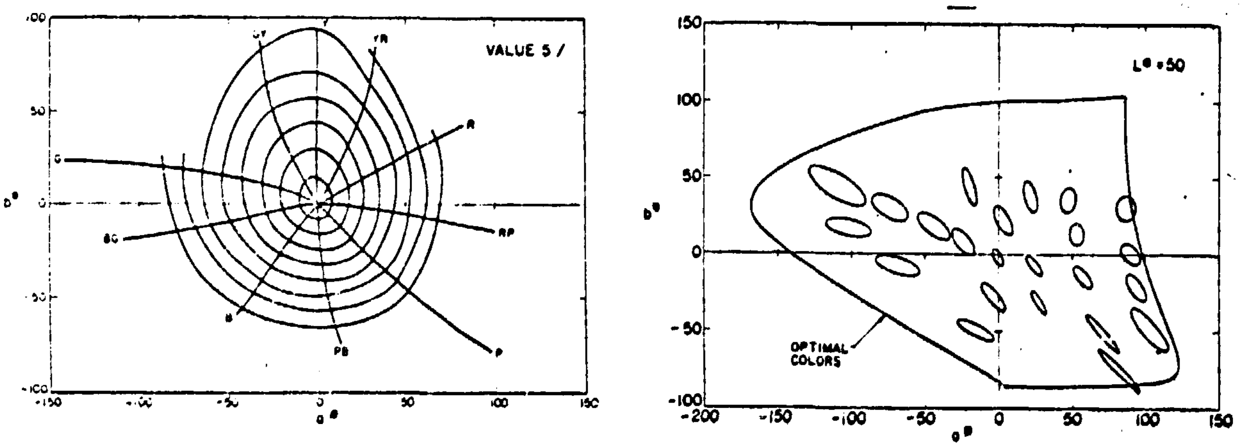
In the 1960's the more and more general use of digital computers made graphical methods unnecessary, and formulae were developed, which transformed - or rather tried to transform - the X,Y,Z system into a better one. The formula developed by Friele, MacAdam and Chickering (see Appendix 1) is extremely complicated, but it does give better uniformity, than the original system. In the USA there was another formula developed by Hunter, which has been as widely used as the FMC (Friele-MacAdam-Chickering) transformation. The Hunter formula uses the L, a, b coordinates of the Hunter system, which can be directly measured on HunterLab instruments, or calculated from X, Y and Z.

Colour difference in the Hunter system is calcula by the Euclidian distance formula:

$$DE(Hunter) = /DL^2 + Da^2 + Db^2/^{\frac{1}{2}} \qquad (2)$$

The Hunter system has been very popular mostly because of its simplicity, but its visual spacing is not as good as that of the most recent CIE recommendataion, the CIELAB system. The CIE 1976 L*,a*,b* (CIELAB) system is the present international recommendation, and although it couldn't be proved, that its visual spacing is superior to all other formulae (e.g. the FMC), this is the one that has to be used to promote uniformity of practice. The formulae for the calculation of CIELAB coordinates can be found in Appendix 2.

Figure 5 illustrates how well (or in some regions how poorly) the CIELAB system approximates a perfectly uniform space.



Munsell loci of constant hue and chroma plotted in the CIE 1976 *a*b** diagram.

