white
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WHITE OR YELLOW LIGHT FOR VEHICLE HEAD-LAMPS?

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white or yellow lights for vehicle head-lamps?

Arguments in the discussion on the colour of vehicle head-lamps

INSTITUTE FOR ROAD SAFETY RESEARCH SWOV

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Foreword

He who unsuspectingly poses the question whether white head-lamps are better than yellow ones should be prepared to a variety of opinions.
For there are a lot of supporters and opponents to yellow light, who have been disputing this matter for years.
Supporters of yellow light mostly mention as advantages of yellow light that it penetrates better through fog and that it causes less glare.
To make an attempt to end the dispute of white versus yellow head-lamps a research has been carried out as complete as possible to the validity of all arguments that have been put forward in the literature about this subject in the course of time.
This publication has been written bij dr.D.A.Schreuder.

E.Asmussen
Director Institute for Road Safety Research SWOV

Summary

The problems of the use of filtered (yellow) incandescent light or unfiltered (white) light are approached from different angles.
Filtering of blue light emitted by an incandescent lamp with the purpose of effecting a yellow light results in a loss of some 15% in luminous output.
In the summer of 1971 approximately 15% of the cars in the Netherlands were fitted with yellow head-lamps.
There is reason to believe that the presence of yellow head-lamps is determined by the equipment supplied by the manufacturer rather than the personal preference of the owner of the vehicle.

A number of physical aspects are discussed that have to do with the question whether yellow light or white light is to be preferred for vehicle head-lamps.
Firstly the optical image in the human eyes is discussed. Although the images are far from perfect, resulting from the structure of the eye, and although effects such as diffraction, refraction and light scatter in the ocular media would suggest a colour-dependency, it turns out that such a dependency, if present at all, is quite inconsiderable. It is likely that this is the result of the fact that several effects mentioned here do counteract each other.
Light scatter in the atmosphere as present in haze and mist depends upon the wavelength. Light with long wavelenght (red light) is scattered less than short-wavelength light (blue). This effect might have some importance for aviation; for road traffic, how ever, it can be neglected. Firstly because the difference between (filtered) yellow light and white light is very small indeed. Secondly because in haze and mist the visibility is still rather good. In fog, however, when the visibility is reduced in such a manner that road traffic is impaired, the light scatter does not depend upon the wavelength.
One may conclude that the physical phenomena do not give raise to arguments in favour of either white or yellow light.

Further a summary regarding the composition and function of the human visual system is given. It deals with the anatomy and physiology of the retina, and in particular with the duplicity theory and the distribution of rods and cones over the retina. It appears that photopic (and up to a point high mesopic) vision is also of importance in night time road traffic. Furthermore the pupil is being dealt with. However, there seem to be no grounds for giving preference to either of the two colours under consideration.
Contrast sensitivity and visual acuity are dealth with in detail. Although some differences between the two colours can be indicated there is no consistent preference for either of them. Besides, all differences are too small to carry any weight as far as night time road traffic is concerned.

Finally, the perceptibility of signal lights is discussed. Under extreme circumstances

that are of no significance to road traffic, the colour dependency of the threshold value proves to be considerable. Few useful data are available as regards the colour dependency of the speed of perception.
The glare and the re-adaptation closely related to it are dealth with in detail. In this connection also a few slight and inconsistent differences between the two colours have been reported, which however do not affect road traffic.
Finally attention is paid to the consequences of ageing. As a rule visual performance declines as age advances. However, there is no material indication that the extent of this decline depends on the colour of the light.

The psychology of perception does not give any useful indication for a preference for any colour for the situations prevailing in road traffic. Some side-effects, notably the psychological glare (discomfort glare), present some preference for yellow light. There is, however, little ground to expect this small difference in discomfort glare to have any appreciable effect on road safety. It may be noted that this (small) advantage of yellow light is hardly mentioned in the literature, not even by the protagonists of yellow light. Although the recognition and the perception of signalling lights might depend upon the colour of light, the difference in colour under consideration here is far too small to be used as a coding dimension.
And finally, there is no reason to believe that fatigue is influenced by the colour of light.

Conclusions

The question as to whether the use of filtered (yellow) incandescent light for vehicle head-lamps should be preferred to the use of unfiltered (white) light has been approached from different angles, mainly based on data published in literature. The most important conclusions are summarised. For the sake of brevity, they will be referred to as 'yellow' and 'white' light.

1. In the summer of 1971 approximately 13% of the cars in the Netherlands were fitted with yellow head-lamps.
2. There are reasons for assuming that the use of yellow head-lamps depends more on the equipment supplied by the manufacturer, than on the personal preference of the owner of the car.
3. By filtering out part of the blue component of the incandescent light (in order to obtain a yellow light) a loss in luminous flux of about 15% is incurred.
4. Chromatic aberration of the lens of the eye, and the diffraction at the edge of the pupil, depend on the wave-length. Since these two phenomena produce opposite effects, no noticeable influence on visual perception results therefrom.
5. On the basis of the distribution and functioning of the photo-receptors in the retina of the eye no arguments can be found in favour of either yellow or white light.
6. Yellow and white light display equal contrast sensitivity.
7. The static visual acuity is almost identical for yellow and white light.
8. There is some difference of opinions concerning the effect of the colour of the light on glare and the time of recovery after glare. Most research workers assert that there is no such effect. Should there be some effect, it would be certainly negligible.
9. No arguments can be found in favour of either yellow or white light, on the basis of the influence of age and its effect on the visual system.
10. The small differences in visibility which were found when comparing yellow and white light and which cannot be clearly interpreted, have no practical relevance.
11. In haze, yellow light is scattered to a lesser extent than blue light. However, the advantage provided by the yellow light in this respect has no importance for road traffic.
12. Light scatter in fog does not depend on the wave-length. This is valid for all kinds of fog which could affect road traffic.

In view of all the factors for perception, which might influence motorised road traffic, the colour of light is unimportant. Yellow and white light are equivalent.

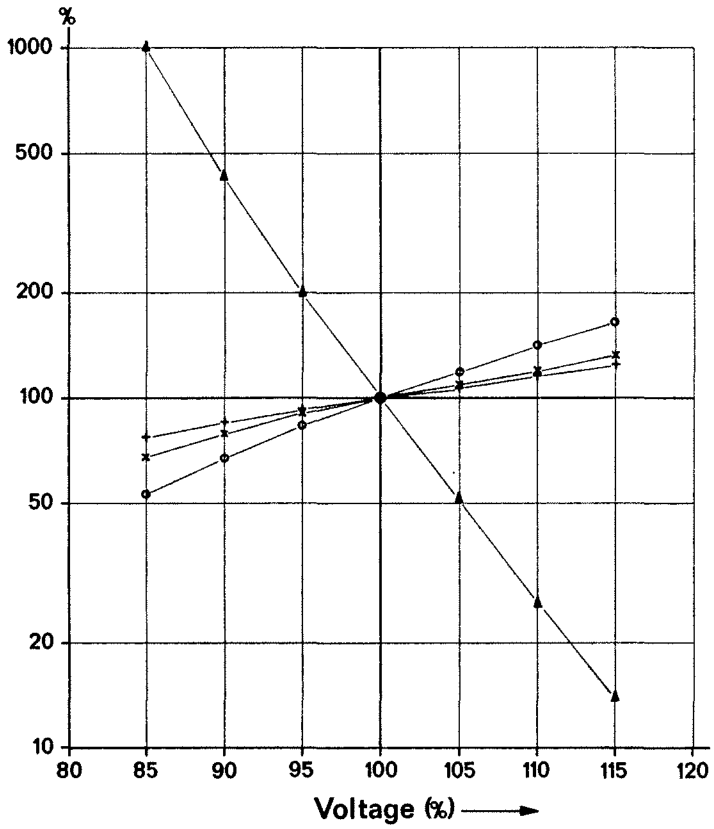
1. General aspects

1.1. Introduction

The question, as to whether cars should be fitted with yellow or white head-lamps, has been discussed for many years. At the beginning the discussions were mainly between specialists in the scientific press. However, when the scientific arguments were essentially exhausted, the discussions were continued in the general press; in spite of the fact that scientific investigations clearly proved that if there were any differences between yellow and white head-lamps, they were of little importance in relation to road traffic, and therefore could be neglected.
The present situation is that yellow car head-lamps (of a precisely defined type) are compulsory only in France. In some countries, for example Germany, yellow head-lamps are banned, while in a number of countries, including the Netherlands, Belgium and Great Britain, both colours may be used.
It should be pointed out, that in the Netherlands both head-lamps must be the same colour (WVR, 1950). As a result of an investigation by SWOV it can be estimated that about 13% of the cars in the Netherlands are fitted with yellow lamps. It is possible that the differences between the larger majority of white lamps and the smaller, yet still significant minority of yellow lamps contribute to the fact that the question – 'yellow or white head-lamps' – receives so much attention in the Netherlands.
It is typical of the discussions, which arise from time to time, that, on the one hand, the arguments are mainly of an emotional character, yet, on the other hand – (due evidently to the underlying problems not being sufficiently understood) various factors are neglected. Thus, for example, the yellow light of car head-lamps is often compared with the yellow light of sodium lamps. Finally, arguments are sometimes persistently raised, which are not based on fact, for example regarding the usefulness of (yellow) sun glasses, for reducing glare; and the advantages of yellow light for penetrating mist.
The object of the following chapters is to clarify once and for all the situation. For this purpose the validity of arguments for and against yellow light, put forward during the years, is assessed on the basis of the relevant literature.
These appraisals confirm the opinion referred to above, that yellow and white head-lamps are equivalent as regards traffic safety, although some people steadfastly maintain a contrary opinion.

1.2. Incandescent lamps

Incandescent lamps belong to the class of temperature radiators, in which an element is heated to such a high temperature that visible radiation is emitted. In electric incandescent lamps a tungsten filament is caused to glow by the conversion of electrical energy to thermal energy. In incandescent lamps a change in voltage results in a change in temperature. As an example, Figure 1 shows the relationship between the relative



○ = luminous flux
× = light output
+ = power input
▲ = life

Figure 1. Effect of the variation of Voltage.

values of luminous flux, power input, etc., and the voltage for a normal incandescent lamp. The sharp reduction of life with increasing voltage is very marked. This is the result of the rapid increase of vapour pressure of tungsten, in the neighbourhood of its melting point. The ultimate maximum output of incandescent lamps is determined by the melting point of tungsten. The output depends, to some extent, on the construction of the lamp, but it does not amount to more than a few per cent of the theoretical maximum. Expressed in terms of specific luminous flux, the output is about 10–25 lumen/watt, the theoretical maximum being about 630 lumen/watt.

In car lamps a low voltage supply is used, mainly 12 volts, but 6 or 24 volts is also sometimes used. As a result the coils of the spiral filament can be closely spaced, and the incandescent filament itself can be short and thick. Due to this, the incandescent elements fitted in the car head lamps can be small in size, which is very advantageous to control the light, by means of lenses and/or reflectors.

1.3. The 'yellow' incandescent lamp

It is essential that incandescent lamps for 'white light' can be converted to emitting 'yellow' light only by filtering out part of the shorter wave-length light.

This means that a yellow incandescent lamp is a normal incandescent lamp provided with an external filter (applied separately, in the form of a yellow layer over the cover-glass, or consisting of a lamp bulb made of yellow glass). All other factors concerning light source dimensions, switching ability, etc. are identical to those of white lamps.

Filters, used in order to produce yellow light emission, are, as a rule, so-called cut-off filters. These filters have good light-transmission (in the neighbourhood of 100%) for the long wave-lengths, but are opaque (or nearly opaque) to the short wave-lengths. The transition can be quite sudden and the wave-length at which absorption becomes effective can be adjusted within wide limits by suitable manufacturing processes.

Thus, yellow light is obtained by absorbing the blue light emitted by the incandescent filament by means of a suitable filter. The blue light evidently, cannot contribute to illumination anymore, and as a consequence, the total luminous flux emitted by a lamp provided with a filter is less than that emitted by the same lamp with no filter. This loss can best be illustrated by placing the same incandescent filament lamp alternately in a clear and a yellow bulb, assessing the total lumen output. If the bulb of the lamp consists of yellow glass, it is not correct to calculate the reduction of the light value simply in accordance with the spectral transmission of the glass filter, since a clear cover-glass does not transmit all the light either.

Literature provides various values for the light loss for yellow bulbs. Based on laboratory measurements Reading (1966) established a relationship between the (photopic) luminous fluxes for yellow and white bulbs, amounting to $\emptyset_g/\emptyset_w = 0.82$ for the same nominal wattages. Devaux (1970) mentions total transmission factors for two cases, of 0.75 and 0.83. Hartmann (1959) established a transmission difference of 1% for a common yellow filter as compared to that for a clear glass, while he found a difference of 10–20% for cut-off filters.

