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Newton Lecture

The third Newton Lecture, delivered by Dr. W. S. Stiles on Thursday, 6 April, glinted like a gemstone in the rich setting of the symposium on *Colour Measurement in Industry*. Dr. Crawford, Chairman of the Group, when introducing Dr. Stiles, said that he had discovered amongst his students in Edinburgh a widespread impression that the owners of the names attached to a certain physiological effect in vision had long since passed into history—yet the present occasion showed that both the authors of the effect were still active, and he was particularly pleased that it had come about that their two names should again be linked.

Dr. Stiles spoke on *Mechanism Concepts in Colour Theory*, a theme taken from the content of his forthcoming book, and he illustrated how much of our understanding of the processes of colour vision could be derived from psychophysical measurements. The large lecture theatre of the Physics Department of Imperial College was filled very nearly to capacity, and though perhaps some of us were unable to follow the swift and elegant clarity of Dr. Stiles' exposition with the depth of understanding that it deserved, no doubt we were all inspired by his example in extracting concrete conclusions from some apparently very indirect findings. When Dr. Stiles had concluded, to much applause, Dr. Crawford presented him with a medal engraved to commemorate the event.

The Colour Group Dinner held in the new South Side Building of Imperial College after the lecture provided an opportunity for some 125 members and their guests to meet each other, drink, eat and enjoy the occasion. Dr. Crawford welcomed the visitors from eight overseas countries, and Dr. Gunter Wyszecki (from Canada) congratulated the Colour Group for organising a useful and timely symposium, for honouring Dr. Stiles, and for providing an excellent dinner.

R. W. B.

Mechanism Concepts in Colour Theory

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Recently I had occasion to look again at various simple concepts used to extend colour theory beyond the basic idea of trichromatic matching, and I thought some discussion of these might be of interest. The concepts I shall speak of are, in fact, psychophysical and in referring to them as "mechanism concepts" I am using the term mechanism in a special sense. In the complex neural systems extending from the end-organs through the retina and beyond, it is not yet possible to identify certain subsystems as the mechanisms that carry colour information to the brain. Clearly, psychophysical measurements can contribute nothing directly to our knowledge of the objective properties of colour mechanisms. In most studies the experimenter ends up with a collection of values specifying physical light stimuli all of which correspond to some fairly elementary visual judgement, such as "complete match" or "just detectable" which the subject is instructed to make. In analysing his results the experimenter will try to arrange them—to organise them—in a particularly significant or striking form which may suggest some rather simple model of what may be happening in the unknown processes between stimulus and response. Such models are often constructed of parts which are dignified with the title of mechanisms. Compared with the actual mechanisms in retina and brain, the psychophysicist's mechanisms have a rather ethereal existence; initially, at least, they may be merely elements in a mathematical analysis of a set of data. Having made this slightly abstract point, I hasten to add that in constructing models based mainly on psychophysical material, all the presently available objective evidence on the early stages of the visual process is pressed into service, and we expect that as more is learnt of the later stages actual counterparts of our models and their mode of action may be identified.

I shall confine myself to two lines of work that lead to ideas of colour mechanisms: asymmetric matching, as used in much work on colour adaptation, and colour discrimination including increment threshold sensitivity.

Ordinary trichromatic matching can be summed up in the equations for a complete match between two stimuli of spectral distributions $\{E_\lambda d\lambda\}$ and $\{E^l{}_\lambda d\lambda\}$ (in quantum units), viewed side-by-side in a bipartite field:

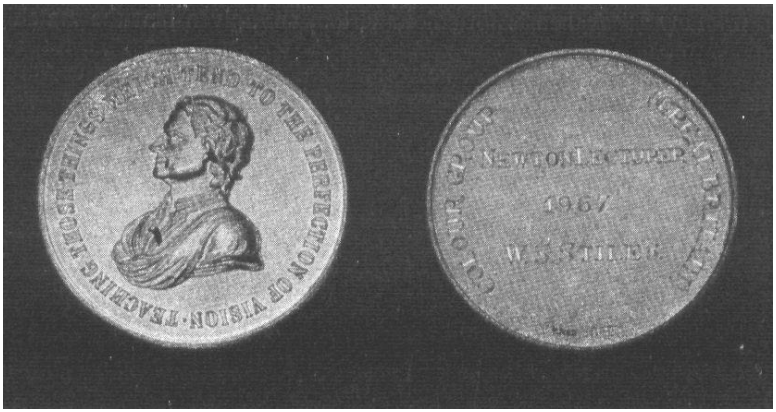
$$U \equiv \int E_l \, \bar{u}_l \, dl = \int E^1{}_l \, \bar{u}_l \, dl \equiv U^1$$

plus two similar equations with $\bar{u}_\lambda, U, U^l$ replaced respectively by $\bar{v}_\lambda$, V, V^l, and $\bar{w}_\lambda$, W, W^l. The colour-matching functions ax, 0), are derived from actual matches, and will be supposed referred to three given fixed wavelengths as primaries. This determines them completely, and the corresponding empirical tristimuius values U, V, W, of any stimulus are uniquely determined. These equations express the strong form of the

trichromatic principle, valid for foveal vision for not too high stimulus intensities. They are exactly those that would hold if the visual effect of a stimulus was produced by the light absorption of three photosensitive pigments contained in the retinal end-organs, and if, for all the end-organs containing a particular pigment, the *relative* spectral absorption factor of that pigment was the same, and remained unchanged whatever stimuli were applied. Here by absorption factor of a particular pigment in an end-organ, containing possibly other pigments, I mean the fraction of the radiation incident on the end-organ which is absorbed by the pigment in question. This definition leaves open whether the pigment in the end-orgn is to be regarded as a uniform thin or thick layer or as being non-uniformly distributed, and whether because of wave-mode propagation in the endorgan—which I think must occur—there is a non-uniform distribution of the stimulating radiation. The condition for the spectral absorption coefficient may well not be satisfied when matching or adapting intensities become very high, but, if it fails, it is almost certain that the trichromatic matching equations will also cease to hold; they would survive only if some other factor counterbalanced exactly the deviations in relative spectral absorption factor. It follows that, within the range of the trichromatic principle, there will be a linear relation between the empirical colour-matching functions and the relative spectral absorption factors (ρ_λ, γ_λ, β_λ) of the three pigments in the end-organs, or, more strictly, of these factors multiplied by the transmission (τ_λ) of the pre-receptor light path in the eye; for example:

$$r_l^* \equiv r_l t_l = p_{ru}\bar{u}_l + p_{rv}\bar{v}_l + p_{rw}\bar{w}_l$$

where $p_{\rho u}$, $p_{\rho v}$, $p_{\rho w}$ are constants.