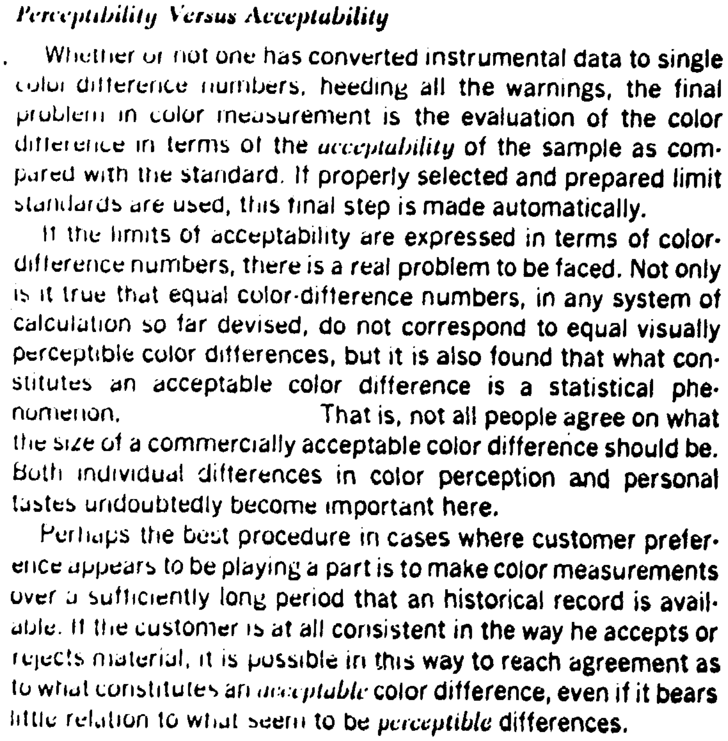
MacAdam ellipses plotted in the CIE 1976 *a*b** diagram.

Figure 5

There is no simple relationship between the various colour difference formulae, we cannot say, that one or the other is "bigger" or "smaller", because the relationship is different for different colours. In Appendix 3 we have tabulated some colour difference values for 5 pairs of samples in HunterLab, CIELAB and FMC-II units.

To conclude this brief description of colour difference formulae we must emphasize, that there is no direct evidence for any colour difference formula to be "better" than another one. To work in an international system, however, the recommendation of the International Committee on Illumination (CIE) is the use of the CIELAB system.

2./ Colour tolerances



Perceptibility Versus Acceptability

Whether or not one has converted instrumental data to single color difference numbers, heeding all the warnings, the final problem in color measurement is the evaluation of the color difference in terms of the *acceptability* of the sample as compared with the standard. If properly selected and prepared limit standards are used, this final step is made automatically.

If the limits of acceptability are expressed in terms of color-difference numbers, there is a real problem to be faced. Not only is it true that equal color-difference numbers, in any system of calculation so far devised, do not correspond to equal visually perceptible color differences, but it is also found that what constitutes an acceptable color difference is a statistical phenomenon. That is, not all people agree on what the size of a commercially acceptable color difference should be. Both individual differences in color perception and personal tastes undoubtedly become important here.

Perhaps the best procedure in cases where customer preference appears to be playing a part is to make color measurements over a sufficiently long period that an historical record is available. If the customer is at all consistent in the way he accepts or rejects material, it is possible in this way to reach agreement as to what constitutes an *acceptable* color difference, even if it bears little relation to what seem to be *perceptible* differences.

It is important to note here that the basic question of what is and what is not acceptable material must be settled in advance by agreement between the buyer and the seller. This is only sound business practice. If instrumental methods are to play a part, they must be defined exactly, including the techniques of measurement, converting the data, plotting or calculating, and evaluating the results. This agreement between buyer and seller is just as much a part of the usefulness of color measurement for purchase specification as are the instruments and computational techniques themselves.

Color Tolerances

In the final analysis, the sale and purchase of colored materials hinges upon the conformance of the samples to certain color-difference tolerances Let us now consider how these tolerances should be set.

Color tolerances are, unfortunately, sometimes set in one of two quite undesirable ways. One is to make the tolerance as tight as possible so long as the vendor can supply satisfactory material. The other is to set the tolerance at the absolute limit of the ability of either the human observer or the instrument to detect a color difference. Both of these methods have a major defect in that they do not relate to what is required. If what is required does call for the utmost in control, then this is what must be furnished, but, to use an example from another industry, it would be foolish (to put it mildly) to order steel bars machined to a tolerance of a thousandth of an inch to be used as reinforcing rods for concrete. One reason this is not done, among others, is the fact that the tighter the tolerance, the higher the price. In this respect the situation in color measurement is unusual in that most requirements (until fairly recently) have called for "exact" matches. In recent years greater understanding on the part of all involved has resulted in some far more realistic tolerances, especially in the provision of limit standards in the several dimensions of color space. Where an "exact" match is needed, an "exact" match can usually be provided if one is willing to pay for it.