It can be concluded that using yellow bulbs for car head-lamps results in a loss of about 15%. This loss must not only be made up, in one way or another, but actually, must be more than made up in order to obtain a positive result for using yellow light.

1.4. The use of yellow lamps

In the summer of 1971, (within the framework of a wider enquiry), the extent to which yellow head-lamps are used in the Netherlands, was investigated. The enquiry was spread over the whole country and in addition in several towns. Based on a preliminary report from this enquiry the following data have been obtained. 234 of the 1774 cars involved in the enquiry had yellow head-lamps (thus: 13 %), with a probability that the value ranges between 11 % and 15 % (margin: 2). No differences depending on the age of the drivers could be established; however, a dependence was observed on the year in which the car was built, in the sense that more new cars were fitted with yellow head-lamps. With regard to the make of car the following observations were made. Firstly the majority of Simca cars were provided with yellow head-lamps, whereas other French types, (such as Renault and Citroën) used yellow head-lamps to a lesser extent. This is all the more interesting since the majority of the former (Simca) were imported from France into the Netherlands, in a completely assembled state, while, of the latter, a smaller proportion arrived in the Netherlands completely assembled. As a preliminary conclusion it can be stated, that the use of yellow or white head-lamps depends more on the equipment delivered by the manufacturer than on the personal preference of the car owner.
The investigation clearly proved, that – as already stated – the majority of cars in the Netherlands are fitted with white head-lamps, although yellow head-lamps are used quite frequently as well.

1.5. Effects on traffic safety

This publication deals with various physical, physiological and psychological aspects, relating to the advantages and disadvantages of yellow light as compared to white light for car head-lamps. Based on a number of theoretical considerations it can be stated that filtered yellow incandescent lamp light has a few, but distinctly noticeable advantages over unfiltered (white) light, however, the opposite may also occur. In the following, it will be investigated to what extent these differences may affect traffic safety. For this purpose practical tests will be discussed, based on measuring visibility distances, since, as the English saying goes 'the proof of the pudding is in the eating'.
Visibility measurements are frequently used in comparing various systems of vehicle lighting. As a rule, these tests are carried out in the following manner: One or more observers sit in a car, which is fitted with the lighting system under investigation. This car drives towards an oncoming car, which is also provided with the lighting system to be tested. Objects are positioned on or along the road at locations which are unknown to the observers sitting in the test cars. The observer indicates the moment at which he observes the object in question. On the basis of this indication it is possible to determine the distance at which he first saw the object. This distance is called the distance of visibility. In addition to the lighting system under investigation the distance of visibility depends on the lateral position, the dimensions, the shape and reflectivity of the objects, on the distance from the oncoming car at the moment of perception and on whether the oncoming car is stationary or in motion, and furthermore on a number of circumstantial factors, and last but not least, on the criterion 'visible'. In view of these additional factors, it is not easy to compare the results of the various series of

tests. On the other hand, it is possible to compare the results of various lighting systems obtained within the framework of one series of tests, thus, under identical conditions. However, measurements of visibility distances, involving the comparison of yellow and white light, have only seldom been carried out. The only reliable data were obtained by Jehu (1954), who found that the visibility distance for yellow light was about 2–3 meters greater than for white light.

In the tests, described by Reading (1966), which can be regarded as a laboratory method of measuring visibility distances, white light was found to be better than yellow light (under identical photopic intensities). However, the difference is not statistically significant.

Monnier & Mouton (1939, p. 184) describe some visibility measurements, carried out under stationary conditions. However, they give few details. Thus, for example, it is not clear what was actually measured and what are the results of calculations obtained from other measurements. As a result, a visibility distance has been established, (obtained by 10 male observers of different ages) which was, (in an absolutely clear atmosphere) 10–15 % better for yellow light than for white light. The measurements of visibility distances obtained under conditions, closely approximating to practical conditions, can obviously lead to rather contradictory results. On the one hand, a slight but significant advantage could be observed for yellow light; while on the other hand, a less marked and non-significant advantage for white light, under less realistic circumstances was observed. Furthermore, advantages of yellow light are indicated as a result of tests, which were described only briefly and most probably were carried out by unacceptable methods. All these differences, however, are slight and, even if they are correct, they would have hardly any effect on traffic safety.

Literature Chapter 1

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2. Physical aspects

2.1. Introduction

In the first chapter, a survey was given of the problems which must be discussed. Moreover, a number of general observations were made concerning the lighting system of cars, more particularly concerning the incandescent lamps used in this system and the manner in which 'yellow' light can be obtained. Also in view of the following chapters, it is important that 'yellow' incandescent lamps are not different from the common 'white' incandescent lamps, the only exception being that some of the blue light is absorbed by a colour filter. This, of course, results in a loss of light. This loss is generally estimated to be not more than 15%. This quite inconsiderable loss of light is not surprising, since a tungsten filament lamp cannot have a very high temperature and consequently emits only a small amount of blue light. Other wavelenghts in the visible spectrum are not affected, so that a yellow incandescent lamp still remains a thermal radiating element. This is not the same as a gas-discharge lamp, which emits a spectrum, consisting almost completely (or to a large extent) of emission lines. Nevertheless, it is possible, that the 'colour point' of a gas-discharge lamp corresponds to that of the thermal radiator, so that both light sources appear to have the same colour.

2.2. The eye as image forming instrument

In all considerations concerning visual perception, the fact that the eye is an optical instrument, is of essential importance. A detailed description of the eye as an image forming instrument was given by Duke-Elder & Abrams (1970, Chapter III). Here we shall confine ourselves to some additional observations.
In popular literature one is often confronted by the over-simplified statement, that the eye resembles a photographic camera, in which the eye lens functions as the camera lens, while the retina corresponds to the film. However, such comparison is misleading. Due to a slight difference in the refraction index between the lens and the adjoining liquids the 'effective' power of the lens is quite small. The image is essentially produced by the cornea, the front part of the surface of the eye. In contrast with the lens, the part of the cornea which forms the optical image, is reasonably spherical. The lens plays a part mainly in focussing adjustments. With regard to the optical image, a) the cornea, b) the pupil, and c) the retina, are of importance.
According to the well-known theories of geometrical optics, the aberrations, which can be expected at a single refracting surface are: monochromatic aberrations, (curvature and distortion of the image, spherical aberrations, coma, astigmatism) and chromatic image aberrations.

Image curvature and distortion, and spherical aberrations play no essential part in the human eye, since the retina is not flat, but nearly spherical. Coma and astigmatism are of reduced importance as far as foveal perception is concerned. The effect of these errors can, consequently, be neglected.

A simple lens produces two sorts of chromatic errors in white light. Firstly, the focal distance is not the same for all colours, so that a sharp image of only one colour at a time, from a white light emitting point source, is possible (see Van Heel, 1950, Chapter IXd). Secondly, there is the so-called magnification colour error: the dimensions of images of the same object, are different for different colours (Van Heel, 1950, p. 247).

The effect of the first type of colour error on human perception is rather well-known. In summary, it can be stated that data from the literature are in satisfactory agreement with one another. As an example, Figure 2 is taken from Le Grand (1956). It is justifiable to assume that for blue light a normal eye is longer-sighted to an extent of about 1 dioptre, while it becomes short-sighted for red light to an extent of about 0.5 dioptre. However, it is doubtful, whether this effect has a great influence, if the blue light is filtered from the light from an incandescent lamp. If this effect was considered to be important, visual acuity should be lower in white light than in yellow light. This problem will be discussed again later.

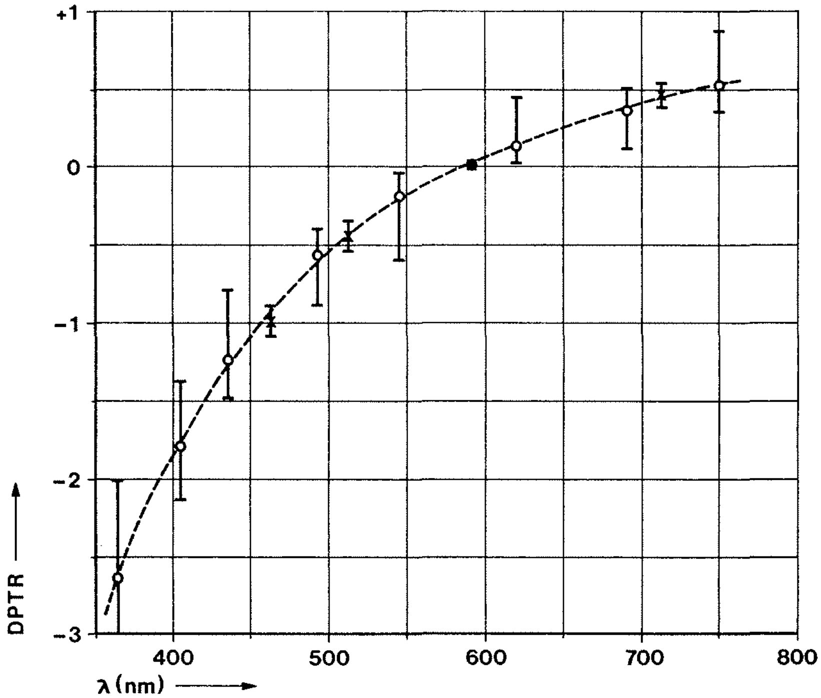
The magnification colour error (the colour aberration of the second type) is, generally, too small to be perceived. Le Grand (1956, p. 23) states that even at an object sustaining an angle of 5°, the apparent width of the spectrum which develops from it, amounts to less than 3 minutes of arc.

A second wave-length-dependent effect, which might influence visual perception, is the effect of diffraction. When light passes through an aperture which is larger (but not much larger) than the wave-length, the propagation is distorted in such a way that a part of the light is diffracted. As a result, instead of a sharply defined point of light being formed, an imperfectly defined light spot appears, the size of which increases with decreasing pupil diameter and increasing wave-length. The deduction established by Moon (1961, p. 425) is given at the end of this section. According to De Waart (1946, p. 22) the diameter of the diffraction circle from a point-shaped light source amounts to 0.0061 mm, with $\lambda = 500$ nm and a pupil diameter = 4 mm. Based on the linear relationship between r_0 and λ, it is evident that if $\lambda = 400$ nm, r_0 will be 0.048 mm, while if $\lambda = 700$ nm, r_0 will be 0.0084 mm. This shows that wave-length has a considerable influence. It also appears that the diameter of the diffraction circle cannot be neglected. However, it can be assumed that the effect of diffraction will not be of very great importance, as it is a well-known fact, that visual acuity increases with decreasing pupil diameter. This means that an increasing diffraction effect is more than compensated for by the decrease of image errors. Thus, the relatively small change in diffraction due to colour effects, will, in general, not have a large influence.

2.3. **Light scatter**

When electromagnetic waves pass through a medium, they will be reduced in intensity. Such weakening is caused by the following factors: reflection at the boundary surfaces, absorption by the medium itself and scattering by particles in the medium. In relation to the present treatise, only the last factor is of actual importance.

In this connection Rayleigh's law, relating to scatter, is the fundamental principle.



○ = measurements of Wald and Griffin
× = measurements of Ivanoff

Figure 2. Colour aberration of the human eye (in dioptres) depending on the wavelength of light (according to Le Grand, 1956, Fig. 1).

For particles, very much smaller than the wave-length λ, the following formula is valid:

$$S = 24\,\pi^3 \left(\frac{n^2 - 1}{n^2 + 1}\right)^2 \cdot \frac{Nv^2}{\lambda^4},$$

where: S = the scatter per unit volume, N = the number of particles per unit volume, n = refraction index, and v = the volume of particles (this formulation of the law has been established by Monnier & Mouton, 1939, p. 90).
From this follows that for identical n and N, scatter for short wave-lenghts (blue light) is much greater than for long wave-lenghts. If the particles are not too small in relation to the wave-length, the scatter is less.
For this case Ångströms approximation formula is frequently used:

$$S = c/\lambda^a$$

For a = 4 the original Rayleigh formula is applicable. 'a' decreases with increasing particle size. If the particle size is approximately of the same order of magnitude as the wave-length, 'a' is about zero, in which case scatter does not depend on the wave-length. When the particles are larger than the wave-length, 'a' approaches to −1; this is the limiting case for large circles, and also for the condition of pure diffraction.
The particle sizes which are important for practical purposes, will be dealt with later. First, it will be briefly explained why visual perception is reduced by scatter.
The ultimate result is that with considerable scatter, all objects have the same colour *and* luminance. The effect of light scatter can be explained in the following way: part of the light emitted from a bright object (for example, a light source) will be scattered in traversing the distance from the object to the eye; thus, the scattered portion does not reach the eye directly. This reduces the 'apparent luminance' of the object. The weakening of 'apparent luminance' can attain such a degree, that the light source becomes invisible. In the case of pure scatter the light is not absorbed. A part of the light (after having been scattered once or several times) can reach the eye from a direction, in which some dark object is present. This object becomes apparently brighter. These effects can increase until complete equality of brightness results. For practical purposes, however, the state where this equality has not been reached, (i.e. a gradual weakening of the contrast), is more important. In the following, we shall discuss the conditions under which this negative effect is dependent on the colour of the light. In this condition there are two cases where the scatter of light is important (and often even *very* important): the scatter in the media of the eye, and the scatter in the atmosphere.

