Simultaneous Colour Contrast.

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The subject of colour contrast presents exceptional difficulties because of the number of factors to be taken into consideration. It is necessary to eliminate the effects of successive contrast. Many of the results which have been put down to simultaneous contrast are really due to successive contrast. The surfaces to be compared should either be viewed by a flash of light of very short duration or by one eye which is kept rigidly fixed upon a definite point.

In a series of important papers Hering* has shown that the explanation of contrast given by Helmholtz is not tenable. I hope to show that another explanation is possible which is even more in accordance with the facts. I propose to review some of the experiments of Hering and to show that in conditions in which, according to the requirements stated by him, colour should be visible no colour is to be seen.

In experiments on simultaneous contrast it is necessary in order to avoid effects of luminosity contrast to have the two surfaces as nearly as possible of the same luminosity. It is also necessary in dealing with mixed colours such as those formed by the light reflected from pigments to take into consideration the effects of chromatic aberration. When a surface reflects lights of different wave-lengths these lights are not all brought to the same focus on the retina. Diffusion circles will extend on both sides of the image of the coloured object on the retina and will influence the colour of another image immediately adjacent. I have made a mosaic of small pieces of coloured cardboard and the effect of the mixture of lights is very noticeable. In general each colour differs as it would do if the other colour had been objectively added to it. These colour changes have been mistaken for effects of simultaneous contrast.

Coloured Shadows.

In the classical experiment which has been the subject of so much discussion an opaque object is placed upon a white surface and illuminated on one side by daylight and on the other by a candle or petroleum lamp.

* 'Pflüger's Arch.,' 1886, 1887, 1888.

By moving the candle the relative luminosities of the two shadows can be so adjusted as to appear similar in brightness.

The shadow thrown by the candle and which is illuminated by daylight appears blue, whilst that formed by the daylight and illuminated by the reddish-yellow candle light appears yellow. It will be noticed that the shadow of the candle which is illuminated by white daylight is really grey, as it is only illuminated by a white light. Helmholtz and Hering therefore have referred to the blue coloration of the shadow as the subjective blue. I propose to show that the blue coloration of the shadow is relatively objective blue in the circumstances of the experiment.

It must be noted that the white surface on which the opaque object is standing and which is free from any shadow is illuminated by both daylight and candle light. Though it is still considered as a white surface it is really objectively yellow, to the extent of the added amount of candle light in the total amount of candle light and daylight which is reflected from the white surface, the degree of objective yellowness amounting to the difference between candle light and daylight in the proportion of the two. The blue shadow is therefore relatively blue in comparison to this white surface reflecting both lights when this surface is set up as a standard of white. In the same way the yellow shadow is relatively yellow in comparison to the whole surface. It must be noticed that daylight is not a fixed unalterable white but differs considerably according to the time of day and source; the light reflected from the sky is much bluer than that of direct sunlight.

All our estimations of colour are only relative and formed in association with memory and the definite objective light which falls upon the eye. In many of the most striking contrast experiments the colour which causes the false interpretation is not perceived at all: for instance if a sheet of pale green paper be taken for white a piece of grey paper upon it appears rose-coloured, but appears colourless when it is recognised that the paper is pale green and not white.

If, in repeating the experiment with coloured shadows, the opaque object be placed upon a dull black surface and two pieces of white paper be placed on this surface for the shadows, care being taken that these pieces of paper are the exact size of or smaller than the shadows, these will appear blue and yellow as before. If we now place a small dot on the paper on which there is a blue shadow and having covered one eye keep the other rigidly directed at this black spot whilst an opaque object is placed in front of the candle so that it no longer illuminates the paper or throws a shadow, both pieces of paper will appear white, being illuminated only by white daylight. The eye being still kept rigidly directed on the spot on the paper, the opaque

object is removed so that the candle again throws a shadow on the paper. The shadow thrown by daylight immediately appears yellow and of greater saturation than before, but the shadow thrown by the candle appears white, as before, and without the faintest trace of a blue colour. The conditions are in every way favourable to the development of the blue colour, but none appears because the observer has been able to form a correct estimate of white. If the blue colour were a real subjective coloration caused by the yellow, blue should appear on the shadow from the candle.