Tolerance specification in practice

The main problem in practical tolerance specification lies in the experimentally proven fact, that even for the same colour the size of the acceptable difference varies with the orientation, i.e. even in a perceptually uniform colour space - where the perceptibility ellipsoids were spheres of equal diameter - the tolerance (based on acceptibility) would be greater in one direction - say lightness - and tighter in another -e.g. hue. That is the reason, why tolerance limits are represented rather by ellipsoids in space (or ellipses in a plane diagram) than by some more symmetrical form. This is shown in Figure 6.

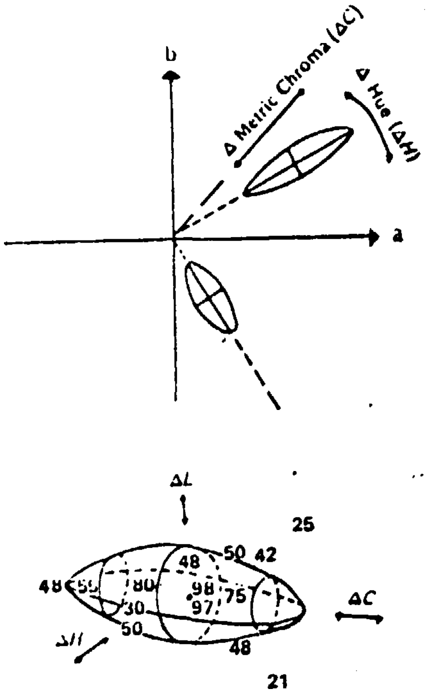


Figure 6. Acceptibility limits (tolerance) in CIELAB space

In many practical cases the limits cannot even be described with an ellipsoid; they can take irregular shapes as illustrated in Figure 7 (p. 11) for a white sample that has been treated with a fluorescent brightening agent.

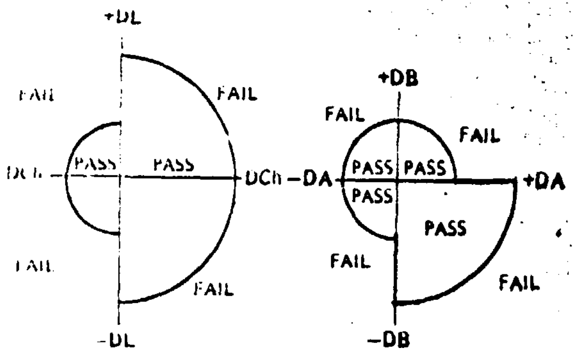


Figure 7 Tolerance limits with preferred direction of change

Unfortunately, even for the same end-use the limits are different in different parts of colour space. Thus Jaeckel has found, that the ratio of the longest and the shortest boundary limits (e.g. for an ellipsoid the ratio of the longest and shortest axis) depend on the location of the colour in colour space. This can be illustrated in an L^*-C^*_{ab} diagram as shown in Figure 8.