The scatter in the eye media is very important because it plays a considerable part in producing physiological glare (disability glare). It is a well-known fact that disability glare is caused to a great extent by light scatter in the various media of the eye (it would be more justified to speak of 'physical' glare).
Firstly, it must be established, which parts of the eye cause scatter. According to Vos (1963, p. 77) the cornea, the lens and the fundus, are responsible for this effect. In general, these three elements of the eye have an equal share in the production of light scatter. According to Wolf & Gardiner (1965) it is the lens alone, which contributes to

the production of glare, and on account of this, in order to establish glare sensitivity, it is sufficient to determine the light scatter in the lens. For our purpose, however, it is important to know, whether scatter depends on the wave-length of light. As mentioned earlier, this is partly related to the size of the scattering particles, but it is also related to the nature of these particles. At present, from the anatomical point of view, not much is known, either about the size, or the nature of particles, consequently, no theoretical conclusions can be drawn. An exception is formed by the inhomogeneities of the vitreous humour. These appear in the form of 'mouches volantes' (see Le Grand, 1956, pp. 161, 162), but, in a normal eye they do not have a great influence on the scatter of light (Wolf & Gardiner, 1965). Thus, if there was any wave-length-dependent effect, it would have no importance.
Not much is known about the wave-length-dependence of light scatter in the individual parts of the eye. According to Vos (1963, p. 77) the 'veil' formation is nearly independent of wave-length.
This statement, however, is based on psycho-physical methods of measurement relating to the entire phenomenon of glare (Vos, 1963, p. 18). This applies to several other data, and therefore it seems more sensible to discuss the colour dependence of light scatter as it is manifested by differences in visual acuity and glare. Literature references concerning light scatter in the various parts of the eye cannot provide reliable support for arguments in favour of either yellow or white light.

Regarding light scatter in the atmosphere, opinions are much more uniform than those regarding scatter in the eye. Thus, with regard to the advantages and disadvantages of yellow light from car head-lamps, in haze and mist, it is not the physical fundamental principles themselves which must be discussed, but the degree to which such principles can be applied to various practical situations.
The atmosphere of the earth is never absolutely clear. In addition to gas molecules themselves, dust particles are present, and in most places, water vapour as well. At locations with heavy car traffic, the atmosphere also contains impurities, caused by the exhaust gases and the wear and tear of cars and road surfaces.
Among the impurities, special attention should be paid to silicon (sand) and carbon (soot). These substances absorb and scatter light. Infrequently, and mostly in confined areas, the concentration of these substances can be so high, that car drivers are hindered in carrying out their driving task due to very poor visibility. The particles present in the atmosphere, are, as a rule, very small. According to Magill et al. (1956) the size of exhaust gas particles amounts to about 0.1 μ (cited by Schreuder, 1964).
In countries with a moderate climate, such as the Netherlands, this is not important because of the open roads. The clouds consisting of such particles, generally, do not become dense enough to impede traffic.
Based on theories and convincing evidence provided by Middleton (1952), it can be expected that, in haze, resulting from very small particles, blue light will be scattered to a greater extent than red light. This opinion is shared by Monnier & Mouton (1939), who, firstly, refer to a considerable volume of literature (p. 113); and secondly describe the measurements they made (op. cit. p. 129). In this connection two observations must be made. Firstly, no precise indication is given as to how much of this advantage is maintained, when the slight difference between incandescent lamps with and without yellow filters is taken into consideration. Secondly, Monnier and Mouton do not indicate whether, under the conditions specified by them, the atmospheric

visibility was such that road traffic encountered no hindrance. This is a deficiency in the arguments of Monnier & Mouton (1939), which at first sight, seem to be very precise. Under closer inspection however, it was found that several results, relating to clear atmosphere, were presented as being relevant for haze or even fog. Concerning visibility in haze it can be concluded that, from both theoretical and practical reasons, little advantage for yellow light can be claimed, and it is of very slight importance for the road traffic.

With regard to light scatter, there is a great difference between haze (and light mist) on the one hand, and fog on the other.

The process of condensation is rather complicated. When the concentration of water vapour and condensation nuclei exceeds a certain limit, the resulting drops will all have a certain minimum size. The number of drops depends on the absolute moisture content, the temperature and the concentration of nuclei, while the size of the drops is always of the same order of magnitude. The associated processes are discussed in detail by Byers (1965, pp. 32–35).

The relative frequency of appearance of drops with different diameters, can therefore be very different; small drops however are not formed when larger ones are present. The term 'large' as used here means with a diameter of at least 2 to 5 μ. This agrees satisfacorily with the frequency size distribution as found in practice, in fog.

Based on measurements, it can reliably be concluded that drops present in fog have a diameter of at least 1–2 μ. This means that the exponent in Ångström's approximation formula is always negative. Thus, if this caused a wave-length-dependent scatter, it would mean that red light is scattered more than blue light. However, such selectivity of scatter cannot be observed in practice.

Based on the theoretical considerations discussed above, it can be assumed that fog, due to the drop sizes which occur therein, scatters light non-selectively. This assumption is supported by several practical investigations. Thus, for example, Devaux (1956) states that fog scatters all colours to the same extent. Luckiesh (1953) has also doubts about the benefit from yellow fog lamps. According to Schober (1967) no improvement can be realised by using yellow light. This is also stated in CIE (1948), with reference to Boelter & Ryder (1940). Finally, Middleton (1952) refers again to several research workers, who did not find any noticeable difference e.g. Luckiesh & Holladay (1941), Born, et al. (1933). Kocmond & Perchonok (1970) also accepted wave-length-independence, on the basis of publications by Arnulf & Bricard (1957). In a very thorough study by Harris (1951) no mention at all is made about the effect of the colour of the light.

Monnier & Mouton (1939, pp. 113) refer to several investigations concerning natural mist. According to Granath & Hulburt (1929) in dense fog, blue light with a wave-length of 450 nm is reduced to 1/100 of its original value at a distance of 800 m, while it is reduced to 1/1000 of its original value at a distance of 1200 m. Regarding red light (650 nm) the corresponding distances are 925 and 1400 m, respectively. Based on measurements of Foitzik (which are not described in detail), it was found that in the case of fog with a visibility of less than 800 m, the penetration does not depend on the colour of light, while with a visibility of more than 1000 m, the penetration of blue light is greater than that of red light, sometimes by as much as 30%. Immediately after this, a statement of Foitzik is cited, that in haze blue light is scattered more than red light! Finally, Born, et al. (1933) are referred to, who indicate that in fog, with a visibility of 300 m, the penetration of light with a wave-length of 483 nm is greater by

5–6 % than that for light with a wave-length of 657 nm (greenish yellow and deep red, resp.).

Diffraction of light at a circular aperture (after Moon, 1961, p. 425).

In the case of diffraction, the illuminance E at point P, at a distance r_o from the optical axis, is expressed by the formula:

$$E = E_o \left(\frac{J_1 (2m)}{m} \right)^2$$

where: $m = \frac{\pi\delta}{2\lambda} \cdot \frac{r_o}{Z_o}$

E_o = E, for $r_o = 0$
Z_o = the distance between the aperture and the receiving surface
δ = the diameter of the aperture
λ = the wave-length of light
$J_1 (2m)$ = a Bessel function of the first order.

According to this, at the receiving surface (in this case the retina) bright and dark circles are formed, in succession, around a bright central point. The first dark ring is expressed by:

$$m = \frac{\pi\delta}{2\lambda} \cdot \frac{r_o}{Z_o} = 1.916.$$

Nearly all the energy is concentrated in the innermost ring. The maximum illuminance in the first bright circle is not more than 1.7 % of the illuminance in the centre of the bright spot. The second ring is weaker still. Thus, it is the innermost bright spot which is effective. The given formula indicates that the 'width' of this spot increases with increasing wave-length and decreasing aperture size.

2.4. Conclusions

From the above-mentioned information several conclusions can be drawn.
1. Monochromatic image aberrations are obviously not dependent on the colour of the light.
2. The longitudinal chromatic image aberrations display a rather large dependence on wave-length. In the case of monochromatic light and the optimum focussing of yellow light, the deviation in blue light amounts to −1 dioptre (thus, the eye is long-sighted), the value being +0.5 dioptre for red light (thus, the eye is short-sighted). Consequently, perception is better in monochromatic light. It is, however, questionable, whether filtering the (small amount of) blue light makes much difference.
3. Transversal chromatic image aberrations (aberrations of the second order) have hardly any effect.

4. Light diffraction has influence on the image forming capability of the eye and this influence is wave-length-dependent. However, it is not clear to what extent perception is influenced by the effects of diffraction; thus, a colour-dependent effect is not very probable.
5. Scatter in the eye media is very important. The effect of glare is one of the most serious sources of disturbances in perception. However, it is not known whether scatter itself depends on the colour of the light. All investigations concerning colour-dependence take glare into account, in all its aspects, thus, providing no special information regarding scatter. Since 'glare' as a general phenomenon does not depend on the colour of light (or only to a limited extent) it is justifiable to assume that scatter in the eye media will not depend on the wave-length either.
6. Scatter in haze is dependent on wave-length in the sense that red light is scattered to a smaller extent than blue light. Such dependence however only occurs in haze or mist, with a visibility of more than 1000 m. Thus, this phenomenon has no consequences for road traffic.
7. Scatter in fog is independent of wave-length. This applies to all kinds of fog, which might affect road traffic.

Summarising, it can be stated that with regard to physical phenomena, no arguments could be found in favour of using filtered (yellow) incandescent lamp light instead of unfiltered (white) incandescent lamp light, for vehicle head-lamps.

Literature Chapter 2

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3. Physiological aspects

3.1. **Introduction**

In this chapter, some physiological aspects are considered, dealing, in turn, with the effects in relationship to the (anatomical) structure of the eye, and to effects which are connected with the various functions of vision within the total field of visual perception, such as contrast sensitivity, visual acuity and glare. Finally, some specific, age-dependent effects are also discussed.

There is a wealth of literature available concerning the structure and function of the organ of vision. This is partly due to the fact that the matter concerned is extremely complicated, and partly because investigations in this field have been carried out for several centuries.

Since in this case an answer is required to a narrowly specified problem (the effect of the colour of vehicle head-lamps) no attempt will be made to achieve completeness. In the following chapter only some aspects will be discussed – when comparing the light from filtered (yellow) incandescent lamps and that from unfiltered (white) lamps – and in which (based on physiological causes) differences in the functioning of the visual system could occur under circumstances which might be encountered with night-time road traffic.

3.2. **Aspects concerning the structure of the eye**

3.2.1. *The retina*

One element of the eye, which in this context is of importance, is the retina. Pirenne (1967) gives a detailed description of the main components of the retina, references are made to this description in the following: The retina is characterised by two types of photo-receptors, the rods and the cones.

The cones are mainly concentrated in the central part of the retina; the fovea centralis (covering an angular area of about 2°) consists entirely of cones. The cones display the following main characteristics:

a. each cone is connected to a separate nerve cell;
b. they are active in the case of relatively high luminance;
c. colours can be perceived by the cone system;
d. the sensitivity is greatest for yellow-green light (555 nm).

On the other hand, the rods are arranged at the more peripheral areas of the retina, they are not present in the fovea. The rods display the following characteristics:

a. they are connected, in variable numbers, to a single nerve fibre (up to about 100, Delay & Pichot, 1968, p. 31);
b. they are active in the case of low luminance;
c. the rod system is only capable of perceiving shades of grey;
d. the sensitivity is the greatest for green light (500 nm).

All this refers to the human eye. The eyes of vertebrates have a similar structure, with the difference, that many animals have only rods or only cones in their eyes. For example, ungulata, to which all game belong, have only rods in their eyes so that they cannot distinguish colours. The argument, sometimes presented, that these animals (and in particular deer) can be run over only by cars with white head-lamps (which would be a good point in favour of yellow light) belongs to the realm of fiction.