The objective detection and measurement of cone pigments in recent years has of course strongly consolidated our belief in the pigment absorption explanation of the trichromatic principle. In this explanation, it is immaterial how the three pigments are distributed among the end-organs, or how the end-organs transduce the absorbed radiation into neural activity, or how the latter is elaborated by neural mechanisms in retina or brain. Conversely, ordinary trichromatic colour-matching gives no information relative to visual processes beyond the pigment absorptions. But asymmetric matching can provide such information

within the limitations of psychophysical models. By asymmetric matching we normally mean matches between stimuli imaged on distinct retinal areas that either have different properties because of their different positions on the retina, or that have been brought intentionally into different conditions by different pre-exposed or surround stimuli. The two areas may be on the same retina, as in the studies of extrafoveal colour by Bailey, Moreland and Cruz and Clarke, in which extrafoveal stimuli are matched with three-colour mixtures imaged on the fovea. They may be on the retinae of right and left eyes respectively in the method of binocular matching pioneered by Wright. Also, it is possible, as shown by the work of MacAdam, to maintain in different states of adaptation the retinal areas covered by the two halves of the monocular image of an ordinary bipartite field, the matching stimuli being applied in brief intermissions of the adapting stimuli. Despite considerable differences in technique and objectives, much of this work can be treated in a common framework.

Suppose that within each of two differently conditioned areas A and B the ordinary trichromatic principle is valid and that we know the two sets of empirical colour-matching functions that apply. These will be the same if the two areas have identical colour-matching properties, even though their conditions are different, because ordinary colour matches persist under different adaptations. We will allow, initially, that the colour-matching functions in the two areas may differ, even if only on account of some difference of macular pigmentation. An asymmetric match between two stimuli applied to *A* and *B* establishes a correspondence between their tristimulus values.

$$\begin{matrix} \{E_l\, dl\}\ in\ A \\ U_A = \int E_l\, \bar{u}_{Al}\, dl \\ V_A, W_A \end{matrix} \quad \begin{pmatrix} U_A \\ V_A \\ W_A \end{pmatrix} \leftrightarrow \begin{pmatrix} U^1{}_B \\ V^1{}_B \\ W^1{}_B \end{pmatrix} \quad \begin{matrix} \{E^1{}_l\, dl\}\ in\ B \\ U^1{}_B = \int E^1{}_l\, \bar{u}_{Bl}\, dl \\ V^1{}_B, W^1{}_B \end{matrix}$$

We cannot say that every stimulus applied to *A* can be matched by some suitable stimulus applied to *B*, or vice versa. Experiment shows that in general this is not possible, but nevertheless for a considerable domain of tristimulus space the usual kind of three-variable matching can be carried out. If, in this domain, enough experimental matches have been made to establish the characteristics of the correspondence, we have the raw material for testing possible mechanism concepts. As a first step we may suppose that in some sense the responses of three mechanisms in area *A* are being made equal to the responses of three corresponding mechanisms in area *B*. Each mechanism is envisaged as a chain of neural processes which is activated by the absorption of light in a selection of the end-organs in the retinal area concerned, and which transmits its response independently of other mechanisms to a higher level where it is brought in relation to a corresponding response from another retinal area. This doesn't get us very far unless we make more specific assumptions. The simplest is that all the end-organs belonging to a particular mechanism contain the same visual pigment. In that case, the mechanism's response to a stimulus is determined completely by the light absorbed in this pigment, i.e. by $J = j \int \rho_\lambda * E_\lambda\, d\lambda$, where j is the factor that converts relative to absolute absorption factors. This factor may in fact be different when the light absorption changes, if the matching stimuli are able to produce some bleaching.

Thus j is some function $\phi(J)$ of the amount absorbed, and this function will in general also contain parameters that represent the effect (constant) of the particular conditioning of the area. We obtain an equation for J: $J = \phi(J) \int \rho_\lambda * E_\lambda \, d\lambda$ whose solution depends only on $\int \rho_\lambda * E_\lambda \, d\lambda$. Thus in an area under fixed conditioning the mechanism's response is a function of J and hence of $\int \rho_\lambda * E_\lambda \, d\lambda$. As the pigment's relative spectral absorption factor is a linear combination of the empirical colour-matching functions, the same linear combination of the empirical tristimulus values of any stimulus will determine the mechanism's response to it.

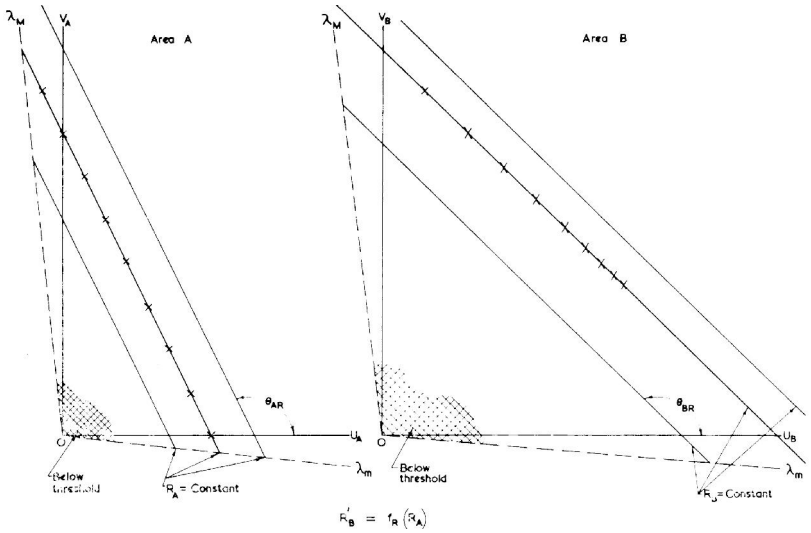


Fig. 1—Correspondence diagram for dichromatic asymmetric matching. For the case illustrated, the special directions θ_{AR} and θ_{BR} define families of parallel straight lines in A and B respectively, all points on one such line in A having their matched counterparts on a corresponding line of the B family. For parallel straight lines in A not in the direction θ_{AR} the corresponding lines in B (generally not straight) do not form a parallel family. (Single pair of special directions.)