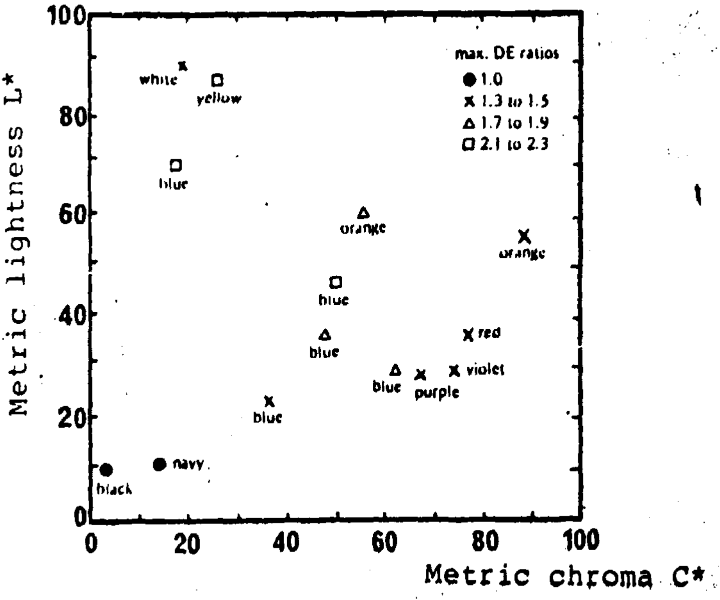


Figure 8 Max DE ratios $\left(\frac{\text{longest limit}}{\text{shortest limit}}\right)$ in an L^*-C^* diagram

We have briefly listed the main problems associated with tolerance specification. What is than the answer to the question: how much is acceptible in CIELAB or FMC or Hunter units?

<u>There is no straight answer to that question</u>. It has to be evaluated individually, for every end-use, for every customer, for every colour. The detailed methods of how to go about setting tolerance limits go far beyond the scope of this paper, but there is a list of up-to-date papers below, which contain hints on how to go about setting tolerance limits. The final answer can only be given by those, who are willing to collect a great number of samples around each standard colour, measure the individual differences in a uniform colour space (preferably CIELAB), evaluate the results with strict mathematical statistical treatment, compare these measured values to visual pass/fail decisions, and thus establish the acceptibility contours around each colour. It is a very time-consuming task, but the reward is more consistent pass/fail evaluation, less unnecessary reject and unjustified accepts, in short:better performance in the dyehouse and in quality control.

<u>Recommended references</u>

<u>Taylor, P.F.</u>: Colour instrumentation in Europe: a colour grading and sorting system.
Trans. Amer. Soc. Quality Control, <u>5</u> (1977-78) 67-90

<u>McDonald, R.</u>: Industrial Pass/Fail Colour Matching I-II-III
J. Soc. Dyers and Colourists <u>96</u>, 7-9 (1980)
Part I. pp. 372-376; II. pp. 418-433 III. pp. 486-496

<u>Jaeckel, S. M. - Ward, C. D.</u>: Practical Instrumental Colour Quality control - the HATRA experience
J. Soc. Dyers and Colourists <u>92</u>, 10 (1976) 353-363

The Friele-MacAdam-Chickering colour difference formula:

$$\Delta E(\text{FMC II}) = [(\Delta C)^2 + (\Delta L)^2]^{1/2}$$

where

$$\Delta C = K_1 \Delta C_1 \quad \text{and} \quad \Delta L = K_2 \Delta L_2$$

$$\Delta C_1 = \left[\left(\frac{\Delta C_{rg}}{a}\right)^2 + \left(\frac{\Delta C_{yb}}{b}\right)^2\right]^{1/2} \quad \text{and} \quad \Delta L_1 = \frac{(P\Delta P + Q\Delta Q)}{(P^2 + Q^2)^{1/2}}$$

$$\Delta C_{rg} = \frac{(Q\Delta P - P\Delta Q)}{(P^2 + Q^2)^{1/2}} \quad \text{and} \quad \Delta C_{yb} = \frac{S\Delta L_1}{(P^2 + Q^2)^{1/2}} - \Delta S$$

$$\Delta L_2 = \frac{0.279\Delta L_1}{a}$$

$$K_1 = 0.55669 + 0.049434Y - 0.82575 \times 10^{-3}Y^2 + 0.79172 \times 10^{-5}Y^3 - 0.30087 \times 10^{-7}Y^4$$

$$K_2 = 0.17548 + 0.027556Y - 0.57262 \times 10^{-3}Y^2 + 0.63893 \times 10^{-5}Y^3 - 0.26731 \times 10^{-7}Y^4$$

$$a^2 = \frac{17.3 \times 10^{-6}(P^2 + Q^2)}{[1 + 2.73P^2Q^2/(P^4 + Q^4)]}$$

$$b^2 = 3.098 \times 10^{-4}(S^2 + 0.2015Y^2)$$

$$P = 0.724X + 0.382Y - 0.098Z$$

$$Q = -0.48X + 1.37Y + 0.1276Z$$

$$S = 0.686Z$$

X, Y, Z being the tristimulus values for either of the two colors constituting the difference to be evaluated, and ΔP, ΔQ, ΔS being the differences between the values of P, Q, and S for these two colors.