According to Devaux (1970), better visibility with yellow light as compared to white light, can be explained by the distribution of rods and cones in the retina: the part of a road which is illuminated by yellow head-lamps, is focussed in the area of the fovea, which is extra sensitive to yellow light, while the border zones of the road, illuminated by a bluish twilight, is focussed at the periphery, which is sensitive to this colour. This argument is hardly acceptable, because it could only be up-held if foveal perception was photopic, and peripheral perception was scotopic or at least mesopic, which however, is not so. Moreover, there is still the problem as to whether a slight difference in spectral emission could cause such a great difference in perception. The reduced peripheral sensitivity with yellow light is presented as an explanation for another phenomenon: sodium lamps cause less glare (psychological glare) than white lamps, for example mercury lamps (see Stiles, 1954, and Schreuder, 1962) under the identical conditions of street lighting.

Some observations must be made concerning these problems. Firstly, it is doubtful, whether it is valid to use photopic luminance for the mesopic area. Secondly, from investigations by Adrian (1965) and Adrian & Kokoschka (1965), it can be established that the colour sensitivity of the rod-free fovea is affected, in a hitherto inexplicable manner, by the rod system. Finally, the pigmentation of the macula must be considered (the area of fovea centralis); here a yellow coloured substance is present, which may function as a filter, whereby changes of colour can be corrected (Walls, 1943, referred to by Riggs, 1965). In contrast to the pigmentation of the lens, the macula-pigment does not increase with age. See Ruddock (1965a, 1965b), Mann & Pirie (1950, p. 89), Said & Weale (1959).

The effect of the macula-pigment on visual perception is not perfectly understood. Since it evidently remains unchanged during the entire life span, it is difficult to assume that it may be of any importance to the present problem. The same can be said of several other indicated facts; the most important part of visual perception, in night-time traffic participation, takes place at the foveal and para-foveal area; the extreme peripheral areas have at best a warning function for moving, superliminal objects.

3.2.2. *The duplicity theory*

The duplicity theory plays an essential part in visual perception. This theory can be described briefly as follows: at low luminance in the outer world (< 0.01 cd/m^2) only the rods are in use. Visual perception is limited to the discernment of forms and, primarily, movement; no colours are perceived; the fovea is inactive (scotopic vision).

At high luminance (> 10 cd/m^2) the cones are functioning, although the rods also display some activity, but this has not been properly understood up till now (Adrian, 1965) (photopic vision). Visual acuity is, primarily, considerable in the foveal range, and colour vision is possible; while the perception of movement is still limited, to a large extent, for the periphery. At intermediate levels both systems are active. At relatively high luminance the cone system prevails, while at relatively low luminance the activity of the rod system dominates. Since both the cones and rods have their own 'sensitivity curve', it seems plausible to assume that at intermediate levels (mesopic vision), a linear relationship exists between the two; the conditions of luminance are directly related to the values for vision purely by cones and rods. This Purkinje-shift (named after the discoverer, Jan Purkinje) is presented in linear form by Cakir & Krochmann (1971). However, this is an over-simplification, according to Walters & Wright (1943) and Kokoschka (1971). In spite of this difference of opinion, we have quoted the simple figure of Cakir & Krochmann (1971), (Figure 3).

It is known that each colour can be defined by a mixture of three suitably chosen primary colours (Bergmans, 1960). Furthermore, it is generally accepted that, from the physiological viewpoint, there are three kinds of receptors for colour perception. However, anatomy nor chemistry provide irrefutable evidence of the existence of three types of cones. A method which may prove that there are three types of cones, each with its own sensitivity curve, would be the individual illumination of separate receptors. Cornsweet (1970, p. 214) describes such a method stating that indeed three types of cones (each with its own absorption curve) were found. He also refers to Wald & Brown (1965). The absorption curves are, however, not in complete agreement either with curves obtained by other methods, or with the sensitivity curves obtained for colour-mixtures.

A typical feature of the phenomena related to the duplicity theory is, that for the luminance levels, usual in night-time traffic, the discrepancies between photopic vision and mesopic vision are insignificant. For easy reference, we have indicated this as 'high-mesopic' vision. With decreasing luminance the eye becomes increasingly sensitive to short-wave-length light while it becomes less sensitive to long-wave-length light. This is pertinent to the problem because:

1. In 'high-mesopic' vision the eye displays a slightly stronger blue-sensitivity than in photopic vision. The discrepancy is so small that no disadvantage results for yellow incandescent lamps taking into account the small 'blue' contribution of unfiltered incandescent light. Advantages for yellow light, however, cannot be expected.
2. In the 'high-mesopic' level, visual acuity, contrast sensitivity, etc. are hardly less than in the photopic range. Neither can it be expected that a slight change in the spectral composition of the light will have any influence. For this reason it is justifiable to investigate light-colour dependence exclusively with regard to the photopic level.
3. The extent of colour vision in the 'high-mesopic' level is only slightly reduced.

The next step to consider is the question whether it is justifiable to state that for night-time traffic just as at day, perception takes place mainly in the photopic and 'high-mesopic' levels, respectively.

The usual starting point is that the state of adaptation of the retina particularly of that part on which the image of the surroundings, which are important to the car driver, is formed (mainly the foveal and parafoveal area) is determined by the luminance of the road surface. Practical measurements have proved that for fixed road lighting, values less than 0.1 cd/m^2 hardly do occur (Westermann, 1967; De Grijs, 1972). The situation cannot be described so simply, when the road is exclusively illuminated by car head-lamps. Although few reliable data are available, it can be assumed that road surface luminance (at least, on dry roads) is, generally, higher than 0.1 cd/m^2 over the first tens of meters ahead of the car (SWOV, 1969, Fig. 3). Although perception of details on the road must often be possible at longer distances, the first area,

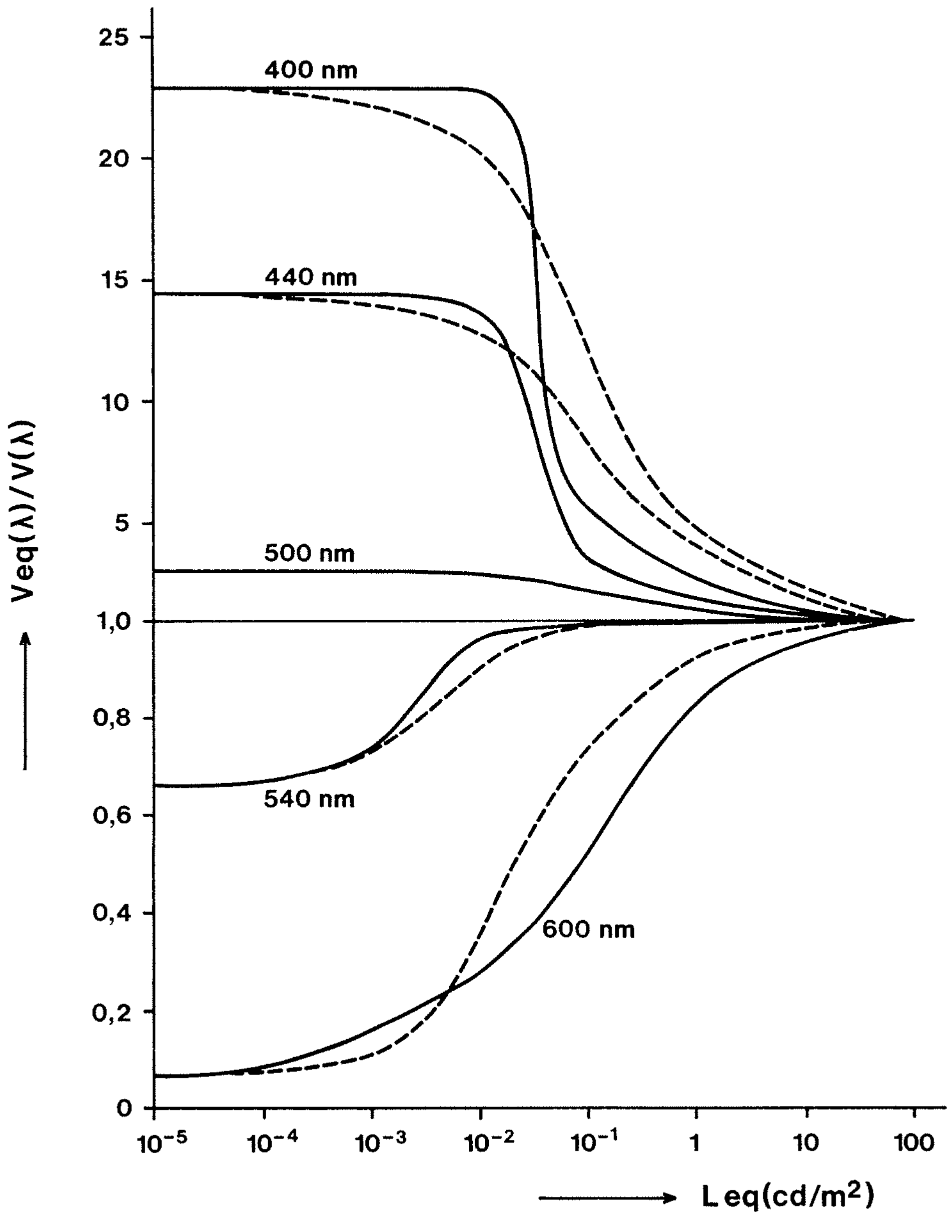

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Figure 3. Relative efficacy (V_{eq}/V) at various wave-lengths, as a function of equivalent luminance (L_{eq}) (according to Cakir & Krochmann, 1971, Fig. 1).

due to the relatively large spatial angle, is decisive for adaptation. For this reason it seems justifiable to state that the foveal adaptation is, as a rule, above 0.1 cd/m^2 for both lighting modes. Usually, however, it is higher, and although exceptions do present themselves, the assumption that 'high-mesopic' vision is prevalent in night time traffic can be made.

3.2.3. *The pupil of the eye*

The pupil is a circular aperture in the iris, which is directly in front of the lens. The size of the aperture is defined by a dynamic equilibrium between the sphincter pupillae and the dilatator pupillae. The mechanism effecting the widening and contracting of the pupil, is imperfectly understood. H.Bouma (1965, p. 74) found that the 'sensitivity curve' which determines the reaction of the stationary pupil, is neither that for photopic vision, nor that for scotopic vision. The wave-length, at which a maximum reaction occurs, is 555 nm for photopic vision, 510 nm for scotopic vision and 490 nm for the pupil reaction. This means that blue light is more effective in causing the contraction of the pupil, than red light, at the same level of luminance. According to H.Bouma (op. cit., p.74) this contraction is still continued at levels of luminance, where vision is purely 'photopic'. This would again mean, that blue light is more effective in causing the contraction of the pupil in the mesopic range, than red light. However, it would not be correct to assume, that due to such colour-dependent pupil-reaction, a colour-dependent effect occurs in the entire visual system. On increasing the luminance level, the pupil diameter is reduced; this results in two effects, which compensate one another. On the one hand, the quality of the optical image is improved, because the chromatic and monochromatic image aberrations in the eye decrease, when the pupil is contracted. On the other hand, diffraction increases, and consequently the colour of the light cannot affect the visual performance by the reaction of the pupil to any appreciable degree.

3.3. **Functional aspects**

3.3.1. *Contrast sensitivity*

One of the most fundamental functions of the human visual system is the ability to distinguish separate areas (for example adjoining areas) with different luminance. This is usually indicated as 'contrast sensitivity'. In this field numerous investigations have been carried out. These investigations begun by Fechner and Weber; it is summarised by Brown & Müller (1965) in a reasonable, but not quite systematic and complete manner. In this instance we will confine ourselves to colour effects.

Jainski (1960b) found, that over a range from about 10^{-3} to 10^2 cd/m^2 the differences in contrast sensitivity between incandescent, sodium and high-pressure mercury light can be neglected. He made the remarkable observation, that the contrast sensitivity with fluorescent tubes at low luminance is higher than for the other three types of lamps. At luminance levels above about 0.3 cd/m^2 the difference is again negligible. It might be assumed, that this is more likely to be a measuring error than a physiological phenomenon. In any case, in connection with road lighting, this is of little importance. In these measurements, filtered (yellow) and unfiltered (white) incandescent light were not investigated separately. However, a difference between these two types of light cannot be expected, because there is no systematic difference between the four rather different light types investigated. Jainski (op. cit.) ends his paper with the statement (without supplying details), that the measurements published by him are in satisfactory agreement with those of Luckiesh & Taylor; Klein & Weigel. Eastman & McNelis (1963) also found no difference in contrast sensitivity, when comparing sodium and mercury lamps, and incandescent lamps. A similar result has been obtained by Hartmann (1959). He found no difference between contrast sensitivity with filtered (yellow) and unfiltered (white) light.

