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THE
PROBLEMS OF VISION IN FLIGHT AT HIGH ALTITUDE

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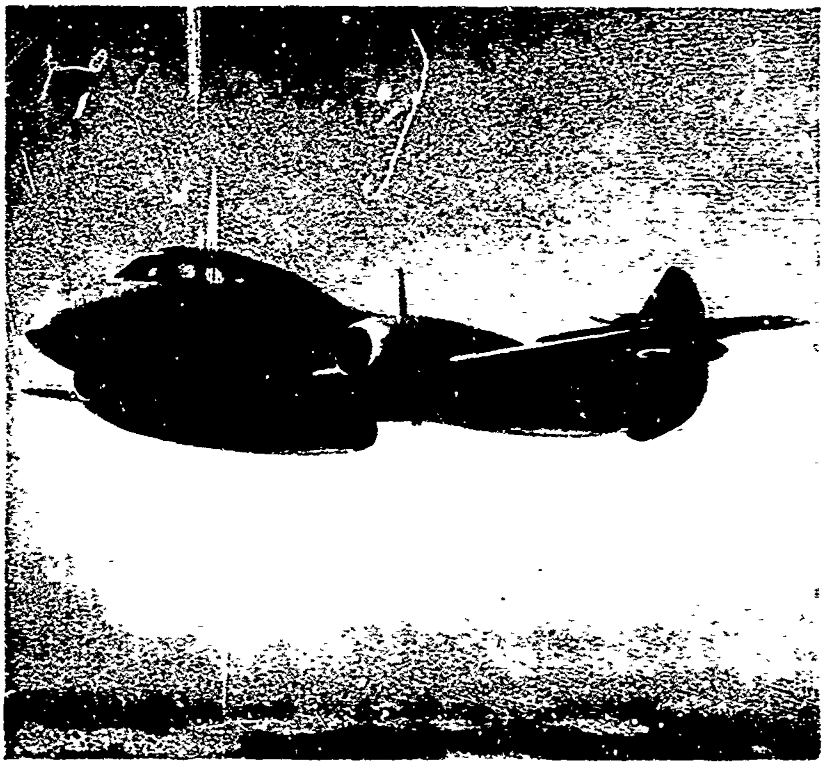

Aircraft employed in flight experiments: Gloster Meteor Mk 7.

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To
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The Aeromedical Panel of the Advisory Group for Aeronautical Research and Development (AGARD), North Atlantic Treaty Organisation, takes pleasure in sponsoring the publication of this book. Its publication as an AGARDograph does not necessarily imply unanimous indorsement on the part of the Panel, and the views expressed therein remain those of the author. However, sponsorship of this work expresses the Panel's opinion that it constitutes an important contribution to the aeromedical literature.

PREFACE

'The eye is a camera' is a phrase which has been used for many years. It has the advantage of conveying an immediate impression of the mode of action of the eye, but it is a dangerous phrase to employ because after having served its purpose in illustrating the formation of the retinal image, the metaphor tends to be carried to extremes and the seed so easily sown becomes a belief most difficult to eradicate. There is no camera today which can simultaneously resolve a line subtending 0·5 seconds of arc, a point of 20 seconds of arc, have an overall range of sensitivity of 10,000 times from dark to light and detect some 200 hues of colour—all this remarkably taking place in an organ 2·3 cm. in diameter and in spite of aberrations in the lens system.

As light enters the eye it is refracted at three surfaces: at the anterior surface of the cornea, and at the anterior and posterior surfaces of the crystalline lens. This lens can alter its shape and therefore its power, so as to maintain a sharp image on the fovea, whether the object is near or in the distance.

The image which is thus formed on the retina is, however, not very sharply defined since spherical and chromatic aberration are present and since there is a limit of definition imposed by the finite size of the mosaic of retinal end elements—the rods and cones. With a spherical lens it is not possible to avoid spherical aberration, but in the eye the lens is not spherical and the centre, being more convex, tends to refract more strongly than the flatter periphery so that, especially in the unaccommodated state, spherical aberration is usually reduced. Its extent may, however, vary greatly from subject to subject.

The other aberration with which the eye copes so well is chromatic aberration which is caused by light of different wavelengths being refracted to different extents. The shorter blue rays are more strongly refracted than the red rays so that they come to a focus nearer the lens. By this difference in refraction white light is broken up into its spectral colours. The eye naturally focuses the yellow rays which are the brightest part of the visible spectrum, and the other colours, slightly out of focus, are superimposed upon the yellow image, giving rise to a blurred white image. If the amount out of focus increases, the image may become either red or blue with blue or red fringes. These colour fringes are suppressed, and even if by means of lenses the chromatic aberration of the eye is doubled, it is not normally detected.

The retina converts the optical image thus produced by the cornea and lens into a pattern of nerve impulses travelling in the optic nerve. The first stage in this process is the absorption of part of the light of the image in the rods and cones, and there is evidence that this absorption results in a photochemical reaction in which each pigment molecule in a rod or cone which absorbs a light quantum is itself structurally altered, and that only one such molecular alteration is required to excite a rod, and only a very few to excite a cone. In the rods the pigment which absorbs light is visual purple, a photolabile chromoprotein biochemically derived from vitamin A. No photolabile pigments have yet been isolated from the cones of mammalian eyes, but they can be found in those of birds and fish, and there is indirect evidence that the concentration of pigment in human cones cannot be much less than that in the rods.

From the retina the pattern of nervous impulses is conveyed to the lower visual centres of the brain—the lateral geniculate bodies and the superior colliculi—and from there they are relayed to the occipital lobes of the cerebral cortex.

At the retina the cones are packed most closely together in the fovea centralis, and, since in this small area each cone is subserved by one axon fibre of the optic nerve, optical resolution and therefore visual acuity are highest in this region. In the other parts of the retina, however, the number of photoreceptors is greatly in excess of the available number of fibres in the optic nerve, and the conclusion is that one fibre subserves several receptors, the number of receptors in one field being greater as one goes towards the periphery. Whilst one cone is not connected to one cell at the cortex, there is nonetheless a 'point-to-point' relationship between a retinal stimulus and its cortical representation.

It seems impossible that all the nuances in the appreciation of an object could be achieved through these retinal stimuli alone, and in consequence, the retinal stimulus projected on to the cortex is now said to result in a 'perceptual pattern'. In this perceptual pattern, the visual stimulus gives rise to a pattern of nervous impulses which either associate with other simultaneously occurring patterns of impulses from the other senses, or which associate with memory of the pattern of impulses received on previous occasions. A circle drawn on paper may thus be appreciated as being the representation of a flat disc. If it is darkened at the edges by shading in pencil, it no longer appears to be a disc but rather as a sphere.

In the process of seeing, it has thus to be remembered that one is dealing not with a camera with its man-made finery of high speed shutters and aplanatic lenses, but with a sense organ which, even with its intrinsic aberrations, results not only in a more sensitive representation of the outside scene but in an appreciation of such properties as the texture, size, and distance of the objects regarded.

The physical, the physiological and the psychological processes thus integrate, resulting in a perceptual pattern which permits one to *see*, namely to appreciate, to evaluate and to recognise the information presented by the visual field.

As in most problems of an applied nature, there are in this instance, many facets which have to be examined individually, and it is only when all have been examined, each in turn, that it is possible to consider them together so as to obtain a comprehensive view of the problem as a whole.

In an attempt to integrate the findings, discussion has been kept to the end when the reader has been familiarised with the different aspects of the problem. Since the results of one experiment usually suggest the next experiment, the reader has been taken through the investigation in the order in which it was tackled. A short summary at the end of each section, together with the opening paragraphs of the next section, ensures continuity of thought. For the same reason, data, and in one case, a complete experiment not in the direct line of argument, have been relegated to the appendix.

An attempt has been made to reach the basic cause of the problems, for it is only in this way that one obtains a useful answer which explains the principles involved so that the reader may be able to predict the many effects produced by the interplay of the causal factors.

The references selected are, in general, key references which lead the reader who desires to follow up a particular subject, to further papers. Much use has therefore been made of reviews of the literature.

Finally, I hope that I may have been able to impart to the reader some of the absorbing interest which this problem has held for me.

T. C. D. W.

Farnborough, 1955.

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I WISH to express my sincere thanks to the Director General of Medical Services, R.A.F., Air Marshal Sir James M. Kilpatrick, for permission to publish this work; to Professor R. C. Garry and to my Commanding Officer, Group Captain W. K. Stewart, for their constant advice and encouragement in the supervision of my work; to Professor Sir Bryan Matthews and the Members of the Vision Sub-Committee of the Flying Personnel Research Committee for their useful criticism; to my friend and colleague Dr. F. W. Campbell for the many hours of discussion on the subject of accommodation and to my colleagues at this laboratory for their useful observations and suggestions. I gratefully acknowledge the advice and assistance of Mr. D. C. C. Gronow in the statistical examination of the experimental data. I would also like to express my gratitude to AGARD for enabling this book to be published.

To Mr. Hills and his staff of the Printing Department, Royal Aircraft Establishment, I express my grateful thanks for their construction of the small dot test plate and for printing the figures accompanying the text. The typists at this Institute receive my grateful thanks for the hours spent in transcribing neatly from the untidy and I confess sometimes almost illegible notes with which I provided them.

To my wife and children I say 'thank you' for having tolerated for so long a preoccupied and temperamental husband and father.

DEFINITION OF TITLE

'FLIGHT at high altitude' refers in general to flight in the stratosphere or in the upper limits of the troposphere. It does not refer to a specific height above sea level, but it always means flight above cloud. In practice the altitude at which observations were made was generally about 40,000 feet but the findings can also be applied to flight outside the earth's atmosphere.

'The problems of vision' dealt with are those which give rise to immediate difficulty in seeing. Whilst some are common to lower altitudes most of the problems investigated appear at present to be peculiar to high altitude.

With one exception the problems dealt with do not arise from speed and so the craft in which these problems arise may be either balloon, civil transport or high performance fighter.

The problems investigated affect only those whose duties require them to look out on the high altitude scene.

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HISTORICAL SURVEY

LITTLE work has been carried out on vision in flight at high altitude and in some respects this province is a virgin field. This is surprising, particularly in view of the interest today in the possibility of space flight. The purpose of this introduction is to show, against a background of the history of aviation, the place of the visual problems of aviation medicine and, in particular, the place of the visual problems associated with flight at high altitude.

THE BEGINNING OF AVIATION

There is evidence in legend and from works of art that man's desire to fly dates from the earliest civilisations. Man did try to fly like the birds, but failed, and in the face of his own failure, he endowed his deities with that attribute which Nature had denied him. History and legend tell of many incidents which were probably attempts to fly—all of them ended in disaster, and consequently in those early times successful flight was regarded as being possible only with supernatural help.

DAVY (1937), in his book, *The Interpretive History of Flight*, points out that the more enlightened writings of John Wilkins (1614–1672, and first Secretary of the Royal Society) classified the methods whereby attempts had been made to fly as

(*1*) by means of spirits or angels
(*2*) by the help of fowls
(*3*) by wings fastened immediately to the body
(*4*) by a flying chariot.

The stories, the legends, tell mostly of failure—failure of the machine. The wings of Icarus melted when he rose too near the sun becaues they were made of wax, while his more prudent father Daedalus flew to safety. Other tales, less spectacular, tell of men who, from the edges of cliffs or from the tops of battlements or towers, launched themselves into the void on mechanisms of feathers, silk, and bamboo. Those who survived these experiments were either dissuaded from continuing or were incapable of repeating them.

To remember that these attempts have taken place since the beginnings of civilisation makes it all the more remarkable that, within the past fifty years, progress should have brought one to the stage of regarding almost as commonplace flights beyond the speed of sound and ascents to heights of ten miles above the surface of the earth. Nor can these improvements be said to be due purely to the development of the internal combustion engine, or, in recent years, to the development of the jet engine, for it is possible today, by the unpowered flight of gliders, to remain airborne with little difficulty for two, three, four or five hours and to travel great distances on a predetermined course—all this with a machine which could have been built by our forefathers.

The first successful experiments in raising man in the air were made in France in 1783 by the brothers Montgolfier with a paper and linen balloon filled with hot air. The passenger who undertook this, the first human ascent, was a young technician, J. F. Pilatre de Rozier.

As a result of the early experiments of the Montgolfier brothers, investigations and experiments had also been carried out with a hydrogen-filled balloon under the direction of the distinguished physicist, J. A. C. Charles. The development of the two balloons, the hot air type, referred to as the 'Montgolfière', and the hydrogen type, referred to as the 'Charlière', was thus proceeding simultaneously.

It was about two months after the first human ascent in a hot air balloon that a human ascent took place in a hydrogen-filled balloon, the passengers being the physicist Charles and one of the brothers Robert who constructed the balloon. Their flight lasted two hours.

Pilatre de Rozier, the first man to fly, was also to be the first man to die in a flying accident. In 1785 he tried to cross the English Channel from France in a balloon of his own design in which he tried to combine the constant lift of a hydrogen balloon with the variable control of the hot air balloon, apparently without realising the dangers of the combination. The two sections were separate, but during the ascent a spark reached the hydrogen causing a violent explosion and de Rozier and his companion Romaine were killed as their car fell on to the rocks below.

These experiments in balloons paved the way for the subsequent work on heavier-than-air machines. It is known that kites were used in China for the purpose of military signalling in the year 206 B.C., but the principles involved in mechanical flight by heavier-than-air machines received no scientific attention until Sir George Caley began his experiments with model gliders in 1796. The result of his experiments and theory was to place the study of aeronautics on a scientific basis, and it was probably owing to Caley's work that Henson and Stringfellow succeeded in producing the first successful flight of a power driven model in 1848. These experiments with model gliders set the scene for the era of practical experiments in the air, experiments in gliding which were first necessary before the application of power could be made.

Apart from the doubtful experiments of the Middle Ages, the first successful glider flight seems to have been made by Le Bris about 1855.

The technique of controlled flight, however, was pioneered in Germany by Otto Lilienthal who in 1890 made glider flights by launching himself from a small artificial hill near the otherwise flat suburbs of Berlin.

In Britain, under the influence of Lilienthal's work, similar experiments of a practical nature were taken up by P. S. Pilcher who, from 1893 until his death in 1899 at the age of 33, was a lecturer in naval architecture and marine engineering at the University of Glasgow. His first glides were made in 1895 from a grass hill overlooking the Clyde at Wallacetown Farm near Cardross (PILCHER). He demonstrated for the first time the usefulness of a wheeled and sprung undercarriage in relieving the pilot of the shock of landing; and he actually had under construction a 4 h.p. engine for his glider, when in 1899 his experiments were cut short by a fatal accident caused by the breaking of one of the guy wires to the tail which collapsed.

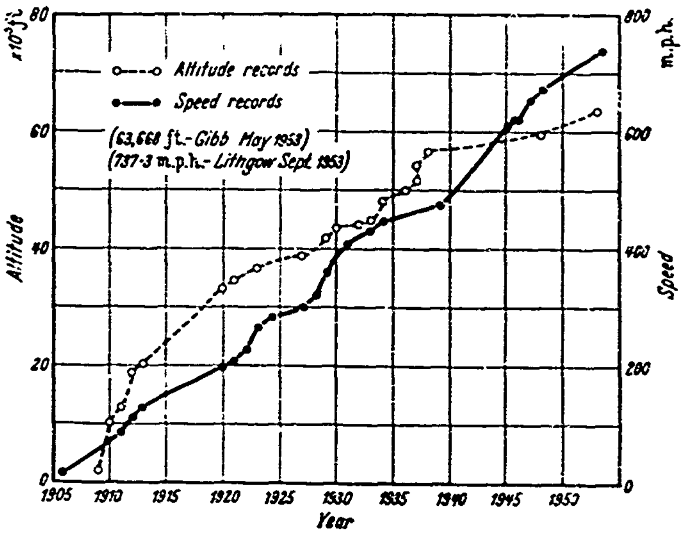

Fig. 1. World records of speed and altitude in powered heavier-than-air machines

In the experiments of Lilienthal and Pilcher, the control of the glider was effected by moving the body about, and it was left to Chanute in America to improve the control by making the main supporting plane movable in a fore and aft direction.

The development had been slow, the successes few, and the failures many, but together, all had built up a fount of knowledge and experiment which provided the Wright brothers with the knowledge necessary for their early gliding experiments. In a number of instances they could not agree with the earlier data and so by careful experiment and observation they made their own measurements.

INTRODUCTION

Three years after the completion of their first glider, the first heavier-than-air, controlled, power-driven flight was made by Orville Wright on 17th December, 1903, at Kitty Hawk in North Carolina. Four flights were made that day, the first lasting 12 seconds. The last, made by Wilbur Wright, lasted 59 seconds and covered 852 feet.

Fifty years separate us from that historic day. At the beginning of the fifty years, a small paragraph in the newspaper announced the successful flight. At the end of the fifty years, an equally small paragraph announced a successful flight at 1800 m.p.h. by Bill Bridgeman in the Douglas Skyrocket.*

An indication of the rate at which progress has taken place in flying can be obtained from *Fig. 1*. The data for the graph were obtained mostly from DORMAN (1951). It is interesting to note that the development of the jet engine merely served to continue the trend already present in the earlier part of the curve, so much so that one wonders if, with the present use of rocket propulsion, the trend may not continue in the same way.

THE BEGINNINGS OF AVIATION MEDICINE

What, according to ARMSTRONG (1952), seems to have been the first physiological link with aeronautics was made in 1874, when two balloonists—Sivel and Croce-Spinelli—presented themselves at the physiology laboratory of PAUL BERT in order to experience decompression in the low pressure chamber and to be initiated in the use of oxygen. They subsequently made, after being furnished with a quantity of oxygen calculated by Bert, a successful balloon ascent to about 23,000 feet. In the following year they were joined in another ascent by Tissandier. On this occasion they did not seek advice as to the quantity of oxygen to be carried and insufficient supplies of oxygen or possibly too rapid an ascent caused the three aeronauts to lose consciousness. Tissandier alone survived this flight.

The powered flight of heavier-than-air machines did not attract much medical interest until the beginning of World War I and then the interest lay largely in the selection and medical examination of pilots. By about 1915, aircraft were capable of flying above 20,000 feet and so it was required to know more relating to the physiological effects of lack of oxygen. Attention was also being paid to easing some of the difficulties of the pilot by methods such as the provision of windscreens, studies on cockpit dimensions, and later on the development and provision of parachutes and oxygen equipment.

On the neurological side, the usefulness of special examination and tests for flying was realised early on, and this led to the development of

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* This does not fulfil the requirements for official world record of speed and is therefore not quoted as a record.

special testing methods and techniques, and to a special interest in visual, auditory and tactile reaction times.

THE EARLY VISUAL PROBLEMS

Of the special senses, the visual sense was that which gave rise to most of the early, basic, physiological work. It is true, audition received much attention and was the subject of many of the early papers on aviation medicine, but principally from the point of view of either deafness caused by the aircraft noise, otitic barotrauma, or the provision of various ear defenders.

In vision, the early basic work dealt principally with the effects of lack of oxygen. In such a study, **Wilmer** and **Berens** (1918), investigating the effects of oxygen upon acuity, accommodation, convergence, and retinal sensitivity, concluded that the visual symptoms taking place during decompression or at altitude, were due to lack of oxygen and not to the reduction of barometric pressure as had apparently been claimed by some authors.

The limitations to performance and to the establishment of records of speed and altitude had been determined largely by failure of the aircraft. Thus, although the pilot was capable of withstanding higher speeds, no machine existed which was capable of testing him to his limits of physiological endurance. In the early 1920's, however, during the various trophy races, symptoms of physiological stress began to appear—symptoms which meant that the aircraft's performance had reached such a stage as to be capable of imposing upon the man factors so far removed from his normal environment that physiological adaptation to them was no longer possible.

The first mention of blackout (the failure of vision due to increased centrifugal force) is attributed by **Mercier** and **Duguet** (1947) to a pilot, Cookfield, who in 1924 reported transient loss of vision during a turn. Waghorn, who won the Schneider trophy in 1929 with a speed of 328·63 m.p.h noticed the same sympton during the turns he had to effect in this race. **Bauer** (1926), in a chapter on the effects of speed, says that in the Pulitzer trophy race of 1922 the winner stated that he became unconscious when making his turns. There is no mention of blackout or of other visual symptoms in this case, but Bauer goes on to state that it is believed the effect is due to blood being carried away from the head by the increase in centrifugal force.

The visual problems which formed the basis of much of the work on visual physiology during World War II appear, from Bauer's book, to have been for the most part already recognised by 1925. There were the problems of air-to-air search, of visual acuity, judgment of distance, depth perception, peripheral vision, night vision, anoxia, glare, and the development of flying goggles. In the early days, however, all these problems had merely been recognised, and only the more obvious aspects had been touched. Furthermore, visual problems of an engineering nature, such as the design of instruments, the presentation of instruments, cockpit lighting, and runway marking had not yet received attention.

As the machine became capable of still higher performance throughout the years, the effect upon the man became more marked and some new problems appeared whilst the old ones became more complex. The new problems were principally those associated with the design of the cockpit and with the presentation of instruments. They were brought to light because the higher speed at which aircraft travelled rendered it still more important that reaction times should be as short as possible and that, for example, no time should be wasted in searching for a particular instrument, or in glancing from one instrument to another.

With the onset of World War II, visual research received a great deal of attention in an attempt to improve selection of pilots and to increase their ability to cope with the physiological problems with which they had been confronted for so many years—problems such as night vision and glare which in peacetime were a nuisance and fatiguing, but which in wartime became of vital importance.

THE NEW VISUAL PROBLEMS

A number of the visual problems which developed early in the history of aviation still present difficulties. Today, however, the visual problems are principally those associated with flight at high altitude, not because they are more important than the other visual problems of flight, but rather because within recent years flight at high altitude has become commonplace and many now invade the lonely emptiness of that world above the world, the sight of which had been in the past reserved for the few pioneers of high altitude flight.

What also makes for greater general interest in this problem is that the factors present affect passengers as well as aircrew, and therefore it is a problem which is, in some respects at least, of interest to civil as well as to military aviation.

The factors which are of common interest to passenger and to aircrew are those associated with the production of glare. At high altitude the principal change in this respect is associated with the reversal of light distribution which takes place with flying above all cloud. Below cloud, and at lower altitudes, light comes from above, but once the aircraft goes above cloud most of the light reflected back into the aircraft cabins comes from below, from the bright cloud floor. Some light does come from the sky above, but the amount of scattered light which comes from the sky at the zenith becomes progressively less as the aircraft goes to higher altitudes, so that with modern aircraft flying at very high altitudes a new problem is created in the exposing of passengers to an environment in which not only the light distribution is altered so that it comes from below, but the little light which does come from the sky above the horizon is greatly reduced. There is thus at higher altitudes a greater contrast between light and shade and the effects of the reversed light distribution become much more marked than they were in the past at lower altitudes.

When exposed to such an environment, one realises again how well man is designed for his terrestrial existence, for one observes that the recession of the eyes into orbits beneath overhanging eyebrows protects not merely from trauma but also from the glare of sky light which normally comes from above. As the cheeks give no appreciable restriction to the visual field, a light source or sky situated below the level of the eyes allows adventitious light to flood into the eyes and cast a troublesome haze over the entire visual field. The passenger of an airliner at high altitude trying to read a book on his knee is therefore virtually at the same disadvantage as the holiday-maker lying on his back on a sunlit beach and attempting to read a book whilst holding it up against the light source of the sunlit sky, the printed page being the while in shadow.

Passengers, of course, do not need to look outside the aircraft, and theoretically at least the windows could be curtained over and artificial illumination provided within the cabin for the duration of the high altitude flight. The aircrew and the pilot in particular must, however, have a good view of the outside scene, which means that they must inevitably be subjected to this source of glare. The result, in their case is an effect not only involving ocular discomfort but also interfering with visibility of instruments and controls within the cockpit. All too frequently, even in modern aircraft, have pilots to shield an instrument with their hand before being able to discern the markings on it, the hand either acting as a shield to keep away specular reflections from the glass cover to the instrument face or else reflecting light back on to the instrument face so that the markings become legible.

In the case of the military pilot. the key-note of the visual problem is variation. As his rate of climb is so great compared with that of a civil aircraft, there occur outside the cockpit rapid changes in brightness, in the type of glare, in the direction of glare, and in the contrast between light and shade. Thus, within the space of a few minutes the comfortable light and shade of a temperate climate may give place to a light distribution more like that of a snow field. In addition, the frequency with which the pilot's eyes must alternate from cockpit to exterior, from near to far, from dark to light, combines with all these factors to produce a visual environment which most readily results in fatigue and difficulty in seeing.

In flight then, the visual stimuli tend to be at opposite ends of the physiological range, and, especially in the case of the fighter pilot, there is usually insufficient time for the visual processes to adapt themselves satisfactorily to the changing conditions. Improvements in radar render more likely the possibility of dispensing with visual search by day and by night. But at present it is still necessary to effect at least a visual recognition of other aircraft, and the problems associated with search at high altitude, for example, are therefore still pertinent.

Another of the visual problems of flight today, which is however not peculiar to high altitude, is caused by the very high speed of modern aircraft. The interval of time between first spotting another aircraft and finally overtaking it is determined by what is referred to as the closing speed. It is greatest, of course, for two aircraft travelling towards one another. As closing speeds increase, the interval of time between spotting another aircraft and finally overtaking it becomes gradually smaller, and at some of the speeds achieved today it is possible for the interval between recognition and overtaking to be shorter than the visual reaction time, so that the target may be overtaken and passed before the pilot's motor response to seeing it can take place. At even higher closing speeds, involving a time interval shorter than the perceptual reaction time, the target may not be 'seen', until after it has been overtaken (Strughold 1949). Thus, in a way, the pilot is flying blind at high speeds, since the distance at which he can see another target is limited by his visual acuity, and this distance, expressed in time, may be less than his reaction time.

In a somewhat similar way, during low level flight the high speed makes map reading very difficult, for, since the aircraft may be only 50 or 100 feet above the ground, the angular speed at which the ground goes past becomes so great that there is no time to look down at the map to verify the part of road, railway or river, which has been crossed.

High speed flight, particularly at low altitude, is accompanied by sharp and rapid vibrations of the aircraft which are due partly to gusts, that is to rising air currents, traversed at very high speed, and partly to the flow of air over the surfaces of the aircraft.

Duguet and Mercier (1951) point out that these vibrations sometimes interfere with vision since they cause the eye to vibrate at its natural frequency which Coermann (1940) places at between 20 and 60 cycles per second. In passing through the speed range from subsonic to supersonic flight an aircraft is subjected to a transient stage of marked turbulence which may be responsible for the effect mentioned by Byrnes (1950). This, as reported by some pilots, consists of a transient blurring of vision during flight in this trans-sonic range.

SUMMARY

A comparison of the visual problems of flying, then and now, will clarify the position as to what the trends are, what has been done and what has still to be done. The visual problems of aviation can be classified into pre-World War II and post-World War II. The former were the problems which had been noted since the early 1920's and which in many cases were understood fully only as a result of the intense research effort concentrated on them during World War II. The post-World War II visual problems relate principally to flight at high speed and at high altitude, but whereas those relating to high speed have for a number of years been known and received attention in studies on reaction times, the problems of high altitude are for the most part new or at least aggravations of previously tolerable effects.

The change in importance of a problem as a result of progress is exemplified in the development of flying goggles. In the pre-war period, problems relating to goggles were associated with the development of a device which could keep wind blast out of the pilot's eyes. But now, in this post-war period, open cockpit aircraft are no longer used even in primary training, and the accent is consequently on protection from glare rather than on protection from wind as a routine measure. Certainly wind protection is required, but as an emergency measure only. This different requirement has thus to be met with a different piece of equipment which has to be specially designed with this point in view. Fortunately this rather simplifies matters because it is very difficult to make a goggle which is effective in keeping all wind blast out of the eyes, and which at the same time also protects the eye from glare.

Although they will be dealt with later, the problems associated with lack of oxygen have lost much of their importance because with pressure cabins and with the present day oxygen equipment no anoxia should be present.

As a result of much work on eye movements and on the presentation of instruments, most of the mechanisms and basic principles involved are now understood. Similarly much of the basic work has been carried out on night vision, on ocular muscle balance, on colour vision, on peripheral vision, visual acuity and depth perception. Search has been studied intensively also. Accommodation, however, appears to have been neglected in these studies, and in particular the accommodation changes during search.

Many articles have been written on the subject of vision at high speed and altitude, but they refer almost solely to the problems of high speed and little, if at all, to the problems of altitude. Whilst some of the problems of vision at high altitude have already been described and investigated, many others have never been mentioned, and, indeed, it seems that their existence was not suspected.

The present investigation is thus an attempt to establish the factors involved, and the way in which these problems arise. Although essentially of an applied nature it has been rewarded by the uncovering of some facts of basic physiological interest.

II. EFFECTS OF CHANGES IN INTENSITY AND SPECTRAL DISTRIBUTION OF SUNLIGHT AT HIGH ALTITUDES

INTRODUCTION

In clear air the intensity of solar radiation from direct sunlight increases with increasing altitude above the surface of the earth. The solar radiation which reaches sea level has been attenuated by passage through the atmosphere, the attenuation by absorption and scattering being greater for the shorter wavelengths than for the long wavelengths. There is thus at high altitude an extension towards the blue end of the spectrum with a relative decrease in the amount of red. With increasing altitude the sky at the zenith becomes darker; at an altitude of 40,000 feet and above all cloud the sky is white at the horizon, decreasing in luminosity towards the zenith at which point it appears rather dark blue.

It seemed likely, therefore, that at high altitude contrast between light and shade in the cockpit would be greater than at lower altitudes since the areas which were not receiving direct sunlight would be dependent only upon the scattered light received from the rather dark sky. It was found, however, on discussing this question of contrast with pilots experienced in flight at high altitude, that there was inconsistency in the apparent severity of the problem. These differences in opinion could not be due to factors of climate or of latitude since the flights referred to took place over England. They suggested rather that the cause lay in the individual or in the aircraft or in a combination of both.

First-hand experience of flight at high altitude confirmed these observations. Above 10,000 feet there was usually difficulty in discerning details in the cabin and in reading instruments which were in shadow, because the shadows appeared darker and because there appeared to be a haze constantly present over the entire visual field. The difficulty was sometimes present at low altitudes as well, but there an almost immediate improvement could be effected by shielding the eyes with the hand. At high altitude similar shielding also improved visibility but only after a measurable interval of about 1–5 seconds and sometimes more. Even with the improvement obtained, however, the shadow areas under observation at high altitude were not seen as clearly as they were at low altitude.

In view of the impression formed during these preliminary observations, it was decided to examine first of all the physical factors so as to determine whether the increase in contrast between light and shade in the cockpit was real, or whether the subjective impressions were without a physical basis.

CHANGES IN INTENSITY AND SPECTRAL DISTRIBUTION OF SUNLIGHT

As it was thought that the haze over the visual field might be due either to fluorescence of the lens caused by increase in ultra-violet light, or to an increase in the intraocular scatter of visible light, some additional flights were planned to examine specifically these two points.

A determination of the brightness of sunlit parts in the cockpit might have been made from existing data on direct solar illumination, but the measurement of illumination of shadow areas, however, could not be calculated from existing data since reflected light was present from so many directions. Measurements had therefore to be made in flight.

CONTRAST BETWEEN LIGHT AND SHADE

RÉSUMÉ OF PREVIOUS WORK

A NUMBER of measurements of sky luminance have been made from aircraft and from balloons, but none can be employed directly to determine what contrast exists within the cockpit particularly at high altitude. From the flights of the balloon Explorer II, which in 1935 reached an altitude of 72,395 feet, there were obtained measurements of sky luminance which TEELE (1936) showed to be directly proportional to atmospheric pressure, the point of sky referred to being 58° above the horizon and at 90° to the sun (*Fig. 2*). No observations at an elevation greater than 38° above the horizon could be made because of the bulk of the balloon above the gondola.

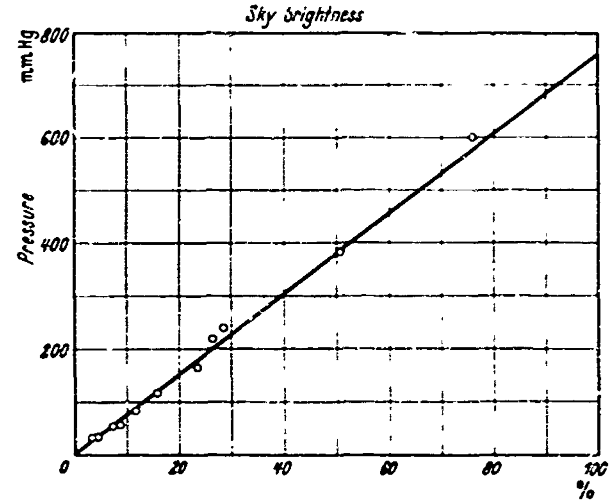

Fig. 2. Relation of altitude to sky luminance 38° above horizon (from TEELE, R. P., 1936, by courtesy of Nat. Geogr. Soc.

The first measurements of sky luminance made from an aircraft flying at high altitude were reported by CHRISTIENSEN (1946). His observations were made from the nose section of a B.17J from which aircraft he recorded the luminance of the horizon, of sky at an elevation of 30° above the horizon, of ground with various types of vegetation, and of various parts of the interior of the nose section, such as the navigator's desk, side wall, etc. His observations were made at altitudes of 10,000 feet to 40,000 feet. He found that with a sun elevation of 45°, a point in the sky at 45° azimuth to the sun and of elevation 30° above the horizon had a luminance of:

1,140 equivalent foot-candles at 10,000 feet
910 „ „ „ „ 20,000 „
760 „ „ „ „ 30,000 „
490 „ „ „ „ 40,000 „

The luminance levels recorded within the nose of the aircraft in the navigator's position were measured only at high altitude In the darkest portion of the navigator's desk he recorded 3·3 e.f.c. whilst the brightest part of the desk was at 260 e.f.c. This figure of 260 e.f.c., however, may have represented the illumination due to direct sunlight for he reports that the luminance of a white surface of reflection factor 84 per cent in direct sunlight was from 7,600 to 12,000 e.f.c. The oscilloscope face of the radar plan position indicator was found to vary from 0·12 e.f.c. to 6 e.f.c.

These measurements were a useful start in the investigation of the problem, but since they give no information as to how the high contrasts are produced or what the effect is, if any, of clouds below the aircraft, they cannot be used as a yardstick to evaluate the contrasts likely to be found on other occasions.

In a theoretical and experimental investigation of sky luminance TOUSEY and HULBERT (1947) present a table of theoretically derived data relating to luminance levels of the sky up to 10,000 feet altitude for various points in the sky and for varying elevations of sun. For similar elevation and azimuth of sun it is found that Christiensen's experimental results are about 2½ times greater than those derived theoretically by Tousey and Hulbert.

HARDING and LAMBERT in 1951 made further measurements of sky luminance from a de Havilland Comet at 40,000 feet altitude. In Harding and Lambert's observations the sun's elevation was 30° above the horizon, whereas in Christiensen's report the elevation was about 45° above the horizon. Making an approximate allowance for this difference in elevation, however, it was found that Harding and Lambert's results gave luminance levels lower than those obtained by Christiensen, and more in accord with those derived theoretically by Tousey and Hulbert. Thus, the results obtained by Christiensen seem, if anything, to be too high and not representative of clear sky conditions.

The results of Harding and Lambert are closely supported by the experimental findings of PACKER and LOCK (1951), who a few months later reported on some measurements carried out from an aircraft flying between 18,000 feet and 38,000 feet altitude.