The Hunter colour difference formula:

$$\text{DE(Hunter)} = /DL^2 + Da^2 + Db^2/^{\frac{1}{2}}$$

where

$$L = 10\sqrt{Y} \; ; \quad a = \frac{17.5\,(1.02X - Y)}{\sqrt{Y}} \; ; \quad b = \frac{7.0\,(Y - .847Z)}{\sqrt{Y}}$$

APPENDIX 2

Formulae for calculating CIELAB coordinates from tristimulus values X, Y, Z

Designations

L^* : psychometric lightness

a^* : red-green axis

b^* : yellow-blue axis

C^*_{ab} : psychometric chroma

H^o_{ab} : " hue angle

DL^*, DC^*_{ab}, DH^*_{ab} : differences in respective quantities

DE^*_{ab}: total colour difference in CIELAB units

X, Y, Z : CIE tristimulus values

X_o, Y_o, Z_o : CIE tristimulus values for absolute white, for the 1931 CIE 2° Standard Observer and Illuminant C the respective values are

$X_o = 98.041$; $Y_o = 100.000$; $Z_o = 118.103$

Formulae

$$L^* = 116(Y/Y_o)^{1/3} - 16 \quad \text{if } Y/Y_o > 0.008856$$
$$= 903.29\ Y/Y_o \quad \text{if } Y/Y_o \leq 0.008856$$

$$a^* = 500\left[(X/X_o)^{1/3} - (Y/Y_o)^{1/3}\right] \quad \text{if } X/X_o > 0.008856$$
$$= 3893.5\ (X/X_o - Y/Y_o) \quad \text{if } X/X_o \leq 0.008856$$

$$b^* = 200\left[(Y/Y_o)^{1/3} - (Z/Z_o)^{1/3}\right] \quad \text{if } Z/Z_o > 0.008856$$
$$= 1557.4\ (Y/Y_o - Z/Z_o) \quad \text{if } Z/Z_0 \leq 0.008856$$

$$C^*_{ab} = \left[(a^*)^2 + (b^*)^2\right]^{1/2}$$

$$H^o_{ab} = \arctan(b^*/a^*)$$

$$DL^{*} = L^{*}_{1} - L^{*}_{2}$$

$$DC^{*}_{ab} = C^{*}_{ab,1} - C^{*}_{ab,2}$$

$$DH^{*}_{ab} = \left[DE^{*\,2}_{ab} - DL^{*\,2} - DC^{*\,2}_{ab}\right]^{1/2}$$

$$DE^{*}_{ab} = \left[DL^{*\,2} + Da^{*\,2} + Db^{*\,2}\right]^{1/2} \qquad = \left[DL^{*\,2} + DC^{*\,2}_{ab} + DH^{*\,2}_{ab}\right]^{1/2}$$

Worksheet 3/a

Colour difference measurement and calculation

Substrate: woven woollen fabric

Sample pair		Hunter				CIELAB			
		L	a	b	(C).	L^*	a^*	b^*	(C^*_{ab})
1 Yellow	1	68.7	-4.2	30.9	31.2	74.2	-4.8	45.8	46.1
	2	69.4	-2.8	30.3	30.4	74.8	-3.0	44.1	44.2
2 Pink	1	53.8	28.4	7.5	29.4	60.6	30.5	9.5	31.9
	2	52.0	25.1	6.5	25.9	58.9	27.5	8.3	28.7
3 Reddish brown	1	34.2	12.8	7.2	14.7	40.6	16.2	11.2	19.7
	2	32.4	11.6	5.5	12.8	38.7	14.4	8.6	16.8
4 Light brown	1	42.2	3.6	14.7	15.1	49.0	4.5	23.4	23.8
	2	36.0	4.6	14.5	15.2	42.5	6.2	25.5	26.2
5 Grey	1	40.7	1.5	4.5	4.7	47.5	1.8	6.1	6.4
	2	40.8	1.6	4.4	4.7	47.6	1.8	6.1	6.4