But there are other possibilities. Each end-organ of the mechanism could contain the same *unvarying* mixture of two or three cone pigments, the absorption of a light quantum by any of the pigments initiating the same effect in the cone. Again the response would be determined by a linear combination of the tristimulus values, but now the coefficients would depend on the composition of the pigment mixture as well as on the spectral absorptions of the pigments. Current objective measurements of the spectral absorptions of individual cones provide little evidence of cones containing more than one pigment, but it is still a possibility. On the other hand, a single response mechanism may be equipped with end-organs, some containing one pigment, some another. Two cases must then be distinguished. The effects of light absorption in cones containing different pigments may combine linearly to produce

a common signal before any non-linear step in the mechanism's response chain is reached. This is the situation envisaged in many zonal theories of colour vision, and, given that the matching stimuli don't modify appreciably the pigment concentrations, the response is once more determined by a linear combination of the tristimulus values. While in ordinary colour-matching we can ignore the actual concentrations of the pigments in the end-organs and deal only with their relative spectral absorptions, this is not always so in interpreting the data of asymmetric matching. When the response of a mechanism depends on the light absorption of more than one pigment in mixtures or in separate end-organs, the absolute absorption factors, which may be modified by pigment bleaching, have to be considered. In addition the effects of light absorption in cones containing different pigments may be subject to some non-linear step before they combine to produce the mechanism's response. Thus mechanisms fall into two groups. Firstly, those of single-fundamental type with a unique relative spectral sensitivity, which may or may not coincide with the relative spectral absorption factor of a single pigment, but for which the response to a stimulus is determined by a linear combination of its tristimulus values. Secondly, mechanisms with more than one pigment in their end-organs, which, because of variations in the pigment concentrations or because a non-linear step intervenes, have no unique spectral sensitivity. For the second type, the response is still determined by the absorptions in the two or three pigments concerned, and, by an extension of the earlier argument, it can be regarded as a function of the stimulus integrals of the two (or three) relative spectral absorption factors : $\int \rho_\lambda * E_\lambda \, d\lambda$, $\int \gamma_\lambda * E_\lambda \, d\lambda$, $\int \beta_\lambda * E_\lambda \, d\lambda$. These, in turn, equal two (or three) independent linear combinations of the empirical tristimulus values. We may fairly describe the second group as mechanisms of multiple-fundamental type.

To illustrate correspondences graphically it helps to switch from a trichromatic to a dichromatic visual system. (Fig. 1). The points in the two half-diagrams represent stimuli applied to areas *A* and *B*, plotted from their empirical distimulus values (U_A, V_A) and (U_B, V_B) respectively. All real stimuli must be represented by points in the sectors defined by limiting lines $O\lambda_M$, and $O\lambda_m$, which will normally correspond to monochromatic stimuli at the two ends of the spectrum. If in area *A* there is a mechanism dependent on a single fundamental, its response to a stimulus will be fixed by a linear combination of the empirical distimulus values, which will be defined as the fundamental distimulus value of the stimulus, R_A say. All stimuli giving some fixed response will have their representative points on a straight line $R_A = const.$ and for different fixed responses the straight lines will be parallel. If in an asymmetric match the response of the mechanism is being made equal to the response of a corresponding mechanism in area *B* which is also dependent on a single fundamental, the match points in diagram *B* of all points on any line $R_A = const.$ in diagram *A* will lie on a straight line $R_B = const$, and these latter lines will also be parallel. Of course the spacing of corresponding points and lines will not generally be the same in the two diagrams. But if we can find a pair of directions, one in *A* and the other in *B*, defining two families of parallel lines with the property just described, we can conclude that in the asymmetric match we are equalising the responses of mechanisms in *A* and *B* respectively, each of single-fundamental type. There may be no such pair of spec:al directions, or there

may be just one pair or just two pairs, indicating a corresponding number of pairs of mechanisms of this type. The only other alternative is that there are indefinitely many pairs of special directions, and that to every direction in the *A* diagram there is a corresponding direction in the *B* diagram. This will be so if, at match, the distimulus values of the two stimuli are related by a fixed linear transformation, which is the necessary condition for the von Kries law of coefficients to be applicable. For the moment, however, suppose we have found in our experimental correspondence just two pairs of special directions. We can at once determine all four fundamental, spectral sensitivities, two for the mechanisms in *A*, from the slopes θ_{AR} and θ_{AG} of the special directions in *A* and the *A* colour-matching functions, and similarly two for the mechanisms in **B**. Also, from the positions of corresponding lines in the two diagrams, the functions (one of which is necessarily non-linear in this case) relating the responses of corresponding mechanisms at match are readily derivable: $R_B{}^1 = f_A(R_A)$ and $G_B{}^1 = f_B(G_A)$. Should any special direction drawn through the origin cut into the sector of real stimuli, it would mean that some real stimuli produced a positive, some a negative response from the mechanism, whose spectral sensitivity would then necessarily change sign in the spectrum and could not arise from a single visual pigment. This is the result to be expected if an opponent colour mechanism played a part in the asymmetric match.

If the colour-matching properties, and hence the colour-matching functions, are the same in the two areas, we should expect the fundamentals to be the same and the directions in each special pair to be parallel. If this was found not to be so, some change in the spectral sensitivity of the mechanism with change in its adaptation would be indicated. This couldn't happen if the end-organs of the mechanism contained just one pigment, but it might arise for other variants of the single-fundamental type. Non-parallelism of the directions in a special pair would be produced by a difference merely in the pre-receptor (e.g. macular) pigment in the two areas, but the colour-matching functions would not then be the same.

The notions developed for dichromatic vision are readily extended to the more practical case of trichromatic vision. Special pairs of directions are replaced by special pairs of planes and there are at most three such pairs, unless the number is unlimited, when the von Kries law of coefficients is valid. Much earlier and some recent experimental work is tied to this law and accepts that the tristimulus values in the two areas are related by a fixed linear transformation. Given this, and making the further assumptions that there are three mechanisms depending on single fundamentals, the same in the two areas, whose sensitivities are changed only by constant factors under different conditioning, a standard calculation leads to the fundamentals and von Kries factors. While this procedure sometimes yields fundamentals in general accord with pigment absorptions, applied to other data it gives complex solutions which are physiologically meaningless. The results of most later studies, notably those of Hunt and Mac-Adam, indicate that under their conditions the tristimulus values in the differently conditioned areas are not linearly related at match. From an intensive analysis of his own and other data, MacAdam has shown that the results can be well fitted by a non-linear scheme which is equivalent to adopting the following matching conditions :

$$a_{1A} + a_{2A}\left(R_A\right)^{a3A} = a_{1B} + a_{2B}\left(R^1{}_B\right)^{a3B}$$

$$b_{1A} + b_{2A}\left(G_A\right)^{b3A} = b_{1B} + b_{2B}\left(G^1{}_B\right)^{c3B}$$

$$c_{1A} + c_{2A}\left(B_A\right)^{c3A} = c_{1B} + c_{2B}\left(B^1{}_B\right)^{b3B}$$