The second experiment which is considered by Hering is that in which a small piece of grey paper is placed in the centre of a large square of coloured paper, and the whole is covered by a thin piece of tissue paper. The centre grey square becomes tinged of the complementary colour of the larger square on which it is placed. This experiment succeeds best when the colour of the ground is green. The grey paper is then tinged with the complementary colour, rose. This experiment, like most others of simultaneous contrast, has its effect much heightened if successive contrast be allowed to influence the result. In successive contrast the eye becomes fatigued for the colour particular to the rays of light which fall upon it.

I agree with Burch* that fatigue of the eye for any one colour does not increase its sensitiveness for any other colour. For instance, if the eye be fatigued for yellow the blue of the spectrum is considerably diminished, not increased. This is probably due to luminosity contrast. In the above experiment, therefore, it is very important that the eye should not see the grey square after having observed the green, as in that case it will be tinged with rose colour from successive contrast, because the eye has become fatigued for the green constituent of the white light reflected from it.

As is well known, the rose coloration is greatly diminished by using black or white instead of grey, or by isolating the grey square by drawing a black line round it. If, however, taking the greatest care that the eye be not moved, by steady fixation of the eye upon a black spot in the centre of the square for 10 seconds, and then looking at a sheet of white paper, a definite after-image is seen, a large rose-coloured square corresponding to the green paper, and a small green square in the centre corresponding to the small grey square, it will be noticed that the rose rapidly encroaches on the green, which disappears, whilst a rapid whirlpool appearance is seen in the centre of the field of vision. This experiment would seem to support strongly the view of Hering that the rose colour is actually subjectively produced on account of the proximity to green. I hope,

* 'Phil. Trans.,' B, 1899, p. 5.

however, to show by a simple experiment that this cannot be the explanation.

Let us consider the factors of the experiment when a grey patch upon a whitish-green ground is under observation: the objective light reflected from the grey patch differs from that on the green ground chiefly in containing less green, that is to say, the light is relatively and objectively rose-coloured in comparison with the whitish-green ground. The white light for this purpose may be divided into two portions, one of which is green and the other is a mixture of the remaining constituents of white light, which give rise to a sensation of rose. If a small portion of the common constituent green be deducted from both the whitish-green and the white the green will appear less saturated, and the white will appear rose. In this case the white light will be objectively rose in comparison to the green. It will be seen, therefore, that there are two ways in which the two coloured surfaces may be objectively considered. If the green be considered of less saturation than it really is, that is to say, a whiter colour, then the white will be rose in comparison with it, but if the white be considered white then the green will be objectively of greater saturation in comparison with it.

A simple experiment which I have devised for the purpose decides this point. If, when the grey square is situated upon the larger green square, another square of white paper of a size midway between the two other squares have a hole corresponding to the size of the small grey square cut in it, on laying this white paper so that the opening corresponds with the grey paper, the grey square will be seen without a trace of colour. A mark should then be made on the extreme left of the grey paper, and whilst one eye is kept rigidly fixed upon this spot the white square is gradually moved to the left until the field is occupied half by the whitish-green ground and half by the grey ground. It will be noticed that the green is greatly increased in saturation, and that not a trace of rose is visible upon the grey ground. If the right eye be kept fixedly upon these two surfaces for ten seconds, and then be directed to a white surface, a brilliant rose-coloured after-image, much brighter and more saturated than the one that was previously visible, and a pale white after-image, without a trace of colour corresponding to the grey region, will be seen. If the colour were really subjectively produced in the retina it should appear in this experiment as in the other. It might be thought that the increased saturation noticed in the green was due to the luminosity contrast of the white paper, but exactly the same result may be obtained with black paper, the green, when uncovered, appearing much more saturated, and the subsequent

after-image formed on the white ground is rose colour for the green portion and dark grey for the white portion. In this case, as with white paper, not a trace of green is seen in the after-image of the grey.

A simple experiment described by Waller* illustrates this relativity of perception very well. If a strip of grey paper be placed upon a sheet of white paper, and then a piece of green paper be placed on either side of the middle third of the grey paper, and the whole covered with a piece of tissue paper, no contrast colour, or very little, will be visible. If, now, the middle third of the strip of grey paper be isolated by means of two pins placed transversely, the middle third becomes strongly tinged with the contrast colour, rose. On repeating this experiment, I find that, when the grey strip is seen as grey, the after-image is also grey, but when it is seen as rose, the after-image is green, and the rose after-image of the green appears less saturated. Also, when the contrast colour is developed, the objective green appears less saturated than when the grey strip appears grey.