Monnier & Mouton (1939, p. 177) found some difference between yellow and white light. The threshold of contrast sensitivity has been determined for five observers. At about 15 cd/m^2 there was hardly any difference between yellow and white light. The difference increases at lower luminance, and at 0.003 cd/m^2 the sensitivity with yellow light is about twice as great as with white light. Since few details are given concerning the methods of measurement and the apparatus used, it seems advisable not to place too much importance on these results, especially, because no other research worker found such a large effect of light colour. The consequences of this statement must be evaluated properly; it is primarily the investigations of Monnier & Mouton that provide the recurring arguments in favour of yellow (filtered) incandescent lights for car head-lamps.

According to Bouman (1952) contrast sensitivity is independent of wave-length at high luminance, 'high' here refers to greater than 3 cd/m^2. However, red light seems to dominate for low luminance values, for scotopic vision, and for peripheral perception.

In the above paragraph the sensitivity to luminance differences has been referred to as contrast sensitivity. It must however, be pointed out, that contrast effects also play a part, in favouring yellow light, which could better be described as psychological effects. A detailed examination of the effects, however, proves that the repeatedly mentioned statement, that contrasts are better in yellow light, is partly an illusion, and can partly be ascribed to other phenomena, which are already well-known (Schreuder, 1976).

3.3.2. *Visual acuity*

The second important physiological function which will be discussed, is visual acuity. In an earlier chapter it has already been mentioned that the maximum theoretical visual acuity cannot be achieved due to image errors in the eye, diffraction and the scatter of light. But it was also found that visual acuity is sometimes better than what should be expected, taking into account those aberrations and scatter. In the following, several investigations will be discussed, in which the visual acuity of the eye has been established directly, in order to ascertain to what extent the conclusions, from physical and optical considerations, can be upheld.

If contrast sensitivity was one of the first of the eye characteristics, to be studied systematically, visual acuity is most probably the characteristic which has been studied most intensely. This interest can be explained by the fact that definitions concerning visual acuity are important both for theoretical reasons and also for practical purposes. Thus, for example, the measurement of visual acuity forms the basis of most eye-tests for car drivers and pilots; eye spectacles are prescribed essentially on measurements of visual acuity. Eye-tests for car drivers are criticised, partly, because the measurement of visual acuity in these tests is often carried out in a rather primitive and unscientific manner (Vos, 1969). For practical purposes, however, the

criticism of Burg (1968, 1971) is more important, based on the fact that (static) visual acuity has, clearly, no effect on traffic safety.
Since however in the present discussion visual acuity is repeatedly referred to as a factor favourably influenced by yellow light, it will be considered more in detail, although it is doubtful, whether the conclusion (whatever it may be) is of any importance for traffic safety.
Visual acuity, generally, is defined as the angle within which the object, which is accepted as a criterion, is still just visible. This statement involves several observations:

1. The final result depends closely on the form, place, surroundings of the object and the manner in which the object forms a part of the larger surroundings. Thus, for example, the classical Snellen chart is more a measure of shape recognition than of visual acuity.
2. The term 'just visible' can be interpreted in various ways.
3. The nature of the test-object itself is of considerable importance; bright objects on a dark background are perceived in a different manner to dark objects on a bright background. Deviation of symmetry can be perceived better than deviation of form, etc.

All this leads to several definitions of visual acuity, which are different from one another. Actually this also means, that the classifications: contrast sensitivity, visual acuity, form recognition, etc. are, to a certain extent, arbitrary; and that all these criteria can be traced back to the same basic characteristic, or, alternatively that they are closely interrelated. More recently, research workers prefer to use gratings as test objects for definition of visual performance.
In general it is customary to concentrate on the foveal visual acuity, as, usually, the perception of objects is foveal perception.
The visual acuity measurements of Lythgoe (1932) have a classical status. They cover a range from 0.03 to 3000 cd/m^2 and have been carried out under white light, with normal eye pupils and using Landolt-rings as the test-object. The representation given by Walsh (1965, p. 64) is shown in Figure 4.
Visual acuity has also been measured with other colours, quite frequently. In general, it was found that monochromatic light gives a higher visual acuity than white light. This, of course, could be expected on the basis of earlier mentioned observations concerning optical and physical disturbances. Some examples will be given of this effect.
Luckiesh (1921, p. 133) describes measurements carried out by himself. It seems, that yellow monochromatic light yields a higher visual acuity than all the other monochromatic light colours of identical brightness (about 10 cd/m^2). It should be pointed out, that these measurements involved the possibility of focussing, i.e. in such a way that a colour error of the first order of magnitude has no influence.
Luckiesh (op. cit.) refers also to several other investigations. In each of them it was found that coloured light with a narrow spectral band yielded higher visual acuities than white light.
Hassel (1951) describes some experiments, in which visual acuity, determined by means of Landolt-rings, is compared for 'daylight'-fluorescent lamps and incandescent lamps. After the elimination of fatigue effects, no difference was found between the two types of lamps.
Oranje (1942, p. 135) observed a higher visual acuity under monochromatic light (Sodium) than under incandescent lamp light.

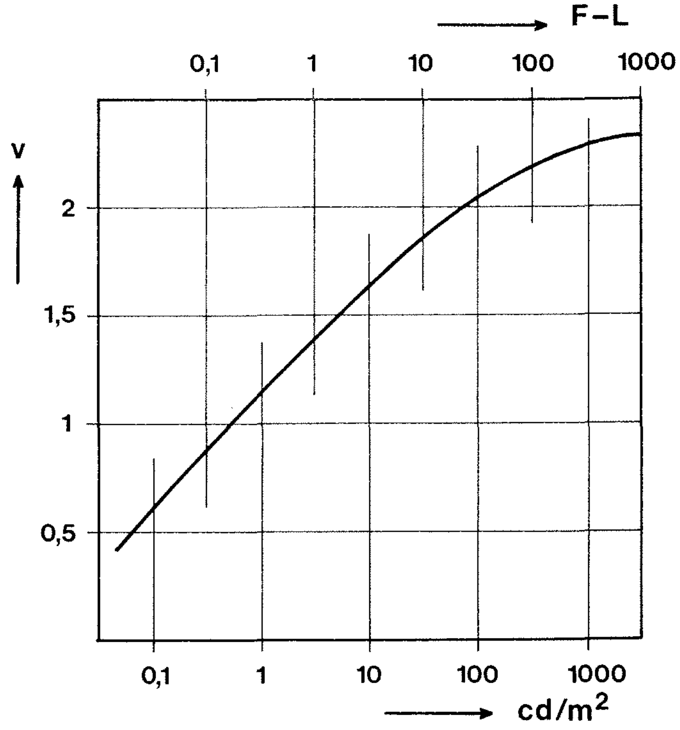

Figure 4. Relation between visual acuity v and luminance (in cd/m^2 and in Foot-Lamberts) (according to Walsh, 1965, Fig. 39).

Schober & Wittman (1938), referred to by Riggs (1965, p. 331) established that for low and medium luminance levels the light sources having line-spectra (Sodium and Mercury) yielded a higher visual acuity than incandescent lamps. No data have been obtained concerning the pupil contraction and concerning the adaptation in these measurements.

Monnier & Mouton (1934) state that visual acuity is 10% higher under filtered (yellow) incandescent lamp light than under unfiltered (white) light. They explain this as being due to a reduction of colour errors in the eye, resulting in improved visual acuity under monochromatic light. Without any further reasons, it is stated, that such an improvement takes place mainly with yellow light of 560 nm. No explanation is given, as to how the absorption of the small proportion of blue light can lead to such difference. Other data are missing as well. Thus, for example, they do not indicate what has been taken as 100%, or at what brightness level, or by whom the experiments were carried out.

Devaux (1970, p. 571) repeats these statements and also neglects the fact, that filtered (yellow) light is not monochromatic yellow light. Devaux (1956) refers to Pagès & Fleury (1956), who found an 8% greater visual acuity for yellow light, while taking no account of the extra absorption effected by the yellow lamp bulb.

In another publication Monnier & Mouton (1939, p. 166) refer to an investigation carried out by Mouton (1935) concerning visual acuity measurements with yellow and white light. It was found in this investigation, that the visual acuity of eight observers out of ten was higher with yellow light than with white light. On average, however, the difference is very small: varying between 5 and 8% for the entire range from 0.03 lux to 100 lux.

P.Bouma (1934) compared visual acuity under (monochromatic) sodium light with that of unfiltered (white) incandescent lamp light. The interpretation of these measurements is rather difficult, because visual acuity has been measured by varying the distance (thereby involving accommodation phenomena). The 'reduced distance' in which form Bouma expresses his data refers actually to the distance of recognisability, so that the problem arises as to whether visual acuity was investigated or some other characteristic of the eye.

Jainski (1960a) published visual acuity measurements, carried out over a range of 0.01 to 400 cd/m^2. In these measurements the following light sources were compared: incandescent lamps, sodium lamps (low pressure), clear mercury lamps (high pressure), high-pressure mercury lamps (with fluorescent bulb), and fluorescent tubes ('white' colour). In the entire range of measurements, the lowest visual acuity was found for incandescent lamps. The results are plotted in Figure 5.

Adrian & Kokoschka (1965) measured visual acuity for luminance in the mesopic range, when varying the wave-length. For this purpose interference filters were used, so that the light was not purely monochromatic. At a luminance of 3 cd/m^2 it is evident, that yellow and yellow-green light give the highest visual acuity, red and green give somewhat lower results, while blue light gives considerably lower results. At a luminance of 0.03 cd/m^2 this effect was no longer observed.

According to Arndt & Dressler (1933) the influence of wave-length is reduced at lower luminance and this was also confirmed by Adrian & Kokoschka. However, it must be pointed out, that this effect does not have much practical importance: monochromatic yellow light provides visual acuity, which is only 6% higher than that of unfiltered (white) incandescent lamp light. Thus, it can be expected that the difference, with

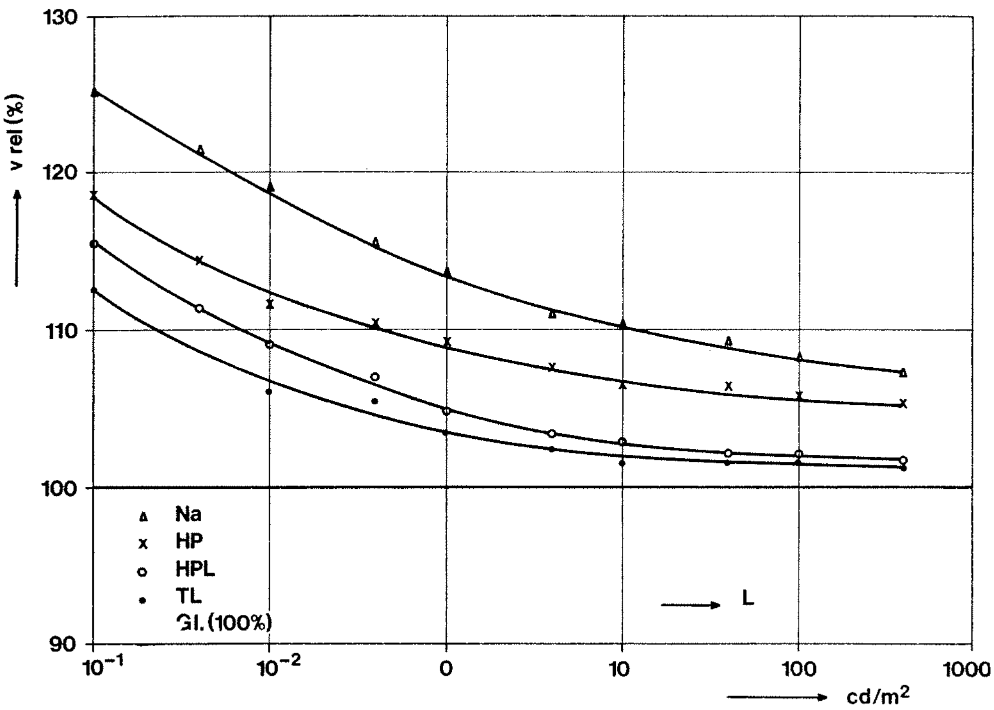

Figure 5. Relation between relative visual acuity (v rel) and luminance L for various light intensities. Incandescent lamp light = 100% (according to Jainski, 1960a, Fig. 4).

filtered (yellow) incandescent light will be still less, due to the presence of red light. Fisher (1965, p. 6) draws the conclusion (mainly on the basis of the literature referred to here) that visual acuity with (monochromatic) sodium light is about 10–20 % greater than with incandescent lamp light.
Finally we state the opinion of Le Grand (1956, p. 104). According to him visual acuity is not improved by filtering out blue from the spectrum, in spite of the reduction of colour aberrations in the eye, referring to Richards (1953) and Blackwell (1953a and b). Contrary to this, Pagès (1954) found a slight advantage for yellow light.