The fundamental tristimulus values are computed from spectral sensitivities carefully chosen as most satisfactory in preliminary calculations on the data. Then for each pair of differently conditioned areas, the constants a_{1A}, a_{2A}. . . a_{1B}, a_{2B}, etc., were derived to give the best fit with the observations. MacAdam refrains from any physiological interpretation of his data fitting, but we may nevertheless look at his equations from the standpoint of mechanism concepts. Clearly they imply, for each area, three mechanisms of single-fundamental type with identical fundamentals in the two areas. Also if we assume that all the parameters with the *A* suffix depend only on the conditioning stimuli applied to the area *A*, all with suffix *B* on the conditioning of *B*, the equations give expression to an important principle of transitivity in asymmetric matching. This says that if we match a stimulus E_1 in area *A* under conditioning C_A with a stimulus E_2 in area *B* under conditioning C_B, and then, in another experiment, E_2 under C_B with a third stimulus E_3 in an area *C* under conditioning C_C, then, E_3 under C_C will match E_1 under C_A. If transitivity does not apply, our notions of mechanisms are much weakened. If it does, we have the valuable rule that the matching conditions must be capable of being written in the form of equations with all quantities relating respectively to the two matching areas on opposite sides of the equality sign. MacAdam's own colour adaptation data were obtained under conditions that seem rather favourable to a breakdown in transitivity, as the adapting stimuli were applied to juxtaposed areas of the same retina. In binocular matching, a breakdown could occur only at higher levels and is less likely.

The most significant parameters in the MacAdam expressions are the power indices, and, using all his material, he succeeds in showing how they depend systematically on the chromaticity of the conditioning stimulus. I shall not try to discuss this interesting dependence, except to note that it is the variation of the power indices with the conditioning chromaticity that is emphasised. In fact, for most of the data fitted, the asymmetric matches were between areas conditioned to stimuli of different chromaticity but not very different in luminance. Another situation arises when the conditioning is by white light stimuli of widely different luminance, as studied by Hunt. I will pick out one salient feature of his work, namely the quantitative picture it gives of the qualitative observation that, when we are adapted to higher brightness levels, colours appear more vivid, more varied. Hunt's data by the binocular matching method show that the chromaticities of stimuli expozed in the area adapted to the higher level are all displaced inwards in the chromaticity diagram towards a point somewhere near the white point, and that for stimuli in the higher level with chromaticities in an outer zone (the most saturated colours) no matches can be made, because all stimuli exposed in the lower level are too desaturated. As stressed by Hunt, the von Kries scheme is quite incapable of explaining this behaviour. Can mechanisms of single-fundamental type with power law response functions do so? Yes, if the power indices

are allowed to depend on the luminance as well as the chromaticity of the conditioning stimulus. To illustrate this, take a very simple power law with indices 2 and 1 for the high and low levels respectively, the same for all three fundamental tristimulus values as we are dealing with white conditioning. As Fig. 2 shows, the matching chromaticities at high and low levels yield the right kind of effect on saturation. But of course it would take a searching analysis of all Hunt's data—not yet done, I think—to establish that a suitable power law would be fully adequate.

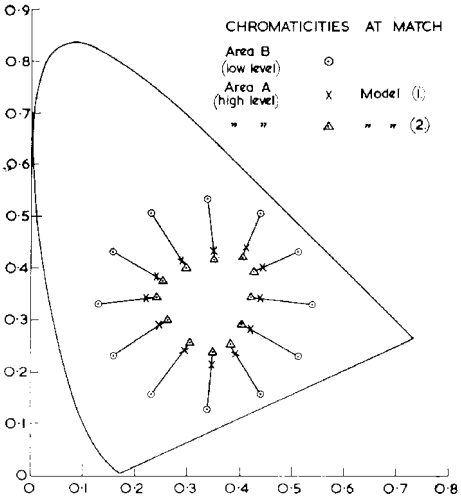


Fig. 2—Chromaticities of matched stimuli exposed in areas A and B, conditioned respectively to high and low levels of white light. Low level: selected chromaticities (Circle points). High level: corresponding chromaticities of the asymmetrically matched stimuli, (1) assuming single-fundamental mechanisms and the power law, $R_B = (k\ R_A)^2$, $G_B = (k\ G_A)^2$, $B_B = (k\ B_A)^2$ *(Cross points), (2) assuming multiple-fundamental mechanisms and the law,* $0.7 \log k\ R_B + 0.3(\log k\ G_B + \log k\ B_B) = \log R_A$ *plus two similar equations with the roles of the tristimulus 03 values interchanged (Triangle points).*

Moreover there are other models, more sophisticated because they do not assume mechanisms of single-fundamental type, but not unattractive on physiological grounds. A model of this kind put forward by Hunt assumes three mechanisms each of which receives signals mainly from end-organs containing one of the cone pigments, but subject to crosstalk, to some transfer of signals carried by the other mechanisms. Thus the final response in each mechanism depends on the absorption in all three pigments, and as the transfer of signals occurs in the neural stages after the almost certainly non-linear transducer process of the end-organs the final response is not determined by any linear combination of the empirical tristimulus values of the stimulus. Qualitatively this certainly can give the right kind of effect of brightness level on colour saturation. To go a little further, suppose that the non-linear step is equivalent to taking the logarithm of the light absorption in the end-organs containing a particular pigment. Put the final response in say the red-sensitive mechanism equal to a major contribution from the erythrolabe pigment, plus a smaller contribution from the other two pigments, i.e.:

final "red" response $= (1 - \alpha) \log R + \alpha (\log G + \log B)$

where a depends on the white conditioning level, and assume similar expressions for the response of the other mechanisms with the roles of *R, G, B* interchanged.