A definite amount of saturation is necessary before a colour can be recognised. This colour becomes much more marked on contrast. A tinted paper which appears pure white without comparison may, when laid on a pure white surface, appear very definitely coloured. If a square of cream-coloured paper be placed on a white ground, it will appear of a decided pale yellow; the colour of the white ground will, however, not be altered. If the after-image of this paper on a white surface be examined, it will appear as a pale blue square on a white ground, but no adjacent yellow is to be seen. The estimation of colour is always relative; for instance, if a pale yellow diamond be given to a man, who has to classify diamonds, as a standard white, he will classify the pure white diamonds as blue, and not sufficiently estimate the amount of yellow in those diamonds which are yellow.

Our power of discrimination of colours is much more limited than is usually supposed. I have shown† that most persons can only differentiate about 18 separate regions in a pure spectrum, and that if one of these regions be examined with a double-image prism, so that the red side of one image be adjacent to the violet side of the other, no difference will be detected. Here we should expect that, if any colour induction were produced, an immediate difference would be observable between lights which are objectively so different.

In examining the two images, the greatest care should be taken to have them both of the same apparent luminosity. It will be noticed that, when the images are of different luminosity, the hue is also different. Both

* 'Journ. Phys.,' 1891, p. 44.

† 'Roy. Soc. Proc.,' B, 1911, p. 116.

images appear monochromatic in themselves, but different in hue and luminosity. This is particularly noticeable in the blue-green region of the spectrum, as this is one of the portions of the spectrum in which the monochromatic divisions possess the fewest wave-lengths. The images are, however, larger, because of the increased separation of the wave-lengths in this region. When viewed with the double-image prism, a monochromatic division shows two monochromatic images side by side, and exactly similar in every respect when the intensity of both is similar, but, if the intensity of one be greater than that of the other, one will appear definitely blue and the other definitely green. I am inclined to think that Prof. Watson's results* are due to this cause, especially in association with stray light of different wave-lengths.

This method is one which enables us to study very accurately the effects of simultaneous contrast. A monochromatic region can be viewed with the double-image prism, so that it appears as two images with a small space between. One of the shutters of the spectrometer can then be moved, so that the two images increase in size and just touch. It will be noticed that the effect of contrast is most apparent at the edges—for instance, if a yellow region be observed, one edge appears green and the other adjacent edge appears orange. The whole of the image appears to be altered, that is to say, the image at which the orange edge is seen appears to be more yellow throughout, and the green one more green throughout. Each appears as if it were moved further from the other in the spectral range. We can, however, make the same wave-length appear as different colours in the following way:—If a monochromatic region be isolated, for instance, yellow, no difference being detected, the whole of the wave-lengths occupying this region appear yellow. If, however, we take the wave-length occupying the central position of the region and move the shutter on the green side until it occupies this central position, we can then move the shutter on the red side until a fresh monochromatic region is observed. This appears absolutely uniform in colour, but the colour appears orange-yellow instead of yellow, including that portion that was previously seen as yellow. We can now move the shutter on the red side till it occupies the centre of the first-mentioned yellow region, and then, extending the shutter on the green side, form a fresh monochromatic region. The colour will appear absolutely uniform as before, but it has now changed, and the whole has become greenish-yellow.

The contrast colour is most developed when the surface on which it is seen is small and situated on a large surface of very pale colour which it

* 'Roy. Soc. Proc.,' B, 1911, p. 118.

is difficult to recognise as coloured without special comparison with a known white surface, as, for instance, if a small piece of grey paper be placed upon a large piece of very pale green paper. If the paper be regarded as white, the light reflected from the grey paper must be regarded as rose, for the subtraction of the small quantity of the green light from the light of the pale green paper in order to make this white is sufficient, when subtracted from the white light reflected from the grey paper, to make this appear rose. When it is recognised that the green paper is not white the contrast colour disappears, and the grey paper is seen as grey. The contrast colour is most developed on grey paper, and not nearly so well, if at all, on white or black paper. It is therefore produced in exactly those conditions in which the subtraction of a small quantity of green light will be most effective in altering the appearance of the colour. It is well known that in most contrast experiments, if a direct comparison be made with a known white surface, the contrast colour disappears. There is no reason why this should occur if the contrast colour were an actually induced colour.