CONTRAST BETWEEN LIGHT AND SHADE

Contrasts between light and shade uncomplicated by reflections from nearby objects or from clouds below have been calculated according to Tousey and Hulbert's data by Ciais (1952). His calculations refer to targets of various reflectivities viewed against a sky background at different altitudes.

None of these results can be employed to determine what contrasts are going to be encountered in the cockpit during flight at high altitude. They give information as to sky luminance, as to the intensity of insolation, as to the brightness of the earth seen from the air (Christiensen), but they do not reveal the factors governing the illumination falling on, say, an instrument panel in shadow. They do not show what are the important characteristics of the aircraft cabin which determine the intensity of illumination, and so, with regard to this particular problem, they neither provide a guide to the design of future aircraft, nor help the physiologist to determine why contrast at high altitude should appear to increase on some occasions and not on others.

An investigation employing a technique somewhat similar to that described later in this section was used by Barr (1950). He was interested primarily in the contrast between the exterior scene and the interior of the cockpit. He found that contrast was maximum when the sun was at 90° to the line of flight of the aircraft. When the sun was either forward or aft of this position, the contrast between exterior scene and the instrument panel in shadow was less. His results refer to three flights at altitudes of 5,000 and 7,500 feet.

In view of the absence of literature from which the data could be obtained, the following work was therefore carried out in an attempt to determine the principles governing the contrast between the sunlit and shadow areas of an instrument panel and to find some solution which might ease the pilot's visual task.

EXPERIMENTS

Ideally the measurements should have been made from only one type of aircraft. This was unfortunately not possible because the aircraft from which most of the measurements were going to be made was a Meteor Mk. 7 in which the cockpit dimensions were so small that the unassessed factor of stray reflections within the cockpit would have introduced complications in the interpretation of results relating to the luminance of shadow areas. Measurements were accordingly carried out initially in a Lincoln aircraft and then later in the Meteor Mk. 7. There were thus two methods employed. The first to determine the intensity of illumination falling on a vertical surface at various azimuth angles to the sun; the second to determine the illumination falling on different parts of the instrument panel whilst the aircraft flew on a constant heading with regard to sun.

Method A—Luminance of a vertical white surface

In order to determine whether shadows were darker at high altitude measurements were made of the luminance (brightness) of a known white surface at altitudes of 10,000-40,000 feet and with the sun at various azimuth angles. As it was believed that stray reflections from within the cockpit might interfere with the demonstration of any trend which might be present with increase in altitude, the measurements were made close to one of the side window panels of the *Perspex* canopy.

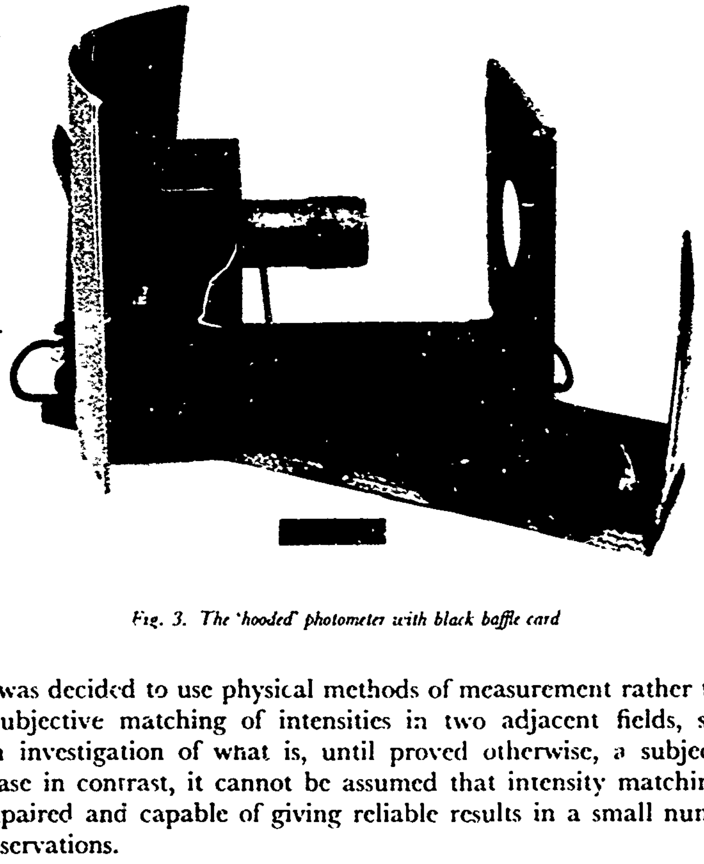

Fig. 3. The 'hooded' photometer with black baffle card

It was decided to use physical methods of measurement rather than the subjective matching of intensities in two adjacent fields, since in an investigation of what is, until proved otherwise, a subjective increase in contrast, it cannot be assumed that intensity matching is unimpaired and capable of giving reliable results in a small number of observations.

As no other instrument was available at the time, the photometer shown in *Fig. 3* was constructed as described in Appendix A. It consists of a barrier-layer Everett-Edgcumbe 'autophotic' cell, which was used in conjunction with a microammeter of suitable internal resistance to allow an almost linear response of the cell. The photocell measured the luminance of a circular white target of diffuse reflection factor about 80 per cent.

The relative colour sensitivity curve of the cell covered a range of from 200 to 800 mμ. To correct the sensitivity range to that appreciated by the eye, that is 400 to 750 mμ with a peak sensitivity at 555 mμ, the manufacturers supplied a special green filter with the cell. The responses of the cell with and without the filter are shown in *Fig. 4*, from which it will be seen that with the filter the cell had a peak sensitivity corresponding to that of the eye. Unfortunately, this filter restricted the sensitivity so much that it was not possible to use it continuously as, when the white target was in shadow, the response of the photocell with the filter was too low to register on the microammeter. Only one reading was therefore taken with the filter on at each altitude so that a subsequent correction could if necessary be made to the other results.

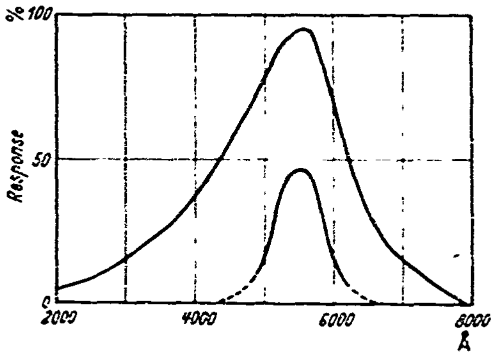

Fig. 4. Response of photocell with and without green filter

The microammeter responded over a range of 0–50 microamps, but by switching in a shunt its sensitivity could be reduced so that the full-scale deflection was 500 microamps. This was found to be sufficient to register all intensities encountered when the photocell was used in conjunction with a hood restricting the field to one of 30°.

Interference by reflection from other parts of the cockpit was reduced by the photometer hood and by a black baffle card 30 × 20 cm. which was fixed behind the cell (*Fig. 3*). In order to have some indication of the value of white surroundings in increasing the luminance of shadow areas, the observations were repeated using a white baffle card of the same size. The angle of incidence of the sun to the target was measured by the position of the shadow cast by a small bolt fitted vertically to the top of the photometer housing.

The observations were made in a Lincoln aircraft, the photometer being mounted on an improvised table immediately behind the pilot's seat. It was placed level with the lower edge of the *Perspex* window behind the pilot as it was thought that the effect of stray reflections from within the cockpit would be thereby reduced to a minimum. The white target of the photometer was about 4 in. above the coaming, and therefore received light from the horizon and from some parts of the cloud floor.

Stages were made at every 5,000 feet during which the aircraft was flown on a constant heading with regard to sun, and readings were taken when the sun was striking the target at azimuth angles of 0 ± 30°, ± 60°, ± 90°. Plus signifies that the sun was in front of the target and minus signifies that the sun was behind the target. As a trend, and not absolute values, was sought in this experiment, it was decided that the angle of elevation of the sun could be regarded as constant, particularly since the flight readings were all made within two hours of local noon, when the solar altitude was about 50°.

Results—Although a number of flights were undertaken, only two gave useful results. The difficulties encountered in other flights were either that cloud was present up to 35,000 feet and haze present above that, or that frosting of the windows took place as a result of which no useful photometric measurement could be made because of the diffusion of light by the frost on the transparencies.

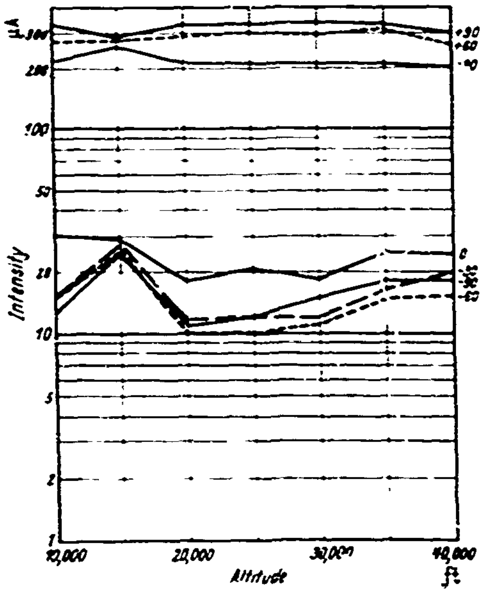

Fig. 5. Relative intensity of a white vertical surface at various azimuth angles of sun (black baffle card

The readings which were obtained are shown in tabular form in the Appendix C and in graphical form in *Figs. 5* and *6*. There were no great changes in luminosity of the white target at different altitudes when it was in direct sunlight. This does not mean, however, that the illumination due to direct sunlight did not increase. It must have increased, as one would expect. The reason it does not show in the data is that the measurements were of total illumination, that is of illumination from direct sunlight and from sky light. The former increases in

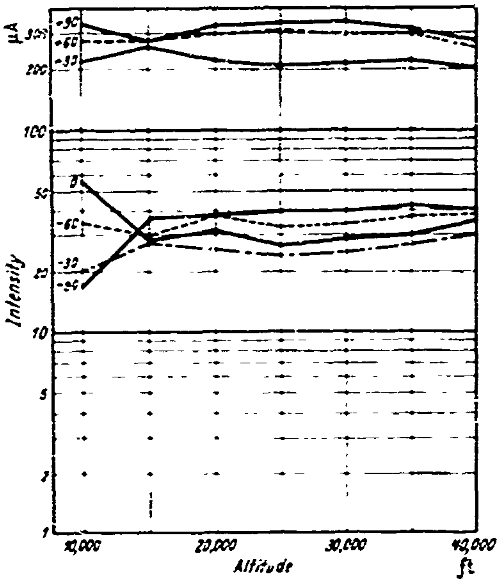

Fig. 6. Relative intensity of a white vertical surface at various azimuth angles of sun (white baffle card)

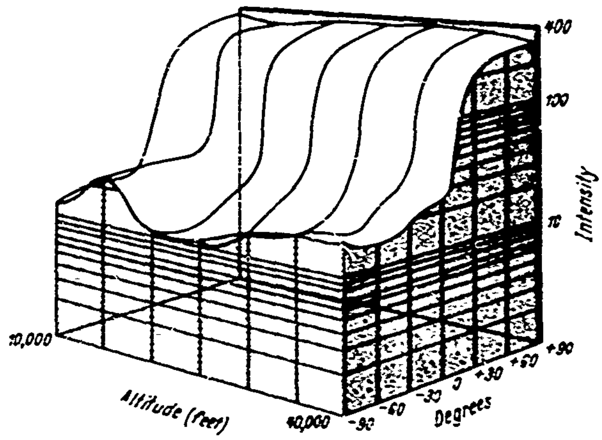

Fig. 7. Relative intensity of a white vertical surface at various azimuth angles of sun (black baffle card)

intensity with increase in altitude whereas the latter, since the scattering particles become smaller and more spaced out, decreases in intensity. The luminosity of the white vertical surface is thus an indication of mean illumination. Also contributing to an increase of luminosity of the white card at lower altitudes was the cloud floor which reflected a considerable amount of light back upwards towards the aircraft. With increasing altitude above the cloud floor the illumination falling on the

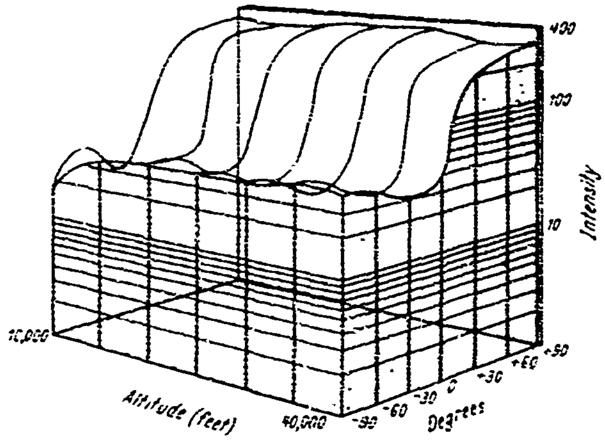

Fig. 8. Relative intensity of a white vertical surface at various azimuth angles of sun white baffle card.

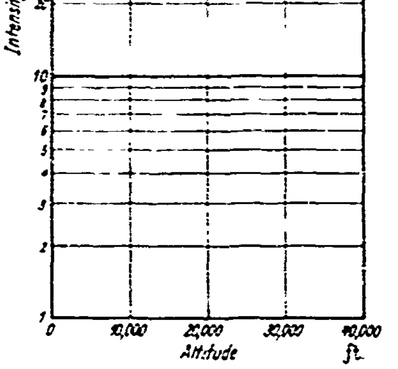

Fig. 9. Total output of photocell with and without green filter

white card from this particular source decreased. The luminance of the target did not change much with increasing altitude—probably because light was still being received from below when the target was in shadow.

In *Figs. 7* and *8* an attempt has been made to represent these changes in a three-dimensional diagram, the construction of which is described in Appendix D. Perspective was introduced into this diagram by adopting a vanishing point towards which all 'parallel' lines converged. Save for the irregularities which are probably due to the presence of layers of haze or to experimental errors, it will be seen that there was little change either in total intensity or in contrast between light and shade with increasing altitude. Indeed, if anything, the contrast appears to have been greater at low altitudes than at high altitudes. By using a white baffle card instead of a black baffle card the luminance of the target in shadow was increased by a factor of almost two, as seen in *Fig. 8.*

The results obtained with and without the green filter over the photocell are shown in *Fig. 9.* It will be seen that the response of the cell with this filter bore a fairly constant relationship to the total output of the cell without the filter. It thus seems that in these measurements the greater sensitivity of the photocell to ultra-violet radiation cannot be solely responsible for the increase in intensity of light recorded at high altitude. The increase in intensity recorded is therefore one which will be appreciated visually.

Method B—Illumination of the instrument panel

In attempting to measure light reflected from the instrument panel it was found that there was insufficient light reflected even from a white surface to give accurately readable deflections on the microammeter. It was therefore decided to make direct measurements of incident rather than of reflected light as in the previous measurements. A barrier-layer photocell similar to that described above was used, but without the restricting hood. It is seen in *Fig. 10.* The green correcting filter was always used in conjunction with this cell, the diameter of which was reduced by about half by a black paper mask so that the intensity of incident light gave a suitable reading on the microammeter*. Whilst these measurements of illumination of the instrument panel were being made, the intensity of sunlight was recorded on the hooded photocell as already described.

Having been thus compelled to use different methods for measuring the intensity of light in direct sunlight and at the level of the instrument panel (Method A measuring luminance and B measuring illumination), it was necessary, in order to compare results, to calibrate one method against the other. This calibration is shown in Appendix B.

It was decided to measure the illumination at the top and at the

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* This procedure entailed the risk of causing local overloading of the cell. According to the manufacturers' specification however there was still a large margin of safety. It would no doubt have been better to employ a diaphragm a few inches in front of the cell but the penalty of increase in size of the photocell was too great. It was essential to employ a photocell which was as far as possible flush with the surface of the instrument panel.

bottom of the instrument panel because there was an obvious difference in the luminosity of these parts. The upper part, being more in line with the cloud floor below the aircraft, apparently received more light than the lower parts of the cockpit, which, subtended by an area of sky without clouds, received little scattered light. The readings were made in the rear cockpit of a Meteor Mk. 7 (unpressurised) aircraft (*Fig. 10*), the aircraft being levelled out every 5,000 feet on a constant heading with regard to sun.

Fig. 10. Measurement of light intensity at top of instrument panel with unhooded photometer in rear cockpit of Meteor Mk. 7

As will be seen from *Fig. 10*, the cell was mounted on a right angle bracket, the long arm of which was about 30 cm., so that the observer could manipulate the cell, laying it with its back flat against the instrument panel, without having to bring his hands near the sensitive surface. This was necessary to prevent reflections from face, clothing, and hands from interfering with the readings.

The cell was placed at the top of the instrument panel against a previously marked spot, a reading was taken, then the cell was placed at another mark at the bottom of the panel and another reading taken. The luminance of the white target of the hooded photometer was then measured in direct sunlight and the presence of cloud or atmospheric haze was noted. This routine was repeated at 5,000 feet intervals to an altitude of 40,000 feet. The entire flight from take off to landing took about forty minutes.

Results—These show that light incident on the instrument panel in shadow decreased with increase in altitude, but that the extent of this change was largely dependent upon the prevailing cloud or atmospheric haze and the altitude at which such cloud or haze was present. Changes in illumination occurred more frequently in the upper part of the instrument panel, the lower part being less influenced by changes due to atmospheric haze or to cloud.

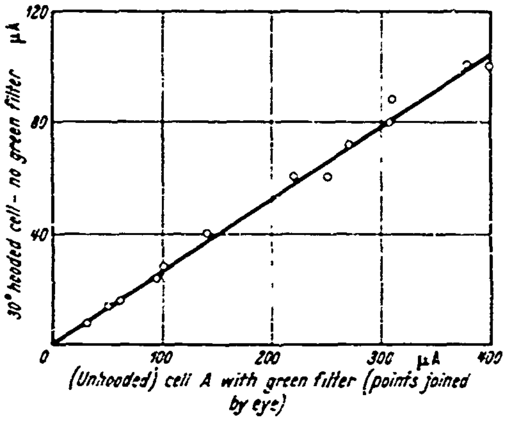

Fig. 11. Calibration graph—hooded and unhooded photometers

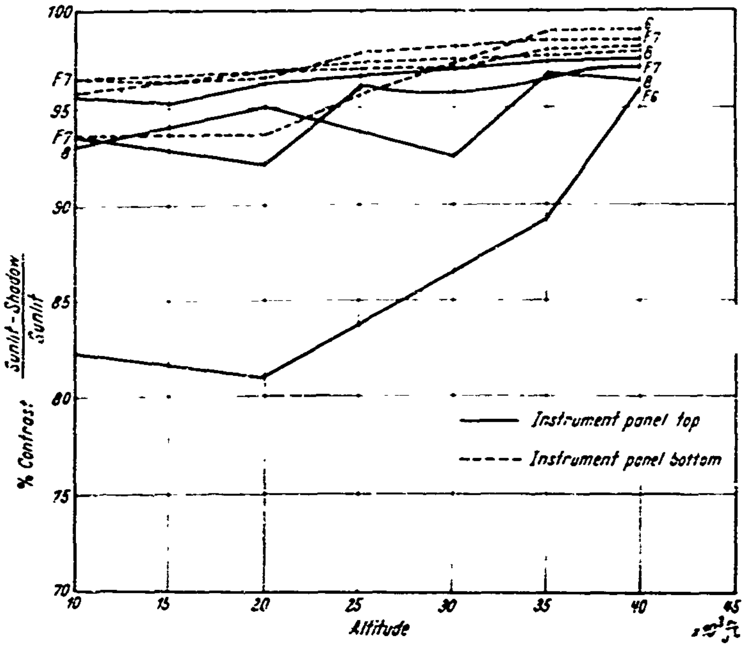

Fig. 12. Contrast at instrument panel 4 experiments

CHANGES IN INTENSITY AND SPECTRAL DISTRIBUTION OF SUNLIGHT

By means of the calibration graph in *Fig. 11* it was possible to compare the illumination of sunlit areas, as measured by the hooded photocell, with the illumination of shadow areas as recorded by the unhooded photocell on the instrument panel. The contrast between sunlit areas and shadow areas at the top and at the bottom of the instrument panel was calculated thus:

$$\text{Contrast} = \frac{\text{intensity in sunlight} - \text{intensity in shadow}}{\text{intensity in sunlight}}$$

The results were plotted and are shown in *Fig. 12* and *Fig. 13.*

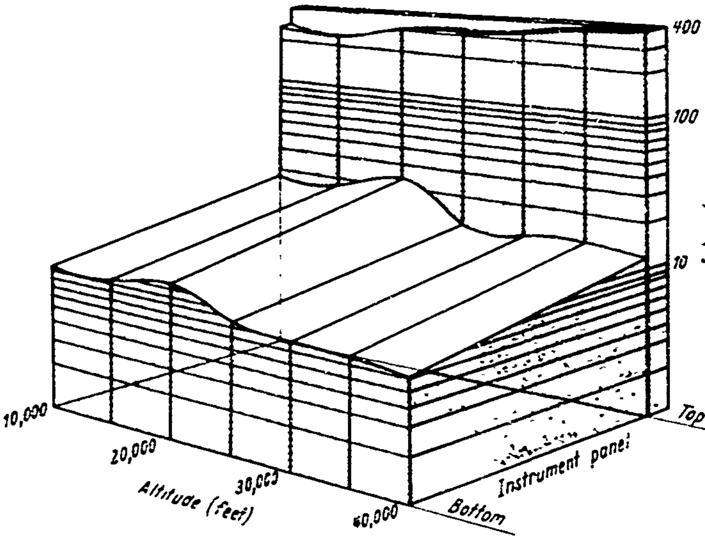

Fig. 13. Relative light intensity at instrument panel

It will be seen from *Fig. 12* that contrast does increase with altitude and that the lower parts of the instrument panel show a greater increase in contrast than do the upper parts. The contrast thus increases especially if there is no possibility of the shadow area receiving light from haze or from cloud beneath the aircraft. In *Fig. 13* the relative intensities of light measured during one experiment show this trend too. The hump shown at 20,000 feet is due to a layer of haze or thin cloud at that altitude. It acted as a diffuser, allowing more light to reach the shadow areas.

These results relate specifically to one aircraft, the Meteor Mk. 7 (rear cockpit).

SUMMARY

In the absence of information on the luminance of a white vertical surface in shadow at altitude, some measurements were carried out.

CONTRAST BETWEEN LIGHT AND SHADE

It was found that the luminance of the shadow was greatly affected by light reflected upwards from the layers of atmospheric haze or the cloud beneath the aircraft. If the shadow area was in direct line with an extensive cloud floor it often became brighter with increase in altitude. When the shadow was not in direct line with either the cloud floor or the horizon and received light only from the cloudless sky, it always became darker with increase in altitude, the darkening being most marked if the shadow area received light only from the sky near the zenith. The shadow area could always be made brighter by a white diffusing surface which, in direct sunlight, could reflect light on to the shadow area. Contrast between sunlight and shadow thus increased with increase in altitude only if the shadow area was not in line with a layer of bright cloud or haze.

Since the luminance of the sky 38° above the horizon is inversely proportional to the altitude of the observer above the surface of the earth, the increase in contrast between sunlit and shadow areas at high altitude is greatest in the lower parts of the cockpit which are in line only with the darker sky near the zenith.

It is concluded that, since at high altitude only the lower parts of the instrument panel in shadow become darker, the greater difficulty in reading instruments in shadow must be due to factors other than that of altered luminance of the instrument panel.

FLUORESCENCE IN THE LENS OF THE EYE

DURING most of the high altitude flights it was found that there was, over the visual field, a subjective haze which seemed to be responsible for the difficulty in seeing instruments when they were in shadow. This annoying haze was continuously present and resisted all attempts to disperse it, such as shielding the eyes from the glare of the cloud floor outside the aircraft. In fact it disappeared only when one descended to lower altitudes. BARR (1950) remarked upon a 'persistent haze' over his visual field—no doubt the same phenomenon—but without putting forward even a tentative explanation as to its origin.

It was thought that this subjective effect, which seemed to be the principal reason for difficulty in seeing inside the cockpit when in shadow, resulted from some inherent difference in the light at high altitude. The first possibility considered was that of an increase in the fluorescence of the crystalline lens caused by the greater intensity of ultra-violet light in solar radiation at high altitude.

RÉSUMÉ OF PREVIOUS WORK

The effect of ultra-violet light on the eye has been studied by many workers, but even with the help of concise reviews of the literature by OGILVIE (1953), who deals with the general effects of ultra-violet light on the eye, and by KLANG (1948), who deals more specifically with fluorescence of the human lens, there was obtained little information relevant to this problem.

The possible effects of ultra-violet light on vision are not confined to fluorescence, and it is of interest to point out that vision in the ultra-violet is accompanied by difficulties in focussing. Thus GOODEVE (1934) has found that in order to focus an ultra-violet source satisfactorily it has had to be no further than 10 cm. from his eye. DE GROOT (1935) has stated that at 313 mμ the eye which is emmetropic in red light becomes 10D myopic. These focussing difficulties are attributed to the greater refraction of ultra-violet light by the optical system of the eye.

Reviewing the literature on fluorescence of the eye, Klang (1948) concluded that most of the fluorescence is in the lens and that the exciting radiation is 300 mμ–400 mμ with maximum sensitivity 360 mμ–370 mμ. Relatively little fluorescence appears in the cornea which is caused to fluoresce by wavelengths of 315 mμ–360 mμ (*Fig. 14*).

Since maximum fluorescence takes place between 360 and 370 mμ and drops to nil at 300 mμ, it is evident that no increased fluorescence will result from the extension of the solar spectrum which takes place at high altitude, since this extension at the short wave end is from 290 to 210 mμ (HULBERT, 1947).

Intensity of fluorescence, however, is generally proportional to the intensity of the exciting wavelengths (PRINGHEIM and VOGEL, 1943). According to STAIR and COBLENTZ (1938) the intensity of ultra-violet radiation within the band of wavelengths shorter than 313 mμ, increases by about three times from sea level to 40,000 feet altitude. Part of their tabulated data is shown in Appendix E. From the data of MOON (1940) it seems that for wavelengths of 300–400 mμ the intensity outside the earth's atmosphere is 2–3 times that of the surface of the earth. It is consequently to be expected that at high altitude, intraocular fluorescence may increase by a factor of only 2 or less.

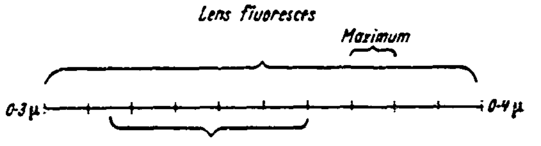

Fig. 14. Wavelengths producing fluoresence of the eye (from data collected by KLANG, 1948

EXPERIMENTS

Method A

There does not appear to be any mention in the previous work of the effect which this ultra-violet 'fog' might have upon vision—whether in fact the fluorescence would be noticeable by an individual who was looking at a bright sunlit scene. A preliminary experiment, using a technique employed by GOLDIE and MATTHEWS (1944), was carried out to obtain some idea of the subjective intensity of fluorescence produced by the ultra-violet light present in daylight at ground level. The experiment was made in a dark room where the only window facing the sky was of 'Woods' glass, which transmits mainly at 360 mμ (*Fig. 15*).

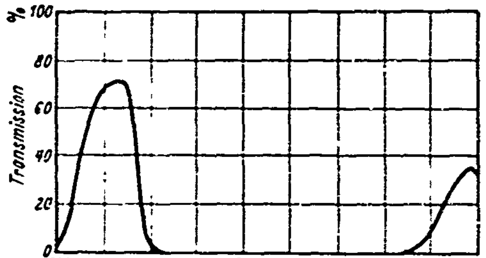

Fig. 15. Transmission of 'Woods' glass. 'Chance' OX1 2 mm.

Results—In the dark room, fluorescence of the lens of the eye was produced by the solar ultra-violet radiation transmitted by the 'Woods' glass filter. The fluorescence was noted subjectively as a grey-blue haze over the entire field, and it could also be seen in others as an apparently very bright and fluorescent pupil. This fluorescence was noticeable on all days even when the sky was so overcast as to be classed by the photographers as 'dull', but as soon as the 'Woods' glass filter was removed, admitting visible light into the room, the fluorescence was no longer seen. It was thus concluded that at ground level (250 feet) there was sufficient ultra-violet radiation present to produce fluorescence of the lens, but that the higher intensity of visible light was so great as to mask it completely.

Method B—High altitude test of yellow filter

Flights were made to 40,000 feet during which a low contrast test object (*Fig. 16*) was observed in the lower part of the cockpit. This test object was designed by **Frederik** (1947) for use in connection with night vision tests. Attempts were made to reduce the haze which was present over the field of vision by using a special filter (Chance 'minus blue'), the transmission curve of which is shown in *Fig. 17*. It will be seen that this filter transmits very little in the band between 300 and 400 mμ where most of the fluorescence of the lens takes place.

Fig. 16. The low contrast test from Frederik, W. S., 1947, by courtesy of 'Philips Technical Review, Eindhoven

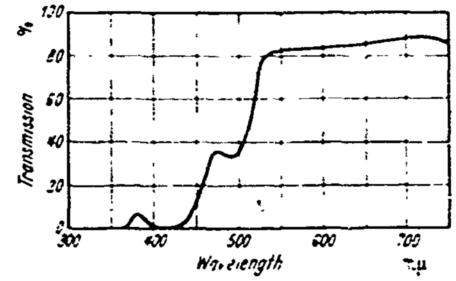

Fig. 17. Transmission of 'minus blue' filter

The procedure employed was to look at the low contrast test object, observing the amount of haze present, and the letter of lowest contrast which was visible, then to bring the yellow filter, which was incorporated in a goggle, down over the eyes for comparison. Any change in the haze was noted, as well as any change in visibility for the low contrast test.

Results—The findings were negative throughout. The haze over the field of vision was quite unaffected by the presence or absence of the filter in front of the eyes, even although this filter reduced by about 90 per cent the intensity of ultra-violet light falling on the eye. The low contrast test was neither seen better nor seen worse with the yellow filter as compared with no filter in front of the eyes. Whilst looking outside the aircraft, however, it seemed that the borders of clouds were more sharply defined when observed through the yellow filter.

In the absence of improvement in visibility and of any change in intensity of the subjective haze when the yellow (-blue) filter was before the eyes it was concluded that the haze effect was not due to fluorescence of the lens caused by ultra-violet light.

SUMMARY

The intensity of ultra-violet radiation between 300 mμ and 400 mμ at 40,000 feet is about three times that at sea level. Since the eye, and especially its crystalline lens, fluoresces most strongly in response to excitation by these wavelengths of ultra-violet radiation, it was thought that intraocular fluorescence might be responsible for the persistent subjective haze which has already been described and which seems to be the basic cause for inability to see instruments on an instrument panel in shadow when flying at high altitude.

Intraocular fluorescence in response to solar radiation at ground level can be demonstrated only in the dark room, into which sunlight is admitted after passing through a filter of 'Woods' glass. The fluorescence which in the dark appears to be strong is none the less completely masked if normal daylight is admitted into the room.

At high altitude when the eyes were covered by a filter which cuts off 90 per cent of this ultra-violet radiation, there was no change in the subjective haze.

It was therefore concluded, firstly, that although lens fluorescence from solar radiation does take place, it is so masked by the visible light as not to be noticeable, and secondly, that intraocular fluorescence from sunlight is, therefore, not responsible for the subjective haze at high altitude.

INTRAOCULAR SCATTER OF LIGHT

When a beam of light passes through a transparent medium containing in suspension small particles the refractive index of which differs from that of the surrounding medium, the incident beam is scattered by the small particles. As the intensity of the incident beam increases, the intensity of the scattered light also increases. If, however, the scattering particles are small compared with the wavelength of the incident light, the intensity of scattered light will depend not only upon the intensity of the incident light, but will also vary inversely as the 4th power of the wavelength (Rayleigh scattering).

As described earlier, increase in altitude is accompanied by a slight relative shift of the intensities in the solar spectrum towards the blue.

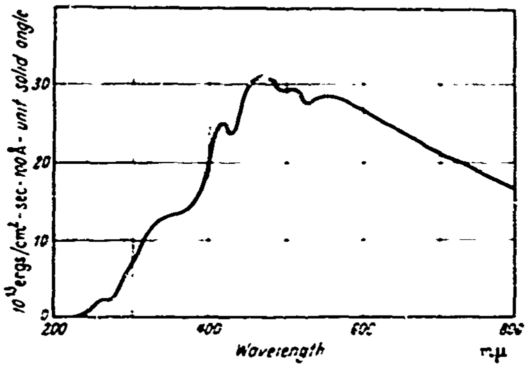

Fig. 18. Spectral distribution of solar radiation. (taken from Nicolet, M., 1952, by courtesy of University of New Mexico Press.

Along with this relative change there is an overall increase in the intensity of light from insolation or direct sunlight, as opposed to that from sky scatter, which decreases in proportion to the reduction of atmospheric pressure (Teele, 1936). These changes in the solar spectrum are shown in *Fig. 18* which is taken from Nicolet (1952).

Knowing that these changes took place it was natural that one should wonder whether the subjective haze at high altitude might not after all be due to the intraocular scatter of light, since the previous experiment had shown that fluorescence from ultra-violet radiation was not responsible.

RÉSUMÉ OF PREVIOUS WORK

According to Van der Hoeve (1919) most of the scattering of light in the eye takes place in the crystalline lens. Bell, Troland and

Verhoeff (1922) refer to the intraocular scattering of light as 'veiling glare'.

The size of these scattering particles seems to be small although it is doubtful whether they are so small as to come within the compass of Rayleigh's equation. It seems that in the aqueous humour of young people some Rayleigh scattering may be present but that in older people large particle scattering may increase. Thus **Koby** (1930) refers to 'Tyndall scattering' taking place in the aqueous humour of the anterior chamber, whilst the observation of **Graves** (1925) that the scattering particles were 'below the lowest limit admitting resolution' and that in the eyes of young adults the scattering was very faint, suggests that the dispersion of light in the aqueous humour may be due to Rayleigh scattering.

The intensity of the haze set up by intraocular scattering of light in relation to either incident intensity or to wavelengths was not known, and the effect upon vision was known only in the general terms of everyday experience. It was therefore decided to attempt to calculate the change in intraocular scatter at high altitude and then to carry out some observations in flight. The 'in flight' observations were carried out concurrently with those described in the previous section.

EXPERIMENTS

Method A—Calculation

The term 'air mass', employed below, signifies the length through the atmosphere of the path of light from a celestial body. Thus when the sun is at the zenith its light traverses an air mass of 1 before reaching the surface of the earth. When the source is not at zenith, but makes an angle θ with the zenith, the air mass traversed is approximately 1 cosine θ. It was assumed that air mass decreased in proportion to atmospheric pressure.

Since attenuation and scatter depend upon the size of the scattering particles, and since the larger particles are found principally at lower altitudes, it will be seen that such an assessment of light at altitude, based upon the assumption that air mass decreases proportionally to atmospheric pressure, is an approximation. **Robinson** (1954) regards this approximation as permissible when the longer visible wavelengths are not being considered and when the altitude is below the ozone layers of the ionosphere.