The above statements refer only to static visual acuity. Frequently an eye characteristic is described which is indicated as the 'dynamic' visual acuity. This indication is only correct, however, insofar as the measurements of the test-object to be perceived are expressed in angular form as in the case of static visual acuity.
The dynamic visual acuity cannot be measured in a simple manner and for this reason only few scientifically reliable publications are available in this field. All confirm the fact established by Burg (1968, 1971), that there is only little correlation between dynamic and static visual acuity.
Measurements on dynamic visual acuity, described in literature, have been carried out exclusively with white light and therefore they do not give much information about the effect of the colour of the light. However, according to general opinion, dynamic visual acuity is of considerable importance for road traffic (Griep & Noordzij, 1972).

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3.3.3. *The perceptibility of signalling lights*

The effect of the colour of flashing signalling lights on their visibility has been studied by Schmidt-Clausen (1971) on the basis of the law of Blondel & Rey (1911): $I_0/I = (a + t)/t$.

This provides the relationship between luminous intensity I and the duration of flashing t, and in which the visibility is equivalent to continuous light of luminous intensity I_0.

It appears that the 'constant' a in the above formula can vary considerably: it has the highest value for red and the lowest for white light. This means that a red flashing light is less 'effective' than blue, green, yellow and white (in this order).

This concerns the chromatic threshold values, i.e. the intensities at which a colour can be recognised. The achromatic threshold, i.e. the threshold at which the light becomes visible, is lower. According to Middleton (1952) the relationship between the achromatic and chromatic threshold (photochromatic relationship 'p') is about 1 for red light and decreases gradually to 2.5 for blue light. The fall-off is different to that given by Schmidt-Clausen (op. cit.). Walsh (1965, p. 78) calculated much higher values for 'p': starting at 2 for red, up to 100–150 for all wave-lengths, from about 550 nm to deep blue!

The difference between these data is, most probably, caused by a difference in the luminance range. Middleton gives values for signalling lights, while Walsh actually refers to the Purkinje-shift. All this shows, that there are very little data available concerning the effectiveness of coloured signalling lights.

3.3.4. *Speed of seeing*

According to Bouma (1934) the speed of seeing relates to two values:

1. the time necessary for recognising a certain object, and
2. the speed at which a series of objects (for example letters) can be deciphered.

Here, the fault, which repeatedly occurs in the work of Bouma – an imprecise definition – is evident. In problems of this kind, it is indispensable to give an exact definition of the term 'seeing' and not to identify it simply with 'recognition'.

The results provided by Bouma (op. cit.) raise the surmise, that the statistical processing of the results has not been carried out with the required care. Since accuracies of measurement, scatter, and reliability intervals are not given, it is impossible to establish to what extent the results are significant. It is extraordinary, that data, represented in such a slipshod manner, should have achieved an almost classical status. This is due, on the one hand, to the insufficient number of really reliable results of measurements, and on the other hand, to the credulity of those, who accepted these data as relevant.

For the sake of completeness we shall give the results, which are as follows:

a. at average luminances (about 1 cd/m^2) the luminance for white light must be higher by a factor of 2.5 than that for sodium light, for equal speed of seeing. The difference in the speed of seeing for equal luminance amounts to about 30% on an average for the luminance of 0.1–3 cd/m^2;

b. at high luminance this difference disappears.

Reading (1966) quotes measurements of De Boer (1959) and Dunbar (1939) concerning speed of seeing, whereby no differences were established between filtered (yellow) and unfiltered (white) incandescent lamp light. However, the reference is not accurately formulated; and therefore it is not clear, whether the measurements refer to the speed

of seeing or to the time of re-adaptation after glare. Most probably they refer to the latter, because that is what De Boer has described.
Fisher (1965) gives a survey of various experimental data, which are interpreted by him in the following way: P.Bouma (1934) found a higher speed of seeing for sodium light than for white light, while Luckiesh & Moss (1935) did not arrive at such conclusions. De Boer (1959) found no difference between filtered (yellow) and unfiltered (white) incandescent lamp light. No difference was established by Dunbar (1939) between sodium and mercury light (although in this respect inaccuracies in the methods of the experiments could have played some part). Finally, Fisher comes to the conclusion that the gain of 0.1 sec. in speed of seeing, as suggested by some authors, does not make a difference greater than 6% in the braking distance (4½ feet in 75 feet at 30 m.p.h.).

3.3.5. *Glare*

Some aspects of glare have already been mentioned in the discussion on the scatter of light in the media of the eye. It is customary to introduce the equivalent veiling luminance (L_{seq}).
Stiles (1929) and Holladay (1927) deserve the credit for having established a single relationship concerning L_{seq} according to which:

$$L_{seq} = k.E.\ \vartheta^{-n}$$

k = a factor (which is sometimes incorrectly taken as constant);
E = illuminance at the plane of the eye of the observer;
ϑ = the angle between the line from the eye to the light causing the glare, and the line from the eye to the object observed;
n = a constant.

This relationship is only valid for point light sources, otherwise ϑ is not defined. This relationship as established by Stiles and Holladay was studied in more detail by several other research workers. These studies mainly concerned the 'constants' k and n.
A survey of the values of n, found in various publications, has been given by Fisher & Christie (1964). In spite of some uncertainties, for practical purposes, n is generally given a single value, i.e. n = 2 (see for example SWOV, 1969; Adrian & Schreuder, 1968, 1970 and 1971).
The factor k was also studied very throughly (Fischer & Christie, 1965). It was found that k varies considerably in different persons. The majority of results however, can be represented by the relationship: $k = d + 0.2A$, where A = the age in years and 'd' a factor which depends on the distribution of luminance within the field of vision. Age effects are very important. This relationship is not easily applicable and as a rule, an average value is given to define k, for example, k = 10 (CIE, 1975) or, in some cases also k = 9.2 (Adrian, 1961). These values are applicable, when L_{seq} is expressed in cd/m², E in lux and ϑ in degrees. When other units of measurement are used, a correction factor must be applied.
Of course, we are primarily interested in the degree to which the spectral distribution of light manifests itself. The influence of scattered light has already been discussed. Special investigations into the effect on n or k are not known; as mentioned earlier, the investigations consist, mainly, of psychophysical measurements. In the following, a survey of a number of measurements will be given.

Vos (1963, p. 20) concludes 'the effect of wave-length of the light causing glare is inconsiderable, if present at all'.
Vos & Bouman (1959) found that physiological (disability) glare is independent of light colour.
Le Grand (1937) states that white and green light are scattered to the same extent, but red light is scattered more, and blue light less than white light.
Wanderer (1955) on the other hand observed that blue always causes greater physiological (disability) glare.
According to P.Bouma (1936) glare due to incandescent lamp light and sodium lamp light is exactly the same for young observers, and is nearly the same for old observers.
Arndt (1933) established the same degree of glare for white light and sodium light sources. The same observation was made by Luckiesh & Moss (1935), Reid & Chanon (1936) and Jainski (1962).
The fact that physiological (disability) glare is not colour-dependent, is also mentioned by Schober (1967), while quoting Luckiesh & Moss (1937).
On the other hand Ostrovsky (1970) finds that glare depends on light colour. He introduces a colour-factor into the formula of Stiles and Holladay, which is 1.0 for incandescent lamps, 1.3 for mercury lamps and 0.85 for sodium lamps. These factors indicate that mercury lamps cause nearly twice as much glare as sodium lamps!

Monnier & Mouton (1939, p. 162) discuss some tests of Faillie et al. (1933). Detailed experimental data are not provided, but, it is stated, that in the case of glare by white light, the reaction time is extended by 20%, while it is unchanged in the case of glare by yellow light; both data refer to the glare-free situation. The investigation of Le Grand (1934) is also quoted, in which no difference was found between yellow and white light. According to Monnier & Mouton (op. cit., p. 165) no account should be taken of this result, since the light source used by Le Grand had a luminance equivalent to a glare-free light ('projecteur non-éblouissant', about 1.5 cd/cm^2). The opinion of these authors is that only glare caused by high-beam head-lamps is of importance ('le seul dont il faille en fait se protéger'). From this they concluded, that Le Grand's work does not refute the argument of Faillie et al., and that therefore Faillie et al. are right. However, the considerations of Monnier & Mouton cannot be accepted, because, in the first place, a non-French investigation, already published at that time, and agreeing with Le Grand, is disregarded, and in the second place, because glare caused by low-beam head-lamps is much more important for practical purposes than glare by high-beam head-lamps.
In more recent investigations Pagès & Fleury (1956) are quoted by Fischer (1965). These authors found no difference between yellow and white light as regards glare. This conclusion is also quoted by Devaux (1956). The same author, however, states later (1970, p. 569) that light with a blue component causes greater glare than light without a blue component. No quantitative data are given in this connection; the statement is based on the consideration, that blue light mainly affects the adaptation of the rods. This is true to a certain extent. Radiologists and radar observers wear red goggles for this reason, in order to maintain their dark-adaptation, when coming out into daylight. For this purpose, however, a *red* filter must be used and not a yellow one, as suggested by Devaux. In addition, scotopic vision only has a limited importance for traffic. This argument is actually put forward by Monnier & Mouton (1934) and has been taken over by Devaux, without referring to the source.

Smart (1969) concludes, that based on his measurements, no advantage could be found, either for white or for yellow light, as regards physiological (disability) glare.
A similar result is given by De Boer (1959) and Jehu (1954), (quoted by Fisher, 1965). Hartmann (1959) and Willemsen (1970) also arrived at the same conclusion.

3.3.6. *Re-adaptation*

In connection with the subject of this discussion, re-adaptation indicates the period of time elapsing after the disappearance of the glare source from the field of vision, until the state of adaptation again corresponds to that state, which existed before the appearance of the source of glare. When an oncoming car is approaching, glare increases gradually and after passing, disappears suddenly. This is known to be a difficult moment for seeing objects. For this reason it is desirable to take suitable measures, by which this difficult period can be shortened. It is sometimes suggested, that such re-adaptation requires less time for yellow light, than for white light.
Monnier & Mouton (1934) describe some measurements made by Faillie (again, without bibliographical references). These measurements show that after a glare lasting for 15 to 25 sec. at an illuminance at the eye of 3.7 lux, the adaptation time for yellow (filtered) light is 15% less than for glare caused by white light.
Monnier & Mouton (1939, p. 187) describe some measurements carried out by themselves. They did not measure the re-adaptation time after glare, but the time of dark-adaptation after the extinction of a light. The re-adaptation time after white light appeared to be (on average) 15% longer than after yellow light. Since only average values are given, it cannot be established whether such difference is significant. It is of more importance, however, that these tests are not very meaningful for actual road traffic. Monnier & Mouton (op. cit.) emphasise the importance of this result by noting the necessity, that, in the case of a complete and sudden failure of the car lights, the car must be stopped safely, with only the light from the night sky. It can, however, be assumed that the 15% gain is regarded by other authors as being related to the re-adaptation after glare, and that therefore Monnier & Mouton are often misquoted.
Devaux (1956 and 1970) quotes investigations of Pagès & Fleury (1956), claiming that the adaptation time necessary with yellow light is 24.4% shorter than that required for white light.
Biegel (1937, see also 1936), describes several experiments, directed towards discovering whether lorry drivers readapt quicker after glare caused by yellow or after white light. The result of these experiments which were actually more in the nature of an examination than that of an experiment, was that for people who did not have much trouble with glare, no difference could be established between yellow and white light. For another group of people, who were heavily handicapped by glare, there was a difference between yellow and white light. It is remarkable that some people had a preference for yellow light, while others had a preference for white light.
Reading (1966) described dynamic tests, comparing re-adaptations for yellow and white light. The conclusion was that re-adaptation depends to a great extent on the age of the person tested. Furthermore it was found that white light permitted quicker re-adaptation than yellow light. The relationship is not age-dependent. Re-adaptation time with yellow (filtered) light was in any case 2–3 seconds longer than with white light (it should be observed that a correction is applied here relating to the reaction time, increasing with age). Finally, Reading quotes, among others, P.Bouma (1947) and Arnulf (1963), who both indicate that re-adaptation requires less time for yellow