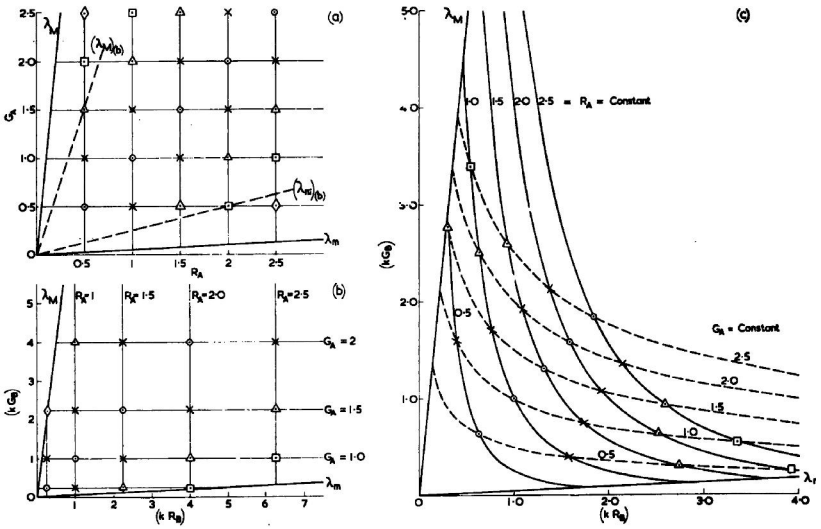


Fig. 3—Asymmetric correspondence diagram (dichromatic) for areas A and B adapted respectively to high and low levels of white light. (a) and (b) *Single-fundamental mechanisms with power law,* $R_B = (k\ R_A)^2$, $G_B = (k\ G_A)^2$. (a) and (c) *Multiple-fundamental mechanisms with the law* $\log k\ R_B + 0.5 \log k\ G_B = \log R_A$, $\log k\ G_B + 0.5 \log k\ R_B = \log G_A$. *Constant hue lines:* G_A/R_A = constant = H_A, G_B/R_B = constant = $H_B = H^2_A$. *All real stimuli exposed at the low level ((b) or (c)) are matched at the high level (a) by points in the sector* $(O\lambda_{M(b)}\ \lambda_{m(b)})$; *the constriction from the sector* $(0\lambda_M\lambda_m)$ *corresponds, in the trichromatic case, to the loss of saturation at low levels.*

Again, as shown in Fig. 2, the right kind of effect on saturation is reproduced when we put α=0.3 at the lower level, and α=0 at the upper. But when we consider the full specifications of the matched stimuli in terms of tristimulus values and not only in terms of chromaticities, the two simple models give radically different asymmetric correspondences. For an analogous dichromatic case, Fig. 3 shows the correspondence when the matching mechanisms are of single-fundamental type with power law response functions (diagrams (a) and (b)), and when they are of multiple-fundamental type with a response expressible as a mixture of the log signals (diagrams (a) and (c)). The axes used here are fundamental distimulus values, but transformations, in particular to the empirical distimulus values, show a no less striking difference in the patterns. The many matches required, especially in the trichromatic case, to determine adequately the correspondence diagrams, makes it less easy than might appear to distinguish the two types of mechanism, but in principle this can always be done. Potentially therefore there is much we can learn about colour mechanisms from asymmetric matching, provided we make enough matches, and an examination of the mechanism concepts themselves can be of value in the most economical planning of the matching experiments.

The ideas of mechanisms with single and multiple fundamentals are equally important in

the analysis of the data of chromatic discrimination. We have then the simplification that the mechanisms involved are all in one retinal area and subject to the same conditioning. The simplest conditioning situation is that used in the two-colour threshold method in which a comparatively large area of the retina is adapted to a uniform coloured field, and discrimination is studied by determining the increment threshold for a small coloured test stimulus applied at the centre, usually as a flash. The analysis of results by this method has been dominated by the notion of mechanisms each dependent on a single fundamental. Imagine such a mechanism acting alone. If, for fixed chromaticities of test and field stimuli, the variation of the increment threshold with the field intensity could be determined, the variation for any other test and field colours would be derivable from the mechanism's unique relative spectral sensitivity.

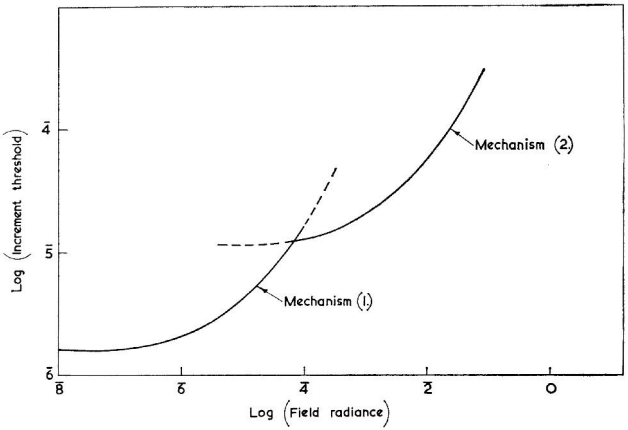


Fig. 4—Log (increment threshold) versus log (field intensity) for two single-fundamental mechanisms. (Based on the actual curves obtained for the green-sensitive (π_4) and the blue-sensitive (π_1) mechanisms in measurements using a blue test stimulus and a green field.)

In a logarithmic plot (Fig. 4) this means that a curve of fixed shape is displaced parallel to the axes of log (threshold) and log (field intensity) respectively, as test and field colours are changed. A second similar mechanism, acting alone, would give another fixed curve but subject to different displacements when the colours were changed because of its different spectral sensitivity. If, when both act, the resultant threshold is equal to the smaller of the individual thresholds, except perhaps for a small summation effect when the two are equal, it is possible to get characteristic two-branch threshold versus field-intensity curves. The observation of such curves for foveal vision of a 1/ test stimulus—so that there was no question of their representing a rod-cone transition—provided the starting point for the scheme of threshold mechanisms known as the Π mechanisms. Without going into details of these and their applications, I would say they have served to organise to a first approximation a mass of threshold data for colour fields extending in some cases to

intensities well beyond the limits of validity of the strict trichromatic principle. But later work has shown, in a direct way, at least one of their inadequacies. The earliest measurements on this point I made in 1959 while a guest worker at the National Research Council, Ottawa, and I would like to mention my indebtedness to Dr. Howlett and Dr. Wyszecki of National Research Council for the facilities given me and to my assistant G. H. Fielder. In Fig. 5 the plotted curves show the log reciprocals of the increment thresholds of the individual Π mechanisms for monochromatic test stimuli through the spectrum when the uniform adapting field is a high or low intensity green. (The shapes and positions on the ordinate scale of these curves derive from earlier work.) The log reciprocal of the resultant threshold should follow the upper envelope of these curves and for the subjects used this checked within expected individual differences. The main experiment was to measure the threshold for various mixtures of two monochromatic test stimuli to see how far the results were consistent with a scheme of mechanisms of this kind.