On this basis it was calculated that when the elevation of the sun is 50° above the horizon (noon, June 15th, southern England) the sun's rays to the surface of the earth would traverse an air mass of 1·3, and at 40,000 feet, where the atmospheric pressure is 140 millimetres mercury, they would traverse an air mass of 0·24. These values were interpolated into a solar energy distribution curve, **Moon** (1940), representing the energy distribution outside the earth's atmosphere, and at the earth's surface, for air masses of 1, 2, 3, 4, and 5. The modified graph is shown in *Fig. 19.*

Within the eye, scattering of light will take place in the intraocular media. The conditions of the scattering medium remaining constant, however, the greatest change in scattering which would take place

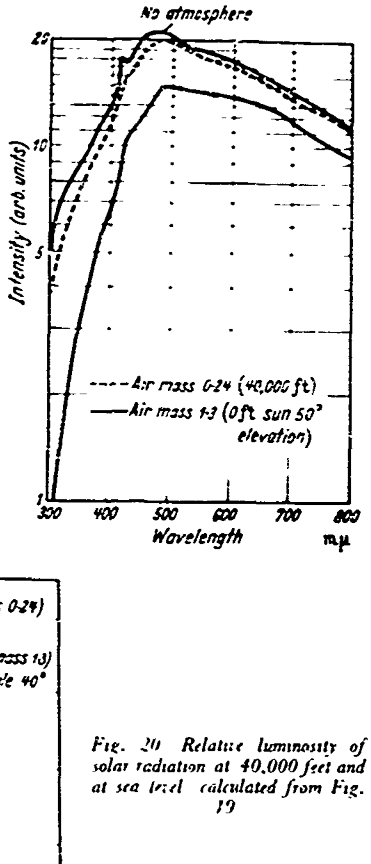

Fig. 19. Spectral distribution of solar radiation at 40,000 feet and at sea level (calculated from graph of Moon, 1940)

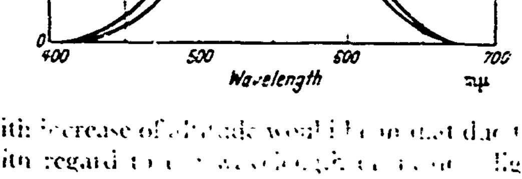

Fig. 20. Relative luminosity of solar radiation at 40,000 feet and at sea level calculated from Fig. 19

with increase of altitude would be that due to small particles—small with regard to the wavelength of incident light. The cause of this is not only the increase in intensity resulting in a greater scattering, but also the greater energy of blue light at high altitude further increasing the intensity of [illegible] [illegible] according to the equations of Rayleigh scattering varies inversely as the 4th power of the wavelength $I \sim 1/\lambda^4$.

To obtain an indication of the worst condition it was therefore assumed that only Rayleigh scattering took place within the eye, and from the data in *Fig. 19* the relative intensities of scattered light were calculated for sea level and for an altitude of 40,000 feet. The intensities thus obtained were physical, so to translate them into values appreciated by the eye each value was multiplied by the appropriate CIE luminosity factor for the standard eye as quoted by Houston. The values thus obtained are shown in *Fig. 20*.

Results—The difference in areas between the two curves which are shown in *Fig. 20* shows the increase in intensity of visible light due to intraocular scatter. It was found by measuring the area of these curves that at 40,000 feet the intensity of intraocular scatter of light would be at the most 1·3 times that at the earth's surface.

Method B—Observations in flight

These were made at the same time as those on intraocular fluorescence described in the last chapter. They were made with the same filters, namely, a yellow filter whose function was to cut out the blue component of the light, a blue filter which would accentuate any effect due to small particle scattering, also without a filter but with an opaque visor which acted as a screen by keeping direct sunlight off the eyes. The low contrast test object previously described was again employed, the procedure being to compare its visibility when using either of the various filters with an opaque visor.

Results—No alteration in the legibility of the low contrast test object was found when the test was being observed through the Chance 'minus blue' filter. Shielding the eyes from the source of glare with the opaque visor did reduce the haze effect but only after about 5–10 seconds. No difference in visibility of the low contrast object was noted, when viewed through the blue or the yellow filter. It was again observed that the visibility of the edges of clouds seemed to be enhanced when these were observed through the yellow filter as compared with no filter. When they were seen through the blue filter they appeared less distinct than they were with no filter before the eyes.

It was therefore concluded that increased intraocular scatter was not *per se* responsible for the subjective haze at high altitude.

SUMMARY

The scattering of light which takes place within the eye is probably partly Rayleigh and partly large particle scattering: the scattering in the aqueous humour of young people may be predominantly from small particles, whereas in the eyes of older people more large particle scattering may take place. Since there is a slight shift towards the blue in the spectral distribution of light at high altitude, the greatest increase in intraocular scatter would take place if the total intraocular scatter obeyed Rayleigh's equation. In this hypothetical case, which is probably not correct but which would give the most marked effect, it was calculated that at 40,000 feet the visible light scattered intraocularly would be only 1·3 times as much as at sea level.

Looking through a yellow filter, which attenuated any relative increase in blue in the sunlight at high altitude, produced no apparent difference in the subjective haze. It is therefore concluded that increase in intraocular scatter of light is not responsible for this haze.

Fluorescence of the eye, as a result of greater intensity of ultra-violet radiation at high altitude, has also been shown not to be responsible. The impression that the subjective haze was a result of some different property of sunlight at high altitude thus seems to be wrong. Having examined and assessed the importance of the three most likely physical causes—light intensity and contrast, intraocular fluorescence and intraocular scatter—attention will now be turned to physiological mechanisms which might be responsible for this particular haze effect.

III. PHYSIOLOGICAL CHANGES AFFECTING VISIBILITY OF OBJECTS INSIDE THE COCKPIT

INTRODUCTION

THE changes which were considered in the previous section were purely physical changes dependent entirely upon the new ambient conditions and taking no account either of the physiological response or of the subjective sensations of the man. The new milieu, however, disturbs normal physiological equilibrium and the normal responses to stimuli are thereby altered. In this section the effects of anoxia and of glare are considered. The former should not, of course, normally be present since most high altitude aircraft today are designed with pressure cabins and in those without them the administration of oxygen under pressure, with counter-pressure on the chest wall, ensures that up to certain altitudes the effects of a low partial pressure of oxygen are fully compensated. In its general sense anoxia is thus an emergency condition.

The visual system, however, is particularly sensitive to lack of oxygen, and a lack of oxygen not sufficiently severe as to be classed as anoxia may yet produce some effects upon it. Thus, in night vision at as low an altitude as 4,000 feet, the effects of lack of oxygen manifest themselves in the failure to attain the lowest threshold of dark adaptation possible under optimum conditions. Anoxia is considered only in this sense here—not the marked anoxia with its characteristic systemic changes, but rather the slight oxygen deficit which apparently manifests itself only in the visual system.

Glare was defined by BELL, TROLAND and VERHOEFF (1922), as 'the sensation produced by light so invading the eye as to inhibit distinct vision'. In contra-distinction to anoxia, glare is normally present and has been since the beginnings of flight. The glare to which the high altitude pilot is subjected, however, is not the same as the glare familiar to those who fly at lower altitudes. It is as has been pointed out earlier, essentially due to a reversal of light distribution: at low altitudes most of the light comes from above, principally as scattered light from the sky, from clouds, and as direct light from the sun. At high altitudes most of the light comes from below, from the brightly lit cloud floor which is almost invariably present or from the bright horizon, and little light comes from the cloudless sky which may be dark blue at the zenith. In addition, it has been seen from the work described in Part II that contrasts may be increased, that shadows may be darker and that the sunlit area is brighter. These conditions acting together produce an environment peculiar to high altitude and give rise to a glare problem necessitating special consideration.

ANOXIA

WITHOUT first-hand experience it is doubtful whether it would have been possible to tackle the problems of vision in flight at high altitude. In some fields of research it is no doubt possible to make use of second-hand descriptions of the phenomena, and indeed it is sometimes necessary to do so, but in this case, in which so much was subjective, the value of first-hand experience was frequently evident.

One of the puzzling phenomena observed was the haze which was present over the visual field during flight at high altitude. It had been attributed to fluorescence of the lens resulting from an increase in intensity of ultra-violet, and when it had been shown that this was not responsible, the effect was tentatively attributed to a greater intensity of intraocular scatter of light at high altitude. As has been demonstrated, this hypothesis was also wrong.

With this problem at the back of one's mind, the dazzle sustained whilst reading a book in full sunlight at sea level became suddenly most interesting. It was observed on looking up from the sunlit page that over the field of vision there was a haze similar to that noticed during flight at high altitude, but it disappeared within a second or two. This haze effect seen on looking up from the white sunlit page was a positive 'after-image' of the page.

When a bright source has been observed, and the eyes are subsequently closed, the image of the source, if sufficiently bright, remains visible as a bright image which gradually becomes darker. This is the 'after-image', and, as in the photographic sense, it is referred to as being either 'positive' or 'negative'. Thus a bright stimulus gives rise to a bright (positive) after-image which is seen either when the eyes are closed or when one is in total darkness. This is sometimes referred to as the 'original' after-image, and in the case of a brief stimulus it consists of a number of rapid oscillations from the positive to negative phase and back again to positive.

The positive after-image which predominates after exposure of the eye to a bright stimulus, indicates a persistance of activity in the visual system after cessation of the primary stimulus. If, while this positive after-image is present, the subject looks at a uniform background, he will see the after-image as negative when the background is bright, and as positive when the background is dark. It is generally accepted that the primary stimulus has an inhibitory effect on the response to subsequent similar stimuli, but that increased excitability to other stimuli results.

In the present instance, however, attention was drawn to the long positive phase occurring after the primary stimulus, the sunlit page. It was felt that the haze effect which this positive phase cast over the visual field resembled so closely the appearance inside the cockpit at high altitudes that the effect observed in flight might well arise in a similar way—the bright cloud floor acting as the primary stimulus, whilst the dark interior of the cockpit allowed the positive phase of the after-image to be visible.

This simple and obvious explanation had not been thought of earlier because the effect observed at high altitude seemed to last much longer than one would have expected. It was felt that if the duration of the after-image, as indicated by the dazzle recovery time, was indeed increased, it might be due either to the increase in luminance of the cloud floor seen from high altitude, or possibly to anoxia.

RÉSUMÉ OF PREVIOUS WORK

What must have been one of the earliest, if not the very first, mention of the visual effects of lack of oxygen was made by Croce-Spinelli in 1874 in a description of the sensations which he and Sivel experienced when undergoing a decompression in a chamber employed by Paul Bert during his studies on the effects of increased and decreased atmospheric pressure. Bert (1878) reports Croce-Spinelli's full description of the experience. With regard to visual symptoms he writes '. . . au-dessous de 35 centimetres, mes regards, qui s'obscurcissaient devenaient très sensiblement plus nets après l'absorption d'oxygène. Je voyais clair après avoir vu noir; l'intérieur de la cloche semblait tout à coup devenir plus lumineux'.

Probably the majority of individuals who have experienced sufficiently marked anoxia have noticed this effect which is precisely as described by Croce-Spinelli. Some, however, do not notice any change, either because, due to greater tolerance to anoxia their threshold is not sufficiently affected, or because they are less observant. The former explanation would appear to be the more likely in view of the failure of Paul Bert to comment on the effect in his otherwise full subjective description of the symptoms of lack of oxygen.

In tests in the decompression chamber at Farnborough it was noticed personally that a dimming of lights was more noticeable on some occasions than on others. In relatively crude experiments with an optical wedge Willmer and Berens (1918) found that 'under the rebreathing test the threshold for light has shown an improvement in 25·9 per cent of cases; 44·5 per cent show neither improvement nor falling off, and 29·6 per cent show a falling off in sensitivity'.

The dimming of the visual field at photopic levels during anoxia is a symptom which usually appears when the degree of anoxia is already marked. It is thus a rather coarse indication that anoxia is present. A useful review, particularly of the more recent work (1937 onward) on the visual effects of oxygen deficiency, is given by McFarland, Evans and Halperin (1941). They state, however, that 'pilots have frequently reported darkening of the visual field whilst flying at great heights without oxygen (18,000 feet and above)'. It should be noted that whilst this was sometimes the case in the past it should not apply today, for aircraft which have to fly at these heights carry a supply of oxygen.

In addition to this change in sensitivity evident during marked anoxia, there occurs a more subtle change which is probably the first detectable symptom of an insufficient supply of oxygen. This change is a raised threshold of absolute sensitivity of the fully dark-adapted eye. It was first studied extensively by McFarland and Evans (1939) who, at normal atmospheric pressure, simulated various altitudes by using appropriate mixtures of nitrogen and oxygen. They found that even at the simulated altitude of 7,400 feet the threshold test light had to be made about one-fourth brighter to be still visible, and at 15,000 feet its intensity had to be increased by 1·5–2 times.

Goldie (1942), investigating the changes in night vision under anoxia, concluded that the absolute threshold deteriorated even at the low altitude of 4,000 feet. His results, expressed in terms of reduction in pick-up ranges, are presented in Table I.

Table I

Altitude in feet	*Average percentage decrease in range of night vision if oxygen is not used*
4,000	5
6,000	10
8,000	15
10,000	20
12,000	25
14,000	35
16,000	40

As to whether the origin of the visual changes in anoxia is from a central nervous mechanism rather than a photochemical peripheral one in the retina, McFarland, Hurvich, Halperin (1943) believe that the evidence is against the photochemical origin since:

(*a*) the sensitivity of the completely dark-adapted eye is reduced in anoxia.

(*b*) in vitro, oxygen has no effect upon breakdown or regeneration of rhodopsin.

(*c*) anoxia produces an equal rise in rod and cone threshold although different pigments are involved.

(*d*) the threshold to electrical stimulation which by-passes photochemical changes also rises in anoxia.

(*e*) the rate of improvement in sensitivity when oxygen is readmitted is more rapid than if pigment regeneration alone were considered.

Their view is supported by the findings of Noell and Chinn (1950). In an electrophysiological investigation on the visual pathway of rabbits, they showed that in anoxia the inexcitability occurs in the following order: (*a*) in cortex cerebri and geniculate bodies of the brain, (*b*) in retinal ganglion cells, (*c*) bipolar, and finally (*d*) in the photoreceptors. The photoreceptors are most resistant to anoxia, as revealed by the long persistance of the electroretinogram.

In this work, however, the interest in anoxia is due to its possible effect upon the duration of the positive after-image. With such a subject one is in immediate difficulties, for the mechanism of production of after-images, even in normal air and at normal pressure, is not understood except in general terms of persistance of activity with regard to the positive phase and inhibition of response to similar stimuli in some of the negative phases.

The investigations on after-images by McFarland *et al.* (1943) and by Gellhorn and Spiesman (1935) deal only with the latent period between cessation of the stimulus and the appearance of the positive after-image. Gellhorn and Spiesman found that the latent period was increased in anoxia and McFarland *et al.* confirmed this. In addition, they showed that, in anoxia, as the intensity of the stimulus decreased the latent period increased. They pointed out that the increase in the latent period cannot be due to the apparent dimming of light in anoxia, because when oxygen is administered the dimming disappears in a few minutes whereas it may require up to 50 minutes for the latent period to return to its normal level.

Apart from a brief note (McFarland *et al.*, 1941) to the effect that more lasting after-images were noted in anoxia, there is no mention of the duration of the positive phase either in normal air or in air poor in oxygen.

McFarland *et al.* (1941) state that 'Aviators and mountaineers have frequently mentioned the increased latency and unusual quality and intensity of the after-image at high altitude'. Subsequently the authors reproduce data showing that the latent period increased from 1 to about 2 seconds. It seems most unlikely that so small a change would be noted subjectively. But, as a result of personal experience and in view of the fact that none of the pilots with whom these problems were discussed had noticed this particular effect of increased latency, it seems probable that the effect 'frequently mentioned' was not increased *latency* but increased *duration*.

EXPERIMENTS

Method A—Recovery time from light-adaptation in flight

As a preliminary experiment, the time was measured between dazzle caused by looking outside the cockpit and recovery to a level sufficient for recognition of a low contrast test inside the cockpit. The observations were carried out from the rear cockpit of a Meteor Mk. 7 aircraft at altitudes from 5,000 to 40,000 feet. The rate of climb was initially 3,000 feet per minute up to 10,000 feet, 2,000 from 10,000 to 30,000 feet, and 1,000 from 30,000 to 40,000 feet indicated altitude.

For the duration of the experiment the aircraft was flown on a constant heading towards the sun. Light-adaptation was effected by fixating for one minute an imaginary point about 4 feet in front of the starboard wing tip. In this way, and with the constant course of the aircraft in relation to the sun, variations in luminance of the adapting field were restricted to those caused by (*a*) change in altitude, (*b*) changing cloud pattern or haze. As the total time during which observations were made was only 25 minutes for each flight, changes of light intensity due to alteration in the elevation of the sun during this period were assumed to be, for experimental purposes, negligible.

The low contrast test was a matt black card of diffuse reflection factor 3·8 per cent on which was printed a 'T' in slightly less intense black. The size of the 'T' was 6 × 4 cm. and its thickness 1 cm. This card was stuck on to the bottom of the instrument panel and was viewed from a distance of about 60 cm. A stop-watch registering in fifths of a second was used for timing and the results were noted on a knee pad. One minute of light-adaptation was followed by the low contrast perception test, the time interval being noted between cessation of light-adaptation and recovery to the extent of being able to make out the complete outlines of the 'T'. The time was read to the nearest half second, after which the altitude was noted and also presence of any haze or cloud. When the 'T' was seen immediately on looking at the test field, the recovery time was recorded as 'Nil'.

Under these circumstances, luminosity, not only of the light-adapting field but also of the 'T' and its background, naturally varied with altitude, but this was acceptable since this was essentially a pilot experiment to determine whether the time taken to discern objects in shadow in the lower part of the cockpit was increased at altitude.

Results—The results are given in *Fig. 21.* It shows that the recovery time from one minute of light-adaptation was longer at high altitude. Between 0 and 30,000 feet the recovery times were all zero with the exception of 7 seconds recovery time at 17,750 feet. The reason for this isolated result is probably that the light-adaptation at this altitude was effected when flying through a partially formed cloud which gave rise to a much brighter light-adaptation field. The irregularity in results between 30,000 and 40,000 feet may be a result of the changing pattern and density of cloud presented to the eye during light adaptation.

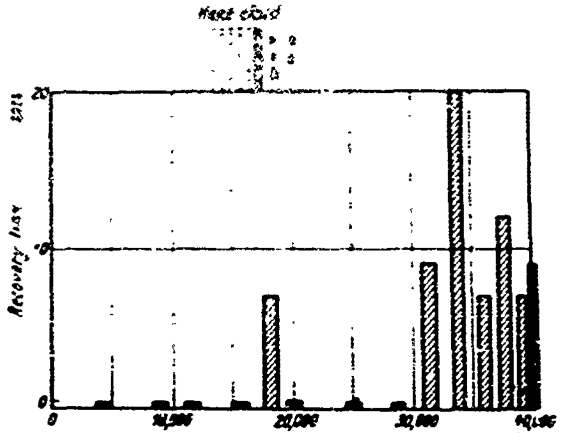

Fig. 21. Recovery times from light-adaptation in flight

Method B—Recovery time from light-adaptation during decompression

In the previous series of observations, carried out in flight it was found that the time taken to recover from one minute of light-adaptation was longer at high altitude. The reason for this finding might have been either an increase in luminosity of the light-adaptation field or a decrease of luminosity of the test object, or, again, another factor affecting the rate of recovery from dazzle. In order to determine more exactly the reason for the increase in recovery time at high altitude, the observations were repeated under carefully controlled conditions in a decompression chamber.

Light-adaptation was effected by looking from a distance of about 1 in. at two opal glass screens of dimensions 3 × 3 in. Each of these screens was illuminated by a 100-watt, 250-volt pearl bulb placed $\frac{1}{2}$ in. behind it and giving it a luminance of 630 foot-lamberts. This apparatus is shown in *Fig. 22.*

The adaptometer which indicated that the retina had recovered its sensitivity to a given level was made up from a battery operated bulb illuminating an opal glass. The intensity of the bulb was monitored by a barrier-layer photocell, adjustments being made by means of a variable resistance. With the bulb at constant intensity, the luminance of the opal glass was adjusted to a desired level by means of a neutral wedge and compensator. The wedges were adjusted to give a disc luminance of 0·03 foot-lamberts. This adaptometer is shown in *Fig. 23.*

Once a required altitude had been attained in the chamber the procedure employed was to light-adapt for 30 seconds. Then, as the light-adaptometer was switched off, a stop-watch was simultaneously

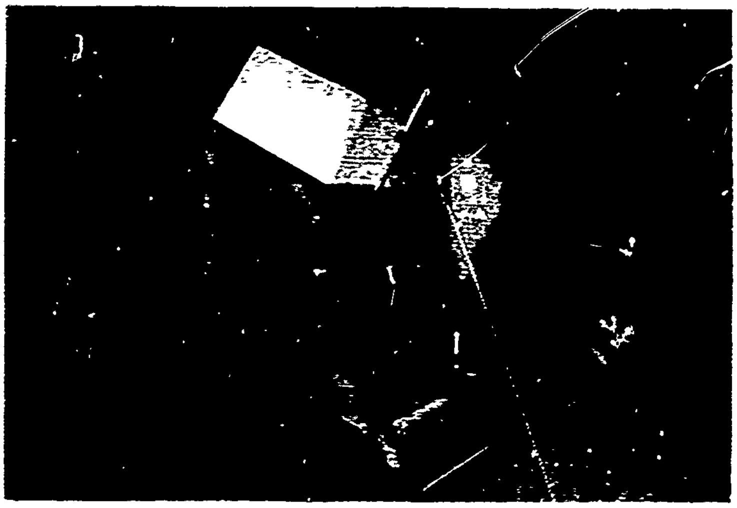

Fig. 22. Light-adaptometer

Fig. 23. Dark-adaptometer

started whilst the subject directed his gaze to the adaptometer. The time taken until the target was seen was noted on a stop watch. The cycle of events was: light-adaptation, recovery test, rest of three minutes. This was repeated at various levels up to the equivalent of 40,000 feet. Oxygen was supplied by a regulator similar to that in the Meteor Mk. 7.

Results—As seen in *Fig. 24* the results show an increase in the recovery time from dazzle during anoxia. This increase is one which would be expected on the basis of previous work relating to the increase in time for dark-adaptation during anoxia (McFarland and Evans, 1939).

At low altitudes, or when there was sufficient oxygen, the positive after-image produced by the light-adaptation field was clearly defined and remained bright until such time as it began to fade. Once it had begun to fade, it vanished in a very short time. It was thus possible in these cases to give a clear-cut answer as to whether the after-image was still visible or not. On the other hand, when there was lack of oxygen, as at 10,000 'feet', the positive after-image faded very gradually almost from the time of its appearance. The visual field furthermore never seemed to be as free from *eigenlicht*, or what Duke-Elder refers to as '*intrinsic light of the retina*', as when there was an adequate supply of oxygen. Thus one felt that the reason for not being able to see the low contrast test in anoxia was not that it was too dark, but rather that the intrinsic light prevented it from being seen.

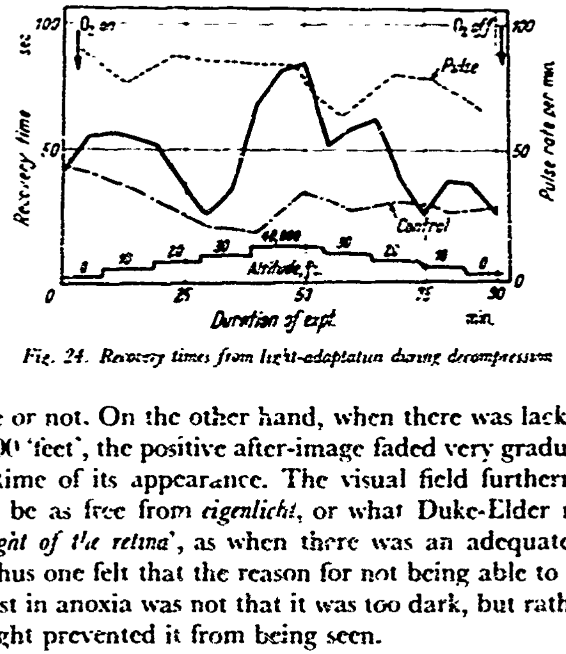

Fig. 24. Recovery times from light-adaptation during decompression

These impressions were tested in the following three simple experiments.

Method C—Time for disappearance of the positive after-image in anoxia
In a completely darkened decompression chamber an apparatus was set up similar to that employed by McFarland *et al.* (1943) for the production of after-images. The light source (a photoflood bulb) was in a box, in the lid of which was mounted a piece of opal glass and a photographic shutter set for an exposure of 0·2 seconds. A white disc was thus presented to the eye at such a distance that it subtended an angle of 2 degrees.

The luminosity of this white disc, seen only when the shutter opened, was 10,000 foot-lamberts. A 3 mm. artificial pupil was placed before the viewing eye. Since the oxygen regulator, employed in the previous experiments, gave to a sitting subject at 40,000 feet the same amount of oxygen as he would obtain from normal air at 10,000 feet, it was unnecessary to carry out the tests at altitudes above 10,000 feet as long as the anoxia was induced by no additional oxygen. In order to accentuate any effects which might be present, however, the experiments were carried out up to 20,000 feet simulated altitude.

The procedure employed was—at a given altitude—to fixate the shutter, and then, after the 0·2 second presentation of the illuminated disc, the subject sat in darkness observing the positive after-image. As the shutter was operated a stop-watch was started and the time in seconds noted from the stimulus to the disappearance of the after-image. Since the end-point was of an arbitrary nature, the mechanical synchronisation of stop-watch and shutter was regarded as unnecessary.

Results—The mean of three observations at each altitude is given in *Table 2*. The time for disappearance of the positive phase of the after-image increased with simulated altitude.

Table 2

Altitude feet	*Duration of positive after-image secs.*
0	17·3
5,000	18·13
10,000	19·46
15,000	20·4
20,000	22·7

It was found, incidentally, that if the eyes were moved, the image tended to disappear much sooner. The after-image was therefore fixated, that is, it was observed carefully and continuously, an act requiring some concentration of attention. (It is interesting to note that Weale (1950) has also mentioned this disappearance of the foveal after-image with eye movement. He also points out that an extra-foveal after-image is not affected by eye movement.)

Compared with its appearance at ground level, the after-image was difficult to discern even at 5,000 feet simulated altitude and the difficulty increased with increasing altitude—it did not seem so bright and its edges were not so sharply defined. The difficulty in seeing the after-image was also increased by the presence of intrinsic light in the unstimulated areas of the retina. When oxygen was administered and the stimulus repeated, it gave rise to as clear an after-image as seen at ground level.

Whereas with full oxygen the positive after-image was clearly defined and bright, remaining so until it faded rapidly, in anoxia the impression gained was that, in addition to being less easily seen, it began to fade very slowly very soon after it had become visible.

Method D — Intrinsic light of the retina during anoxia

In the decompression chamber, observations were made of the appearance of intrinsic light at different altitudes with and without oxygen. The experiment was preceded by 15 minutes dark-adaptation to eliminate unwanted after-images and was carried out in complete darkness.

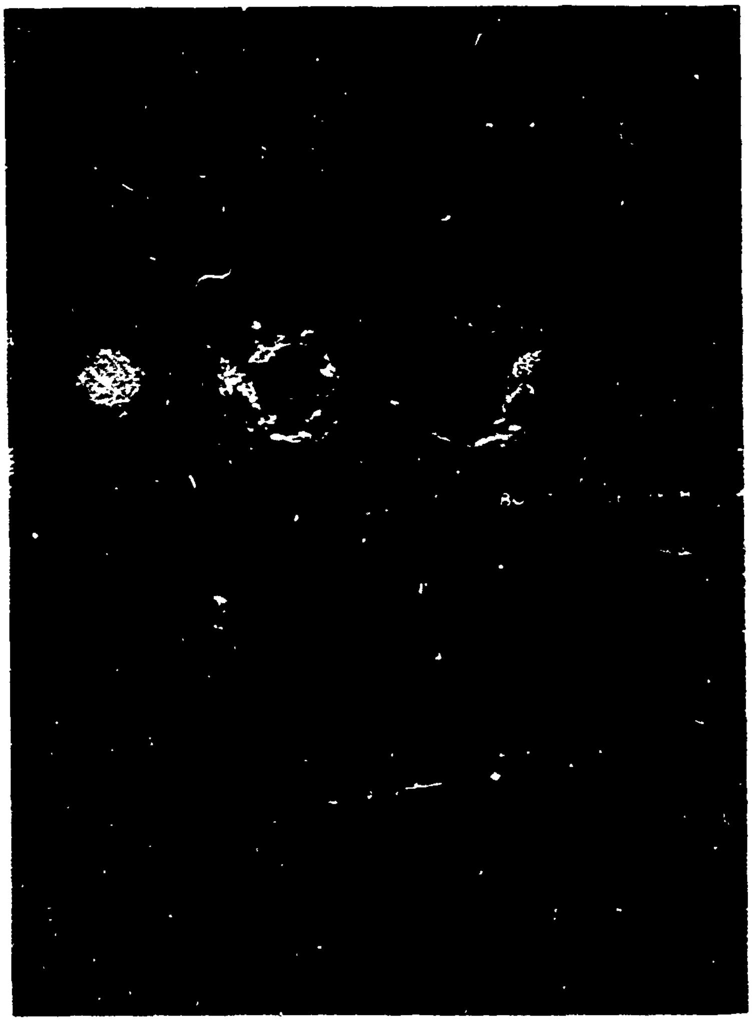

Fig. 25. Intrinsic light of the retina—anoxia

Results—The observations, as dictated on a tape recorder, are reproduced verbatim, and the changes in appearance of the visual field are shown in *Fig. 25.*

Ground level—Field uniformly dark with normal amount entoptic light, if anything more in the periphery than central field. Ascending to 10,000 feet—during the ascent entoptic light increasing and taking on flickering pattern appearance.
10,000 feet– Entoptic light seems to have increased—flickering pattern has now disappeared and it is now steady and uniform. Going up to 15,000.
15,000 feet—Field is uniformly bright—after 2 minutes the field is still uniformly bright and there is no detectable difference between central and peripheral fields. After 4·5 minutes at 15,000 still no detectable difference between central and peripheral fields. Field is uniformly bright. Going up to 20,000.

20,000 feet—Still no difference in the fields—3 minutes nearly—slight detectable difference—central field seems to be a bit darker.

Switching on oxygen—Big increase in luminosity of field—central darker—like a 5 degree negative after-image. The brightness of the peripheral field is gradually decreasing, and as it decreases, the central dark spot disappears. The whole field is now much darker and more uniform. There is no detectable difference between central and peripheral field, but that previously mentioned difference was very marked. It is now 4 minutes at 20,000 feet and I have had oxygen on for about 40 seconds. The peripheral field is a good bit darker now. It is almost black, but in the central field for a 5 degree area there is a brighter spot which is becoming quite marked. It is now fading and becoming a wee bit darker and the difference between the peripheral field and the central field is becoming less. It is now rather difficult to distinguish the central brighter area
Time—5 minutes at 20,000 feet: Going off oxygen now.
Off oxygen now—The whole field is uniformly dark. Some entoptic light is gradually appearing in splashes uniformly distributed over the field. If anything, it seems to be more marked in the peripheral field.
Time—6 minutes: Entoptic light increasing—the lower half of the field seems a bit darker than the upper half.
Time—7 minutes: The entoptic light which was previously stationary and uniform now appears to flicker a bit—rather like an aurora borealis. It is getting brighter.
Time—8 minutes: The central field of 5 degrees seems if anything to be a little bit darker than the periphery. The flickering has now disappeared—it was a transient phenomenon. I am sitting at rest and making no unnecessary movement.
Time—9 minutes: The central field does seem to be slightly darker than the peripheral, and whereas the lower part of the

peripheral field seemed darker at first, it now seems equally bright with the rest of the peripheral field. The central field is slightly and distinctly darker than the peripheral. Feeling a bit light-headed from anoxia.

Time—10 minutes: Going on to oxygen—if I can find the control lever. Got it!

On to 100 per cent oxygen. Central field becoming very bright with flickering lights, but now the central field is quite dark. Peripheral field bright—peripheral field fades and merges into central field, and the entire field is getting quite black after about 30 seconds of oxygen. The spot in the central field which was dark is now slightly brighter and the entire field has got a wee bit greyer—less jet black.

Time—11 minutes: The entire field is uniform now and slightly grey—no further change.

Time—12 minutes: Central field is uniformly dark now and the greyness which had been there is now replaced by blackness over central and peripheral areas.

Time—13 minutes: The effect of switching on oxygen was most marked at the time and the transient increase in luminosity was accompanied by great flickering splashes of light. The whole effect was over in about 30 seconds.

Time—14 minutes: Descending, since no further change seems to be taking place in the field of vision.

Ground level—Having descended from 20,000 feet with full oxygen there were no subjective changes in the visual field. Since the last description it was uniformly dark.

Method E—Intrinsic light of the retina during pressure ischaemia

After 5 minutes in total darkness at normal atmospheric pressure the palms of the hands were pressed over the eyes for 50 seconds so as to produce a degree of retinal ischaemia. The amount of pressure applied was sufficient to cause temporary blindness. The visual sensations were noted. Pressure was released and the appearance of the visual field was again noted.

Results—The results are reported verbatim, whilst the appearance of the visual field is shown in the drawings in *Fig. 26.* These drawings of the appearance of the visual field (*Figs. 25* and *26*) were made from memory and with the assistance of the observations reported here.

Normal amount of entoptic light uniformly over the field.

Applying pressure—The field becomes brighter all over. After about

20 seconds pressure, the central field seems to be a little darker. After 50 seconds, is momentarily darker and then merges partially with the periphery so as to give a uniformly bright field, but the difference at the central area is always noticeable. After 50 seconds pressure released.

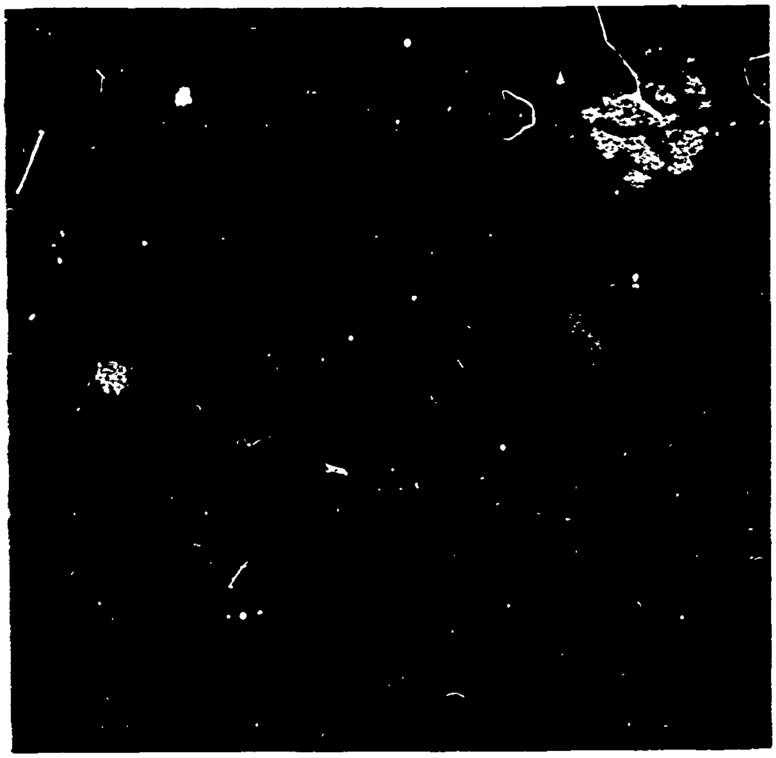

Fig. 26. Intrinsic light of retina–pressure ischaemia

Pressure released—Whole field clears from centre outwards—central bright, peripheral bright—central bright, peripheral dark—central vanishes, merging into the blackness of the periphery. The entire field is very black and seems to be getting still blacker. The central area is now becoming a little brighter than the periphery—the periphery is still black, but the central area is now distinctly brighter. The difference between central and peripheral field luminosity is increasing. The central field is still bright but seems to be spreading out towards the periphery. At first the apparent 'texture' of the central bright area was speckled, but now it is a smooth 'texture'.