My conclusion, therefore, is that the contrast colour developed in simultaneous contrast is due to the perception of an actual objective relative difference—in fact, the greatest difference which is perceptible in the circumstances, white being not a fixed objective quality, but a sensation produced by admixture of light of certain wave-lengths. If the sensation of one colour induce that of the complementary in the adjacent portion of the retina, there are many circumstances in which the colour ought to be visible and yet is not found. I have never yet, for instance (excluding negative after-images), seen the faintest trace of green on the dark surfaces in a photographic dark room illuminated by a pure red light. Neither have I come across any other person who has seen green in these circumstances. On coming out of the dark room white objects only appear slightly tinged with green, if any change be noticed at all. Not the faintest trace of green is to be seen round red lights at night, and I find the greatest difficulty in obtaining an after-image even by staring fixedly at the red light, if this be not of considerable intensity.

The subject of induction of colour by simultaneous contrast can be investigated in another way, that is by entirely eliminating red or any other spectral colour and then studying the effects of simultaneous contrast. This may be accomplished by viewing objects through coloured glasses which are opaque to light of certain wave-lengths. In the case of red light we can use blue-green glasses, which are impermeable to the red rays. I have therefore had a pair of spectacles glazed with blue-green glass. This blue-green glass is absolutely opaque to the red rays from the termination of the

spectrum to λ 646. There is considerable absorption from λ 646 to λ 588. The yellow rays are partially obstructed, whilst the glass is practically transparent to the green, blue, and violet rays. When objects are viewed through these spectacles not a trace of red is to be seen either directly or by contrast. An ordinary coal fire appears to consist of only yellow or yellow-green flames, no orange or red being visible. The yellow light of the spectrum or a yellow object adjacent to a green one still appears yellow, and the colour appears if anything to incline towards green rather than red. Reds appear black, or in a very bright light, and when they reflect orange rays, a dull brown. Yellow, green, blue, and violet can be seen through the blue-green glasses. White objects at first appear blue-green, but after a short time again appear white. Objects corresponding to the dominant wave-length of the blue-green glass appear white or pale blue or pale green according to the composition of the colour. All contrasts are modified in a similar manner. For instance a grey square on a green ground, in circumstances which give a bright rose contrast colour, appears pale blue through the blue-green glasses, and a grey on a blue ground yellow-green. No colour is seen the light of which cannot pass through the blue-green glass. Sir W. Ramsay, whose vision on my classification* is trichromic (that is he describes the bright spectrum as consisting of red, red-green, green, green-violet, and violet), examined my series of contrasts through the blue-green glasses and in no instance called yellow red. He rather tended to call yellow yellow-green, or, to use the term which he prefers, green with a very small amount of red in it. It would appear, therefore, that the exaggerated simultaneous contrast which I have found to be characteristic of these cases is not found in the absence of the objective exciting light.

These facts point to the conclusion that the sensation of red is not produced by simultaneous contrast in the absence of objective red light. They also support the conclusion at which I had previously arrived from the study of colour fatigue† that yellow is a simple sensation and not compounded of a red and a green sensation. I can also find no evidence of the induction of colour by simultaneous contrast in the absence of objective light of that colour.

Summary.

1. The colours seen by simultaneous contrast are due to the exaggerated perception of a real, objective, relative difference which exists in the light reflected from the two adjacent surfaces.

* 'Hunterian Lectures on Colour Vision and Colour Blindness,' Kegan Paul and Co. 1911, p. 24.

† 'Trans. Ophth. Soc.,' 1909, p. 211.

2. A certain difference of wave-length is necessary before simultaneous contrast produces any effect. This varies with different colours.

3. A change of intensity of the light of one colour may make evident a difference which is not perceptible when both colours are of the same luminosity.

4. Simultaneous contrast may cause the appearance of a colour which is not perceptible without comparison.

5. Both colours may be affected by simultaneous contrast, each colour appearing as if moved further from the other in the spectral range.

6. Only one colour may be affected by simultaneous contrast as when a colour of low saturation is compared with white.

7. When a false estimation of the saturation or hue of a colour has been made the contrast colour is considered in relation to this false estimation. That is to say the missing (or added) colour is deducted from (or added to) both.

8. A complementary contrast colour does not appear in the absence of objective light of that colour.

9. The negative after-images of contrasted colours are complementary to the colours seen.