For a mixture of two wavelengths both on a section of the envelope provided by one mechanism, Π'_5 say, the mechanism integrates completely and at the threshold of the mixture the quantities of the constituent wavelengths are fractions adding up to unity if these quantities are expressed in un:ts equal respectively to the thresholds for the separate wavelengths. For an equal mixture these fractions are equal, and minus the logarithm of their values is defined as the summation index, equal in this case to 0.301. On the other hand, for two wavelengths in sections belonging to different mechanisms, the summation index will be smaller, as the mechanisms are assumed independent and can only collaborate in determining a resultant threshold by what is known as probability summation. This arises because the threshold corresponds to a fifty per cent chance of seeing the test stimulus, and, if two completely independent mechanisms each give a fifty per cent chance, the resultant chance is seventy-five per cent, corresponding to a lower threshold. From the steepness of experimental frequency-of-seeing curves it is found that because of probability summation the summation index cannot be less than 0.1 log units or a little more. In Fig. 6 are plotted measurements at the high field intensity of the summation index for pairs of wavelengths of which one is kept fixed at 640nm on the Π'_5 section while the other is varied through the spectrum. Despite inevitable scatter, the points are in tolerable accord with expectation when the second wavelength is also on the Π'_5 section, or when it is on the Π_1 section. The striking discrepancy occurs for intermediate positions around 530nm where the summation index drops to zero. This is inexplicable if the discrimination mechanisms are independent and each has a single, always positive, fundamental. The conclusion holds whether or not the properties ascribed to the Π mechanisms are accurate; no set of independent mechanisms with always positive spectral sensitivities can lead to a summation index less than 0.1 log units. Comparable anomalies occur in other similar data which include measurements by Boynton, Ikeda and Stiles in which the summation index for mixtures of a positive increment of one wavelength with a negative increment of another was studied. Some modification of the scheme of Π mechanisms must be made but the form this should take is not yet clear. In fact, these summation anomalies present a complicated picture.

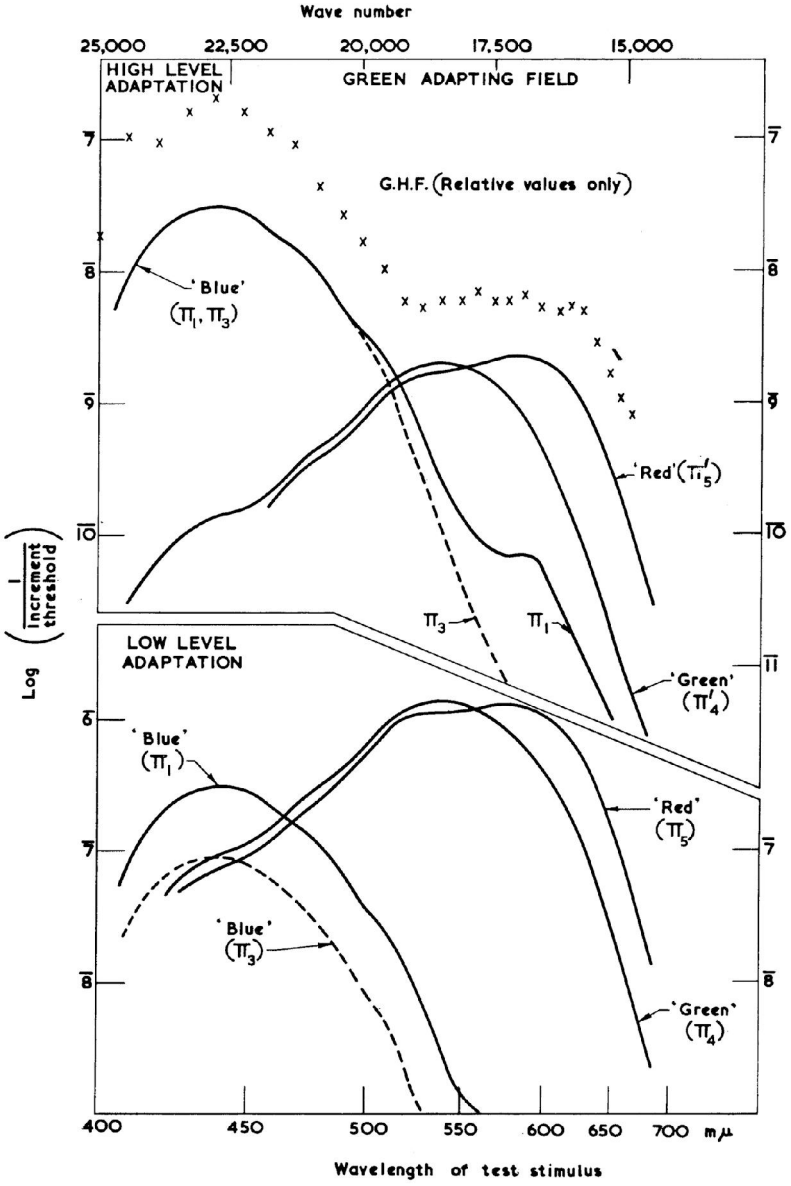


Fig. 5—Log (reciprocal increment threshold) versus test wavelength for the Π mechanisms adapted to unifrom green fields (filter band 510 to 630 n peaking at 555 nm) of approximate intensity of 30,000 Trolands (high). 200 Trolands (low).

For example, on reducing the intensity of the green adapting field to a much lower value, the anomaly disappears, and Ikeda has found that it is also absent if very brief increment flashes of about one hundredth of a second are used. It seems likely that two complicating extensions may have to be made. Firstly, differences in the signals transmitted by two main mechanisms may make an independent contribution to discrimination. This corresponds to introducing a supplementary colourdifferencing mechanism. Secondly—and this applies particularly to the red-sensitive mechanism—the effective spectral sensitivity to the test stimulus may differ from the spectral sensitivity to the adapting field. Clearly any acceptable modifications must continue to provide explanations of the data to which the scheme of II mechanisms has been successfully applied.

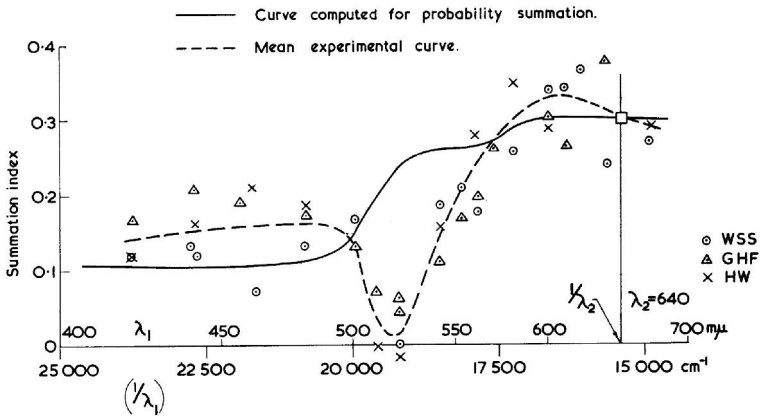


Fig. 6—Summation index for high intensity green field, and for test wavelengths λ_1=640 nm. (fixed) and λ_2 variable through the spectrum. Test stimulus: 1/, 0.2 sec.