light than for white light.
De Boer (1960) gives a very detailed description of a series of interesting tests, comparing sodium light, mercury light, and filtered and unfiltered incandescent lamp light. However, he provides few results relating to seeing, only some values, given by way of example. In the first place it is remarkable that immediately after the extinction of the source of glare, the threshold value of seeing increases. The result, given by De Boer as an example, shows that this increase is identical for yellow and white incandescent lamp light; for sodium light it is lower and for mercury light higher. The most important conclusion, however, is that when re-adaptation is defined as the period within which the necessary increase in luminance between the test object and the background is reduced to 10% above the value at which glare started (in every aspect a very reasonable value), no difference could be found between the various colours, the relevant period being 0.5 sec. ('... ergibt sich dass ein signifikanter Unterschied in Wiederherstellzeit für die verschiedenen Farben nicht festgesteld werden kann'). In view of his conclusion, however, it is quite incomprehensible, how De Boer could make the following statement in the Summary: that yellow light leads to some 60% reduction. ('Die Readaptationszeit nach Blendung ist unter Einwirkung gelber Lichten ... bedeutend kürzer als bei farblosen Lichten. Es wurden Verkürzungen dieser Wiederherstellzeit der Sehfähigkeit nach Blendung bis zu ein Drittel der Vergleichswerte festgestellt'.) These two statements contradict one another. Since, apart from a small group of observations, given as illustration, no experimental data are provided, it is impossible to establish, which of the two statements is the right one.
A report of the G.T.B. (1955), however, is quoted in this connection. This report gives no description of tests, but discloses the following test results: At glare-causing luminance of 0.2 lux there was no difference in re-adaptation time for yellow or white light. With a glare source giving 2.2 lux the eight test persons could be divided into three groups. For three observers the same re-adaptation time of about 0.3 seconds was established both as regards yellow and white light. Two other observers had a re-adaptation time of about 9 sec. for white light and about 3 sec. for yellow light. Again for three other observers, the re-adaptation time for white light amounted to 4–6 sec. with an improvement for yellow light of about 30%. In more simple terms: the average re-adaptation time required for white light was 5.2 sec. while for yellow light it was about 3.1. sec. thus, an improvement for yellow light, of about 40%.
Smart (1969) observed that the progress of re-adaptation depends to a large extent on the observer. It could be established, for nine out of ten observers, that, to a level of 3 dB below the dark-adapted level, the re-adaptation time for white light was significantly shorter than for yellow light. It is, however, concluded that all differences are very small and could, under altered circumstances, be reversed.
Hartmann (1968) describes similar measurements. However, he found no difference between white and yellow light as regards re-adaptation time after glare of a few seconds. Neither did he find any difference for sodium light.

3.4. Effect of age

During our discussions we often encountered age-dependent effects. For example, an increasing discoloration takes place in the various elements of the eye, mainly in the lens, on account of this, blue light is absorbed to an increasing extent.

Mann & Pirie (1950, p. 89) state, that the lens of the eye of a child allows the transmission of 90% of the blue light, while the lens of the eye of a 78-year-old person allows only 15% to be transmitted. This statement is supported by Coren & Girius (1972), who established that, for $\lambda = 490$ nm, the absorption of the lens of the eyes of children aged 10 amounts to 15%, while at the age of 40 to 20%, at the age of 60 to 30%, and at the age of 80 to 50%. This is not in accordance with the opinion held by Devaux (1970), that people with the weakest eyes benefit most from the yellow headlamp. In any case, the blue light which might be emitted from a white lamp, is absorbed (and not scattered!) in the lens, thus causing no harm.

Furthermore, it was found that the macula-pigment, which absorbs blue light, is not age-dependent (Ruddock, 1956b). This finding is also supported by Bone & Sparrock (1971). According to Ruddock (1965a) the receptors themselves do not age, and the increasing absorption of blue light is only the result of the lens turning yellow. He arrived at this conclusion from measurements carried out by himself (Ruddock, 1956), and also quotes Said & Weale (1959).

It is a well-known phenomenon, that visual performance, in general, deteriorates with age. Le Grand (1956, p. 108) gives a summary of data to this effect. Fortuin (1951) found a close dependence on visual acuity. Comprehensive literature is available on this subject, which however, has no bearing on the present discussion, since the tests, as a rule, were carried out in white light, and as a result, no conclusions could be drawn as to colour-dependence.

One thing, however, should be noted. As a rule, the hardening of the eye lens and the increasing rigidity of the iris (Le Grand, op. cit., p. 108), and the increasing discoloration of the elements of the eye (Ruddock, op. cit.) are responsible for the deterioration of visual acuity. It is interesting, however, to note that all of the three above-mentioned changes (at least from the physical point of view) should tend to decrease the image errors of the eye (or at least should have no effect upon them) and thus improve visibility at increasing age! Based on this, we would (very cautiously) come to the conclusion, that other effects also play a part in the processes of ageing. Since, at the moment, we cannot show such effects, a colour-dependence should not be excluded 'a priori'.

Many investigations were carried out into the effect of age on glare (Fisher & Christie, 1965). According to Said & Weale (1959), the transmission of the eye lens is constant between the ages of 4 and 20, after this, it decreases logarithmically till the age of 63. Such decrease of transmission is wave-length dependent; a sharp decrease having been established at $\lambda = 430$ nm. Boettner & Reimer (1962) ascribe this decrease primarily to the increasing light scatter in the lens. Not much is known, as yet, about the physical background of such an increase in scatter.

Tiburtius (1969) and Aulhorn & Harms (1970) provide some information as to the influence of age on the re-adaptation after glare. Tiburtius (op. cit.) states that re-adaptation time after glare has a linear relationship, from 15 seconds at the age of 10, to 65 seconds for people at the age of 80. This retardation of re-adaptation is, according to Tiburtius, connected with a general slowing down of metabolism and the re-adaptation of 'Sehpurpur' connected with this. It is remarkable, that the age-dependent scatter of light in the elements of the eye is also indicated as a factor contributing to the increase of re-adaptation time! Aulhorn & Harms (op. cit.) adjusted the conditions to night-time traffic: they established glare as being caused by high-beam head-lights, the surrounding luminance being taken as 0.1 cd/m^2, and the duration of glare, as 10 seconds. They found that re-adaptation depends on age. The average re-adaptation time increases from 3.5 sec. for the age group 20 to 30 to about 7 sec. for the age group 70–80. The age-dependence manifests itself, in the first place, by the increase of long re-adaptation times. No reference is made to light colour in the latter two investigations; thus, it can be assumed that all investigations were carried out in white light.

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4. Psychological aspects

4.1. Introduction

The psychology of perception is an important part of scientific psychology. Perception is regarded as one of the four basic human functions (perception, cognition, emotion, volition), and being perhaps the principal and perhaps even the most important of them (Duijker et al., 1968, p. 99). In most text books on psychology, considerable space is allotted to the function theory, dealing with the above-mentioned functions and, more particularly, with perception. In the so-called theory of behaviourism, which regards man as a composition of chemically controlled, conditioned reflexes (Guthrie, quoted by Thomson, 1968, p. 229) and in which many conceptions, usually considered by the layman as being of a specifically human nature (such as free will) are considered as superstitious (Skinner, 1965); in this theory perception is strongly emphasised.
There cannot be the slightest doubt that visual perception plays an essential part in the procedures of traffic. Furthermore, it is quite probable that the psychological aspects of perception are strongly influenced by the colour of the light. This chapter, however, pays hardly any attention to perception psychology itself, because, against all expectations, no literature is available, which could be directly applied, and which would supply relevant data about possible colour dependence. For this reason most psychological aspects are not taken into account. Actually, discussions are limited to, what is called psychological (discomfort) glare, because it is strongly asserted that yellow light has advantages in this respect. Therefore, this aspect will have our main attention while some issues of the recognition of the colour of lights, and fatigue, will also be discussed.

4.2. Psychological (discomfort) glare

As mentioned earlier, there are two kinds of glare, namely physiological (disability) and psychological (discomfort) glare. The first one is characterised by the fact that perception is impeded (mainly by scatter within the eye). The second manifests itself in a sensation of being hindered – this can also happen even if a deterioration in the perception abilities has not yet commenced.
An important question is, whether it is necessary to introduce these different types of glare into our considerations. Such a distinction is meaningful, if it can be indicated that two, essentially different, fundamental processes are involved.
Furthermore, such a distinction is desirable, if it has practical relevance. We are now confronted with the strange situation, that there really is a relevant difference, that the relationship of both phenomena to the surroundings is also different, but, that there are actually no physiological or physical effects as a result of which such difference can be explained.

The most important theoretical argument in favour of such distinction, is the dependence on the luminance of the sourroundings. When, under otherwise identical conditions, the luminance of the glare sources and the surroundings are assumed to increase in the same proportion, light scatter will also increase at the same rate, and so will L_{seq}. At a first approximation there will be no change in physiological glare.
Subjective tests, however, show that disturbance caused by glare – thus psychological (discomfort) glare – increases. In other words, for an unchanged degree of disturbance, with increasing luminance of the surroundings, the luminance of the glare source may increase as well, but to a considerably smaller extent. Thus: $(L_b)^a = cL_g$, where L_b and L_g are the luminance of the background and the glare-source, respectively, 'a' indicating the relationship which is intended and 'c' being a constant, depending, among other things, on geometric conditions.

Many investigations were described concerning the value of 'a'. Several investigations were quoted by Millard & McGray (1928). It was found, that the results of Blanchard, Reeves, Nutting and Luckiesh & Holladay can be satisfactorily interpreted by a = 0.3. De Boer & Van Heemskerck Veeckens (1955) gave 'a' as being approximately 0.33; Hopkinson (1940), approximately 0.45, De Boer & Schreuder (1967), 0.3; Adrian & Eberbach (1967) 0.314. According to Hopkinson (1952) all the data available at that time could be summarised as giving 'a' = 0.5.
Thus, in spite of there still being some uncertainty about the exact value of 'a', it is evident, that this value is somewhere between $\frac{1}{3}$ and $\frac{1}{2}$: much lower than the value found for disability glare. Consequently, we must accept the fact, that disability *and* discomfort glare must both taken into consideration.
Another difference between the two types of glare is the additivity. In the case of more than one source of light, physiological (disability) glare has undoubtedly an additive character: the glare of the individual sources can directly be added. This is not so in the case of psychological (discomfort) glare. There still is some difference of opinion in this respect, which can be seen from the fact, that different laws of addition are quoted for indoor lighting installations than for street lighting installations (Arndt et al., 1959).
The last question is, whether this distinction is of such practical importance, that it deserves consideration. However, only practice could give an answer to this question. Practical experience actually shows the distinction as being reasonable, mainly because there are many lighting installations in use, which cause distinct discomfort glare, while no disability glare can be established. As a matter of fact, the converse may also happen (Adrian & Schreuder, 1970). For this reason it is justifiable to make a distinction between psychological (discomfort) and physiological (disability) glare in the literature on lighting techniques. Definitions concerning the nature of the phenomena involved are, of course not obtained from this. For this reason some authors are persuaded to change to the opinion, that we are concerned here with essentially different effects (Hartmann, 1959; Adrian & Eberbach, 1965). The fact that it is the same light source causing these effects is sometimes used as an argument for accepting that we are concerned with the same effect, but that it has two different aspects (Adrian, 1961; Schmidt-Clausen, 1971).
First we shall investigate the adverse effects of discomfort glare. According to Christie & Moore (1970), and Fisher et al. (1970), it is no more than a disturbance of the aesthetic sensation. They regard the avoidance of psychological glare simply as a

luxury, which they think to be much too expensive. This opinion is often encountered in Anglo-Saxon countries.
Other authors find it necessary to limit such discomfort or to relieve it completely, because the sensation of discomfort might distract the attention of the driver from his driving task. This seems an acceptable argument, which, however, cannot be supported by facts, partly due to not knowing precisely the essence of 'attention', and therefore not being able to establish the effect which might be caused by 'distracting a part of the attention'. The opinion, that discomfort must be relieved, is mainly held on the Continent of Europe (De Boer, 1957 and 1967; Devaux, 1956; P.Bouma, 1936; NSVV, 1974). Benz (1966) should also be mentioned, who established a relationship between psychological glare and changes in the Electro-encephalogram. Stone & Groves (1968) found no connection between psychological (discomfort) glare and visual performance, which, in view of the definitions, could hardly be expected. Finally, Fry & King (1971) ascribe the hindrance caused by psychological (discomfort) glare to the irritation of the pain sensing nerve fibres, which terminate in the iris.
Decisive arguments for the limitation of discomfort glare, evidently cannot be supplied at present. In spite of this, we shall investigate to what extent discomfort glare depends on light colour, mainly because (as mentioned earlier) this dependence is regarded as the most important advantage of yellow vehicle head-lamps.
In discussing the experiments carried out on this effect, care should be taken not to confuse the advantages and disadvantages of yellow (filtered) incandescent lamp light with the advantages and disadvantages of yellow (monochromatic) sodium light as compared to white light.
An important experiment was described by De Boer & Van Heemskerck Veeckens (1955). They studied for two degrees of discomfort glare (just permissible and satisfactory) the admissible luminance of the light sources of a street-lighting installation, in relation to the luminance of the road surface. The significance of differences between the colours of the light is, however, slightly doubtful. The measurements have also been repeated for a single value of road surface luminance ($L = 1$ cd/m^2), and, most probably for a small number of light sources, of different luminance, which, however, are not detailed.
The results are expressed in the relationship $q_{1/2}$ between the admissible luminance of light sources at light colours 1 and 2.
Three combinations were studied:
a. sodium light as compared to fluorescent tubes (S/T)
b. sodium light as compared to high pressure mercury lamps (S/M)
c. filtered (yellow) light as compared to unfiltered (white) incandescent lamp light (Y/I).
The results can be summarised as follows: the average value of $\hat{q}$ is, in the abovementioned cases (and with a reliability of 95%), within the following limits:
a. $1.1 < \hat{q}_{S/T} < 1.5$
b. $1.2 < \hat{q}_{S/M} < 1.8$
c. $1.1 < \hat{q}_{Y/I} < 1.4$
Thus, it seems that, on average, yellow light may have 1.25 times greater luminance (see also Figure 6). Reference is made to Ferguson et al. (1953) who provide comparable results.
The following remarks can be made on these results. The geometry is that of the street lighting, in which the image of the lamps is formed on the cone-depleted periphery of