The central bright area has now spread into the periphery, diminishing in intensity as it did so; and now the entire field is uniformly grey with normal entoptic light.

SUMMARY

Attention is drawn to the fact that the visual system is particularly sensitive to lack of oxygen, and that even at 4,000 feet altitude there has been reported diminution in absolute sensitivity of the dark-adapted eye to a light stimulus.

It is shown by experiments in flight and in the laboratory that the time required for the eye to recover its sensitivity after light-adaptation is longer in anoxia, the increase in recovery time being evident even at altitudes below 10,000 feet. A slight degree of anoxia, which has hitherto been believed to have an effect only upon night vision, thus also affects day vision, in that, after looking at a bright cloud floor, the time required to recover sensitivity to an extent sufficient to enable instruments in shadow to be visible, is increased. In flight the increase in recovery time may frequently be still longer, since the cloud floor, seen from a high altitude, is frequently brighter and more extensive.

It is concluded that the 'subjective haze' observed in flight at high altitude is a positive after-image of the bright cloud floor. This after-image persists for a much longer time at high altitude, because although oxygen is being supplied, there is nonetheless up to 40,000 feet (without pressurisation) a relative anoxia corresponding to altitudes up to 10,000 feet. The 'haze' is continuously present because in flight it is usual to look inside the cockpit for, at the most, 3 to 5 seconds before returning the gaze to the exterior scene. In the preliminary observations in flight, the time allowed for recovery from dazzle had been only about 30 seconds, whereas in fact 1–2 minutes may be required for the subjective haze to disappear.

It is shown that even in the absence of light stimulus, in total darkness, there appears before the anoxic eye a subjective light which seems to arise in the retina either in response to deprivation of oxygen or to interruption of the blood supply.

Slight degrees of anoxia which are otherwise tolerable, apparently having no effect upon judgment or other higher cerebral functions, thus have the visual effect of increasing the duration of the positive after-image of a cloud floor, and thereby producing a persistent haze over the visual field at high altitude. The effects of the reversed light distribution at high altitude, without reference to anoxia, are dealt with in the next section.

GLARE

In this section is described an investigation into methods of minimising the ocular discomfort associated with flight at high altitude. The results of work mentioned in the previous sections now enable one to describe in more precise terms, the condition of *high altitude glare* which, as a complaint provided the initial stimulus for this entire investigation.

It has been shown that there is a reversal in the normal distribution of light in the visual field, for, with increase in altitude the sky becomes less bright whilst, below the aircraft, there is frequently a very bright cloud floor. This altered light distribution results in more light reaching the upper part of the cockpit, and in less reaching the lower part which is therefore darker than it would be at a lower altitude. There may thus be also, at high altitude, an increase in contrast between the lower parts of an instrument panel in shadow and the exterior scene.

To a certain extent, the effect of these light changes could be reduced by retinal adaptation to the different environment, but in many cases there is insufficient time for such adaptation to take place. The fighter pilot, in particular, is exposed to a rapidly changing light field. Thus, within 30 seconds he may be transported from the comfortable light and shade at ground level in this latitude, to a light field which is a combination of higher sunlight intensity, like that of the tropics, and a highly reflecting cloud floor like the snow fields of the Polar regions.

The essential feature of glare encountered in flight is its variable nature. It is variable in intensity and in direction, and whilst the pilot may be subjected to these variations very quickly within the space of seconds, he may on the other hand be exposed to glare from one direction for a period of several hours.

Bell, Troland and Verhoeff (1922) subdivided glare into three types, and it has been found convenient to employ this classification. The three types are defined as follows:

> '*Veiling glare* is produced by light somewhat uniformly superimposed on the retinal image, thus reducing the contrast and hence the visibility.' It is this type of glare which prevents one from seeing clearly between two skylit window spaces.
>
> '*Dazzle glare* is produced by adventitious light so refracted and scattered as not to form part of the retinal image.' The headlights of an oncoming car at night give rise to this type of glare.
>
> '*Scotomatic glare* is produced by light of intensity such as to fatigue the retinal sensitivity to below the comfortable limit for visual

images.' When searching for an aircraft in the direction of the sun, one is subjected to this type of glare.

The authors regard dazzle glare as the commonest and most serious of the three and veiling glare as 'comparatively rare'. Whilst this is true on the ground, it is not true in the air, and the pilot, as has already been shown in the preceding pages, is affected most frequently and most severely by veiling glare.

Veiling glare, which is thus in flight the commonest of the three types, is fortunately the easiest with which to deal, since all that need be done to effect a real improvement in visibility is to shield the eyes with the hand. In dazzle and scotopic glare, all that can be done, short of obstructing direct vision of the source, is to look through a filter which reduces the luminosity of the visual field. The use of a filter in these circumstances seldom produces an improvement in visibility such as is possible when shielding the eyes from veiling glare, its main function being merely to improve comfort.

RÉSUMÉ OF PREVIOUS WORK

The discomfort caused by the reversed light distribution in the visual field seems explainable quite simply by the fact that more light gets into the eyes from below than from above, since the lower part of the visual field is greater than the upper part which is restricted by the orbital ridges and eye-brows. This reduction in field is shown diagrammatically in *Fig. 63.*

Sensitivity of the upper and lower halves of the retina

As regards the possibility of differences in retinal sensitivity between upper and lower parts of the retina, it is interesting to note the results of the following investigation—After night flying a few pilots reported temporary loss of visibility of the horizon on dark nights without moonlight. They had thereafter inadvertently allowed the aircraft to go into inverted flight, whereupon they had immediately again seen the horizon. The reappearance of the sky, after its image had fallen on a part of the retina which normally receives the image on the ground, had suggested that there might be a difference in sensitivity between the upper and lower halves of the retina. Cibis (1952) carried out an investigation into this effect, and concluded that there was no evidence of a difference in sensitivity between the upper and lower halves of the retina, the effect being explainable entirely on the basis of retinal adaptation: Thus, the upper part of the retina had reached an equilibrium state of adaptation suitable for the stimulus of the dark earth. Likewise the lower part of the retina had reached an equilibrium state of adaptation suitable for the slightly brighter sky. When the subject was upside down, as in inverted flight, the image of the sky fell on the more dark-adapted part of the retina which had up till then been receiving the image of the darker earth, so that the sky suddenly became brighter, and the horizon again became visible.

There is, therefore, no sufficient difference in sensitivity between the upper and lower halves of the retina which could explain the discomfort associated with the reversed light distribution, and one is left with the conclusion that this discomfort is due solely to the greater size of the lower part of the visual field and the consequent admission of more light to the eye.

Physical discomfort of Glare

A visual field of high luminance is uncomfortable to look at, but it appears that some individuals experience more discomfort than others under equal physical conditions. Complaints of high altitude glare came from some pilots, whilst others flying under similar conditions apparently experienced much less discomfort. De Silva and Robinson (1938), in an investigation on the glare caused by head lamps at night, divided their 1,200 subjects into those with light irides and those with dark irides (irrespective of colour). They showed that those with 'light eyes' were unable to perform as well in the presence of glare as those with 'dark eyes', presumably because a dark iris transmits less light. They also found that older people were more susceptible to glare than were young people.

Morone (1948) carried out pupillographic studies on subjects exposed to the light of a 500-watt bulb at a distance of 1 metre. His pupillographic records show a diminution in the amplitude of contraction in response to a light stimulus. This, Morone concludes, is evidence of fatigue of the sphincter pupillae as a result of the sustained contraction whilst the glare source was being observed. It seems unlikely, however, that this reduction in amplitude of contraction should be due to fatigue, because Campbell and Whiteside (1950), in an investigation on the rate of contraction of the iris under repeated stimulation of the eye by light, point out that they found no evidence of fatigue either in the sphincter or in the dilator pupillae. The reduction in amplitude of contraction found by Morone seems more likely to be due to progressive light-adaptation, with the result that the light employed to produce the pupillary contraction became a less effective stimulus.

Brightness of surrounds

With regard to legibility of the instrument markings on an instrument panel in shadow, the task is made harder not only by the smaller amount of light reaching the instrument panel, but also by the higher luminosity of the visual field outside the aircraft which contributes towards a decrease in legibility.

It is to be expected that the higher brightness of the outside field would reduce visibility of darker objects inside the cockpit, for LYTHGOE (1932) employing a test object of constant brightness found that visual acuity depended upon the brightness of the surrounds to the test. (His subjects sat in a whitened cube, the brightness of whose walls could be varied.) The optimum acuity was obtained if the surrounds were of the same brightness as the test. When the surrounds were either brighter or darker than the test, visual acuity deteriorated, the drop in acuity being most marked when the surrounds became, as in the present instance of high altitude flight, brighter than the test object.

Blue light and Glare

The blue colour of the sky at high altitude may also be a contributory factor in the production of glare, for IVANOFF (1947) showed that a blue source produced more dazzle than either red, yellow or green. He measured the effects of these light sources by the changes in the index of dazzle (V):

$$V = \frac{\Delta B}{B}$$

where ΔB is the apparent diminution in brightness of a test object when the glare source is present. The colours which he employed were red (640 mμ), yellow (586 mμ), green (525 mμ), blue (470 mμ). He found also that there was no 'inhibition' in the non-dazzled eye even when the dazzle stimulus was as close as 1 degree from the fixation point. He concluded from this that the 'inhibition' caused by dazzle is at a retinal and not at a central level.

Whilst it is tempting to think in terms of intraocular scatter of light to explain some of these findings, particularly the greater dazzle effect of a blue light, it seems from STILES (1929) that when a glare source is present in a field of vision, the rise in threshold of the visibility of a test object is due principally to causes other than light scattered in the eye media. He calculated that the scattering effect can play only a minor role in the phenomenon.

Sharpness of shadows and simultaneous contrast

A factor, which is not associated with light reversal, yet may contribute to difficulty in seeing at high altitude, is the greater sharpness of shadows cast by sunlight.

At low altitudes the sun is surrounded by an aureole of very bright sky which is attributable to large particle scattering in the atmosphere. At high altitude, however, the large particle scattering is greatly reduced and consequently the size and intensity of the aureole is very much smaller. The interest this may hold with regard to visibility in the cockpit, is that a larger source, such as the sun seen from a low altitude[*], will produce a more blurred shadow border than will the relatively smaller source of the sun without aureole at high altitude. Thus at high altitude the delineation between shadow and sunlit area will be sharper than at low altitude.

When a dark and a bright area are adjacent, the phenomemon of simultaneous contrast causes the bright area to appear brighter and the dark area to appear darker. It seems probable that the extent of the simultaneous contrast may depend partly upon the sharpness of the border between the bright and dark areas. This would cause the effect to be more marked at high altitude and it might well explain the fact that the increase in contrast at high altitude appears to be much greater than that which is found on photometric measurements. In support of this theory is the observation of LE GRAND (1933) who found that there is a drop in the precision of photometric matching when a black line separating two adjacent fields becomes greater than one minute of arc. There is a further deterioration in matching when the line increases in size to five minutes of arc. With further increases, loss of precision in matching deteriorates more slowly. The initial rapid deterioration seems to be due to a transition from judging the disappearance of a boundary to the more difficult task of judging the equality of two separate fields. The implication is, thus, that the closer together are the two fields the greater is the simultaneous contrast.

When all these factors are taken into consideration, it is evident that the cutting off of the exterior scene from the field of view will greatly improve visibility inside the cockpit. However, if this is done, as with the skip of a cap or an opaque visor, the result is a reduction in the field of view, which is not permissible for a pilot in charge of an aircraft.

FLIGHT TEST OF VISOR

The panacea for glare of any description has generally been sun-glasses which were uniformly tinted or graded in density from top downwards or from below upwards so that the part of the visual field from which most of the glare was expected was viewed through a darker area of filter. Sun-glasses were used because nothing better was available, but they were by no means satisfactory, for whilst they reduced the luminance of the outside scene, bringing it to a comfortable level, they also reduced unnecessarily the luminance of the already dark interior of the cockpit. What was gained on one hand was lost on the other. Spectacles which have a clear lower segment are more useful, for it is possible through the lower segment to have an uninterrupted view of the interior of the cockpit, whilst through the upper part the luminosity of the outside scene is

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[*] Height above ground, not solar altitude

reduced to a comfortable level. However, if, whilst wearing them, the head is turned to one side or moved nearer one of the sides of the transparent canopy, the eye will be unprotected from the glare coming from below the aircraft.

Spectacles, however, have either to be on or off, and if they are removed in flight it is difficult to put them back on again without unhooking the oxygen mask and taking off the helmet. It was therefore thought that a more useful way of obtaining protection from glare in flight would be to provide a filter which could be either fixed in intermediate positions over the eyes, or else pushed up out of the field of vision when not required. With this end in view, the visor shown in *Fig. 27* was designed and constructed in prototype form by the author.

Fig. 27. The aircrew anti-glare visor

The visor consists of a *Perspex* transparency of approximately neutral appearance. Its transmission curve is shown in *Fig. 28*, the peaks being due to the dyes employed in obtaining this colour of *Perspex*. It is not at present possible to obtain a suitable mix which is more neutral, that is which transmits more uniformly particularly in the visible spectrum. More neutral filters are, of course, available, but they are not suitable for visors because their colour is often obtained by a pigment which, even in its most finely divided state, gives rise to appreciable scattering within the *Perspex* when illuminated from the side. A soluble dye, on the other hand, does not increase the amount of light scattered within the *Perspex*.

The transparency is adjustable in position as shown in *Figs. 29* and *30*. It is retained on the head by an elastic strap and slip buckle and can therefore be worn with or without a flying helmet*. It is attached at the sides to a fibre headband padded with sponge rubber, the attachment being, on one side a stiff nut which gives a monitoring friction, and on the other side a wing nut with which the transparency can be locked in any intermediate position.

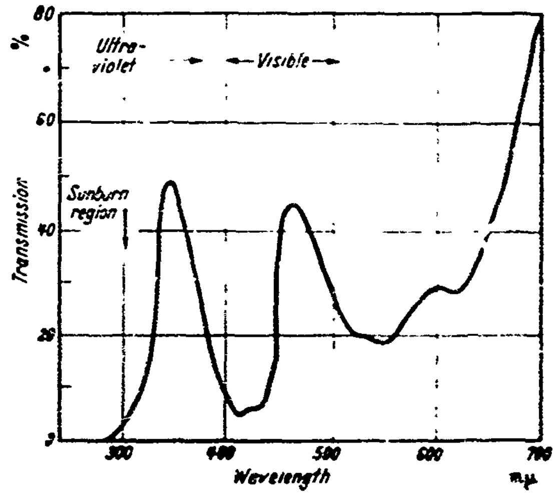

Fig. 28. Transmission Curve of I.C.I. 'Acrylic 900'

Fig. 29. Anti-glare visor—protection from ceiling glare

Fig. 30. Protection from dazzling glare

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*The visor has been modified so that it may be used on the crash-helmet at present employed.

GLARE

The visor was designed to protect the eyes, particularly from veiling glare, and to improve visibility. When veiling glare is present the visor should be used in the half-raised position, like the skip of a cap, and the wearer should look out ahead from below the lower edge of the transparency (*Fig. 29*). When flying directly over bright cloud or in haze or directly into sun, it may be necessary to wear the visor in the fully down position, since the outside scene may be uncomfortably bright. In this position the lower edge of the transparency is designed to coincide approximately with the coaming, so that the wearer has an uninterrupted view of the interior of the cockpit.

The visor, described here and in use in the Royal Air Force, has a uniform transparency. To help in the high altitude glare problem, however, it would probably be better to have a visor which was darker at the bottom and lighter at the top. Technical difficulties have unfortunately up to the present prevented its manufacture.

Results—The results of tests carried out in flight by about forty subjects show that the visor is more useful than either sun-glasses or goggles in giving protection from glare. It was also noticed personally in flight that there seemed to be less head movement when wearing a visor than when wearing goggles. The separate experiment described in Appendix F was therefore carried out. It showed that in looking at objects on either side, there was more head rotation but less eye rotation when wearing goggles than when wearing a visor. This finding was regarded as being associated with the restriction of the nasal field and the unconscious desire to obtain, in so far as possible, a binocular view of the object looked at.

SUMMARY

The glare effects obtaining at high altitude are reviewed. They are due to—

(*1*) the reversal of normal light distribution in the visual field, the bright 'sky' being, at high altitude, below instead of above;

(*2*) the high luminance of the exterior as compared with the luminance of the interior of the cockpit;

(*3*) possibly the blue colour of the sky;

(*4*) the greater sharpness of shadows cast by the sunlight at high altitude possibly increasing simultaneous contrast and accentuating what has been shown to be, at the most, a slight increase in contrast between sunlit and shadow areas in the upper part of the instrument panel.

There is no evidence of a difference in sensitivity between the upper and lower parts of the retina, and the discomfort caused by the reversal of light distribution is due to the absence of restriction in the lower part of the visual field. The position of the eyes in relation to the bony structure of the forehead, the base of the nose, and the cheek bones, ensures, firstly, that the eye is protected from the direct light of the brightest part of the field of view (normally the sky above) and, secondly, ensures ease of visibility downwards where the restriction to the visual field is least. When, as in flight at high altitude, the light comes mainly from below, the protection of the forehead and eyebrows is lost, and light floods unhindered into the eyes.

Since visual acuity is greatest when the surrounds of a test object are at the same brightness as the test and decreases rapidly as the surrounds become brighter than the test, the very bright exterior, which acts as a source of lateral glare when one is looking inside the darker cockpit, consequently interferes with visibility of the instrument markings.

The use of sun-glasses or other filters is reviewed and a specially designed anti-glare visor is described. It is pointed out that, except in the special circumstances of viewing coloured test objects (see p. 127), looking through a filter merely improves comfort without improving visibility. An improvement in visibility is, however, possible when one employs the filter as an eyeshade to keep direct sunlight out of the eyes without actually looking through the filter. This technique effectively combats the most frequently occurring and most troublesome type of glare encountered at high altitude, namely, the veiling glare due to the intraocular scatter of light.

IV. PHYSIOLOGICAL FACTORS AFFECTING AIR-TO-AIR VISIBILITY

E

INTRODUCTION

After the completion of some thirty sorties to 40,000 feet altitude in connection with the experiments already described, it was realised that when one had been at high altitude, other aircraft had been seen on only three or four occasions, and this in spite of the fact that the flights were made in an area in which one would have expected the sky to contain a relatively large amount of aircraft both civil and miltary. It seemed on the majority of occasions that one was quite alone in what is frequently a completely cloudless hemisphere of blue sky.

This cloudless blue sky usually failed to produce any impression whatsoever either of depth or of distance—so much so that when the horizon was not visible, as when one was sitting in the cockpit with the seat in the fully lowered position, the cloudless blue sky gave no more impression of distance than would have been obtained from blue paper pasted over the transparencies of the aircraft canopy. The same effect was noted subjectively, but not quite to the same extent, when the horizon was in the field of view; on these occasions the effect was observed when one was searching in the cloudless sky some 10° or 20° above the horizon.

When searching for another aircraft at high altitude, one was told what the altitude, distance and compass bearing of the target aircraft were, so that the direction from which it would appear was known. In spite of this help, when the target aircraft *was* seen it was almost invariably detected clearly and suddenly and was much nearer and bigger than would have been expected. One had the impression of being taken by surprise by not looking in the correct direction.

This effect cannot have been due solely to inexperience of the writer in air-to-air search, for the apparent difficulty in focussing the eyes and the suddenness of pick-up of a target is a common observation even amongst pilots experienced in air-to-air search at high altitude. In searching the cloudless hemisphere of blue sky, the impression of the difficulty in focussing was so strong as to give rise to a sensation of disorientation such as is sometimes experienced when one is in total darkness.

In meditating over this effect, it was soon realised that under these circumstances accurate focussing of infinity was possible only if the emmetropic eye in the relaxed accommodation state is, as we are taught, focussed for infinity. A camera, which has no focussing scale, is focussed by observing a ground glass plate on which is seen the image of the scene to be photographed. If the scene contains no visible detail it is obviously not possible to focus the camera. The same difficulty would apply in the case of the eye focussing at infinity in the absence of visible detail which could be employed as a cue to accommodation, unless the teaching is correct that the emmetropic or normal eye, when completely relaxed, focusses for infinity. The question to be answered was—'Is it indeed possible for the emmetrope to focus infinity when there is no detail in the field of vision which can be used as a reference point in the process of adjusting the refractive power of the eye?' The existence of the phenomenon known as *night myopia* suggested that the effects observed during search at high altitude might conceivably be due to a similar phenomenon taking place under photopic conditions.

In the investigation of this problem and a number of other visual problems of flight at high altitude, frequent reference was to be made to the type of visual field so frequently encountered—a type of field the significance of which does not appear to have been recognised by others and which, it seems, has not received special attention. With regard to a convenient way of describing this visual field, with its absence of detail which could be focussed, the term *stimulus free field* had been employed at first. This term, however, is inaccurate since the field may be bright and in this respect not stimulus free. The term *empty visual field* was therefore chosen in preference. It is defined as *a visual field in which there is no cue upon which accommodation can act* (WHITESIDE, 1952).

To give rise to it, there must be no detail present which can be sharply focussed. An empty visual field may therefore be produced by total darkness, by dense fog or by a clear blue sky. In such a field the accommodation mechanism might be expected to assume a position of rest, and, according to current theories on accommodation, this position would be for infinity in the case of the emmetrope. The assumption that in the emmetrope the accommodation mechanism is at rest when the eye is focussed at infinity has, however, never been verified experimentally under physiological conditions. The aim of the investigations described in subsequent chapters is to determine the behaviour of accommodation in such an empty visual field.

GENERAL RÉSUMÉ OF PREVIOUS TECHNIQUES

Since the problems associated with vision in an empty visual field have never in the past been selected for special consideration, there is no literature directly relevant to the problem of the behaviour of accommodation in a bright and empty visual field. Under the name *night myopia*, however, one finds a subject which is relevant to the present problem, since the conditions of darkness or of poor illumination under which this phenomenon shows itself constitute, in fact, an empty visual field as already defined.

The techniques employed in the investigations on night myopia are, in general, unsuitable for the examination of the behaviour of accommodation in an empty visual field at daylight illumination levels[*]. In a review of the previous work on 'twilight myopia' or night myopia, Campbell (1951) summarises the various methods which have been employed to measure the degree of night myopia.

The 'adjustable sight method' consists in asking subjects to focus adjustable binoculars for maximum acuity of a test, first under photopic conditions and then under scotopic conditions. The difference between the two settings gives a measure of the change in refraction attributable to the altered illumination. Such a method might have been adaptable to the present investigation by comparing the setting given to the binoculars, when observing under daylight conditions, with the subject's far point as indicated by the greatest amount of tolerable blurring caused by altering the focus of the binoculars so that light rays converged towards the eye. Even with this modification, however, the technique was not suitable, because individuals who have been instructed in the use of binoculars have been taught to focus their eyes on the distant object and then to raise the binoculars to the eyes, having first set them so that there is no appreciable change in accommodation when viewing the scene directly as compared with viewing it through the binoculars. Such trained individuals would thus have given settings which might not be representative of the most comfortable setting.

The detectability of a patch of light at threshold level depends upon its being accurately focussed so as to produce as sharp an image on the retina as the optical system of the eye will allow. If, due to inaccurate focussing, the image formed at the retina is blurred, the threshold patch of light will not be seen. On correcting the accommodation error by means of spectacle lenses the light will then be detected when at its lowest intensity. Such a method cannot be applied to photopic tests.

What is virtually a modification of this test consists in measuring the minimum form sense instead of the absolute threshold. As previously carried out, it, too, is unsuitable in that it cannot be readily applied to tests carried out at photopic levels.

It is difficult to make a sharp distinction between the tests of absolute threshold and form sense, and those of contrast perception at low luminance levels. A technique depending upon contrast perception at photopic levels was employed by Luckiesh and Moss (1940). In an investigation on relative accommodation in emmetropic subjects, they wished to obtain an indication of the degree of accommodation exerted without giving the subjects a test upon which they could focus. They accordingly presented their subjects with tests at a fixed distance, and interposed between the test and the subject's eye a circular photographic wedge. The subject initially looked through the densest part of the wedge

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[*] Campbell 1956 has succeeded in obtaining continuous records of accommodation to an accuracy of about 0.1D. by using a kind of infra-red optometer.

and could not see the test. The wedge was then slowly rotated so that it gradually became less dense, and the point at which the test suddenly became visible was noted. Convergence was maintained throughout by a special fixation mark which did not stimulate accommodation. This technique of Luckiesh and Moss is of interest because it is, in a sense, similar to the technique described later in this chapter and employed in the present series of experiments.

Measurements of refraction under photopic and scotopic conditions have been made by employing a red light beam so as not to stimulate rods during measurements made under scotopic conditions. It is not possible to adapt this technique to the present problem since under photopic conditions there is no way of preventing the examining light from becoming a stimulus for accommodation.

The reflections of light from the anterior surface of the lens give rise to an image which an observer can see varying in size as the subject alters his accommodation from far to near and from near to far. Since the image is formed by a surface of the lens which becomes more convex during accommodation for near, this change causes the image of the light source to become smaller. This reflection—the third of the *Purkinje-Sanson images*—can be photographed. Thus if the light source is a very rapid flash, it is possible to photograph the changes in shape of the lens which occurred whilst the eye was in darkness and before the reaction to the light flash could take place. As will be seen later, this technique has been applied to the investigation of the accommodation changes in an empty visual field at photopic levels.

These constitute the principal methods which have been employed to measure the degree of night myopia. Some are subjective, others are objective; some measure changes in the retinal image, whilst others measure changes in the shape of the lens. The night myopia affecting vision by night, and what may be a similar condition affecting vision at high altitude by day, are, however, essentially subjective conditions; and so the technique to be preferred in their investigation is a test of what is happening at the retina; a test of visibility and therefore a subjective test. Such a test enables one to determine whether, under certain conditions, the refraction of the eye is altered. Whether such changes of refraction as may be demonstrated are due to changes in the shape of the lens, in the resolving power of the eye, or in chromatic aberration, can, if necessary, be determined by subsequent experiments employing different techniques, and by discussion.

EXPERIMENTAL TECHNIQUE

The technique consists essentially in giving the subject a bright and empty visual field to look at. Whilst he is looking at this field, a test is brought gradually closer to his eyes. The test consists of a number of small black dots which are so small as to be about threshold size, and, being so small, when they are not in sufficiently sharp focus they cannot be seen. As this test comes into the same plane as that in which the subject's eye is focussed, he suddenly sees the small dots appearing in the centre of the empty field before him.

In this simple theoretical case, the point at which the dots are seen is indicative of the point at which the subject is focussed, or in other words how much accommodation he is exerting. By means of a positive lens 'optical infinity' is brought to a convenient working distance of 25 cm.

The above is an exposition of the purely theoretical test. Whilst the practical test retains the advantages of directness, ease and rapidity of administration, it is however somewhat complicated by factors requiring special consideration or control.

In preliminary experiments it was found that when the subject was observing the dots moving away from him, he was able to follow them further than the distance at which he was able to recognise them when they came towards him in an empty visual field. Whilst this result suggests that there was a difference in the accommodation exerted in an empty field as compared with that exerted when there was visible detail present, it could equally well have been due to the following factors, any one of which could have given the same result:

(*1*) *Looking in the wrong direction*—When the test was visible, it could be fixated and its image kept on the fovea. When the test was appearing from below threshold, particularly in this technique in which there was no fixation mark, the image might not happen to fall on the fovea, in which case the lower acuity of the para-fovea or of the periphery would require the test to be brought nearer before it became visible.

(*2*) *Error of habituation*—There is a constant tendency for one to remain unaffected by small changes in the environment. It is fortunate that this is so, for otherwise one would be aware of every small change of movement, of light, of noise or of temperature.

Guildford (1936) refers to this as the 'error of habituation' and he points out that it affects determinations of threshold in which the presentation of the stimulus is not randomised. Thus, if in a determination of threshold, the stimulus is presented in a decreasing order of intensity, the subject perceives it to a lower intensity. On the other hand, when the stimulus is presented in an increasing order of intensity the subject does not detect it until it has passed the threshold level. This effect can be avoided by using discontinuous changes in intensity of the stimulus and by randomising the order of presentation of the stimulus at various intensities.

In the present experiment the 'habituation' was in one case to the empty visual field, whilst in the other it was to a stimulus which was becoming gradually smaller and more blurred.

(*3*) *Speed of presentation*—The test plate, on which was superimposed the small test dots, might have been moved too quickly towards the subject, so that by the time he had recognised the small dots and called out to the observer who in turn stopped moving the test plate, this plate would be nearer the subject than the point at which he had recognised it. This difference would be greater when the plate was moved faster.

Before attempting to calibrate results so as to know how many dioptres of accommodation were being exerted when the test pattern was seen at a given distance, the effect of the following known variable factors had to be considered and controlled:

(*1*) *Variable size of the test*—The angle subtended by the small dots of the test plate was not constant but depended upon their distance from the subject's eye. In the present test they were above threshold size. By reason of their being above threshold size the test dots became visible before reaching the point at which the subject was focussed.

(*2*) *Depth of focus of the eye*—Within a certain range on either side of the point of optimum focus there is little deterioration in the sharpness of an image. If only a small amount of blurring is tolerable, the depth of focus will be smaller; if on the other hand greater blurring is tolerable, then the depth of focus is greater. Beyond the depth of focus, as determined by the acceptable blurring or size of circle of confusion, the sharpness of the image deteriorates rapidly. Whilst the term 'depth of focus' is generally used, it is more correct to refer to the range of distances over which an object can move without becoming noticeably blurred as 'depth of field'. In this technique it was possible, by reason of depth of field, to see the test objects before they actually came into the plane in which the eye was focussed.

Apparatus

The apparatus (*Figs. 31* and *32*), consisted of a clear glass plate upon which was superimposed photographically a star-shaped pattern of small black dots, each of diameter 0·06 mm. The distance between the dots was about 3·5 mm. The constructional detail of the test plate with the small black dots is given in Appendix G. This glass plate could be moved back and forwards on an optical bench between the subject and the background, the distance of the plate from the subject's eye being indicated by a ruler fixed to the bench and by a pointer fixed to the saddle which carried the test plate.

In some experiments involving the use of the small dot test plate, it was found to be more convenient, particularly since time was a factor of importance, to adopt a slightly different method of recording results. The saddle to which the test plate was attached was on these occasions linked by means of a thread through a system of pulleys to the vertical pointer of a Kymograph drum (*Fig. 33*). Another pointer on the kymograph was connected to a time-clock and functioned as a time-marker.

Recordings of the level of accommodation could thus be made more rapidly since the experimenter did not require to stop in order to read and to record the distance from test plate to the lens. A further advantage of this modification was that the records of accommodation were thereby placed on a time base.

Fig. 31. Apparatus—subjective method

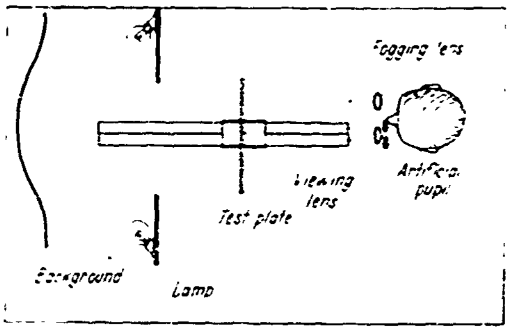

Fig. 32. Apparatus—diagrammatic sketch

The background (*Figs. 31* and *32*) consisted of a single sheet of white cartridge paper evenly illuminated by means of three photoflood bulbs to a luminance of 400 to 450 foot lamberts and to colour temperature 3000° Kelvin. The bulbs were screened so as to prevent direct light from reaching the subject's eyes.

The subject's head was supported by a chin and forehead rest, and, in order to bring optical infinity to within the confines of the laboratory and at a suitable distance, the test field was observed through a + 4 dioptre lens in front of one eye. Thus the emmetrope, observing the test object at a distance of 25 cm. from the lens, was focussed at infinity and the rays of light entering the eye were parallel. Also, by means of the lens, any detail accidentally present in the background was so blurred as to be made invisible. In this way, only the test object dots were visible and no other detail was present in the field of vision within 20° of the line of fixation.

The test object could be seen by only one eye and through an artificial pupil of 2·9 mm. diameter, the other eye being presented with a blurred view of the background through a + 10 dioptre lens without pupil restriction. This monocular presentation of the test was necessary to eliminate any accommodation cues which the subject might otherwise have obtained by the convergence reflex. Final recognition of the test was thus monocular, but the technique was nonetheless essentially binocular, since up to the instant of recognition of the test dots the subject looked at the empty field binocularly.

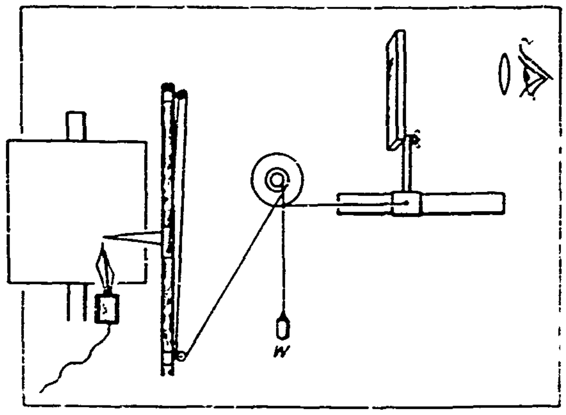

Fig. 33. Apparatus for kymographic recording

When the small dot test was out of focus there was no recognisable detail in the field of vision, either with the right eye or with the left eye, and in this respect the fields before the two eyes were identical in appearance. The fields, however, were not identical in size, for before one eye there was an artificial pupil of 2·9 mm. diameter, whilst before the other eye, which viewed through the + 10 dioptres 'fogging' lens, there was no artificial pupil to reduce the size of the field. No artificial pupil was used in this case, partly because it was regarded as unnecessary, and partly because the presence of fixed artificial pupils before each eye, by giving small fields of identical size, would have enabled subjects to detect more easily changes in their own convergence. They would thereby have obtained information as to changes in their accommodation. The apparent movement of the two fields towards, or away from one another during changes in convergence was, of course, not eliminated by using fields of different sizes, but the effect was not as obvious as it would have been with fields of equal size.

In order to reduce the importance of the search factor the small dots were arranged in a regular pattern and the subject was familiarised with the appearance of the test and with the direction from which it appeared, this being always the same.

The use of an engraver's half-tone plate had originally been considered for a test object; since as it consisted of small dots uniformly distributed throughout the entire plate it would have more completely eliminated the search factor. Practical difficulties, however, prevented the modifying of such a plate.

EXAMINATION OF TECHNIQUE

Method A—Preliminary experiments

The subject was seated at the apparatus and the test plate was gradually moved towards the viewing eye until the test pattern of black dots had been recognised. This procedure was carried out three times, so that the subject might be familiar with the appearance of the small dot pattern and its position in the field of view. The test plate was then moved away from the subject and beyond the focus of the + 4 dioptre lens before the viewing eye.

Whilst the subject looked at what was now a bright and empty visual field, the test plate was gradually brought nearer at as uniform a rate as could be judged by the experimenter. When the subject called out that the test was visible, the plate was stopped and its distance from the lens was noted. This distance at which the dots were recognised indicated the amount of accommodation exerted by the subject. Thus, in a theoretical case with no depth of focus, if the test was recognised at 20 cm. instead of 25 cm. which was the focal length of the viewing lens, the power of the lens and eye combination would be 5 dioptres. Since the power of the lens alone was 4 dioptres, the eye was accommodating by 1 dioptre—the focussing of parallel rays from infinity being regarded as zero dioptres of accommodation. The subject, however, might be hypermetropic, in which case the 20 cm. at which the test was recognised would indicate more than 1 dioptre of accommodation. If on the other hand he were myopic, by say 1 dioptre, the 20 cm. at which the test was recognised would indicate that no accommodation was being exerted and that the subject's eye was completely relaxed.