The notion of colour-differencing mechanisms is already firmly entrenched in various formulae used to define equal steps in lightness-colour space, or in tristimulus space. These formulae, based on data such as the Brown-MacAdam discrimination ellipsoids, and on much earlier work by a variety of methods, refer to observational conditions which differ a good deal from those of the two-colour threshold method, and which allow a possible conditioning effect of a surround on a comparatively small discrimination area. Each of the formulae has its special interest and I shall touch only on one or two general points in their interpretation in terms of mechanisms. According to most formulae the condition for two neighbouring colours to differ by a fixed or threshold step is that the sum of the squares of three terms should be a constant, each term being dependent on the tristimulus values (*R, G, B; R+ΔR, G+ΔG, B+ΔB*) of the two colours (or on some of these values) evaluated for a special set of fundamentals which in some cases can be identified with the spectral absorption factors of the pigments. The terms correspond in effect to the contributions to discrimination of three independent mechanisms, which assist each other by probability summation to the extent represented by the sums of squares form. This form for just two

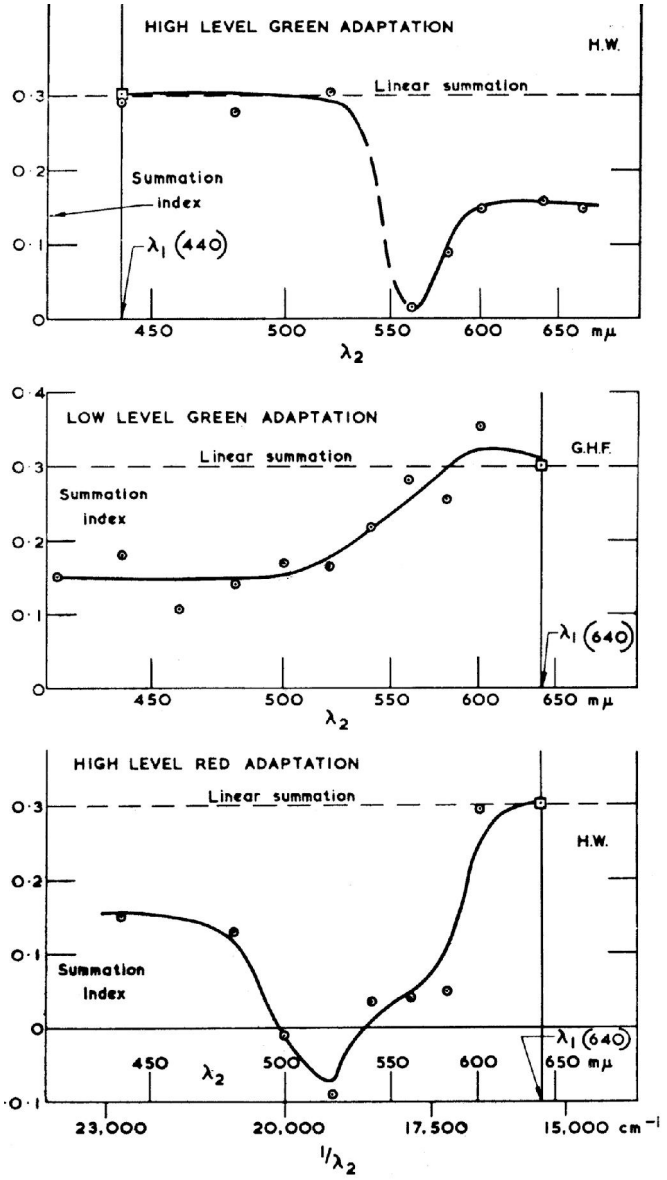


Fig 7—Other summation index measurements for 1/,0.2 sec. test stimulus.

mechanisms would correspond to a summation index of 0.15 log units which is a reasonable value. The way a term depends on the tristimulus values *R*, *G*, *B*, and the differentials *ΔR*, ΔG, ΔB (which normally enter only as first powers) implies certain characteristics of the corresponding mechanism. A term containing only one differential *ΔR* and the related tristimulus value *R* indicates a mechanism of single-fundamental type. Its response function will be some function of *R—F(R)* say—and neighbouring colours will generate a difference *ΔF* that will be seen if *ΔF* exceeds a threshold *T*. If the threshold is constant we obtain a term

$$\frac{\Delta F(R)}{T} = \frac{1}{T} - \frac{dF}{dR} \cdot \Delta R = f(R), \text{where } \frac{F(R)}{T} = \int^{R} f(R).dR$$

Thus given *f(R)* we can always find a response function *F(R)* associated with a constant threshold. If a term while still involving only one differential *ΔR* depends also on more than one tristimulus value, the response of the mechanism must still be a function of *R* only. But the threshold cannot be a constant nor dependent only on the mechanism's own response. A term with two differentials, *ΔR* and *ΔG*, and the corresponding tristimulus values *R* and *G* will be of the form: $f_R(R, G).\ \Delta R + f_G(R, G).\ \Delta G$. Its response function must be dependent on both *R* and *G - F (R, G)* say —but for the threshold there are two alternatives. Firstly, $f_R(...)$ and $f_G(...)$ may depend on *R* and *G* in such a way that with a suitably chosen response function *F(R, G)*, the associated threshold is a constant or is dependent only on the mechanism's own response : $T = T\{F(R, G)\}$. Alternatively f_R and f_G may be such that this is impossible and, however the response function is chosen, the associated threshold depends on *R* and *G* in a way that cannot be expressed in the form $T=T\{F\}$. This means, in effect, that the responses of the other mechanisms will contribute to determining the threshold. Finally, for terms involving all three differentials, the response must be a function of all three tristimulus values, and for the threshold there are similar alternatives to those of the previous case. If we cannot find a response function with which is associated a threshold whose value depends only on the mechanism's own response, the mechanism cannot be regarded as independent in the fullest sense. While independence corresponding to probability summation of the contributions to discrimination of several mechanisms may be retained, the fact that other mechanisms help to determine the threshold implies a degree of interdependence at some level. Physiologically this might mean in some cases no more than a spread of "neural noise" from the signals in different mechanisms.