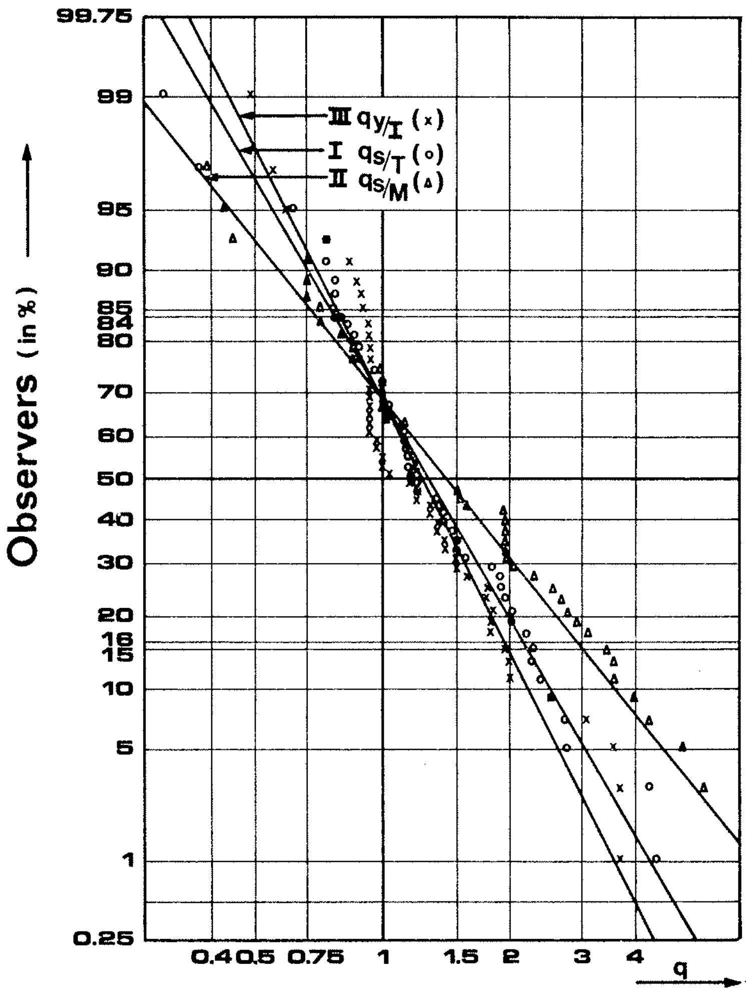

Figure 6. Percentage of observers finding a ratio q greater than the value plotted along the abscissa.
Curve I represents the ratio $q_{S/T}$ of the just admissible light-source luminance under sodium light and the corresponding light-source luminance under the light of tubular fluorescent lamps.
Curve II represents the ratio $q_{S/M}$ of the just admissible light-source luminance under sodium light and the corresponding light-source luminance under the light of mercury lamps with fluorescent bulb.
Curve III represents the ratio $q_{Y/I}$ of the just admissible light-source luminance under incandescent light seen through a yellow filter and the corresponding light-source luminance under unfiltered incandescent light.
(The fact that the three curves cut each other in one and the same place is accidental).
(According to De Boer & Van Heemskerck Veeckens, 1955).

the retina, while the image of the road surface is formed on the cone-rich fovea. Stiles (1954) and Schreuder (1962) suggested that this also contributes to the favourable effect of yellow light with regard to glare. If this is true, it can be expected that the effect in the case of car lighting (with a smaller 'glare angle') will be less significant.

It is remarkable, that Monnier & Mouton (1939) do not refer to psychological (discomfort) glare in their comprehensive work on car lighting. This is all the more notable, since, in the first place, psychological (discomfort) glare is one of the few domains where yellow light seems to have some advantage, and in the second place, because to date, it is just this effect which is most strongly emphasised by the non-scientific press.

The report of the G.T.B. (1955) provides some indication about the relative hindrance caused by yellow and white light. In a situation, without any glare caused by oncoming cars, a significant preference for white light was observed, both on wet and dry road surfaces. In the case when glare was present, the opinions differed so that no meaningful result could be obtained. A small majority found yellow light less glaring, but in general, a preference was found for white light.

Devaux (1970) only remarks that '... the effect of a yellow lens for tired eyes [is] ... a sensation of calm'. Also in an earlier publication (Devaux, 1956, p. 39) the aspect of comfort is only mentioned incidentally.

Thus, it can be concluded that, in general, sodium light is found less glaring than mercury light, and filtered (yellow) light is also being found less glaring than unfiltered (white) incandescent light.

4.3. The perceptibility of signalling lights

4.3.1. *Recognition*

In SWOV (1969), definitions are given regarding perceptibility, visibility, recognition and conspicuousness. Some further remarks are added here.

One aspect which aroused only little interest in connection with the problems concerning the colour of the light of car head-lamps is the possibility of using the colour of the light for coding the various categories of road vehicles. On the other hand investigations have been made as to whether colour can be used in coding movement characteristics. However, opinions differ in this respect.

Projector et al. (1968) discard the idea on the basis that too many variables would be involved.

Anon (1968) indicates that colour can be applied as a secondary code, but that it is unsuitable for *all* drivers and *all* driving situations.

The necessity for establishing a clear marking of categories, which could be perceived in the dark as well, was suggested by Roszbach (1971). In this respect the rear of the vehicles received the greatest attention.

We shall now indicate some questions concerning the front of the car, and more particularly, concerning the recognition of colour, while limiting our considerations to yellow and white only.

In the first place the observation of P.Bouma (1946) is important, which states that in the case of light sources, which project their light directly into the eye, the spectral distribution plays hardly any part. Indication of the colour temperature should be, in general, sufficient for characterising the kind of light (op. cit., p. 276).

The second point of interest is the fact, that as a threshold value, the normal human eye is capable of distinguishing a very large number of hues (see Judd, 1936, quoted by Nimeroff, 1968).
For information on maps (for example for air traffic) 28 different colours seem to be available (Shontz et al., 1971). In any case, it must be taken into account that colours, both as regards their apparent intensity and degree of saturation, change in relation to their background (Ishak et al., 1970).
The number of colours, however, which is still available for various codings of signalling lights, is much lower. One should not forget that upon perceiving a signalling light, there is no possibility of direct comparison; furthermore, interpretation should be effected while the attention of the driver is directed to other activities, such as driving. The signals should be distinguishable by people with impaired colour discrimination. All these circumstances reduce the number of possible colours to about seven (McCormick, 1964). For everyday practice, however, no more than five are left, i.e. blue, green, red, yellow, and white. Using both yellow and amber could be confusing. Some data in this respect are given by Walraven (1972).
On the basis of results already mentioned in this publication, it can be expected that the difference between the commonly used (filtered) yellow and 'white' incandescent lamp will be much too small for ensuring a satisfactory distinction. In practice this would mean, that yellow car head-lamps should have the colour which is nowadays normally used for traffic lights. This means a drastic reduction in the yellow lamp's luminance, so that the assumption made throughout this publication concerning a small, even negligible loss of light, would no longer be valid.
Finally, the following should be said: filtering out the blue light as is done in yellow lamps, naturally reduces the possibility of distinguishing colours of road markings. This is of small importance in view of the road surfaces, which, as a rule, have a neutral gray colour. The indication of certain routes and of other road markings, as applied at some locations as an experiment (Sparten, 1971) would then be less effective. The possibility of making a distinction between yellow and white road markings is much more important. This could cause problems, when such difference is used for making technical traffic and legal distinctions.

4.3.2. *Conspicuousness*

From the definitions given by SWOV (1969), it follows that the concepts of perceptibility and conspicuousness overlap to a certain extent. They coincide in that considerably more information must be transmitted, than that which is necessary for simple 'detectability'.
Connors (1969) describes experiments in which the colour of small objects, which were visible for only a short time, had to be recognised. Also in these experiments an achromatic zone could be established. Furthermore it was found that under the given test conditions, red was detected correctly most frequently and distinctly. Finally, the findings of Boynton & Gordon (1965) and Weitzman & Kinney (1967) were partly corroborated from statements that yellow and amber are often detected as red with a short exposure time. This effect, which can be observed sometimes in connection with flashing lights, means that yellow flashing light can be more easily confused with a red flashing light than with a white flashing light. In this respect one must take into account the colour shift towards red, caused by the fact that a flashing incandescent lamp does not always reach the normal operating temperature.

4.4. **Fatigue**

Finally, some observations are made, summarised under the heading 'fatigue'. It is not our intention to give a definition of the phenomenon of fatigue, or to describe its many and diverse aspects and effects, or even to indicate how fatigue can affect traffic and traffic safety. We shall confine ourselves to discussing some aspects related to the problem in which we are here interested. One of these is the psychological (discomfort) glare and the fatigue, which may be caused thereby. There are aspects of fatigue which can develop after having been exposed to physiological (disability) glare for a long period of time. Hartmann (1963) carried out some experiments in this connection. It is, however, still, doubtful whether the deterioration of a certain skill, which most probably is related to driving a car, can really be ascribed to increasing fatigue or, whether fatigue is a consequence of physiological (disability) glare. For our purpose this is not so very important, since it could be clearly established, that disability glare does not depend on the colour of light. Bartlett (1943) describes an interesting experiment, showing that various skills deteriorate selectively when the person is exposed to disturbances for a long time. In view of the experiment conditions, however, this result is not very important with regard to road traffic.

Devaux (1970) states that fatigue depends on the colour of the light. He found that under yellowish-green light fatigue is inconsiderable, while under ultraviolet light it is increased (due to the harm which is caused by this light). Furthermore, he suggests that in addition to ultraviolet light, blue light is also dangerous, and comes to the conclusion that yellow lamps are preferable, in view of the large amount of U.V. light emitted by normal incandescent lamps. ('U.V. rays harmful to the retina, are those which induce the phenomena of eye fatigue. These rays exist in large quantities in the light produced by the incandescent lights presently in use ...' Devaux, op. cit., p. 569).

The following can be said about these rather categorical statements. Firstly, there is not any quantitative or even some more detailed qualitative information concerning the statement that yellowish-green light is less fatiguing than blue light. No more is said about the harmful effect of blue light. Ultraviolet light can be harmful at high intensities, but not for the retina, because it has already been absorbed, before arriving there. Damage is done to the mucuous membrane of the eye and, in extreme cases, to the lens and cornea. All this exclusively concerns shortwave ultraviolet light, which is completely absorbed by normal glass. This statement of Devaux can be regarded as fictitious.

Finally, the relationship between risk and fatigue is not supported by any fact. Summarising: the advantage of yellow lamps, indicated by Devaux on account of their assumed fatigue-reducing effect, has no scientific basis whatsoever.

4.5. **Conclusions**

1. It is possible that the coding of roads by means of yellow and white road markings, can be unfavourably affected by the (possible) use of yellow head-lamps.
2. Yellow light causes less psychological (discomfort) glare than withe light. The significance of this difference is not fully elucidated. No effect on traffic safety can be established.
3. There are no reasons to assume that fatigue depends on the colour of the light.

4. The colour of the light is only considered for secondary (redundant) coding.
5. The colour difference between the colours of the light discussed above is also much too small for secondary (redundant) coding.

Literature Chapter 4

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