Worksheet 3/b

Sample pair	Hunter				CIELAB				FMC - II				
	DL	DC	DH	DE	DL^*	DC^*_{ab}	DH^*_{ab}	DE^*_{ab}	DL	DCRG	DCYB	DC	DE
1 Yellow	-0.7	0.8	1.3	1.7	-0.6	1.9	1.5	2.5	1.8	3.7	-2.8	4.6	5.0
2 Pink	1.8	3.5	0.0	3.9	1.7	3.2	0.7	3.7	-4.3	-7.6	-1.8	7.8	9.0
3 Reddish brown	1.8	1.9	1.0	2.8	1.9	2.9	1.8	3.9	-4.2	-6.5	-4.5	7.9	8.9
4 Light brown	6.2	-0.1	1.1	6.3	6.5	-2.4	1.0	7.0	-14.3	8.8	6.0	10.6	17.8
5 Grey	-0.1	0.0	0.2	0.2	-0.1	0.0	0.0	0.1	0.3	0.0	0.0	0.0	0.3

Worksheet 3/c

Worked example of calculating colour differences

Substrate: woven woollen fabric Formula: CIELAB

Values for YELLOW pair	1	2
X	44.4	46.0
X/X_0	0.45287	0.46919
$(X/X_0)^{1/3}$	0.76794	0.77705
Y	47.0	48.0
Y/Y_0	0.47000	0.48000
$(Y/Y_0)^{1/3}$	0.77749	0.78297
Z	19.5	21.0
Z/Z_0	0.16511	0.17781
$(Z/Z_0)^{1/3}$	0.54860	0.56232
L^*	74.2	74.8
a^*	-4.8	-3.0
b^*	45.8	44.1
C^*_{ab}	46.1	44.2
ΔL^*	-0.6	
ΔC^*_{ab}	1.9	
ΔE^*_{ab}	2.5	
ΔH^*_{ab}	1.5	

ANNEX No. 6.

to Mission Report
Egypt, 26 October - 24 December 1981
DP/EGY/77/008
by Dr. Robert Hirschler

Major manufacturers of colour measuring equipment in Europe and the United States.

APPLIED COLOR SYSTEMS INC.
P.O. Box 5800, US Highway One
Princeton, N.J. 08540 USA

in Europe
Erlbrüggerstr.2a, D-4370 Marl
West Germany

DATACOLOR AG
CH-8305 Dietlikon - Zurich
Brandbachstrasse 10, Switzerland

DIANO Corp.
8 Commonwealth Avenue Woburn,
Mass. 01801 USA

in Europe
Pausch Beratung, Eisenbahnstr.28.
D-5657 Haan 1. West Germany

GARDNER INSTRUMENTS
P.O. Box 5728, 5521 Landy Lane,
Bethesda, Maryland 20014 USA

in Europe
Hans Grimm LABORTECHNIK
D-8232 Bayerisch Gmain,
Weissbachstr. 19 b. West Germany

HUNTER ASSOCIATES Laboratory, Inc. 11495 Sunset Hills Road
Reston, Va. 22090, USA

in Europe
BFO - Postfach 1370
D-6482 BAD ORB, West Germany

IBM Instrument Systems
System Product Division
1000 Westchester Avenue,
White Plains, N.Y. 10604 USA

in Europe
IBM Deutschland GbmH,
DV Branchezentrum, Düsseldorf,
West Germany

INSTRUMENTAL COLOUR SYSTEMS 13 Bone Lane, Newbury
Berkshire RG14 5TE, UK

Macbeth division of KOLLMORGEN Corp. Drawer 95o,
Little Britain Road,
Newburgh, N.Y. 1255o USA

PRETEMA AG CH-89o3 Birmensdorf-Zurich
Switzerland