Helmholtz's early formula for chromatic discrimination and my later modification both use three terms of the single-fundamental type. Another early expression due to Schrodinger has terms all of which imply mechanisms whose thresholds depend on the response of other mechanisms. Dr. Friele's first formula (see Table I), designed to represent the data of the Brown-MacAdam discrimination ellipsoids, has a lightness term *ΔL*, and a first colour-differencing term for both of which the response functions—F_1 and $F_2{}^1$—can be chosen so that the associated threshold is constant, although for the colour-differencing term a simpler response function—F_2—still with a threshold—$T_2(F_2)$—dependent only on the mechanism's own response, may be physiologically preferable. Friele's third term,

$$\Delta L = \frac{1}{0.030}\left(\frac{\Delta R}{R} + \frac{\Delta G}{G}\right)$$

$$F_1(R, G) = \ln R + \ln G;\ T_1 = \text{constant} = 0.030$$

$$\Delta C_{r\text{-}g} = \frac{1}{\beta}\left(\frac{\Delta R}{R} - \frac{\Delta G}{G}\right);\ \beta = \frac{0.015\,R^2}{R^2+G^2} \quad \text{for } R>G$$

$$= \frac{0.015G^2}{R^2+G^2} \quad \text{for } R<G$$

$$F^1{}_2(R, G) = \ln R - \ln G + Z;\ T^1{}_2 = \text{constant} = 0.015$$

$$\text{where } Z = \tfrac{1}{2} - \frac{G^2}{2R^2} \quad \text{for } R>G$$

$$= \frac{R^2}{2G^2} - \tfrac{1}{2} \quad \text{for } R<G$$

$$F_2(R, G) = \ln R - \ln G;\ T_2(F_2) = 0.015\,(1+e^{-2|F_2|})^{-1}$$

$$\Delta C_{y\text{-}b} = \frac{1}{\gamma}\left(\frac{\Delta R}{2R} + \frac{\Delta G}{2G} - \frac{\Delta B}{5.3B}\right);\ \gamma = 0.015 \quad \text{for } G<2.5B$$

$$= \frac{0.015G}{2.5B} \quad \text{for } G>2.5B$$

$$F_3(R, G, B) = \frac{\ln R}{2} + \frac{\ln G}{2} - \frac{\ln B}{5.3}$$

$$T_3(F_1, F_2, F_3) = 0.015 \quad \text{for } x<\ln 2.5$$

$$= \frac{0.015e^x}{2.5} \quad \text{for } x>\ln 2.5$$

$$\text{where } x = 5.3F_3 - \frac{F_2}{2} - \frac{4.3F_1}{2}$$

Table I. Terms of Friele's formula resolved into response functions and thresholds.

a second colour-differencing term, $\Delta C_{y\text{-}b}$, implies a mechanism whose threshold $T_3(F_1, F_2, F_3)$ depends on the response of all three mechanisms. Friele's formula has been used merely to illustrate a general point; an adequate interpretation of it and of Dr. Friele's later formulae would of course demand a much fuller discussion.

I have devoted this talk to simple mechanism concepts, and I think that to recall them from time to time is of value. But my concluding remark must be that the over-riding need in colour theory is more experimental data, determined under carefully controlled, and perhaps to some extent standardised conditions.

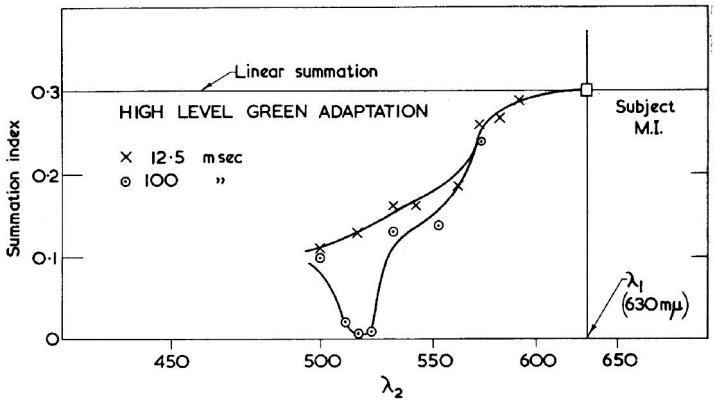


Fig. 8—Summation index for high intensity green field, λ_1=630 nm., λ_2 variable. Test stimulus: 10 min. diam., 0.012 or 0.1 sec. flash period. (M. Ikeda.)

Summer Visit

The Annual Summer Visit has become one of the social pleasures of the Colour Group and an occasion when, deserting the Lecture I heatre for the Real World, we see those centres of activity where colour problems are studied and solved. We also learn some curious and fascinating facts.

his year we were the guests of the Unilever Research Laboratories, Col-worth House, Sharnbrook, and once again there were wide interests other than Colour, though colour aspects were emphasised for us. The fine old house and modern blocks are in such spacious layout that it was hard to believe that two thousand work there. We were welcomed with coffee and an introductory talk by the Head of the Laboratories, Mr. K. Durham.

In Biology Division, products and constituents destined for contact with the human body, either as foods, cosmetics or detergents, are very rigorously tested for safety. Biological tests are additional to analytical tests. Hair dyes or their solvent media are not released until their effects on guinea pigs are completely known. It is not enough for food additives to be non-lethal. The slightest effects on laboratory animals are measured and translated into terms of the long-lived animal, Man. Subtle effects on activity are revealed by the movement of rats in rows and rows of cages, and registered by way of low voltage cage bars sending information to a data-processing unit with typewritten read-out. Meanwhile closed circuit television displays any cage at choice in Big Brother's office. So they think their little antics are unseen and they are not disturbed by an alien presence.

Consumer prejudice dictates that kippers must be brown, although improved methods do not produce the brownness of the older wood-smoking process without special

additives. Also sausages must be pink. Consequently a section is devoted to the testing of the brown and pink pigments both for colour and for safety.

Hospitality at lunch was worthy of a company so aware of the importance of both flavour and appearance. If Technology contributed to the excellence of the trout and the peas, Nature owed nothing to additives in the perfection of the strawberries.

From the dining room to the Food Technology Division was a short and logical step, and here the importance of colour is fully recognised. The sterilisation process for peas and the storage conditions for dried carrots and fresh meat must be controlled to preserve an appetising colour. Rice boiled in a glass container is much whiter than that from an aluminium vessel. It is not enough for potato chips to be delicious; like Justice they must also be seen to be so. So watch the quality of frying oil.

In Animal Research Division consumer prejudice is again taken very seriously, and even its geographical vagaries are devotedly studied. In France egg yolks must be orange in colour. In this country a mid-yellow is preferred, and in the United States a pale yellow. The flesh of the broiler fowl, however, must be as white as possible here but yellow in the United States. An international company producing poultry food must cater separately for all these needs. Annatto, the food additive controlling these colours (and also, incidentally, the colorant for margarine), is assessed in this division.

All Colour Group members who were present will be grateful to the Directors and Mr. Durham and his staff for making this visit such a pleasure and so instructive. On my way back to London I thought how glad we should be that our safety is in such good hands, but shall I confess to some misgivings? Should the country's precious scientific manpower be used to reinforce prejudice with respect to the colour of the kipper and the egg-yolk? Shall we tie another generation to the old memory of the wood-smoking days? M. MORRIS.

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