To know how much accommodation a subject was exerting, it was therefore necessary in every instance to measure his far point. This was done as follows:

After the subject had recognised the small dots, the test plate was gradually moved away from the eyes until he reported that the small dots could no longer be seen. The distance from the plate to the lens was then noted. In the purely theoretical case this would have been an accurate measure of the far point. For example, if the dots had disappeared at 33 cm. from the lens, the power of the lens-eye combination would have been 3 dioptres. As the power of the lens was + 4 dioptres, the eye in that case was exerting − 1 dioptre of accommodation; that is to say it was focussing rays converging towards the eye, and was therefore 1 dioptre hypermetropic. Preliminary tests were carried out on a small number of subjects.

Some tests were also carried out to determine whether the results obtained with a binocular presentation differed from those obtained with a monocular presentation. The monocular presentation was achieved simply by putting an eye-shield over the eye which was not viewing the test pattern.

Results—With all subjects tested it was found that in an empty visual field the test plate had to come proximal to the far point before the test pattern dots were recognised. When they were recognised, they were almost always seen clearly and suddenly.

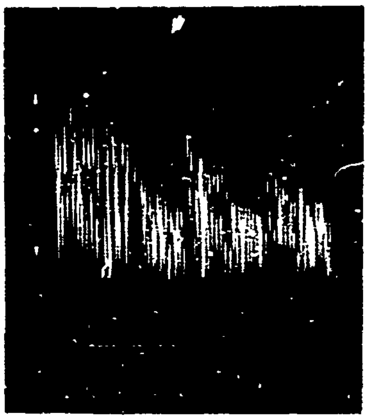

Fig. 34. Effect of monocular and binocular view of the empty field

The recognition of the small dots in an empty field took place at a greater distance from the eye when the test was a binocular one. This agrees with the observation familiar to refractionists—that when both eyes are used accommodation can be relaxed more easily than when only one eye is used. The results are shown in *Fig. 34.*

Method B – Paralysis of accommodation
Into one eye of a subject 5 drops of homatropine in cocaine (ca. 2 per cent) were instilled at 20-minute intervals for a period of one hour so as

to paralyse completely the accommodation mechanism. By retinoscopy it was then found that + 1·75 dioptres were required to correct the eye to infinity. The range of accommodation was nil.

Being hypermetropic the subject was unable to see the small dots on the test plate, so, for this experiment only, the − 4 dioptre lens was removed and replaced by a − 8 dioptre lens. The procedure previously described was again employed, the test plate being brought towards the subject until he recognised the small dots. Its distance was noted, after which it was withdrawn beyond the point of focus until the small dots disappeared, the distance being again noted.

It was found that if the test plate was brought too near, the dots again disappeared. A simultaneous set of measurements was therefore also made at the proximal limit of the depth of field. The test plate was brought towards the subject until the dots disappeared and then, beginning with the test plate very near the subject, it was gradually moved away until he saw the small dots.

Results—The results for one subject are given in the following table:

Table 3

Far point		*Near point*	
Coming towards cm.	*Going away cm.*	*Coming towards cm.*	*Going away cm.*
16·2	16·9	11·7	12·7
16·1	17·3	11·6	12·4
16·1	17·0	11·8	11·9
15·9	16·8	11·1	12·0
16·6	17·1	11·8	12·3
16·4	17·1	11·8	12·0
16·8	17·0	11·6	11·9
16·6	17·0	11·5	12·1
16·4	17·2	11·5	11·9
16·7	16·9	10·8	12·3
163·8	170·3	115·2	121·5
16·38	17·03	11·52	12·15
Difference 0·65 cm.		Difference 0·63 cm.	

When accommodation is paralysed there is thus still a difference between the distance at which the test appears and that at which it disappears. The distance, however, is small (0·65 cm.). At the near point the difference is of the same order, being 0·63 cm.

Method C—Speed of presentation of the test

In the preliminary experiments it had been found convenient to move the test plate towards the subject at a speed of approximately 2 cm. per second. This test was carried out in order to determine whether the subject would be able to see the test further out if its speed of presentation was reduced to 0·5 cm. per second.

The experimenter judged the speed of the test plate by a centimetre rule at the side of the optical bench and by a time marker which gave an audible click at second intervals.

Results—The record of this experiment is shown in *Fig. 35.* As will be seen, the distance at which the dots were recognised when they approached at 2 cm. per second did not differ appreciably from the distance at which the test plate was seen when it approached at 0·5 cm. per second. It was concluded from this that as long as the test plate was moved at approximately the same speeds of 0·5 to 2 cm. per second there would be little variation in results attributable to variation in the speed at which it approached the subject's eye.

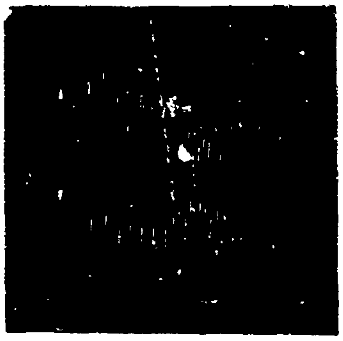

Fig. 35. Effect of speed of presentation of the test

Method D—Calibration

The principle employed was to cause the subject to accommodate to a known extent by means of a large fixation mark, and then to bring the spots towards him until they became visible. The distance at which they became visible thus corresponded to a known degree of accommodation. As was revealed by pilot experiments, however, such a simple method was not accurate, because it depended upon the false assumption that if a fixation mark is presented at, say, 50 cm. and focussed as accurately as is possible, 2 dioptres of accommodation will be exerted. What happens in fact is that when the test fixated is near, insufficient accommodation is usually exerted, whereas when the test approaches to the subject's far point, too much accommodation is usually exerted. Subjects are quite unaware of these inaccuracies in focussing, because depth of focus of the eye maintains a sufficiently sharp image at the retina although the point at which the eye is focussed is not necessarily in the same plane as the test object.

It was therefore decided to employ an objective method to measure the accommodation actually being exerted when a subject focussed a test object at a given distance. The Fincham Coincidence Optometer was ideal for this purpose. This is an instrument which sends a small pencil of parallel rays into the eye, and which measures the change in vergence of this pencil of light as it emerges from the eye after being reflected by the retina. This optometer showed with certainty changes in accommodation of the order of 0·2 D., and when a mean of three results was taken the accuracy was probably nearer 0·1 D., which is the level of accuracy the manufacturers claim for the apparatus.

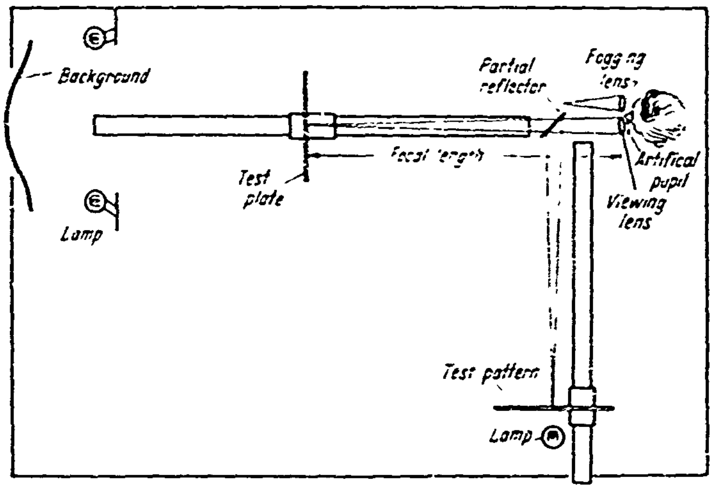

Fig. 36. Optical bench apparatus

The fixation test consisted of a transilluminated piece of black painted *Perspex*, through the black paint of which the fixation pattern had been scratched. As the test employed was two vertical and parallel bars of light, the meridian principally concerned with focussing them was the horizontal. Optometer readings were therefore taken only in this meridian.

The arrangement of apparatus is shown in *Figs. 36* and *37*. As in the case of the optical bench apparatus, the subject had to look at the test through a + 4 dioptre lens. It was not possible to have the same lens-to-eye distance in the optometer test, so, in the calculation of the amounts of accommodation expected, the effectivity of the lens–eye combination was calculated by the formula:

$$D = D_1 + D_2 + dD_1D_2$$

where D is the total refraction of the lens–eye combination, D_1 the refraction of the lens, D_2 the refraction of the eye (accommodation), and *d* the distance (in metres) from lens to eye. All tests were carried out with an artificial pupil of 2·5 mm. diameter.

The same test object was fixated first on the optometer apparatus and then on the optical bench apparatus, and in each case it was presented at several distances from the eye so as to require the subject to exert several degrees of accommodation. On the optometer apparatus, the optometer measured the refractive change of the eye, or the accommodation really exerted, whilst on the optical bench apparatus the distance at which the small dots appeared indicated a different amount of accommodation.

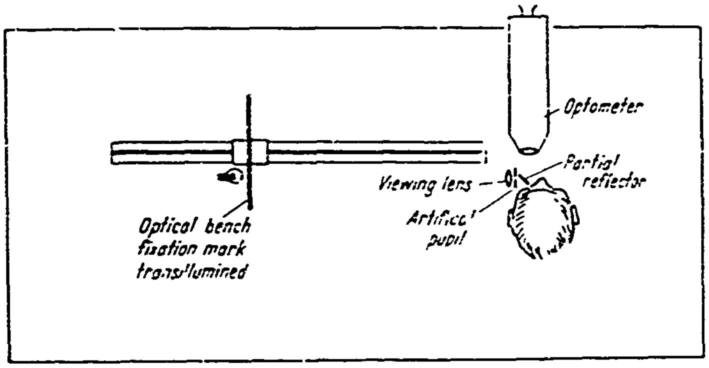

Fig. 37. Optometer apparatus

On the optical bench apparatus. the amount of accommodation indicated by the distance at which the small dots appeared differed from the accommodation really exerted by half the depth of field.

Thus, when fixating on a test object at 20 cm. the eye might be focussed at 25 cm. In this case, the *expected* accommodation would be 5 D., whereas the eye was really exerting only 4 D. The small dot test, on being brought towards the eye, might under these circumstances, be seen at 33 cm. by reason of the depth of field of the eye focussed at 25 cm. Thirty-three cm. or 3 D., would here be referred to as the *indicated accommodation.*

The test was set up at several distances, at each of which the following procedure was carried out:

(*1*) On the optical bench apparatus the distance was found at which the small dots appeared whilst the subject fixated and focussed as accurately as possible the parallel bar fixation test. This gave the *indicated accommodation.*

(*2*) Whilst the subject fixated the parallel bar test at the same distance from the eye as in the previous case, the optometer was employed to measure the change in refraction. This gave the *real accommodation.*

(*3*) The *expected accommodation* was known from the distance between the parallel bar test and the eye. In every case, three readings were taken in succession.

Results—Six subjects were tested as described, the differences being found between the *real* and *indicated* accommodation. The results for five of the subjects were consistent and showed regular trends, but the results for the sixth were erratic. The results for this subject have in consequence been omitted from the calculation as it is probable that the differences were due to fatigue or to insufficient cooperation. There were no signs or symptoms of abnormal visual functions, and a retest of this subject was not possible as the apparatus was no longer available when the discrepancy was discovered. The real and indicated accommodation at different levels are given in *Table 4*.

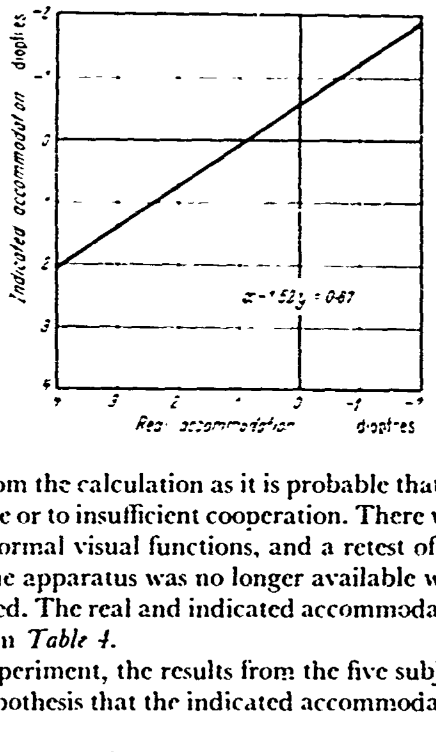

Fig. 38. Calibration graph

Within the limits of the experiment, the results from the five subjects were compatible with the hypothesis that the indicated accommodation

Table 4. Relation of accommodation indicated on optical bench apparatus to real accommodation exerted

Subject A		*Subject B*		*Subject C*		*Subject D*		*Subject E*		*Subject F*	
Real	*Indic.*	*Real*	*Indic.*	*Real*	*Indic.*	*Real*	*Indic.*	*Real*	*Indic.*	*Real*	*Indic.*
-1·83	-0·65	-1·27	0·2	-2·6	-1·1	2·0	-1·1	-1·25	0·15	-1·47	-1·00
-1·35	-0·3	-0·32	-0·2	-2·75	-0·8	1·33	-0·85	-0·4	-0·2	-1·13	-0·65
-0·67	-0·12	-0·15	-0·5	-2·2	-0·5	-1·07	0·55	0·3	0·4	-0·4	-0·25
+0·78	-0·1	-0·3	-0·7	-1·6	-0·25	-0·68	-0·37	0·2	-0·47	-0·33	-0·05
-0·2	-0·32	-0·33	-0·85	-1·57	-0·1	-0·63	-0·15	0·25	0·67	-0·07	-0·05
-0·2	-0·42	0·4	-0·95	0·62	0·13	-0·6	-0·2	0·13	-0·8	-0·23	-0·2
0	0·53	-0·68	-1·05	-0·67	0·25	-0·48	0·1	0·57	-0·95	-0·07	-0·42
-0·27	-0·6	-0·67	-1·15	-0·28	0·5			-0·33	-0·97	0·05	-0·8
-0·3	0·7			-0·28	-0·5			-0·83	1·0		
-0·68	0·75			-0·3	0·57						
-0·47	0·85										
-0·67	-1·03										

bears a linear relationship to the real accommodation. The best line to predict real from indicated accommodation is represented by the equation:

$$x - 1{\cdot}52y = 0{\cdot}87$$

where x is the real and y the indicated accommodation. This equation is graphed in *Fig. 38.*

This calibration should apply to all subjects tested on this apparatus at this level of background luminance, provided they have visual acuity which is normal or which is capable of being corrected to normal limits.

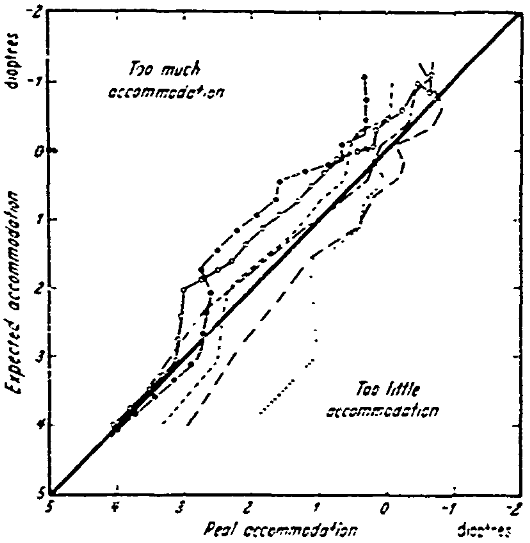

Fig. 39. Accommodation exerted with a test at various distances

Fig. 39 shows the relationship between real and expected accommodation. Apparently the tendency is always either to under-accommodate when viewing a near object or to over-accommodate when viewing a distant object.

DISCUSSION

The results of experiment B show that the factors of 'search' and 'error of habituation'* can account for a difference of 0·65 cm. between the distance at which the test dots appear and that at which they disappear during the measurement of far point. Thus any difference in excess of 0·65 cm. must be due to the factor of accommodation, which was controlled in this experiment.

If the test is brought towards the subject, the factors of attention and

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* Page 77.

reaction time of the subject and observer are a possible source of error, because by the time the subject has seen the test and called to the observer (who in turn stops the movement), the point at which the test stops is somewhat nearer than that at which it was first seen. The results of experiment C as shown (variation of the speed at which the test was moved) show that this factor produces a discrepancy which must vary only with marked changes in speed. Halving the speed produced only slight changes in the results. As constant a speed as could be judged by the observer was therefore well within the permissible limits.

An interesting point shown by the calibration experiments is the tendency of subjects to under-accommodate for near objects and to over-accommodate when looking at distant objects. By far the most important reason for this tendency is the depth of focus upon which the subject can depend to obtain a sufficiently sharp retinal image with the minimum of effort. Thus the difference between the accommodation actually exerted (real accommodation) and the accommodation which the subject might be expected to exert by reason of the distance from the fixation test object to the eye (expected accommodation) seems to be due to a form of economy of effort. This in turn implies that the position of rest of the accommodation mechanism in the emmetrope may not be for a focus at infinity but at a finite distance.

A similar economy of effort in the act of accommodation has been observed by **Adamson** and **Fincham** (1939). On the basis of the hypothesis that this difference between real and expected accommodation is due to an economy of effort, it would be expected that when the test was one requiring better acuity, the difference between real and expected accommodation would be less. **Campbell** (1952) has made such an observation. He found, on photographing the Purkinje-Sanson image reflected from the anterior surface of the lens, that when an emmetrope with a — 6 D. lens before his eye read a test card at 6 metres, instead of exerting 6 dioptres of accommodation, he in fact accommodated less than this. Furthermore, the discrepancy was greater when reading large letters.

Also contributing to the difference between real and expected accommodation is the above-threshold size of the small dots, which increases the amount of blurring tolerated before they disappear. The image of the dots initially comes to a focus in front of the retina when they are coming towards the observer. The image formed on the retina is thus blurred, but providing its size and its contrast with the background are sufficiently great the stimulus will be appreciated.

It was found during measurements on the optical bench that the distance at which the small dots were seen did not reach a definite maximum, such as would be expected when the fixation test was at the far point. It suggests that in the determination of the far point by this method, there may be some difficulty in making subjects relax their accommodation completely. It seems as though, given time and practice in looking at the distant stimulus, a subject may be able to relax his accommodation more than in the first determination.

This does not affect the finding of involuntary accommodation in an empty visual field, for the involuntary accommodation shows itself as a difference between the point at which the dots are recognised in an empty field, and the far point measured at that time. As the tendency is for the far point to be underestimated, the difference measured will certainly not be more and is more likely to be less than the difference between the point at which the dots are recognised in an empty visual field and the point corresponding to full relaxation.

SUMMARY

It is concluded that provided one employs the same background brightness, artificial pupil, and a calibrated test object, the apparatus and technique described are capable of giving information which can be interpreted in terms of accommodation exerted. The subject being tested must, however, have acuity which if not normal, is capable of being corrected to normal standards.

THE AMOUNT OF ACCOMMODATION EXERTED INVOLUNTARILY IN AN EMPTY VISUAL FIELD

Method A—Subjective technique

THE subject was seated at the apparatus and the tests were carried out in the usual way by bringing the test plate slowly forwards towards him until the dots were recognised, whereupon the test was withdrawn beyond the far point so that the dots were no longer visible and the subject was again presented with an empty visual field. It was felt, however, that in this procedure an error might be introduced by the fact that the subject, having recognised the test dots, could see them subsequently being moved towards the far point by the experimenter in preparation for the next presentation of the test. It was thus possible that each determination, accompanied as it was by a momentary glimpse of the receding stimulus, affected the next determination by helping the subject to focus nearer his far point.

When the small dots had been recognised it was necessary to remove them from the field of view in such a way as to give rise to no accommodation stimulus. Since this was not possible, it was decided to counteract any trend of accommodation in one direction. Accordingly, the experiment was carried out in such a way as to balance the possible error by causing the tendency to accommodate for distance to alternate with the tendency to accommodate for near. This was done in the following way:

The test plate was brought towards the subject from beyond his far point until he recognised the small dots. The plate was then rapidly moved as close to the eye as possible, thus causing the small dots to disappear, since the subject now focussed beyond them. The test plate was then gradually moved away from the eye, and when it came to the proximal limit of the depth of field the small dots were again recognised. The test plate was then moved rapidly to beyond the far point, and the entire procedure repeated. Thus after one presentation of the test the tendency may have been to relax accommodation further, whilst after the subsequent presentations of the test the tendency was to increase accommodation. Results were recorded on the kymograph, and calibrated by means of the calibration graph in *Fig. 38.* The indicated accommodation was calculated from the distance at which the small dot test pattern became visible.

Results—In *Figs. 40* and *41* are shown two kymographic records obtained in the course of this experiment. The record shown in *Fig. 40* was made by bringing the test in from the far point, whereas that shown in *Fig. 41* was obtained by alternatively bringing the test from far to near and from near to far as described above. On the time axis marks were made at 30 second intervals, whilst the vertical axis was calibrated in dioptres of accommodation exerted by the subject, zero dioptres being the subject's far point. The kymograph pointer moving from below upwards corresponded to the test being brought from the far point towards the subject. In *Fig. 41* the point at which the subject recognised the test is indicated by a short horizontal stroke.

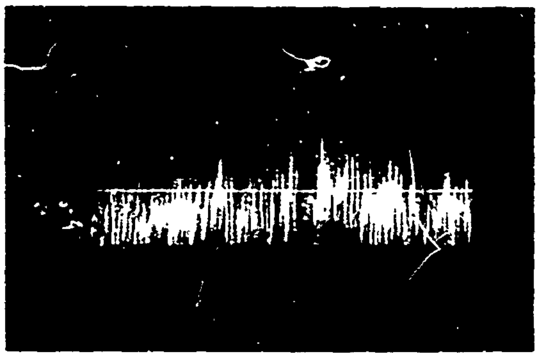


Fig. 40. Accommodation in an empty visual field

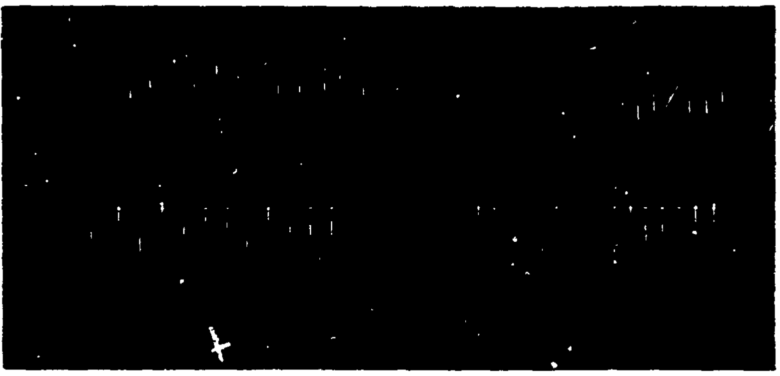


Fig. 41. Accommodation in an empty visual field

It will thus be seen that in *Fig. 41* the lower of the two vertical strokes corresponds to the point at which the test was recognised when coming from the far point towards the subject. It is therefore this mark which gives an indication of the amount of accommodation exerted.

The recognition of the test when it moved from near to far is indicated by the upper set of short horizontal lines and indicates the proximal limit of the depth of field.

It is seen from these two tracings that the subject, in the absence of any detail in his visual field, was unable to relax accommodation to the far point. In *Fig. 40* the tracing shows a fluctuation of small amplitude, occurring at intervals of about one minute, superimposed upon larger fluctuations occurring at 5 to 6 minute intervals. These larger fluctuations are also seen in *Fig. 41*, and in this case they caused a corresponding fluctuation in the upper set of horizontal strokes, thus excluding the possibility that fluctuation is due to one presentation of the test affecting the response to the next presentation. The small fluctuations are not so well seen in *Fig. 41*, probably because the presentation of the test was not made at sufficiently close time intervals.

In *Fig. 40* accommodation seems initially to have been completely relaxed; as the experiment progressed it gradually increased, eventually reaching a steady level between 1 and 2 dioptres. In *Fig. 41*, on the other hand, at the start of the experiment the subject was exerting between 3 and 4 dioptres of accommodation. In this case, however, as the experiment progressed accommodation relaxed towards the far point, eventually showing little change and fluctuating between ½ and 2 dioptres.

Method B—Objective measurement of accommodation

The extent of accommodation exerted was determined by photographing and measuring the images reflected from the anterior surface of the crystalline lens. These images, known as *Purkinje-Sanson images*, are seen when an incident ray enters the eye obliquely. The first image formed by an incident ray (*IR* in *Fig. 42*) is reflected from the anterior surface of the cornea, the second from the posterior surface of the cornea, the third from the anterior surface of the lens and the fourth from the posterior surface of the lens. If a double light source is used, their appearance is as shown in *Fig. 43*. The second image is not visible because of its low brightness.

Attempts had been made to take a cine-film record of the changes in size of the third image whilst the subject looked at a cloudless sky, but with little success. In these unsuccessful experiments the images photographed were the images of the sun reflected from the anterior surface of the crystalline lens, the sunlight being reflected on to the eye by means of two small mirrors so that two images might be formed. The difficulties encountered were caused by three factors.

Firstly, the very bright and extensive sky caused the pupil to constrict considerably, so that difficulty was experienced in seeing the two images simultaneously on the surface of the subject's lens. Secondly, with no diaphragm or artificial pupil before the eye it was uncertain whether subjects could fixate sufficiently well to give reliable results (see pp. 98, 107). Thirdly, difficulty was introduced by the faintness of the image reflected from the anterior surface of the lens. This necessitated the use of both a fast film, with its concomitant large grain size and poorer resolution, and a wider camera stop than was permissible to retain the image in sharp focus on the film as it moved through different planes during the process of accommodation.

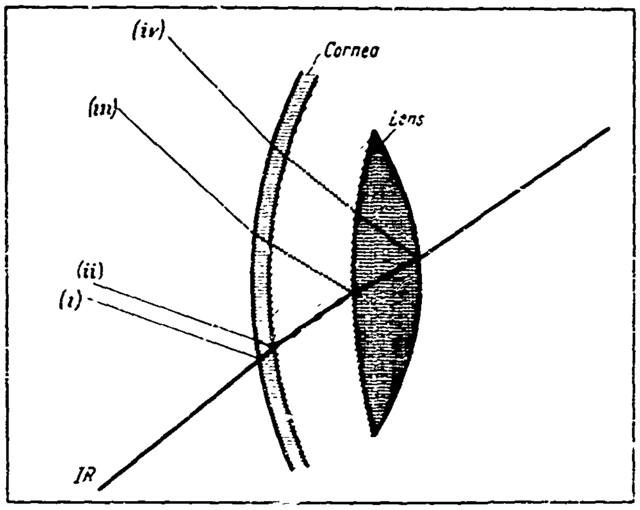


Fig. 42. Formation of Purkinje-Sanson images

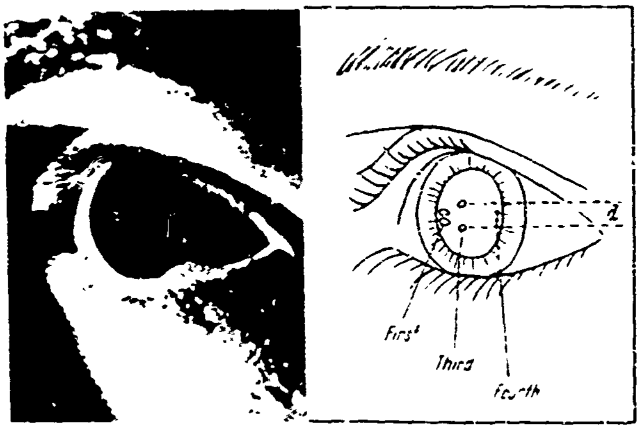


Fig. 43. Purkinje-Sanson images

In view of the difficulties in obtaining photographs of sufficient sharpness, the opportunity of carrying out this experiment in collaboration with F. W. Campbell and of applying his technique to the problem was particularly welcome. Campbell had previously carried out experiments on night myopia, taking photographs of the third Purkinje-Sanson image in darkness by means of an electronic flash tube.

The apparatus is shown in *Fig. 44*. The camera employed was a 35 mm. *Wrayflex* fitted with a 50 mm. *f* 2 lens and 50 mm. extension tube. Photographs were taken at an effective aperture of *f* 16. 45 exposures could be taken at 20 second intervals without reloading. The single lens reflex camera is essential to obtain the accurate focussing and aligning which the technique demands. The photographic light source was a 200-joule electronic flash tube placed three feet from the eye. To facilitate measuring the size of the reflected image the source was doubled by placing mirrors above and below the tube and a screen before it. For focussing purposes a 100-watt compact filament lamp was placed in front of the screen.

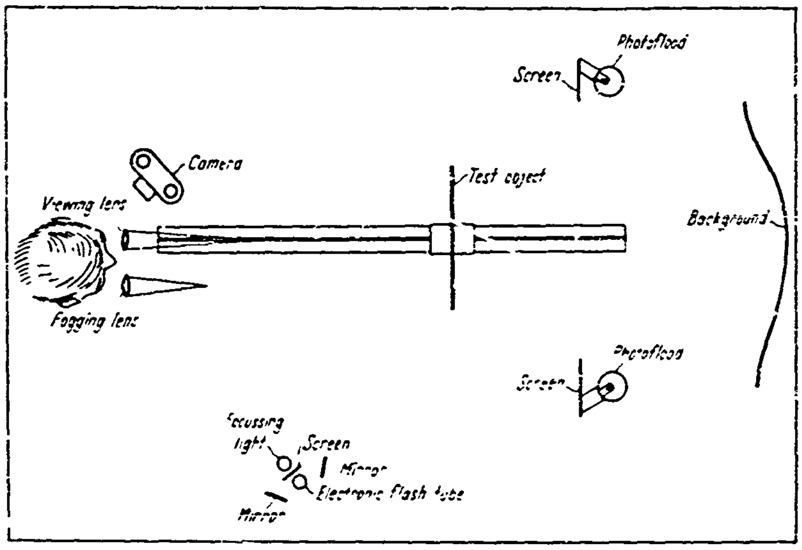


Fig. 44. Apparatus for photographing Purkinje-Sanson images

The size of the third image was measured directly on the negative by means of a travelling microscope. The size of the image was taken as the distance between the centres of the two reflections formed by the double light source on the anterior surface of the lens (*d* in *Fig. 43*). In other respects, the apparatus was similar to that already described, in that the same bright background, test object, and viewing lens were employed.

The purpose of this series of experiments was to observe the behaviour of accommodation when a small test object was gradually moved from near to far until, going out of focus, it finally disappeared from view.

The small test object was moved away in 2-cm. steps and at each step a photograph was taken, the time interval between photographs being 20 seconds.

Results—Five subjects were examined, but the results from subject F.W.C. were more consistent than those from the other four subjects. Since fixation is particularly important when taking these photographs with a view to subsequently measuring the size of the third image, the more consistent results from subject F.W.C. may be attributed to this subject's greater ability (by reason of experience) to maintain steady fixation during the course of the experiment. Since F.W.C. was myopic it was possible in his case to carry out the experiment with no lens in the apparatus. The results for subject F.W.C. are given in *Fig. 45* whilst those for the other subjects are shown in *Fig. 46*.

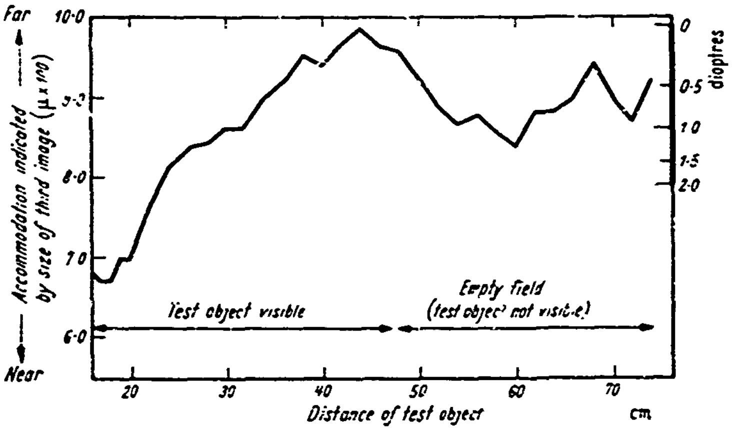


Fig. 45 Size of third image when viewing, (a) Test object, (b) Empty field

In *Fig. 45* the degree of accommodation is indicated by the size of the third Purkinje-Sanson image. An increase in the separation of the two images formed on the lens surface indicates diminishing accommodation. As would be expected, the maximum amount of accommodation was exerted when the test object was at its shortest distance from the eye. As the test receded, so the accommodation decreased, the minimum being reached in this case when the test was at a distance of 44 cm. from the eye. As the test moved still further, it went beyond the subject's far point, became blurred and finally disappeared. It will be seen that as the test disappeared, accommodation increased over a period of about one minute, after which the level of accommodation fluctuated although never again reaching the minimum value previously attained when the test was still visible.

Similar results were obtained on a further four subjects (*Fig. 46*).

ACCOMMODATION EXERTED INVOLUNTARILY IN AN EMPTY VISUAL FIELD

In every case it was found that when the test object disappeared, leaving the subject looking at an empty visual field, there was an involuntary increase in the degree of curvature of the crystalline lens, as indicated by a decrease in size of the third Purkinje-Sanson image.

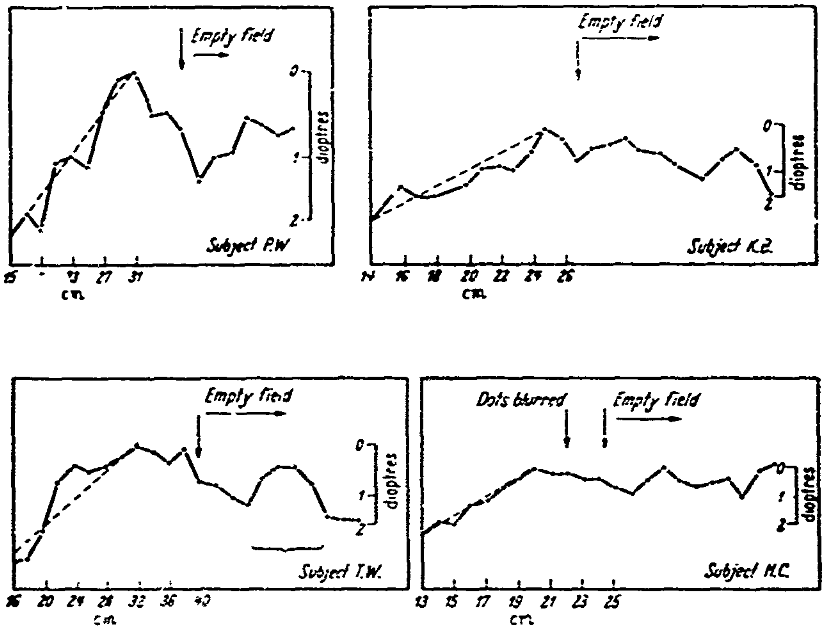


Fig. 46. Degree of accommodation in an empty visual field (4 subjects)

In the graph of results for subject T.W. (*Fig. 46*), at the point in brackets T.W. was attempting to achieve more complete relaxation by using convergence cues—with partial success.

Table 5. Accommodation in an empty visual field (5 subjects. Figures in dioptres)

Minimum	*Mean*	*Maximum*
0·07	0·26	0·40
0·41	0·68	1·32
0·15	0·63	1·22
0·26	0·48	0·88
0·05	0·39	0·71
Mean 0·19	0·49	0·91

For the purpose of calibration, the far point was taken as the position of the test object corresponding to the maximum size of the third Purkinje-Sanson image. This point was regarded as 0 dioptres of accommodation, and from it were found the points on the ascending curve in *Fig. 45* which corresponded to 0·5, 1, 1·5, and 2 dioptres of accommodation. Campbell had found in previous experiments that the size of the third image bore an approximately linear relationship to the accommodation from 0 to 2 dioptres. The calibration was therefore not carried out beyond 2 dioptres of accommodation. The accommodation exerted by the five subjects whilst observing the empty visual field is given in *Table 5.*

SUMMARY

In high altitude flight, just as the reversal of light distribution is the basic cause of difficulty in seeing inside the cockpit, so the frequent absence of cloud in the sky above the aircraft is the basic cause of difficulty in seeing outside the cockpit. The cloudless sky at high altitude is referred to as constituting an *empty visual field*, which is defined as a visual field in which there is no detail capable of being accurately focussed. Common examples of an empty visual field are: total darkness, fog, a uniformly overcast sky, a cloudless blue sky.

To examine the behaviour of accommodation in such an empty visual field it is not possible to employ the usual examining methods, since they usually provide the subject with a stimulus of detail which effectively prevents the visual field from being empty. There has therefore been devised a technique which consists in placing at various distances from the subject's eyes a test pattern of dots so small as to be visible only when they are sharply focussed. They are brought towards the subject's eyes, and are not seen until they come to the point at which he is focussed, whereupon they appear suddenly and clearly in the visual field. Since they are not seen before this, the field remains empty up to the instant of recognition.

A second and objective technique, measuring photographically the changes in curvature of the anterior surface of the crystalline lens, was also employed. It has the advantage of being an entirely objective technique, but has the disadvantage of requiring more elaborate apparatus and more accurate eye fixation on the part of the subject. It was therefore only employed in an experiment which confirmed the findings by the other technique.

It was shown that in the presence of an empty visual field, subjects cannot relax accommodation completely. Accommodation is shown to be in a state of constant activity fluctuating about a level of 0·5–2 dioptres, sometimes approaching the far point but never quite reaching it.

The subject with normal eyesight is thus unable to focus at infinity if there is no detail at infinity which is capable of being sharply focussed. Under these conditions, the furthest he can focus is a point about 1–2 metres away. He thus becomes effectively myopic by this amount. Attention is drawn to the similarity between this new phenomenon, and that known for some years under the name of ***night myopia.***

RATE OF RELAXATION OF ACCOMMODATION

Many investigators have made measurements of the speed of accommodation, but always from a near stimulus to a distant stimulus or *vice versa*. In this particular instance it was required to know how long it would take a subject, after looking at a near object, to relax his accommodation in an empty visual field to that level which is the minimum possible without the stimulus of detail at infinity.

It is possible to accommodate for near in the absence of a stimulus for accommodation; but it is probable that this may be accomplished by a voluntary convergence of the eyes, the relatively loose nervous linkage between convergence and accommodation causing, incidentally, some change in accommodation. When the subject has been given a near stimulus to focus, he may thus be able to keep accommodating voluntarily even after the near stimulus has been removed. When he has been presented with a collimated stimulus which has subsequently been removed, he can likewise increase his accommodation voluntarily.

What it was required to know, however, was: Firstly, with the stimulus near, and secondly, with the stimulus at the far point, how quickly would accommodation reach the 'resting level' which it had been found to assume in an empty visual field?

After the presentation of the near stimulus, the subject in this experiment therefore attempted to relax his accommodation as rapidly as possible, whereas after presentation of the stimulus at the far point, he attempted to remain focussed at the far point as long as possible.

EXPERIMENTS

Method A—Subjective technique (continuous recording)

By means of the apparatus already described (p. 72), and by employing kymographic recording, it was possible to obtain, on a time base, a measure of the changes in accommodation which took place after the momentary presentation of a stimulus on which to focus.

10 subjects took part in the experiment. The subject was instructed to look binocularly at a fixation point 15 cm. in front of the eyes. Whilst he did so a signal was made on the smoked drum. The subject then sat forward, put his head on the chin rest and searched the empty field for the small dot pattern. The level of accommodation was measured by bringing the small dot test plate into the field of view as already described. This procedure was repeated three times for each subject, after which a measurement was made of the far point, this being the

point at which the small dots disappeared as the test plate was moved beyond the subject's field of focus. The smoked trace was then calibrated as already described (p. 82).

The function of the viewing lens was to prevent the background from having visible texture and to bring the far point to a suitable working distance. In the case of one subject who was myopic, it was possible to dispense with this viewing lens, since even without it he could neither see the texture of the background nor any detail which was accidentally present. This subject took part in the experiment, first of all employing the viewing lens in the usual way and then repeating the experiment without any lens whatsoever in the apparatus.

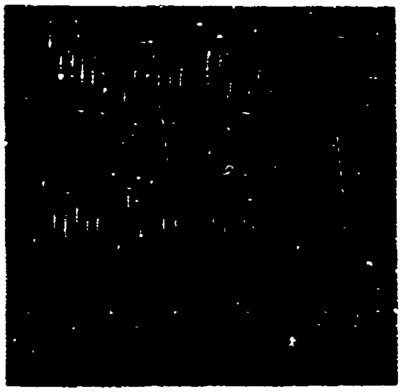


Fig. 47. The effect on accommodation of looking at a near object. (Myopic subject with correction)

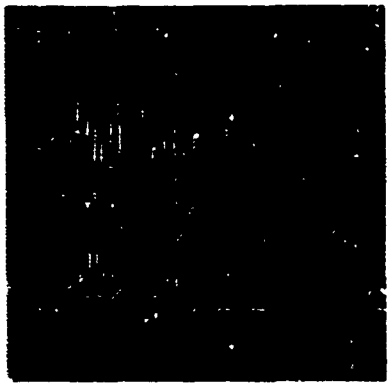


Fig. 48. The effect of accommodation of looking at a near object. (Myopic subject—no lens in apparatus

In a few instances a separate determination was made of the behaviour of accommodation after the subject had been presented with a stimulus at the far point as well as with a near stimulus. To do this, a special fixation stimulus was set up. It consisted of a piece of black painted *Perspex* through the black paint of which had been scratched the fixation pattern—a large cross. The *Perspex* was then illuminated from behind by means of a separate light, and the bright cross was seen with the left eye by partial reflection off a glass coverslip inclined at an angle of about 45 degrees to the line of sight. The arrangement of the apparatus was as shown in *Fig. 36.*

Results—Ten subjects were examined, and it was found that although an attempt was being made to relax accommodation to infinity a mean of 1·7 dioptres was being exerted within 10 seconds of looking at a point 12–18 inches away. Progressive relaxation took place until after about 45 seconds a mean of 1·16 dioptres was reached. Beyond this there was little improvement in relaxation. The majority of the subjects were slightly hypermetropic, the mean value of the far points being —0·06 dioptres (standard deviation 0·619).

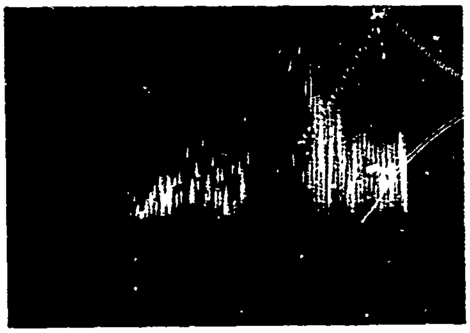


Fig. 49. Behaviour of accommodation after loss of (a) *a near,* (b) *a distant stimulus*

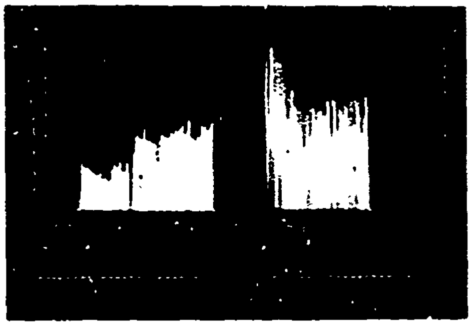


Fig. 50. Behaviour of accommodation after loss (a) *a near,* (b) *a distant stimulus*

Figs. 47 and *48* show the accommodation changes in the case of the myopic subject with and without viewing lens. It is seen that the involuntary accommodation in this subject is unaffected by the presence or absence of a lens in the apparatus.

The times required for accommodation to reach the resting level after the loss of a stimulus, (*a*) near the near point, and (*b*) at the far point, can be compared in *Figs. 49* and *50* in which it will be seen that the times are similar, being in both instances about 60 seconds.

Method B—Objective technique; photography of Purkinje-Sanson image
A cinematographic record of the changes in convexity of the anterior surface of the lens would have been useful since it would have enabled some 25 measurements to be made per second. Difficulties, caused essentially by insufficient light reflected from the anterior surface of the lens, prevented this technique from being used. Some preliminary experiments in the photography of Purkinje-Sanson images, however, afforded results which were interesting although not directly applicable to the present problem. These results, which relate to the time course of the accommodation change in looking from a near stimulus to a distant one and back to the near one, are shown in Appendix H.

The experiment already described (p. 87) in which photographs were taken at 20 second intervals, yielded information as to the rate of change of accommodation in an empty visual field.

Results—Looking again at *Fig. 45*, it will be seen that after reaching minimum value accommodation increased and that about 80 seconds after losing the stimulus it had reached its resting level. The increase of accommodation after reaching the minimum, actually began before the small dot test had disappeared—it will be suggested later that this effect is due to the blurred dots constituting an insufficient stimulus for the accommodation (see p. 133). Thus, although the small dots were still visible at the beginning of this 80-second period, the field could be regarded as being 'empty' by definition from the beginning of the involuntary increase in accommodation.

The accommodation exerted by each subject at selected times after loss of the accommodation stimulus was measured and is presented in *Table 6*. It is evident that after losing sight of the far point stimulus

Table 6. Accommodation exerted at different times after loss of the distant stimulus

Subject	*Time (seconds after loss of stimulus)*									*Mean accommodation*
	20	40	60	80	100	120	140	160	180	
FWC	0·27	0·07	0·19	0·15	0·40	0·31	0·40	0·15	0·40	0·26
PW	0·47	0·41	0·54	1·32	0·94	0·85	0·41	0·47	0·69	0·68
TW	0·20	0·44	0·15	0·64	0·79	1·04	1·22	0·64	0·51	0·63
KB	0·26	0·35	0·35	0·35	0·26	0·44	0·44	0·65	0·88	0·48
HC	0·21	0·21	0·41	0·41	0·56	0·71	0·6	0·41	0·56	0·39
Mean accommodation	0·282	0·356	0·328	0·574	0·59	0·67	0·494	0·464	0·608	0·49

subjects were unable to remain focussed at the far point, and involuntarily increased their accommodation by about 0·6 dioptres within 80 seconds.

SUMMARY

When a stimulus at the far point is suddenly removed, accommodation increases involuntarily until it reaches the resting level of about 0·5–1·0 dioptre. It is possible to increase accommodation voluntarily by causing the eyes to converge, but it is not possible to remain focussed at the far point if the stimulus there has disappeared. This experiment measures the rate at which accommodation assumes its resting level after loss of a stimulus at the far point and after looking at a near stimulus.

It is not possible to give rigid values, since the resting level of accommodation fluctuates between 0·5 and 2 dioptres; but, in general, the results show that after losing sight of both a near and a distant stimulus accommodation takes about 60 seconds to reach its resting value. After loss of the near stimulus, 60 seconds are required before relaxation can take place to the resting level. After loss of a distant stimulus, although the subject with normal eyesight tries to remain focussed at infinity his eyes inevitably focus at the resting level about 0·5–2 metres away within 60–80 seconds.

THE RELATION OF THE EFFECTIVENESS OF A STIMULUS AT THE FAR POINT TO ITS ANGULAR DISTANCE FROM THE FOVEA

WHEN there is no detail in the distant field of view which can be used as a reference point in the process of accommodation, it has been seen that it is not possible for accommodation to be relaxed to the far point. This means that the emmetrope becomes virtually myopic. If the stimulus of detail is present, it seems likely that the greatest improvement in relaxation of accommodation will be obtained if the stimulus is fixated so that its image falls on the fovea. The purpose of this experiment was to determine how near the line of sight a stimulus at the far point needed to be so as to prevent the onset of the involuntary accommodation exerted when viewing an empty visual field.

EXPERIMENT

The stimuli employed were bright circles which were viewed against the background of the test field. The advantage of employing circles was that the necessary fixation could thereby be achieved without having recourse to a fixation stimulus, since the subject fixated what he judged to be the centre of the circle. Four pieces of black painted *Perspex* were used, through the black paint of which the appropriate circles were scratched. The test in use was illuminated from behind and the bright circle was seen by partial reflection off a glass coverslip inclined at an angle of about 45° in front of the eye being tested. The circles were placed at the subject's far point which was 28 cm. from the viewing lens of focal length 25 cm.

The size of the circles was calculated so that they subtended angles of 2·5°, 5°, 7·5°, and 10°. When the centres of these circles were being fixated, the circumferences consequently made angles of 1·25°, 2·5°, 3·75°, and 5°, with the foveal line of sight. Although it was so small that it could have been neglected, the magnification due to the distance of the viewing lens from the eye was taken into account in calculating the size of the circles. Since the eye-to-lens distance was 3 cm., and the focal length of the viewing lens was 25 cm., the magnification was

$$\frac{1}{1 - dF} = \frac{1}{1 - 3/25} = 1{\cdot}136$$

The far point at which the circles were placed was 28 cm. from the lens, so the diameter of a circle subtending θ° was

$$\frac{28 \tan \theta}{1{\cdot}136}$$

ANGULAR DISTANCE BETWEEN STIMULUS AND FOVEA

Whilst the subject fixated the centre of a circle, the small dot test plate was brought slowly towards the eye until the small dots were recognised. The distance of the test plate from the lens was noted. Twenty measurements were made with each size of circle, and after each measurement the light illuminating the circle was switched off and a measurement made of the distance at which the small dots appeared when the field was empty.

Results—There was very little scatter in the results which were obtained from one subject who had taken part in a number of earlier experiments.

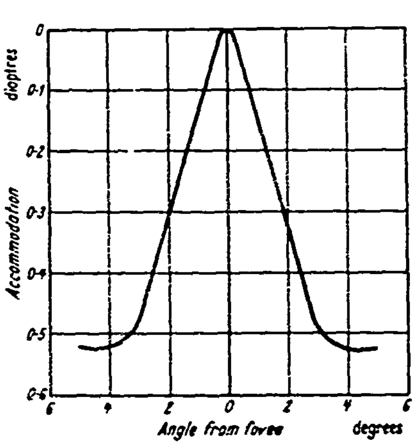


Fig. 51. The relation of effectiveness of a collimated stimulus to its angular distance from the fovea

This subject, a hypermetrope of 1·5 dioptres, had the particularly good fixation necessary for this experiment. It was therefore regarded as permissible to take the arithmetic mean of each group of 20 results for each size of circle employed. The far point at 28 cm. was regarded as zero dioptres of accommodation, and, by means of the calibration graph, results were calibrated in dioptres of accommodation. The results are shown in *Table 7*, and in graphical form in *Fig. 51*. It can be clearly seen that a distant stimulus of detail, making an angle of 4° or more with the fovea, constituted but a weak stimulus for the accommodation reflex.

Table 7

Angles from fovea	0	1·25	2·5°	3·75°	5°
Dioptres of minimum accommodation	0	0·19	0·41	0·528	0·526

SUMMARY

The presence in the field of view of a stimulus of detail which can be sharply focussed prevents the involuntary focussing for near, which takes place when the visual field is empty. The effectiveness of such a stimulus, however, depends on how near it is to the line of sight. When it is in the line of sight it is most effective, and beyond 2° from the line of sight it rapidly becomes less effective in making the subject focus at infinity. By the time it is at 5° from the line of sight it loses almost all its effect in making the subject focus at infinity.

COMPARISON OF THE EFFECTIVENESS OF SIX COLLIMATED PATTERNS IN BRINGING ABOUT ACCOMMODATION FOR INFINITY

HAVING found that involuntary accommodation caused an 'empty field myopia' of the order of 0·5 to 1·0 dioptre, it seemed that an effective means of overcoming it would be to place a collimated pattern in the subject's visual field. The purpose of this stimulus was not to bring about maximal relaxation of accommodation, since in the case of the hypermetrope this would result in the focussing of rays of light converging towards the eye. It was desired that the collimated stimulus should bring about an accurate focussing of parallel rays, so that the eye should thereby be accurately focussed at infinity.

Preliminary experiments had revealed that whilst all the collimated patterns tested made subjects focus near infinity, some patterns were apparently more effective than others in making the subjects focus accurately the parallel rays from optical infinity. This experiment was therefore carried out in order to determine whether the difference between collimated patterns was sufficiently great to be of practical importance. The variable measured was the range at which a distant target could be 'picked up' (detected) with the help of various collimated patterns superimposed on the search field.

EXPERIMENT

The technique employed was basically the subjective technique which has been already described (p. 75). Previously, however, accommodation had been measured by changing the vergence of light towards the eye. In the practical case of air-to-air search, however, the target is always at infinity. In this experiment, therefore, to simulate the practical case the tests were always presented at optical infinity and were increased in angular size from below threshold until they were finally recognised whilst still at infinity—the variable measured, being the angular size of the test when it was finally seen.

If, in such an experiment, the subject can see the test becoming gradually smaller, or if, whilst not yet seeing the test, he has a suitable collimated pattern to focus, the test becomes virtually a determination of the minimum visual angle. If, however, the subject is not focussed at infinity, as may occur when the field is empty, the angle subtended by the test when it is finally seen will no longer be the minimum visible but the angular size at which the out-of-focus image on the retina finally becomes a stimulus of which he is conscious.

With regard to the human eye, an object farther than 30 feet may be regarded as being at optical infinity (CAMPBELL and WEIR, 1953), so that in the case of air-to-air search a target is always at optical infinity its angular size alone changing with its distance from the observer. Since, in the modified technique, the test was always at infinity, it gave an answer which was more easily interpreted in terms of practical importance.

The apparatus is shown in *Fig. 36.* The inclined glass coverslip placed before the observing eye allowed the reflection of the collimated stimulus to be seen by the subject whilst he looked at the otherwise empty visual field.

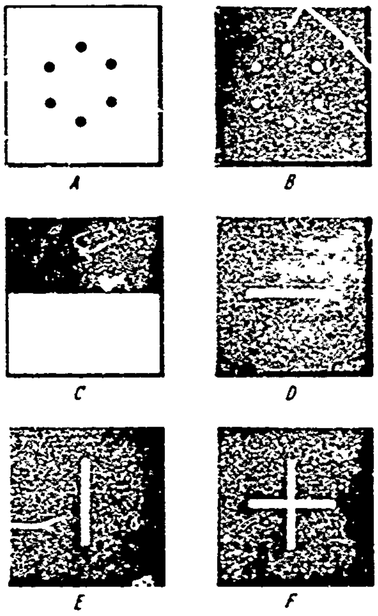


Fig. 52. The collimated fixation patterns

Six collimated fixation patterns were employed, one of which was a hexagon of black dots. The diameter of each dot in the hexagon was 1·5 mm. and the diameter of the hexagon was 25 mm. This pattern, being opaque, was placed in apposition to the small dot test plate and was therefore viewed directly. The other five patterns were transilluminated and seen only after partial reflection from the inclined coverslip. Of the five transilluminated patterns four were scratched on to black painted *Perspex.* The fifth was a piece of opal glass whose reflection, when superimposed on the test field, simulated a bright uniform cloud floor with a well defined horizon. These fixation patterns are shown diagrammatically in *Fig. 52.* A selection of biconvex lenses of focal lengths from 3 to 24 inches enabled the small dot test and the fixation pattern to be maintained at optical infinity whilst they were step by step brought nearer the subject.

After a short explanation of the purpose of the investigation the subject was given a familiarisation run so that he could recognise the small dots and be familiar with the direction from which they appeared. A lens of focal length 24 inches was then placed before the observing eye (the left eye in these experiments) and the small dot test plate was moved 24 inches away from the lens. It was thus collimated, since the rays from it, having passed through the lens, emerged parallel towards the eye. The angle subtended by the dots varied inversely as their distance from the lens, and, at 24 inches distance, this angle was always below threshold (less than 20 seconds of arc).

When the subject said that he did not see the small dots, the 24-inch lens was removed, a 20-inch focal length lens substituted, and the test dots and fixation pattern moved to 20 inches from the lens. Again the subject looked, and if he still did not see the dots the procedure was repeated, the distance always decreasing whilst the tests were maintained at infinity by means of the appropriate lens.

Each subject was tested with the empty visual field, that is, without a fixation pattern, and then with each of the six fixation patterns in turn. To eliminate the effects of learning and of familiarisation, 18 subjects were examined and a balanced order of presentation of the test was employed. The scores recorded when the small dots became visible were the distances in inches from the small dot test plate to the lens. A high score thus indicated a good performance whilst a low score indicated a poor performance. Nine subjects were tested with the empty field first, and nine with the fixation pattern presented first.

In some cases the subject did not see the entire pattern, or, having seen it, it alternately appeared and disappeared although in fact quite stationary. Unknown to the subject, it was therefore accepted as 'seen' only when at least 3 dots were continuously visible.

Results—The results for the 18 subjects are given in *Table 8*. On examination of the data by analysis of variance, it was found that the collimated pattern associated with the greatest pick-up distance was the hexagon of black dots superimposed on the small dot test plate. The fixation patterns, arranged in their order of usefulness in regard to procuring accurate focus at infinity, are as follows:

Black spot hexagon—*best*
Bright cross
Bright spot hexagon
Bright vertical bar
Bright horizontal bar
Bright simulated cloud floor and horizon—*worst.*

Most of the subjects reported that when the small dots appeared they did so quickly and suddenly. A few subjects, however, reported that the small dots appeared and disappeared in a fluctuating manner. When they were made larger they were seen with no fluctuation.

It is interesting to note that those who observed this fluctuation were usually those who derived little benefit from having a collimated pattern to look at. It may be that these people have a resting position of accommodation at about infinity. This resting position they would involuntarily assume when there was nothing to look at, as when they were viewing an empty visual field. On several occasions in the empty field experiment, subjects reported that they had momentarily seen the small dots as they began to look into the apparatus but that the small dots had immediately afterwards disappeared.

Table 8. Mean scores for each of the 6 tests, together with significance of the difference between these means

	Mean score	*Test A*	*Test F*	*Test B*	*Test E*	*Test D*	*Test C*
Test A	18·1		none	•	••	•••	•••
Test F	16·4	none		none	none	••	••
Test B	15·4	•	none		none	none	none
Test E	14·7	••	none	none		none	none
Test D	13·9	•••	••	none	none		none
Test C	13·8	•••	••	none	none	none	

• Significant difference at 5 per cent level; •• significant difference at 1 per cent level; ••• significant difference at 0·1 per cent level

SUMMARY

Some collimated patterns are more effective than others in making subjects focus accurately at infinity. Of six patterns tested, the best was a hexagon of large black dots. The remainder in order of effectiveness were:

A bright cross
A hexagon of large bright spots
A bright vertical bar
A bright horizontal bar.

The least effective was a bright simulated cloud floor. It seems in general that the most effective stimulus is that which approximates in shape and size to the target finally to be recognised.

THE EFFECT OF EMPTY FIELD MYOPIA UPON THE MINIMUM VISUAL ANGLE FOR A DISTANT TARGET

THE failure to focus at infinity does not necessarily imply failure to see clearly at infinity, for a small pupil which has the effect of increasing depth of focus of the eye may compensate sufficiently for inaccuracies in focussing. If, on the other hand, depth of focus does not compensate sufficiently for inaccurate focussing, a distant target, which when accurately focussed subtends the minimum visual angle, will no longer be seen when its retinal image becomes blurred. The angular size of that target will therefore have to be increased until the blurred retinal image becomes so large that it is capable of arousing attention and of initiating an accommodation reflex.

This experiment was designed to determine—in a large group of subjects—what reduction in distant acuity was thus caused by the involuntary accommodation made whilst viewing an empty visual field.

EXPERIMENTS

Method A—Normal accommodation

The apparatus employed has already been described and is shown in *Fig. 32.* As in the previous experiment, any one of 19 biconvex lenses of focal lengths from 3 to 24 inches could be placed before the eye which was presented with the test pattern. Each time a different lens was used, by adjusting the distance of the test pattern and fixation pattern from the lens it was possible to obtain a step-by-step change in the angular size of the test pattern dots, whilst maintaining them and the fixation pattern at optical infinity.

The fixation pattern employed in this series of observations was a hexagon of large black dots, which could be superimposed on the test pattern of small dots as shown in *Fig. 53.* This particular fixation pattern was employed since it had been found to be the most useful of six patterns with regard to procuring accurate focus for infinity (see p. 104). The diameter of each dot in the hexagon fixation pattern was 1·5 mm., and the diameter of the hexagon was 25 mm. The star-shaped small dot pattern, which will be referred to as the *test pattern*, has already been described. The diameter of each dot in this case was 0·06 mm. and the distance between dots was 3·5 mm.

The test consisted essentially in measuring the following three variables in each subject.

(*a*) The far point.
(*b*) The angular size of the collimated small dots when they were detected in an empty field.
(*c*) The threshold angular size of the collimated small dots when they were seen beside the large dot collimated fixation pattern.

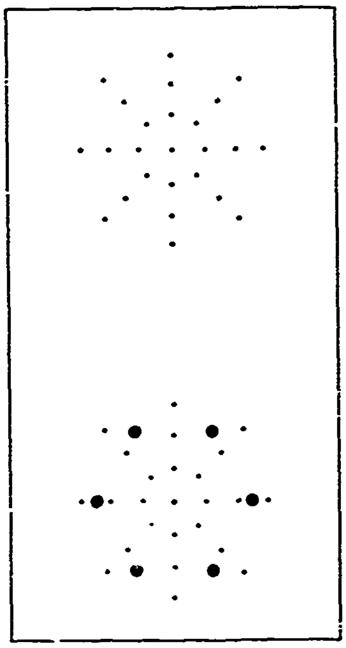


Fig. 53. The small dot test superimposed fixation pattern

Of the 63 subjects who took part in this test, 54 were pilots and 9 were either navigators or air gunners. A subject was first given the following instructions which were read to him:

Instructions to subjects: air-to-air search

> This test is in connection with the air-to-air search problem. As you know it is more difficult to pick up a target at high altitude than at lower altitudes, and this investigation is an attempt to find out why this is so. We are not in this test comparing your performance with that of anybody else, and the results which you score do not affect you personally, nor do they find their way on to your medical documents, whether you do well, badly or indifferently. None the less do your best. Now to the test:
> The target which you will try to see is a pattern of small black dots, arranged like that pattern on the wall over there. When you look into the apparatus try to imagine that you are looking into the sky and that you are in fact searching for a formation of aircraft—

> a formation which is dead ahead of you all the time and at the same altitude as you are. Sometimes I shall put up a hexagon of large black dots, similar to a gyro gun-sight pattern, and this is to help you look in the correct direction. With this large hexagon in position the pattern of small dots will appear in the centre of the hexagon, as I shall show you presently.
>
> When there is no pattern present, what you see represents in a way the sky at high altitude above all cloud and without any visible condensation trails to help.
>
> Forget that this test is taking place a short distance from you, and remember throughout the test always to look away in the distance as if you were searching in the sky.

A determination of the far point was then carried out as follows: Before the left eye, which in this series of tests was the one with which the test pattern was recognised, a positive lens of 10 inches focal length was placed, and at the focus of this lens the test pattern and fixation pattern were set up. When the subject reported that he could see the test pattern inside the hexagon of the fixation pattern, the test pattern, together with the superimposed fixation pattern, was moved slowly away from him until he reported that it had disappeared. The distance through which the test had moved was then noted. As this movement took the test pattern beyond the focus of the viewing lens, it resulted in rays converging towards the eye. Hypermetropes were therefore able to follow the test further out than emmetropes, although depth of focus and the angular size of the test pattern dots accounted for the fact that all subjects could tolerate some movement away of the test before it disappeared. In the far point determination the small dots subtended about 9 minutes of arc and were therefore well above the minimum visual angle. They disappeared because they became blurred. From this determination of far point, the real refraction was found by employing the calibration graph in *Fig. 38.*

When the far point determination was complete, the subject was presented either with the empty field or with the fixation pattern, and his task was to report when the small dots of the test pattern became visible. When the test pattern was being used without the fixation pattern, the subject was told that they would appear in the centre of the field, and the area was indicated before the test. The test was always started below threshold, that is, with the test pattern at its furthest from the subject.

In this experiment the test was binocular as in the practical case of air-to-air search. The recognition of the test pattern, however, was monocular. The subject was helped to look in the correct direction by being told that the test would appear in the centre of the diffraction ring caused by the 2·9 mm. artificial pupil.

With all subjects measurements were made of the distance at which the target was picked up (*a*) in an empty field, and (*b*) with the help of the collimated fixation pattern; but to cancel out the learning factor half the subjects were given the empty field test before the fixation pattern test and half were given the empty field test last. The order of presentation was changed after each subject.

Frequently the entire test pattern was not seen, particularly when it was near threshold; so unknown to the subject a 'seen' response was accepted if at least 3 dots were visible simultaneously and without fluctuations.

An indication of the subject's experience was obtained from the proforma reproduced below.

FLYING EXPERIENCE PROFORMA

Name
Rank
Squadron
Date

1. Controlled Interception Exercise: How many sorties of this type above 25,000 feet since 1/1/50?

By day ..... sorties
By night ...... sorties

2. Number of flying hours in fighter squadron since 1/1/50?

...... hours

3. Approximate total number of flying hours?

...... hours

4. Were you flying operationally between 1939–1946?

Yes No

5. Korea service: Number of operational sorties .....
Type of aircraft . .. .

Question 1 was an attempt to assess the number of high altitude sorties, because high altitude sorties are not usually designated as such in the log book entry.

Results—The experimental data are tabulated in the Appendix I. The distance at which the small test pattern dots were recognised in an empty field (subsequently referred to as *no stimulus distance*), was always less than that when the collimated fixation pattern was present (subsequently referred to as *with stimulus distance*). This latter was virtually a determination of the minimum visual angle, since the subject was accurately focussed at infinity. The means are given in *Table 9.* It was observed that in the majority of cases recognition of the test pattern in an empty visual field was a sudden process in that the hesitation which usually accompanies any determination of threshold was not present; either the test was seen or was not seen. When the fixation pattern was present, however, recognition was more gradual.

Table 9. Distance at which the collimated target is detected with and without the help of a superimposed collimated fixation pattern

	Mean	*Standard deviation*	*Range*
No stimulus distance	9·9	4·0	4·5–18·0
With stimulus distance	19·0	2·1	12·0–24·0

These distances are inversely proportional to the angle subtended by the target so, whilst they are measured in inches, they can equally be regarded as miles or any other unit of length.

The performance of each subject was expressed as a ratio of the *with stimulus* to the *no stimulus distance.* A high ratio thus represents a poor performance with a big reduction in range when the fixation pattern is removed. A low ratio indicates a good performance, the best possible ratio being 1·0 when there would be no reduction of range if the fixation pattern were removed. The mean value of this ratio for the 63 subjects was 2·21. The Standard Deviation was 0·82 and the range 1·11 to 4·00. This means that the minimum visual angle for a collimated, round, black target against a white background has to be increased

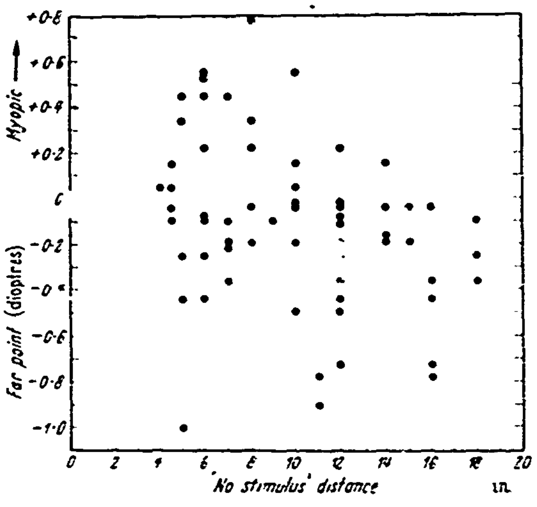


Fig. 54. Correlation of no stimulus to far point (see text)

by more than two times before the target is detected in an empty visual field.

The no stimulus and with stimulus distances (in inches) were found to correlate closely with the far point in dioptres (*Figs. 54* and *55*). Correlation coefficients were —0·33 and —0·55, significant at the 1 and 0·1 per cent levels respectively, showing thereby that hypermetropes searching in an empty visual field detected the target at a greater distance than did emmetropes or myopes. No correlation was found between the ratio of with stimulus : no stimulus and far point.

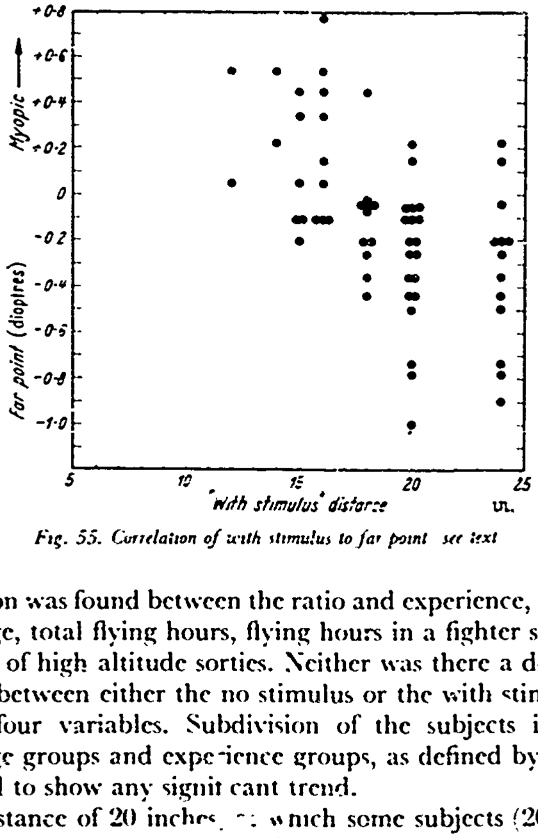


Fig. 55. Correlation of with stimulus to far point see text

No relation was found between the ratio and experience, as measured by either age, total flying hours, flying hours in a fighter squadron, or the number of high altitude sorties. Neither was there a demonstrable correlation between either the no stimulus or the with stimulus values and these four variables. Subdivision of the subjects into various arbitrary age groups and experience groups, as defined by total flying hours, failed to show any significant trend.

At the distance of 20 inches, at which some subjects (20 out of 63) recognised the test with the help of the collimated pattern, the small black dots each subtended an angle of 25 seconds. Other subjects, recognising the test at 24 inches, were recognising a black dot subtending 21 seconds of arc.

The order of presentation of the test seemed to make little difference, for when the no stimulus test was carried out immediately after the far point determination it had a mean value of 9·8 inches, and when it is given last it had a mean value of 10·0 inches.

Method B—Fixed accommodation

If a test object is not in focus, it becomes blurred and consequently more difficult to see; and, if it is so small as to subtend the minimum visual angle, the out-of-focus blurring causes it to disappear. For such a test object to remain visible its size has to be increased by varying amounts according to the degree of out-of-focus blurring which is present. The effects of inaccurate focussing are mitigated to a certain extent by depth of focus, as determined by the pupil size. It should be noted, however, that this experiment does not measure depth of focus which, in the usually accepted sense, is the range over which the power of the lens can be changed without producing noticeable blurring of the object focussed. The thresholds measured here were not at the level of 'most noticeable blurring' but at the other end of the scale, when the blurring was so marked that the small object could no longer be seen.

A cycloplegic was employed to fix accommodation and to enable known amounts of out-of-focus blurring of a collimated test object to be produced by the interposition of suitable spectacle lenses before the eye. The cycloplegic—hymatropine and cocaine guttae (at 2 per cent)—was instilled into the conjunctival sac at 20-minute intervals on three occasions, so that after 1 hour there was complete paralysis of the accommodation mechanism. A 2·9 mm. artificial pupil was used.

The small dot test object, which has already been described, was again employed. It was always presented at infinity, and its angular size was varied by employing collimating lenses of various focal lengths, the test object always being at the point of focus of the lens. The size of the collimated test could thus be increased step by step from below threshold until it became visible. Because of its bulk it was not possible to employ a 'zoom' lens: the zoom lens, frequently employed in television cameras, is a lens of continuously variable power by means of which continuous changes in angular size of the test object could have been obtained.

The out-of-focus blurring was produced by placing in front of the viewing eye both positive and negative spherical lenses which varied by steps of 0·25 dioptre. At each level of out-of-focus blurring there was measured the increase necessary in angular size of the test object to make it visible once more.

Results—In *Fig. 56,* dioptres of out-of-focus blurring were plotted against the increases in size which were necessary for the collimated test object to remain visible. The power of the blurring lens with which the test object was seen subtending the smallest angle was taken as corresponding to the optimum correction for the homatropinised eye. By means of that lens the image was presumably focussed as accurately as possible on the fovea centralis, so that increases or decreases in power of the blurring lens caused the image to fall in front of or behind the retina. This lens, which gave optimum correction, was therefore regarded as being zero dioptres; and, as in the experiment it was −2·5 dioptres, this was subtracted from all measurements, the abscissa being thus shifted so that zero dioptres blurring corresponded to the minimum visual angle.

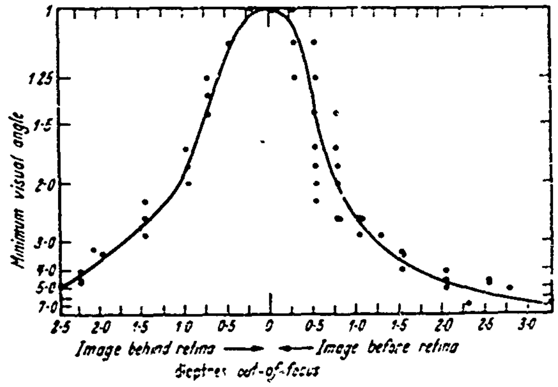


Fig. 56. The increase in size necessary for a small black object to remain visible in spite of out-of-focus blurring

Fig. 56 shows that when the subject was focussed accurately on the test object at zero dioptres, ±0·25 dioptre of blurring could be tolerated. When there was more than 0·25 dioptre of blurring, however, in order to be still visible the size of the test object had to be increased. The graph shows that a given amount of blurring, caused by the image falling in front of the retina, necessitated a greater increase in size of the test object than did the same amount of blurring caused by the image falling behind the retina. Thus, blurring increasing from ±0·3 to ±0·75 dioptre necessitated an increase in angular size of the test object of about 2 times. An equal amount of blurring, caused by the image falling behind the retina, necessitated an increase of only 1·5 times. The general form of the curve is thus seen to be skew.

The graph in *Fig. 56* clearly shows that if one considers that the extent of involuntary accommodation in an empty visual field is 0·5 dioptre, the angle subtended by a collimated test object of threshold size has to be increased by 1·5 times so that it may remain visible in spite of being out of focus. 0·75 dioptre of excessive accommodation requires that the size of a small test object be doubled. Thus on the basis of this experiment, it is to be expected that a pilot searching for a target aircraft in a cloudless sky would detect it at about half the distance at which he could detect it with the assistance of a stimulus at infinity such as a background of clouds or condensation trail.

SUMMARY

63 subjects took part in a test to determine the difference between pick-up ranges in a visual field with detail at infinity, and in an empty visual field. In basic terms, this was to determine what increase was necessary for a target subtending minimum visual angle to be still detectable in spite of the out-of-focus blurring caused by the involuntary accommodation exerted on looking at an empty visual field. It was found that a target had to come to half the distance, or in other words, it had to become twice as big before it could be detected in an empty visual field.

An experiment in which accommodation was paralysed showed that such an increase of two times is associated with an experimental 'myopia' of 0·75 dioptre. Thus the experiments confirm one another:

(*1*) In an empty field the lens has been shown to change convexity to an extent associated with 0·5 D. to about 1·0 dioptre.

(*2*) It has been shown that a small distant target has to be twice threshold size to be visible in an empty field.

(*3*) The findings of (*1*) and (*2*) above are linked in the finding that an increase of twice in the minimum visual angle is associated with 0·75 dioptre of 'myopia'.

No correlation was demonstrated between performance in search in an empty visual field and flying experience. A strong positive correlation exists between far point and

(*a*) minimum visual angle of a distant target;

(*b*) performance in search in an empty visual field.

Slightly long-sighted people are therefore better at search, both in an empty visual field and where detail is present, than are 'normal sighted' or short-sighted subjects.

V. DISCUSSION

GLARE

The visual problems associated with flight at high altitude fall into two groups: the problems of glare, due principally to the reversed light distribution, and those of air-to-air search, due principally to the empty visual field. In each case, the difficulties encountered are peculiar to flight at high altitude, and especially to flight in the stratosphere. Although there are problems of glare and of air-to-air search also at low altitudes, their origin is different and they do not give rise to the same effects as those encountered at high altitude.

One of the first indications of the existence of special visual problems at altitude was the frequently mentioned difficulty in reading instruments whilst flying towards the sun with the instrument panel in shadow. Difficulty is seeing instruments on an instrument panel in shadow is not a new problem, but at low altitude it is usually observed only when flying towards a sun which is low in the sky, as in the early morning or in the evening. At high altitude this difficulty was more often present and was, furthermore, observable at all times of day, irrespective of the altitude of the sun above the horizon.

It was known that, with increasing altitude, shadows became darker and sunlit areas became brighter, but what was frequently forgotten in the assessment from theory of changes in contrast between light and shade at different altitudes, was that a great deal of light is reflected up from below the aircraft. Layer clouds, constituting a uniform cloud floor, are not alone responsible for this reflected light, for, even on days on which the sky appears from the ground to be blue and cloudless, the lower layers of the atmosphere may contain a sufficient density of large scattering particles of moisture and of dust to reflect back an appreciable amount of light to the eyes of an aviator at high altitude.

During high altitude flight there is thus usually present a cloud floor which becomes more uniform and more extensive when seen from greater heights. At very high altitudes (40,000 feet upwards) one is looking at what is really the top of the layers of cloud and haze which give brightness to the sky seen from ground level. Thus there is usually much light coming from below—more than from the sky above—the effect being that of a reversal of the usual light distribution in the visual field.

The problems of glare at altitude have therefore a simple origin, but they are in practice complicated by the interplay of other factors which have to be taken into account in the assessment of the problem.

DISCUSSION

The reversed light distribution has two effects. The first, dealing with contrast and the illumination of shadows, can be assessed in physical terms The second, dealing with the effect of the altered light distribution on retinal sensitivity, has to be assessed in physiological terms.

CONTRAST MEASUREMENTS

The use of two methods in examining the light changes which took place at high altitude was necessary, since when the experiment was done there was no photometer immediately available which was sufficiently small to be used in the restricted space of the Meteor Mk. 7 cockpit and had a range sufficiently great to enable measurements to be carried out of the illumination of a surface in direct sunlight and then in shadow. The two methods employed, however—one measuring luminance of a white surface and the other measuring illumination of the instrument panel—can fortunately be compared since one was calibrated against the other. That the units in which the light measurements were recorded are not absolute units is a pity, since it would have presented a more complete picture; but it does not really interfere with the main purpose of this experiment, which was to determine the principles governing the illumination of shadow areas at high altitude.

The simplicity of the solution makes one wonder whether the experiment was really necessary. The existing literature on the subject, however, suggests that it was, since in no case is this theme of *reversed light distribution* fully investigated and commented upon.

The changes in illumination which take place with increase in altitude have been examined in the first chapter of Part II in which it was shown that the contrast between sunlight and shadow increases with altitude only if the shadow is not in line with a layer of cloud or haze from which it could receive much reflected light. With increase in altitude the horizon remains bright, whilst some 40° above the horizon the sky luminance decreases in direct proportion to the atmospheric pressure. The result of this decrease in sky luminance is that whilst all shadows which are not in line with the cloud floor below the aircraft become darker, this change is more marked for those shadows which are in line only with the areas of sky nearer the zenith.

A glance at the changes of atmospheric pressure with increase in altitude (*Fig. 57*) shows that the difference in pressure between, say, 30,000 and 40,000 feet is less than that between 20,000 and 30,000 feet. From this one deduces the next fact of importance, namely that the changes in sky brightness, and therefore the changes in contrast between light and shade, from 30,000 to 40,000 feet are less than those occurring between 20,000 and 30,000 feet. The differences in light intensity thus become progressively less for equal increases in altitude.

The increase in contrast between light and shade with increase in altitude is due principally to the shadows becoming darker, and not to the sunlit areas becoming brighter. It should be noted, however, that even outside the earth's atmosphere shadows will never become absolutely black, not only because they usually receive light from neighbouring illuminated areas but also because they receive some light from the dark sky, from stars, and, according to HULBERT (1948), from the interstellar dust which is responsible for the intrinsic luminance of the night sky. To a certain extent one can experience this peculiar light environment today, under the special conditions of high altitude flight at dusk or at dawn. Here one may be flying in sunlight, whilst below all may be dark. In these conditions, when flying towards the setting sun, the instrument panel receives light only from the twilight sky behind the aircraft.

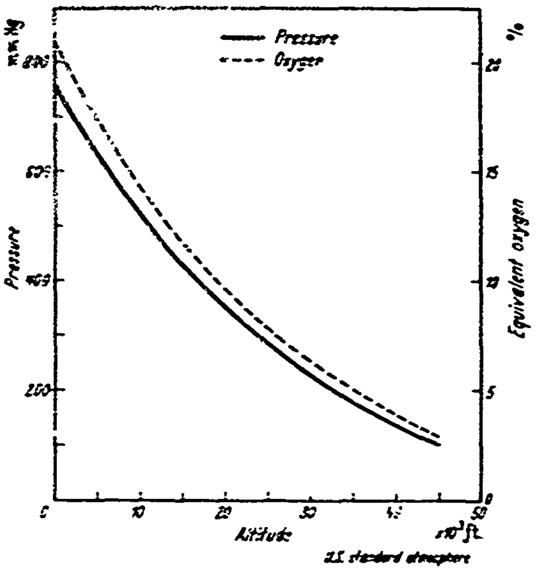


Fig. 57. Change of atmospheric pressure with altitude

A point calling for special attention is the finding that there was little or no increase in the luminance of sunlit areas at altitude. This result does not imply that the intensity of insolation or direct sunlight did not increase with altitude, since the measurements made were of the effect of *total* illumination on a vertical white surface—a surface which received light from direct sunlight as well as from sky scatter. The illumination derived from sky scatter decreased with increase in altitude, whereas that derived from direct sunlight increased, the two changes apparently balancing one another. That with increase in altitude the loss from one source should be so balanced by the increase from the other that the total illumination showed little change suggests such a remarkable effect of natural compensation that one is tempted

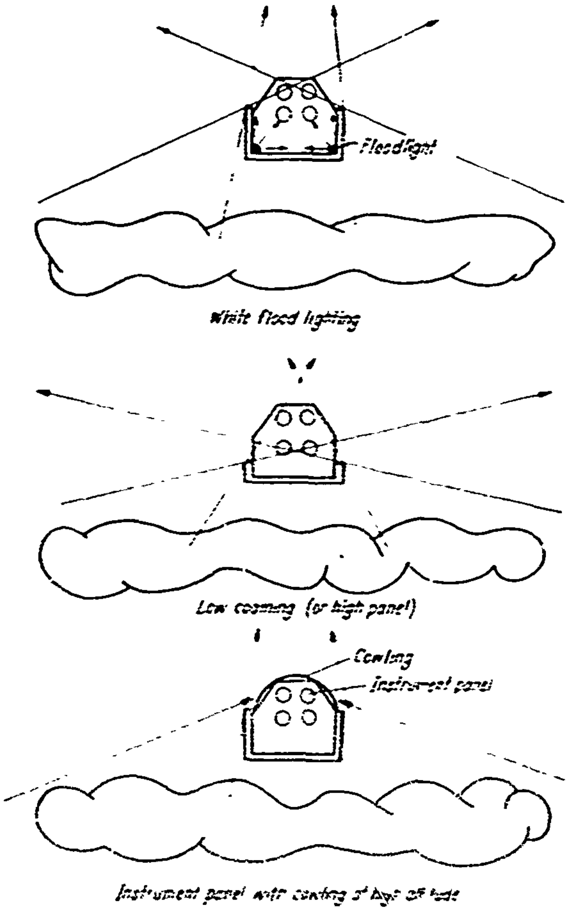
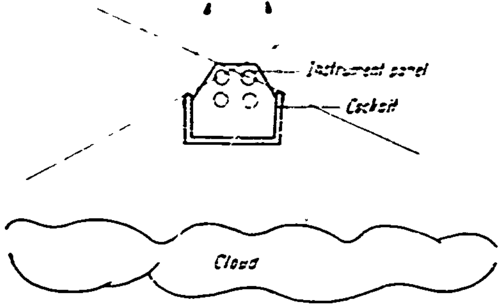


Fig. 58. Light distribution in the cockpit

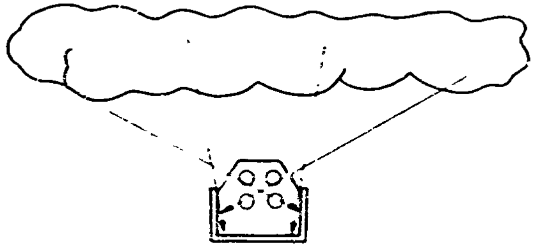
to extend the argument and to suggest that outside the earth's atmosphere the visible illumination from direct sunlight may well be of the same order as the total illumination received at lower altitudes from direct sunlight and from skylight.

The essential difference in the visible light coming from above on to a surface at high altitude is thus that the total light becomes more directional as the proportion due to sky scatter decreases.

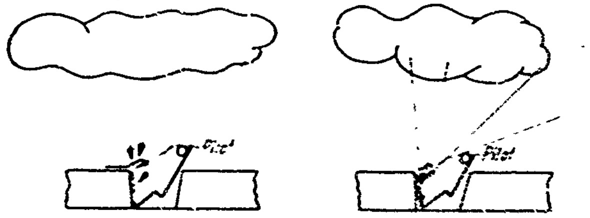
The principles governing illumination of a shadow area are shown in *Figs. 58* and *59* and can briefly be enunciated thus: If, at high altitude, a part of the cockpit is in such a position as to be subtended by a sufficiently large area in the hemisphere of 'sky' below the horizon, it will be sufficiently illuminated, even when in shadow, to enable instruments to be read. If it is subtended only by an area in the upper hemisphere of sky, its luminance when in shadow will vary inversely as the altitude above sea level. The effect will be more marked as the area of sky subtended approaches to the zenith. In such a case it will be necessary to make special provision for lighting the instrument panel in shadow. In all cases, however, the luminance of the instrument panel at high altitude would be increased by painting as much as possible of the interior of the cockpit, especially behind and at the pilot's side, in some light coloured paint, preferably a matt white



Light distribution at high altitude (Low cloud)



Light distribution at low altitude (Clouds above)



Instrument panel with cowling   Instrument panel without cowling
(Low altitude)

Fig. 53. Light distribution in the cockpit

which would diffusely reflect light on to an instrument panel in shadow whilst the aircraft was being flown towards the sun's quarter.

DISCOMFORT CAUSED BY GLARE

It might be expected that on teleological grounds there would be a difference in sensitivity between the upper and lower parts of the retina. No such difference in sensitivity has however been demonstrated, and one must consequently look elsewhere for an explanation of the discomfort caused by the reversed light distribution at high altitude.

The condition is, like most glare effects, due to the stimulation of the parafovea and periphery of the retina by light, which reduces the sensitivity of the unstimulated areas of the retina. This effect is accentuated if one is placed in an environment in which most of the light comes from below, because the lower part of the field of vision is not restricted like the upper part by orbital ridges and eyebrows. The position of the eye in relation to the bony structure of the forehead and cheek-bones is ideally suited to cope with excessive light which normally comes from above, at the same time allowing unhindered vision below; but when the light distribution is reversed, what was an advantage becomes a marked disadvantage since light floods unhindered into the eye from below. A much greater area of the retina is consequently stimulated by the cloud floor beneath the aircraft than is normally stimulated by the sky above.

A reversal of light distribution in this way is sometimes an advantage, as in the case of footlights on a stage, in preventing a performer from seeing the audience, but it causes a marked disadvantage in the air, and its effect may be accentuated by the adoption of a prone position from which the pilot is expected to fly, search sky and land an aircraft visually. By comparison, the adoption of a supine position, where visual flight is to be carried out, has marked advantages. The head does not need to be tilted backwards in order to see above the horizon, and similarly much of the lower field of view, if distressingly bright, can be cut off by having the head more in line with the supine trunk.

Whether it be due to neural interaction or to stray light within the eye, the depression in retinal sensitivity caused by the glare source in the periphery accentuates the effects due to the physical decrease in luminance of the shadow areas at high altitude. Not only is the pilot subjected to a glare source in the periphery of his field of view, but his central field of view is physically darker than it would be at lower altitudes. Thus, on all occasions when flying to a sufficiently high altitude and towards the sun, the instrument panel will become darker; and when there is a uniform cloud floor beneath the aircraft, the luminance of the instrument panel in shadow may be rendered subjectively even lower by reason of the depression in retinal sensitivity caused by a peripheral glare source of increased intensity.

The speed with which these changes in ambient light can occur contributes much towards producing discomfort, especially amongst the pilots of fighter aircraft who are liable to be subjected to the most rapid changes in altitude. Less than one minute after take-off they may be transported from an environment of light and shade normally encountered in Britain to one which is rather like a combination of glaring, polar, snow fields with tropical sunlight (see Author's note p. 127).

ANOXIA

The subjective haze effect which had been observed in the visual field at high altitude afforded much speculation as to its cause. There seems little doubt, however, that it was due to a depression in sensitivity of the retina caused principally by the greater extent and uniformity of the cloud floor when seen from high altitude. On subsequently looking into the darker cockpit, a large positive after-image of this cloud floor was seen to cover apparently the entire field of view.

This haze, however, persisted and the experiments carried out in the decompression chamber showed that the persistence was probably contributed to by the slight anoxia which was present during the flights at 40,000 feet with oxygen at ambient pressure. Employing the oxygen regulator on its highest setting for use at heights above 25,000 feet, the sitting subject at 40,000 feet is known to be under the conditions of mild oxygen deprivation such as would exist in breathing normal air at 10,000 feet altitude (BRINK, 1944).

Whilst it is known that the effects of oxygen lack on scotopic vision are evident at as low an altitude as 4,000 feet, it is generally accepted that changes in photopic vision take place only in marked anoxia. It was therefore particularly interesting to find evidence of such changes in the visual system at as low a simulated altitude as 5,000 feet.

Earlier it had been suggested that the haze effect might be due to a persistent positive after-image of the bright cloud floor. Experiment has shown that such a positive after-image, seen in darkness, would indeed last longer in anoxia. Just as in scotopic vision the recovery of retinal sensitivity is prolonged in anoxia, so in photopic vision the longer duration of the after-image suggests a similar effect.

The longer recovery time after dazzle thus seems to be a symptom which appears in *slight* oxygen deficiency; whilst on the other hand the general depression of retinal sensitivity, as evidenced by the common observation of darkening of the visual field, seems to take place only when the degree of anoxia is already marked.

The experiment on the recovery time from light-adaptation during decompression (*Fig. 24*) shows a shortening of recovery times occurring between 25,000 and 35,000 feet. At 25,000 feet the flow-meter was switched on to high flow of oxygen, but the improvement actually took place before this change in flow was made.

Grandjean (1948), carrying out tests on several functions of the central nervous system at about 10,500 feet on the Jungfraujoch, found that, compared with the threshold at 2,500 feet, there was at altitude a lowering of threshold, which disappeared after the administration of 100 per cent oxygen and reappeared when the oxygen administration was stopped. He points out that the reason other investigators were unable to demonstrate a similar effect in experiments carried out in the decompression chamber is that subjects were given insufficient time in the lowered oxygen environment before being subjected to tests. He found, on repeating the tests in the laboratory under low oxygen tension (13·5 per cent), that the lowering of threshold of cutaneous sensitivity was detectable only after 15 minutes, and increase in amplitude of the patellar reflex was demonstrable only after 45 minutes.

It seems as though the effect on diminished recovery time which was observed in the present experiment in the decompression chamber, is similar to that observed by Grandjean. It will be noted that in this experiment the time taken to reach 40,000 feet was 45 minutes, the whole experiment lasting 90 minutes. On the other hand the results obtained could be, at least in part, due to the failure to control pupil size during the experiment.

The changes in pupil size with anoxia do not show a definite or consistent response. **Duguet** and **Mercier** (1952), in an investigation of the changes in pupillary area during anoxia, found that the pupil paradoxically tends to dilate in light, whereas in the dark it tends to constrict. Their findings (in percentages) were as follows:

	Darkness	*Light*
Dilatation	27·7	50·0
Contraction	55·5	18·8
No reaction	16·8	31·2

It is thus difficult to predict what pupillary changes would take place in this experiment but, on the basis of the work of Duguet and Mercier, it would be more likely that a dilatation would take place whilst undergoing light-adaptation and that a constriction would take place whilst the subject sat in darkness waiting for the adaptometer to become visible. In both of these cases the effect would be to prolong the recovery time. The increased recovery time at 40,000 feet might thereby be explained, but not the diminished recovery time between 25,000 and 35,000 feet.

In the experiment on the duration of the positive after-image in anoxia, pupil size was controlled; therefore in this case the longer duration of the after-image is attributable either directly to anoxia or to some general change taking place as a result of anoxia.

Eigenlicht

To refer to the sensation of light which arises spontaneously in the absence of a physical stimulus of light as 'intrinsic light of the retina' is rather begging the question, since it is not known whether the origin is central or peripheral. The term 'eigenlicht' (own light) is thus more suitable. In the case of the light sensation occurring as a result of pressure ischaemia, the sensation must have a peripheral origin; but in the case of the light sensation occurring either spontaneously or as a result of anoxia, the origin of the sensation has never been ascertained.

The observations of the eigenlicht in anoxia were carried out in order to determine whether, by preventing the test from being clearly seen, eigenlicht was a factor contributing towards the longer recovery time from dazzle in anoxia. It was found that the sensation of light did increase with anoxia, the effect being visible at 10,000 feet. On supplying 100 per cent oxygen after a period of about 5 minutes at 20,000 feet without oxygen, the sensation of light increased greatly within a few seconds, lasted about 10 seconds and then gradually decreased.

When these changes are examined in detail it seems that their origin is more likely to be retinal than cerebral. The most striking feature is the similarity to the light sensation occurring when pressure is applied to the eyes so as to produce retinal ischaemia. The similarity in the two conditions can be seen by reference to *Figs. 25* and *26*.

LATHAM (1951), in an investigation of the oxygen paradox, concluded that the changes occurring within 12 seconds of administration of oxygen after a period of anoxia were due predominantly to a disturbance of the central nervous system—possibly as a result of momentarily increased cerebral anoxia caused by the fall in blood pressure which follows upon the readmission of oxygen. This fall in blood pressure is apparently associated with a reflex vasodilatation and consequent increased peripheral blood flow beginning 2–4 seconds after the return of oxygen and having its maximum effect in about 30 seconds. On this basis the visual effects could be explained in terms of the increased retinal blood flow alone.

The picture presented by the retinal ischaemia differs from that due to anoxia only in the central area of the retina. This clears before the periphery in the recovery from anoxia, and after the periphery in the recovery from pressure ischaemia. This difference might be explained by the different mechanisms by which the normal blood supply is resumed.

On readmission of oxygen after anoxia, the vasodilatation affects all the small vessels simultaneously, so that the central area of the retina with its very small blood vessels would receive its augmented blood supply at the same time as the peripheral retina. On the other hand, when pressure is released from compressed blood vessels, recovery will take place along the course of the blood vessels, the central area being therefore affected after the periphery. It will be seen that it is thus unnecessary to invoke cerebral changes to explain the sensation of light occurring in the recovery from anoxia, but one cannot state that cerebral changes play no part in the phenomenon. In fact, the findings of NOELL and CHINN (1950) that anoxia affects first the cortex, then ganglion cells, bipolar cells, and lastly the photoreceptors, renders more likely the possibility that during the onset of anoxia at least some of the light sensation observed may be of cerebral origin.

It is therefore concluded that the origin of the sensation of light occurring spontaneously in anoxia may be either retinal or cerebral or both. The sensation of light on readmission of oxygen, however, is more likely to be of purely retinal origin. The subjective light, whilst possibly having a visible effect upon photopic vision, is more likely to be of importance only in scotopic vision where its presence in the visual field would interfere with the visibility of a threshold source by subjectively reducing the contrast between that source and its background. It might thus be a factor contributing to the raising of the absolute threshold to light during anoxia.

Colour Vision

During the high altitude flights it had been noticed that, along with the appearance of haze in the visual field, colours appeared to be desaturated. One had the impression of not being so conscious of colours as at lower altitudes, and such colours as were visible seemed to be more blue than they would have been at lower altitudes. On one of the high altitude flights, tests carried out with Ishihara plates revealed no abnormality of colour vision.

In retrospect, the effect seems to have been due to the lowered retinal sensitivity caused by the bright outside scene and by the slight oxygen deficit at 40,000 feet. The description 'cold', employed by artists in reference to colours, describes precisely the altered appearance of colours at high altitude. Colours are referred to as 'warm' when they contain more red than others with which they are being compared, and they are referred to as being 'colder' when they contain more blue. It has been observed that when retinal sensitivity has been lowered by light-adaptation, all colours in the visual field become 'colder'. This difference, which is dependent upon the colour temperature of the adapting light, seems to be a useful and sensitive test for determining differences in adaptation between the two eyes.

Haze Cutting Filters

An interesting effect observed during the tests carried out with the 'minus blue' amber coloured filter was the apparent improvement in the visibility of clouds. This improvement was entirely subjective in that it could not be demonstrated, for when a wisp of cloud just visible through the filter was again sought, but without the aid of the filter, [illegible] just as clearly as it had been through the filter.

Claims have frequently been put forward by the manufacturers of sunglasses that their product is effective in 'cutting haze' by absorbing the scattered blue of haze and thereby improving contrast and the visibility of distant objects. These claims have never been substantiated, and, in an investigation on such claims, VERPLANCK (1947) concluded that there was no improvement in the discrimination of neutral coloured targets at a distance of about 4 miles when these were viewed through so called 'haze cutting' as well as through other coloured and neutral filters.

Viewing a coloured target against a coloured background, however, it is possible to improve contrast and therefore visibility by looking through a filter which transmits the lighter colour and is opaque to the darker colour. Thus, the contrast of a yellow object against a blue sea may be improved by looking at it through a yellow filter which is opaque to blue and therefore makes the sea appear darker. By looking through such a filter, brightness contrast is increased but colour contrast is lost; and, if there are white crests on the waves, the loss of colour contrast between the white crests and the yellow target will be much greater than the advantage gained by the slight increase in contrast between the yellow target and its background.

The improved visibility of clouds, when viewed through the amber filter, is probably due to an increase in contrast between the yellowish clouds and their background of blue sky. The wisps of haze, being less yellow, would not show the same increase in contrast. During a flight at 40,000 feet on a rare occasion on which there was no cloud below the aircraft and very little haze, the author, who was wearing red dark-adaptation goggles, found that he could see at once the entire Belgian coast as far as Holland, the French coast as far as Le Havre, and the entire Thames estuary—a radius of visibility of about 120 miles. When the goggles were removed, it was not possible to see nearly so much of the Continental coast. The effect was attributed to the red goggles, which on this rare occasion gave an advantage by making the sea appear black and the yellow sandy coastline appear brighter.

As one leaves the atmosphere below, the sky becomes progressively darker and one would expect stars to be easily seen. Their visibility, however, will always be impaired because of the high contrast between dark sky and sunlit areas of the cabin unless special design can prevent direct sunlight from reaching the interior of the cabin or from illuminating nearby external objects in the field of view. Difficulties surmountable by careful design may also be caused by light reflections off the inner surfaces of the windows.

The difficulty in seeing stars during flight at very high altitude or outside the atmosphere can thus be likened to the difficulty in seeing stars at night when looking through the window of a brightly lit room (CIBIS, P. A., 1952, deals in greater detail with the problems of visual contrast in flight). T.C.D.W.

SEARCH

EMPTY FIELD MYOPIA

THE investigation of the problems of vision at high altitude has uncovered the fact that many of the difficulties encountered are caused by the absence of visible detail in the visual field outside the aircraft. Clouds below the aircraft may not always be visible, particularly if the aircraft is far above the cloud floor or if the pilot is sitting low in his seat. Whilst searching the sky for another aircraft there is thus frequently nothing in the distance on which the eyes can focus. In the absence of detail in the sky it also becomes difficult to scan in a regular pattern as is normally done. This type of visual field, which thus takes on a new importance by virtue of the frequency with which it is encountered at high altitude, has been called an *empty visual field.* This term purposely does not specify the luminance of the field but merely refers to a visual field in which there is no detail sufficiently sharp to constitute a stimulus for the accommodation mechanism.

The most striking effect associated with vision in an empty visual field is the involuntary increase in the power of accommodation which takes place in spite of a subject's attempt to relax accommodation to infinity. The effect of this change is that the emmetrope, searching in an empty visual field, becomes virtually myopic.

By varying the brightness and the contrast of a test object, LUCKEISH and MOSS (1940), employing a subjective technique, demonstrated a change similar to that which has been found in these experiments. They found, furthermore, that it occurred when the visual axes were parallel as for infinity. The significance of their findings, however, does not seem to have been generally realised.

In the course of the present experiments it was found that when the subjects were presented with an empty visual field they exerted, on an average, about 0·5 dioptre of accommodation. The conditions under which this *empty field myopia* shows itself are similar to those which give rise to the phenomenon of *night myopia.* In the latter case the empty field, which is necessary to give rise to the condition, is produced either by the total absence of light or by a reduction of light to a level sufficiently low to prevent visible detail from acting as an accommodation stimulus.

In both these conditions there is thus a similar response to lack of a stimulus—so much so that one is led to the conclusion that there is a common physiological basis for the refractive changes which occur under both photopic and scotopic conditions.

The empty field myopia occurring by day has never before been described. In the case of night myopia, however, it has been known since 1883 that vision in twilight can be improved by placing before the eyes negative spectacle lenses. This phenomenon has been independently rediscovered on several occasions, and the extensive literature on the subject has been reviewed by KNOLL (1952) and by O'BRIEN (1953). The opinion generally held today is that the total effect of night myopia is contributed to by spherical aberration, by chromatic aberration and by an accommodation change. There are fairly large variations in the estimations of the extent of night myopia by various authors, but it seems to be generally regarded as being between 1 and 1·5 dioptres.

The change in illumination from high to low involves a shift in spectral sensitivity from cone to rod vision. The effect of this change, acting in conjunction with chromatic aberration of the eye, is to cause the eye to become virtually myopic by about 0·5 dioptre. WALD and GRIFFIN (1947) estimated that chromatic aberration would account for 0·4 dioptre of myopia.

As seen from the work of IVANOFF (1947), the extent and the type of spherical aberration can vary greatly between individuals. There is little doubt, however, that under scotopic conditions, when the wider pupil exposes the outer zones of the lens for which the focal length is less than for paraxial rays, there results an effect which can account for about 0·5 dioptre of the total night myopia.

In the present instance the interest lies mainly in the third condition, namely the change in refractive power of the lens. Most of the work on this aspect of night myopia was carried out originally by Otero and his collaborators. By employing a flash technique of photographing Purkinje-Sanson images from the anterior surface of the lens, they made measurements of the refractive changes occurring in the lens in darkness. OTERO (1951) concluded that 1·25 dioptres of accommodation was involuntarily exerted by the eye in darkness.

The most obvious criticisms which can be levelled at the experimental findings of involuntary accommodation exerted whilst searching an empty visual field are these: Firstly, it is not a special effect due to the empty field, since it is common knowledge that most people, on looking into an apparatus containing a lens, accommodate involuntarily from the knowledge that the objects they are looking at are near. Secondly, it may be said that what has been determined in the laboratory may not apply in the field.

The first of these is a criticism frequently levelled, and the example cited is the strong negative setting which students unaccustomed to the use of the microscope select in focussing that instrument. The accommodation, of which this is evidence, is however, not caused by the knowledge of the nearness of the object, because when viewing distant objects by binoculars a similar negative setting has been found to be the most comfortable (**Wald** and **Griffin**, 1947). The findings of Wald and Griffin refer principally to the setting of binoculars at night, but to a lesser extent there is a similar trend in the optimum setting by day. Now, as already pointed out, the usual practice in focussing binoculars is to observe the distant object directly and then to raise the binoculars to the eyes, adjusting the focus so that no obvious accommodation change should take place when changing over from direct viewing. The tests by Griffin and Wald may not have been purely of the optimum setting, since the setting obtained may have been influenced in this way by previous training. It would thus seem that, if anything, still more negative settings would have been obtained under conditions in which subjects were not permitted to view the distant objects by naked eye.

One can therefore see that the first criticism consists of two distinct parts which are sometimes mistakenly believed to be dependent upon one another. The tendency to accommodate when looking through a lens system shows itself only in the selection of a negative setting, when the focussing system of the apparatus is a variable one. That such a change in accommodation does take place under these circumstances is undisputed, but, whereas the critics make this accommodation change the primary cause, the evidence of experiment and observation shows that it is merely the effect, the primary cause being the involuntary accommodation adopted in the absence of a stimulus for the accommodation mechanism. This tendency to accommodate, though put forward as a criticism, is thus rather a point in support of the findings since it indicates that the accommodation mechanism takes up a position of rest not only in the absence of a stimulus but also when that position can be adopted without detriment to the sharpness of the retinal image.

There is no direct evidence that the knowledge of the stimulus being near is not a factor responsible for the involuntary accommodation. However since this involuntary accommodation has been found to be present in the viewing of distant objects (night myopia and binocular settings) it can be but a contributory factor at the most. Even so, if it does indeed contribute, its effect is likely to be very slight in these experiments, because the extent of the refractive change in day myopia was found to be of the same order as that occurring in night myopia whilst viewing distant objects. The knowledge of the distance of the test object could hardly be responsible for the failure of the myope to relax completely in the absence of any lens or correction before his eyes.

A further point of criticism is that the failure of the myope to relax accommodation completely, when viewing the test object directly without intervening lenses, might have been caused by convergence and the associated accommodation link. The test, however, was presented monocularly; and, furthermore, the experiments of **Luckeish** and **Moss** (1940) show that some involuntary accommodation took place even when the visual axes were parallel.

The linkage between accommodation and convergence would lead one to believe that the adoption of the resting position by the accommodation mechanism would be accompanied by a convergence of about 1 prism dioptre. Experiments using the small dot technique showed that when the eyes are allowed to relax in the way referred to as 'gazing into space'—as when one is tired—accommodation goes to the resting position. It seems likely that this resting position of accommodation would be adopted in anoxia too; and in this connection it is interesting to note that **Neely** (1953) found that in anoxia there was a tendency for the visual axes to converge as would be expected if accommodation were increasing. He found that in anoxia exophores improved, the exophoria disappearing and the visual axes becoming more parallel. Esophoria, on the other hand, became more marked, causing the subjects to suffer from diplopia. There is thus a tendency for the visual axes to converge irrespective of whether they are, or tend to be, divergent, parallel or convergent.

Although it does detract from the completeness of the investigation, the failure to demonstrate involuntary accommodation in a field experiment is not a serious failure, since data on the reduction of pick-up ranges in air-to-air search at high altitudes amount to a confirmation in the field of the experiment carried out in the laboratory. In practice it is found at high altitude that the range at which the target aircraft is detected is, in general, about half the range at which the same target can be detected at low altitude.

NATURE OF ACCOMMODATION MECHANISM

It thus appears that, irrespective of whether the environment be bright or dark, an involuntary accommodation occurs if there is no visible detail which can be sharply focussed. The accommodation mechanism, in other words, adopts a position of 'physiological rest'.

It has been shown independently by **Fincham** (1951), and by **Campbell** and **Primrose** (1952), that the stimulus for the accommodation reflex is one involving cones. In the absence of such a stimulus it is not possible for the accommodation mechanism to relax completely, which in the case of the emmetrope would be for a focus at infinity.

The nature of the accommodation stimulus itself is, however, not clear. Fincham, for example, suggests that his findings are in favour of a mechanism which usually depends upon the detection of chromatic fringes in order to assess whether accommodation has to be relaxed or increased in order to focus an object. The writer, in fact, has been a subject for Mr. Fincham in this type of experiment and has experienced this difficulty in focussing a test object illuminated by monochromatic light, whilst no difficulty was experienced when the same test object was illuminated by polychromatic light of the same spectral hue. Some of his subjects apparently do not rely on this process, since they are able to focus targets without regard to whether the light illuminating the target is monochromatic or polychromatic but of an identical hue. This group of subjects, Fincham says, obtain a clue as to the direction in which the accommodation change must take place, so as to focus the target by small involuntary scanning movements of the eye. It is difficult to believe that the eye could detect the small changes in graduation and in distribution of colours round a focussed image and interpret them correctly without hesitation so as to determine in which direction the correction has to be made to bring the image to a sharp focus. If one sets up a small screen on an optical bench and focusses an image of a black object on to this screen by means of a simple lens, chromatic fringes are obvious; but if the object is placed out of focus, looking at the appearance of the chromatic fringe upon the screen gives no indication as to whether the image is falling in front of or behind the screen.

Fincham's other hypothesis—that of the part played by eye movements—is supported by the personal impressions gained during the course of the investigations on accommodation. It was noted that the small dot test sometimes became visible at an apparently greater distance if one deliberately scanned slightly from side to side.

In *Figs. 40* and *41* it is seen that accommodation fluctuates about the resting level. Small fluctuations are seen superimposed upon much larger fluctuations occurring at about one minute intervals. These larger and slower fluctuations, which occur in an empty field, are probably of little use in determining in which direction to change accommodation so as to focus an out-of-focus object with little delay. ARNULF (1951), however, has demonstrated small fluctuations of the order of 0·1 dioptre, occurring very rapidly. These fluctuations, which are normally present, would not be seen on the optometer employed by Fincham since they are of such a small order; but there seems to be no reason why they should not afford the clues necessary to bring to a sharp focus an out-of-focus retinal image.

Further evidence of the existence of micro-fluctuations is afforded by the comments of HELMHOLTZ on the appearance of concentric circles when these were observed monocularly at reading distance. Some parts of the circle appeared darker, the darker lines together forming a diabolo shape. Helmholtz pointed out that this was evidence of the effect of astigmatism on accommodation. On re-investigation it was personally noted that this diabolo was seldom stationary. It moved now in one direction, now in another, giving an effect similar to that obtained when observing a rapid-moving spoked wheel with an inaccurately tuned stroboscope. The diabolo appearance is due to astigmatism, so the movement of the diabolo can be regarded as evidence of fluctuation of accommodation

Two further observations were made which support the view that the movements of this diabolo were due to changes in accommodation. The first is that when the circles were observed through a stenopoeic disc, which introduces great depth of focus, the apparent movement ceased. The second is that when a − 2 D. cylinder was placed before the eye, the diabolo was much more easily seen and was fixed in the axis of the cylinder. When a marked accommodation effort was then made, the diabolo was seen to move rapidly through 90°, remaining stationary in its new position as long as accommodation was maintained.

In the course of the experiments with the small dot test, fluctuations in the visibility of the receding test were often noticed before it eventually disappeared. In the cases in which the target was being increased in size whilst being maintained at infinity, similar fluctuations in its visibility usually took place before it was clearly seen. This effect was noted particularly by subjects whose resting position of accommodation was near the plane in which the target was situated. This fluctuation of accommodation could well be the link in Fincham's observations of the difficulties experienced by some subjects in focussing a target illuminated by monochromatic light. The fluctuations in accommodation would have the same effect as moving the screen either towards or away from the point of optimum focus. When one introduces movement in this way to the screen, the direction in which one must go to correct the blurring becomes at once obvious because the fringes from spherical and chromatic aberration diminish when one goes in the correct direction. If the target is illuminated with monochromatic light, the fringes due to chromatic aberration disappear and the movement of the screen then results in changes in the degree of smaller blurring.

The work of Campbell (1954a) on the light minimum required to elicit the accommodation relaxation in darkness might suggest that the stimulus required for accommodation was one of light alone; but the fact that a uniform light field does not elicit reflex relaxation of accommodation to the far point shows that it is a stimulus of detail, and therefore more probably a perception of brightness difference, which is necessary to elicit the reflex. Brightness difference at threshold level is an insufficient stimulus—as demonstrated by the fluctuations in sharpness of the barely discernible small dots—and, by Campbell's findings of a sub-threshold light stimulus at photopic and at scotopic levels, may be regarded as evidence that a stimulus of detail, although visible, may yet be sub-threshold in mediating relaxation of accommodation to the far point.

The conclusion to be drawn is that for the stimulus to be effective in producing a reflex relaxation of accommodation, its retinal image must be sufficiently sharp to show changes in sharpness with alterations in the refractive power of the eye. If the retinal image is so blurred, either by inaccurate focussing or by a blurred stimulus as in the experiments of **KNOLL** (1952), that it is not possible to detect differences in sharpness of the retinal image in response to changes in the refractive power of the eye, the stimulus of detail, although visible, will be ineffective as an accommodation stimulus.

The implication of this deduction is that accommodation is altered in the correct direction in response to a simple process of trial and error. The finding that some very blurred stimuli do not stimulate the accommodation reflex suggests that reflex relaxation of accommodation can take place only when the retinal image shows changes in sharpness with the small trial and error fluctuations. If the retinal image is already very blurred, it will obviously not show an appreciable change in response to these small fluctuations and it will therefore not act as an accommodation stimulus.

In this hypothesis, what seems to be a discordant note is struck by the fact that the small fluctuations of accommodation of the order of 0·1 D., which are being invoked to explain the process, do not give rise to subjective blurring since they are within the range of depth of focus of the eye. In a way not yet clear, chromatic aberration of the eye may play an important part in the mechanism by which the slightly blurred image is brought to an accurate focus; for it has been shown by **CAMPBELL** (1954b)* that the eye is most sensitive to out-of-focus blurring in the wavelength of light about the middle of the visible spectrum, even when one compares different wavelengths of apparently equal luminosity.

FIXATION PATTERN

The tests carried out on the suitability of various patterns with regard to procuring an accurate focus at infinity revealed the interesting fact that some collimated patterns were less effective than others. The pattern which, in general, was the most effective was the one whose shape resembled most closely that of the small threshold target—in this case, a round black dot. This is really quite understandable because, if there is an astigmatic error in the eye, the accommodation exerted when looking at a horizontal line will not be the same as that required when looking at a vertical line. It is therefore conceivable that the subject who is focussed on a vertical fixation mark at infinity would yet not be focussed at infinity with sufficient accuracy to see a small horizontal line of threshold size.

It may seem strange that depth of focus of the eye should not permit the test object to be visible in spite of inaccurate focussing. The reason,

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*The apparatus Dr. Campbell used in the objective method was purchased with a grant from the Ross Foundation (Scotland).

however, is probably to be found in one of the observations made during the calibration experiment. This was that there is a form of economy of effort in the act of accommodation, in that the accuracy with which an object is focussed depends partly upon its size and partly upon its distance from the natural resting point of the accommodation mechanism. If the test is a large object, there will be a greater permissible margin of error in focussing; and if it is a small object, it will require to be more accurately focussed. If it is near the subject's far point, he will tend to focus too near; and if it is at his near point, he will tend to focus beyond it.

Thus with all test patterns at infinity there is a tendency for the emmetrope to focus too near—the larger the pattern, the greater being the tolerable inaccuracy—and of course if the subject is astigmatic, it now becomes evident that whilst he may be focussed with sufficient accuracy on a vertical fixation mark, he may well be so far from an accurate focus in the horizontal meridian that a round target of near threshold size would not be visible.

Two other findings in this section require alternative explanation. They are the differences in effectiveness between the vertical and the horizontal stimulus, and between the black dot hexagon and the bright dot hexagon. In the first instance the difference may be related to physiological astigmatism which, according to DUKE-ELDER (1949), is almost invariably present, being a corneal astigmatism attributed to deformation of the cornea by the pressure of the upper and lower lids. The lesser curvature is thus frequently in the horizontal axis, as a result of which the eye will tend towards hypermetropia when viewing a horizontal line target. The accommodation exerted by the emmetrope in order to see a horizontal line target will, therefore, differ from that required for a small round target to be within the circle of least confusion.

In the second case, in which the target was a hexagon of luminous dots, the difference may be related to the fact that a point source of light is detectable against a black background not by reason of its angular size, but by reason of the amount of light reaching the eye.

It is, in consequence, evident that the fixation mark employed in any test requiring accurate focussing should be as similar in form and size to the final test as is permissible—the similar form being necessary so that the same circle of least confusion should be adopted by the subject, and the similar size so that there should be least departure from accurate focussing attributable to economy of effort.

ANGULAR DISTANCE OF A STIMULUS FROM THE FOVEA

The results obtained regarding the relation of the effectiveness of a collimated stimulus to its angular distance from a fovea show a striking similarity to the graph of visual acuity at various angular distances from the fovea (*Fig. 60*). The similarity is to be expected, since the accommodation reflex is mediated through the stimulation of cones.

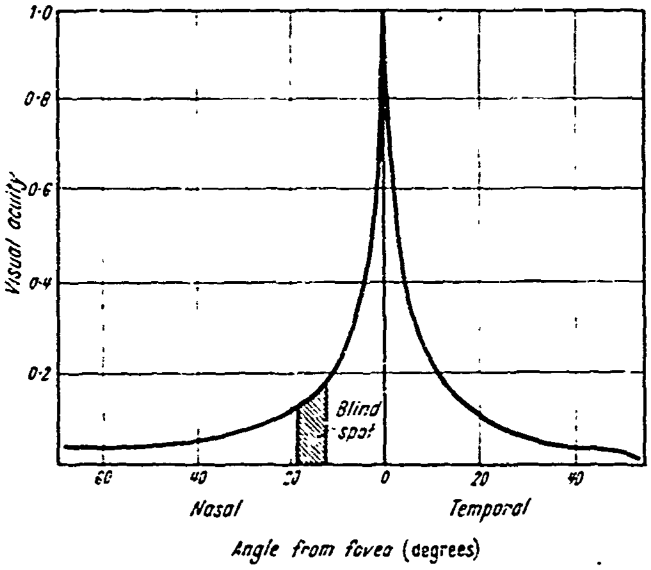

Fig. 60. Visual acuity and angular distance from the fovea from WERTHEIM, by courtesy of *Z. Psychol.*

EMPTY FIELD MYOPIA AND ACUITY

The most interesting of the accommodation experiments, however, was undoubtedly the final one, in which were assessed the effects of empty field myopia upon the minimum visual angle for a distant target. It must be confessed that this experiment had been carried out in the hope of demonstrating a correlation between flying experience and the ability to search in an empty visual field. No such correlation was found, and the main purpose of the experiment turned out to be the demonstration of a strong correlation between the subject's far point and his acuity at infinity.

It is felt that the failure to demonstrate a correlation between experience and the ability to search in an empty visual field is rather a criticism of the method employed than an indication that the two factors are unrelated.

It has been seen that in the measurements of the extent of the involuntary accommodation exerted in an empty visual field there was a great fluctuation in results, not only from subject to subject but in one individual; and the kymographic tracings have shown that accommodation is seldom stationary but fluctuates. When a subject searches in an empty field, the best he can do is to relax his accommodation to this fluctuating level. He can, however, increase his accommodation, unwittingly thinking that he is achieving a greater degree of relaxation. In the experiments in which the optometer was being used to calibrate the apparatus it was noticed on a number of occasions that subjects, even those familiar with visual experiments, were quite unable to determine whether they were increasing or decreasing their accommodation if there was no target visible.

The significance of this observation is that if an over-anxious subject makes a distinct effort to relax his accommodation to infinity, he may well merely succeed in increasing his accommodation. It thus seems likely that those who are unfamiliar with search in an empty field may thus unnecessarily accentuate the difficulties; whereas their more experienced colleagues, by making no distinct effort, would allow their accommodation to reach normal resting level, thereby achieving the best performance possible without the help of a collimated stimulus.

The correlation between the far point and the pick-up range in an empty field shows that the subjects who can pick up a target furthest are those with a more remote far point. It would thus seem that hypermetropes of about 0·5 D. would have the greatest advantage, in that when looking at an empty visual field their involuntary accommodation would bring them to a focus at infinity. Whilst the relation between the far point and the pick-up range is easily followed in the light of knowledge relating to the resting state of accommodation, the relation between the far point and the minimum visual angle at infinity when an accommodation stimulus is present is less obvious.

That emmetropes should perform better than myopes requires no elaboration; but the better performance of hypermetropes gave rise to surprise at first, for there appeared to be no reference to higher distance acuity occurring amongst low hypermetropes. As will be shown, the explanation of this finding probably lies in what has already been referred to as the economy of effort in the act of accommodation.

If a subject is presented with a collimated test of near-threshold small dots surrounded by much larger dots, and if he decides to focus primarily upon the easily seen larger dots, he may find that whilst his resolution, by reason of inaccurate focussing, is sufficient to allow him to see a large stimulus, it may yet be insufficient to allow him to see the threshold stimulus. Unless just detectable blurring is different for big and for small objects, the implication is thus that when a large object is being observed there is some blurring which, whilst detectable, is suppressed at a higher level. When the task is one requiring more careful focussing —as when attention is directed to some detail in the large test object or to a small test object beside it—the suppression must be overcome, and the accuracy of focussing be determined by the level of just detectable blurring. Thus some subjects who could not see the small dots, on being told to look carefully at the large dots frequently exclaimed that they could suddenly see clearly the near-threshold pattern of small dots.

In observing a stimulus which gradually became smaller it was found in many cases that, as the end-point was reached, subjects reported that although they were fixating the small dots these became blurred and shortly afterwards disappeared without further reduction in size being necessary. This may be because as the dots become smaller they reach a critical size at which, as was pointed out above, they may be still visible and yet not constitute a sufficient stimulus for the accommodation reflex. In such a case, even if the stimulus becomes no smaller, it is only a matter of time (less than a minute) before accommodation, in the absence of its stimulus, increases beyond the optimum focus for the far point.

Such a sequence of events is well seen in *Fig. 15*, in which the objective measurement of accommodation showed that as the test object went beyond the far point and became smaller and more out of focus, accommodation began to come towards the resting level although the blurred dots were still visible.

In an empty visual field the detection of small dots seems to take place first of all by the blurred image falling on the periphery and initiating a fixation reflex, whereupon it is brought on to the part of the retina capable of initiating the accommodation reflex.

In view of the way in which the small dots are seen when there is other larger detail present, it is thus to be expected that low hypermetropes should perform better than emmetropes by reason of their more accurate focussing at infinity, and, more basically, by reason of their resting level of accommodation being nearer infinity. For a task necessitating good acuity, one would thus expect that the best performance would be by hypermetropes of 0·6 D., irrespective of whether the visual field was empty or not.

With this point in mind one may look again at *Figs. 54* and *55* showing the correlation between far point and 'no stimulus distance', and between far point and 'with stimulus distance', and it will be seen that performance does deteriorate with far points above and below 0·6 D.

Because of the economy of effort in accommodation, which thus results in too little accommodation being exerted when the near point is observed, it is probable that the figures for amplitude of accommodation obtained by Duane (1922) with a modified Princes rule are in excess of the real amplitude of accommodation.

It appears that emmetropia—defined as the condition in which the unaccommodated eye focusses at infinity the yellow-green corresponding to the maximum of the photopic luminosity curve—is not the condition most favourable to tasks involving a high degree of acuity for distant objects. From this there emerges an interesting point. The chromatic difference of focus between the yellow-green at 550 mμ and the blue at 450 mμ is about 0·8 D. (IVANOFF, 1947). If one considers depth of focus, which for a 3 mm. pupil would be 0·1 D. (CAMPBELL and WEIR, 1953), this difference could be reduced to 0·7 D. Thus the subject who in his unaccommodated state can focus the entire visible spectrum at infinity, is incidentally also the subject who is most suited to carrying out tasks demanding high degree of acuity for distant objects.

The luminance of the background with which these tests were carried out was of the same order as that of the daylight sky in which there is no cloud but some haze present. In flight, however, the light would have been coming from all directions and the glare effect would have been more marked. This was borne out subjectively in that there was less ocular discomfort in viewing the test field than was usually experienced in flight. Under these conditions of equal luminance of field in the practical and experimental case, the reduction of the field angle caused by the apparatus effectively prevented light from entering the eye from the periphery, so that the uncontrolled pupil size in the experiment might have been somewhat larger than that obtaining in flight. The use of the 2·9 mm. pupil, whilst helping to standardise conditions, may thus also have made the experiments more like the practical case with regard to resultant depth of field.

OTHER PROBLEMS OF EMPTY VISUAL FIELD

'*Arctic white-out*'

Much has been heard recently of the phenomenon known as 'arctic white-out'—a form of visual disorientation which may arise when travelling over snow fields. It is said that for the phenomenon to be experienced, the sky must be uniformly overcast and merging into the ground so that little or no horizon is visible. Under these conditions all sense of depth is lost and detail present in the distance disappears, with the result that, apart from objects which are extremely close, nothing else is visible. One pilot reports in a colourful way that it is 'like flying inside a ping-pong ball'. No satisfactory explanation of this phenomenon has been put forward; but the descriptions of the sensations and of the predisposing weather conditions strongly suggest that the cause factor may be an empty visual field in which loss of the visual cues at infinity has resulted in the establishment of a day myopia.

Under these circumstances, and indeed when search is being carried out in any empty visual field, the accommodation mechanism will adopt its state of rest at about 0·6 dioptre, and it will not be possible for less accommodation to be exerted as long as the field of vision remains empty. It is probable, however, that more accommodation than this may frequently be exerted, particularly by an inexperienced individual who is over-anxious to locate a target or who feels strongly the difficulties of focussing under these conditions.

Reaction time and Acuity

Reaction time alone has little practical significance, and only when it is linked to the speed at which the environment is changing does it become a useful measurement. It is thus obvious that reaction time becomes more important at higher speeds, but it must be remembered that to the reaction time of the man there must be added the time required for the machine to respond. One might thus refer to 'useful reaction time', which would be the reaction time of the pilot *plus* the time taken for the aircraft to respond, the two together constituting a time short enough to result in a successful outcome whether in avoiding a collision or intercepting another aircraft.

Since acuity is least in the periphery and improves as the stimulus comes nearer to the line of sight, an object in the periphery has to come closer before it can be seen 'out of the corner of the eye'. This reduction of acuity in the periphery thus imposes physical limits on the field of vision in which threshold targets are detectable. This makes the visual field roughly cone-shaped, the apex of the cone being away from the observer and on the line of fixation. If one considers the time taken to see an approaching object, the size of the visual field is restricted even more.

Suppose the image of an object four miles away to fall on the retina and the time for motor response to be one second. If one were approaching the object at one mile per second, one would be only three miles from it before the motor reaction took place. If the object had been seen in the periphery, the time taken for the fixation reflex would make the reaction time even longer, and the object would be nearer still by the time the reaction took place. If an accommodation change is required the reaction time will be longer.

It is not yet known, but it may be that some accommodation change does take place during the eye movements if one knows how far away the fixation point is going to be. Thus it was occasionally found in the course of the experiments that, on looking into an empty field after looking near, a subject exclaimed that he saw, or had momentarily seen, the small dot pattern. This could be due to the point of focus, on being released from the near stimulus, travelling rapidly back towards its resting point and overshooting towards the far point before eventually reaching its resting level after a number of small oscillations. *Fig. 64* (analysis of the film record) seems to show such a change even when a visible target was present. The existence of a rapid and momentary overshoot in this way, after looking at a near stimulus, was suggested by some of the unpublished data on the speed at which accommodation reaches its resting level.

The effect of greater speeds is thus effectively to reduce the angular size of the visual field within which the appearance of a stimulus may result in a useful reaction. *Fig. 61* shows the reduction in minimum visual angle with stimuli at various angles from the fovea. The data of Craik was employed, the reciprocal of the minimum visual angle being plotted since it can thus be referred to as the range at which the target is seen. A correction was made in foveal acuity to allow for empty field myopia.

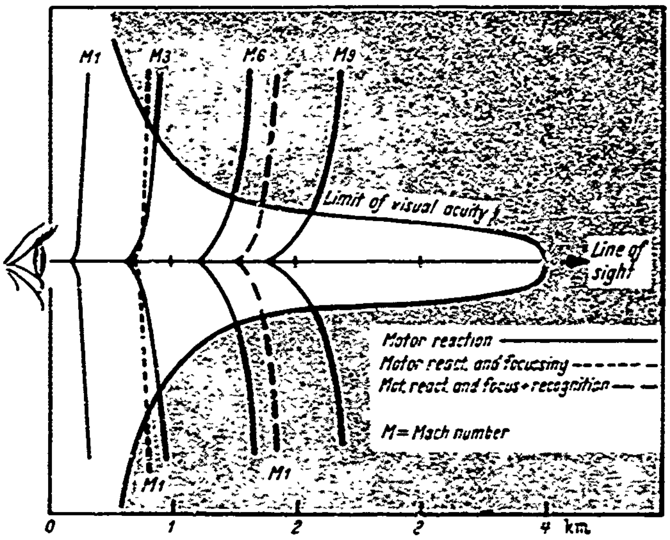

Fig. 61. Restriction of the visual field by reaction times at high speed

These total times to fixate a peripheral stimulus were calculated from the data of Strughold (1951) and of Byrnes (1951). They were expressed in terms of distance travelled at various speeds.

The effect of the higher speeds, as shown in *Fig. 61*, is to restrict the field of view in which it is possible to present the unaided eye with a target and still have sufficient time to initiate a motor response. The time taken for the aircraft to respond to the movement imparted to the control column has not been shown. In one case, it has been shown that if recognition of the target is considered, the effect is greatly accentuated. It is obvious that as the fields become smaller, there will eventually be reached a speed at which the time for the reaction will be longer than the time taken to reach the target. In such a case, there would be no possibility of taking useful avoiding action unless the visual range were increased artificially. Binoculars and telescopes were unacceptable in the past because of their field restrictions. At high speeds, with the narrower field, this does not apply.

DISCUSSION

SPEED AND DISTANCE JUDGMENT

The empty visual field also impairs the judgment of distance, speed, and size. One would expect that the clearness of the atmosphere—with consequent absence of areal perspective—would make objects, such as other aircraft, appear to be nearer. In fact they appear to be *further* away. Consequently, when approaching another aircraft one is frequently surprised by realising that it is much nearer than one had thought. The illusion is probably similar to that which results in the moon appearing smaller when it is near the zenith and larger when near the horizon.

Since there is no detail, either beyond the target aircraft or between it and the observer, there is no parallactic displacement to give a clue either as to the distance or to the speed of the target relative to the observer.

One of the most important factors in the perception of depth or distance is that of parallactic displacement: When an object in the middle distance is fixated whilst the observer is moving, that object will appear stationary, whilst objects behind it appear to move in the same direction as the observer and objects nearer than the point fixated appear to move in a direction opposite to that of the observer. The relative distances of the object, observed with regard to the detail in the near plane and in the distant plane, can thus be accurately estimated. A cat, raising and lowering its head in preparation to leaping on to a ledge, may be employing such a mechanism.

If the visual field contains no detail other than that of the object fixated, these clues obtained from parallactic displacement will be lost, and consequently judgment of distance, relative speed and size will be seriously impaired. The difficulty in catching a ball, seen against a cloudless sky, is no doubt associated with such an impairment of depth perception.

The cloudless sky at high altitude is therefore responsible not only for difficulty in focussing when the field is empty, but also for the difficulty in judging the distance and speed of another aircraft once it has been detected.

VI. CONCLUSIONS AND APPENDIXES

CONCLUSIONS

With the background of the experimental work and observations described in Parts II, III, and IV, one can now integrate the findings and paint the picture of the visual problems of flight at high altitude. The entire problem is now seen to be quite simple, although the interaction between the many different factors makes it appear to be complicated.

There are two basic physical causes for all these problems: One is the reversal of light distribution at high altitude where the bright sky, formed by cloud and haze, is below and the darker blue sky is above. The other is the clear blue sky which is frequently present in the hemisphere above the horizon—a sky without trace of cloud and constituting an empty visual field.

The reversed light distribution is responsible for the glare problems, particularly with regard to visibility in the cockpit; whilst the clear blue sky is responsible for the problems associated with vision outside the cockpit—judgment of speed, size, and distance of target, and particularly air-to-air search.

Some individuals tolerate glare better than others, but variations in severity of the glare problems are due largely to the variations in the cockpit design of different aircraft. As is seen in *Fig. 58*, if none of the light from below can reach the instrument panel, it will be in very dark shadow and consequently difficult to see. The remedy is simple—at least to the physiologist: Either raise the instrument panel, or lower the coaming, or have a transparency low down in the side wall of the cockpit. If this is not possible, the interior of the cockpit behind the pilot might be painted white, thus allowing direct sunlight to be reflected on to the darker shadow areas. Additional electric flood-lighting might also be employed, the sources being in the lower parts of the cockpit and so directed upwards as not to constitute a glare source.

The glare problems of vision outside the cockpit are almost solely due to the high brightness of the lateral parts of the visual field. This sets up the intraocular scatter of light which casts a haze over the entire field of view. A visor or eye-shade, so disposed as to keep both direct sunlight and the reflected light from the cloud floor effectively out of the eyes, removes or reduces the intraocular scatter and improves visibility. These glare effects are accentuated and prolonged by even the slight degree of anoxia which results after rapid decompression to an altitude equivalent to 10,000 feet without oxygen.

The empty visual field of the cloudless blue sky reduces considerably one's chances of focussing at infinity during air search for a yet unseen target. The slightly long-sighted individual is most likely to perform well since his eyes may come to a resting focus about infinity. Even he, however, may be handicapped; for the empty field gives no sensation of depth or of distance, in consequence of which he may make a conscious effort to focus in the distance, with the result that he unknowingly focusses even nearer than the resting position. Under these circumstances, the pilot searching the sky may suddenly realise that his eyes are focussed not in the distance but on spots of dust on the windscreen.

Difficulty in picking up other aircraft at high altitude is thus due essentially to the fact that the visual field contains no detail which can be used as a guide to focus the eyes at infinity. Even when it has been recognised, however, the estimation of an aircraft's distance, size, and relative speed at high altitude, is impaired by the absence of clues from parallactic displacement in the cloudless sky.

APPENDIXES

Appendix A. Construction of the hooded photocell

THE photocell employed was a barrier-layer Everett-Edgcumbe cell (Autophotic). The lower the resistance of the moving coil instrument recording the current output of the cell, the more exactly was that output proportional to illumination. The resistance of the microammeter employed was 200 ohms, which allowed a very nearly linear response to 100 milliamp current output after which the current output of the cell became relatively less than the increases in illumination falling on it. The constructional detail of the cell is shown in *Fig. 62.*

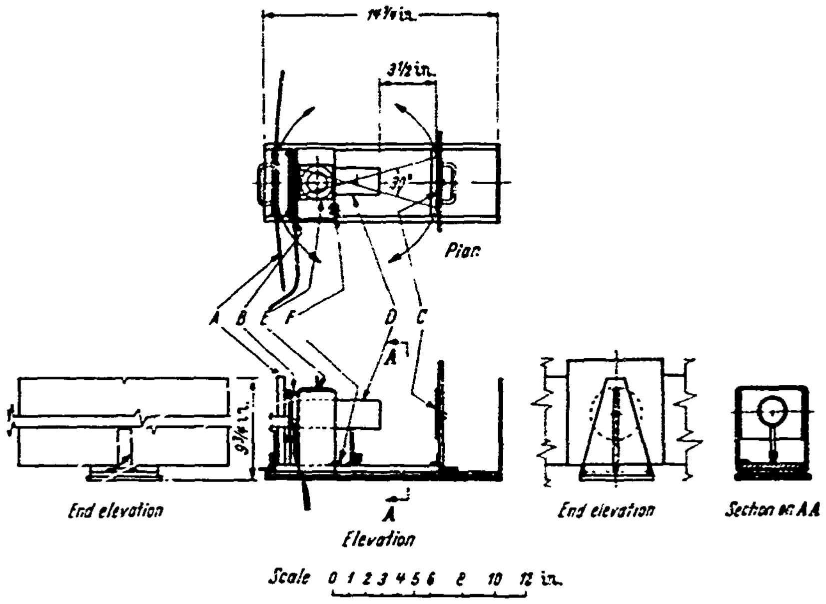

Fig. 62. Constructional detail—A. Baffle plate; B. Barrier layer photocell; C. White target; D. Hood restricting field to 30°; E. Sun azimuth indicator; F. Spirit level

Appendix B. Calibration of luminance and of intensity measurements

So that the photocells should have the same spectral response as during measurements of light at altitude, the calibration was made in sunlight. The green correcting filter was used with the hooded and the unhooded photocells. The procedure employed was to measure the luminance of the white circular target used with the hooded photocell, and then to place the unhooded photocell over the white target and record the intensity of light falling on it. The results were plotted, and further observations were made at different intensities of sunlight obtained by partially shielding the sun from the target and from the cell. As the distribution within the range measured appeared to be linear, the points were joined by eye as shown in *Fig. 11*. This graph was employed to compare the intensity measurement made at the instrument panel with measurements of luminosity made in direct sunlight with the hooded photocell.

Appendix C. Luminance of a white vertical surface

	Altitude (feet)	*Degrees of sun azimuth*						
		−90	−60	−30	0	+30	+60	+90
Black baffle card	10,000	17	35	20	55	220	280	335
	15,000	36	30	28	29	265	280	280
	20,000	39	39	26	32	225	300	335
	25,000	40	34	24	27	215	315	340
	30,000	40	35	25	29	210	300	350
	35,000	44	38	27	30	220	300	320
	40,000	40	38	30	36	200	260	285
White baffle card	10,000	13	15	15	30	220	280	340
	15,000	25	26	28	29	265	280	290
	20,000	11	10	11	18	215	295	335
	25,000	12	10	12	21	210	310	335
	30,000	15	11	12	18	210	295	335
	35,000	18	15	16	25	210	310	330
	40,000	18	15	19	24	200	260	285

Figures for luminance are in relative units

Appendix D. Construction of three-dimensional graph

A right square prism was drawn in perspective by adopting an arbitrary vanishing point towards which all parallel lines converged. With this 'three dimensional' drawing as a base, the graphs shown in *Figs. 7, 8,* and *13* were constructed. Such graphs have been employed by others, but without the introduction of perspective; this has the disadvantage of making equal values at either end of the graph appear to differ in that the more distant appears to be greater than the nearer value. The introduction of perspective into the diagram eliminates this impression.

The plotting of points was rather tedious in that each point was on a different scale. However, by the use of proportional dividers it was possible to interpose accurately all intermediate values irrespective of the change in scale. The construction of each diagram took about one hour, but it is regarded as being a useful method of presenting three related variables in such a way that the relation between the three can easily be remembered by the reader.

Appendix E. Ultra-violet solar intensities shorter than 313mμ

Altitude (thousands of feet)	*Intensity* $\mu W/cm^2$	*Altitude (thousands of feet)*	*Intensity* $\mu W/cm^2$
0	88	32	197
4	114	36	208
8	132	40	222
12	147	44	235
16	156	48	253
20	166	52	275
24	176	56	303
28	185	66	342

(From Stair and Coblentz, 1938, by courtesy of National Bureau of Standards, Washington)

Appendix F. Head movement and obstruction of the nasal field

Introduction—As it had been observed that during visual search in flight the amount of head movement involved seemed to be greater when wearing flying goggles than when wearing a visor, a simple experiment was arranged in order to measure the amount of head rotation which took place when a subject was instructed to look in various directions in a given horizontal plane while wearing (*a*) goggles and (*b*) a curved *Perspex* transparency which did not restrict the visual field in any way.

Method—A circle of radius 3 feet was constructed from brass strip, and on it were marked off 5° arcs extending to 125° on either side of a common origin or zero mark. A cursor was made from cardboard, and on it as a fixation point was a black circular spot 1/8th inch in diameter. In order to reduce the rotation of the trunk, the subject was seated in a pilot-type seat and tightly strapped in with the seat harness. A flying helmet with a pointer fixed to the crown was worn by the subject, so that by sighting along the pointer the observer could obtain a reading for the amount of head rotation in a horizontal plane.

The subject having been strapped in, the position of the perimeter was adjusted level with his eyes, so that the zero mark was directly in front of the centre of the seat, and the 90° marks were in line with the vertex of his head as he sat looking at the zero mark. The helmet and pointer were then put on and adjusted so that when the subject looked at the zero mark, the pointer was also in line with it.

Ten subjects were observed, and the procedure adopted in each case was as follows: The head pointer having been adjusted, the subject was told to look at the fixation mark always in such a way as to distinguish its outline clearly. He was told that head movement was permitted. In each case the fixation point was placed at 10°, 20°, 40°, 60°, 80°, 100°, 125° on one or other side of the zero mark. The order of presentation of these positions and the side of presentation were randomised. Each subject was tested while wearing an experimental visor type B, and then with Mk. 8 flying goggles. Five of the subjects were tested first with the visor, and the others first with the goggles. This was to eliminate any difference between the first and second sets of results for one subject, which might arise as a result of familiarisation with the experiment.

Results—The results were examined statistically for each of the angles of presentation in turn, the hypothesis being that in each subject, for the angle of presentation in question, there was no difference in the results obtained with the visor or with goggles. For angles of 20° and over, this hypothesis was disproved, the mean of the difference differing significantly from zero as shown in *Table 1*.

Table 1

Angle of presentation	*Mean head movement*		*Diff. in head movement*	*Value of 't'*	*Level of probability at which significant*
	Goggles	*Visor*			
10	1·4	1·4	0	0	—
20	7·4	4·9	- 2·5	3·33	0·01
40	27·2	19·5	- 7·7	2·305	0·05
60	41·7	33·9	- 7·8	3·066	0·02
80	55·7	47·9	- 7·8	2·933	0·02
100	67·5	61·2	−6·3	3·839	0·01
125	85·5	82·5	- 3·0	3·67	0·01

Figures in the first four columns are in degrees

The differences between the results are seen in column 4. It will be noted that when looking 40°–80° to either side, if goggles are worn the amount of head movement is increased by about 8°.

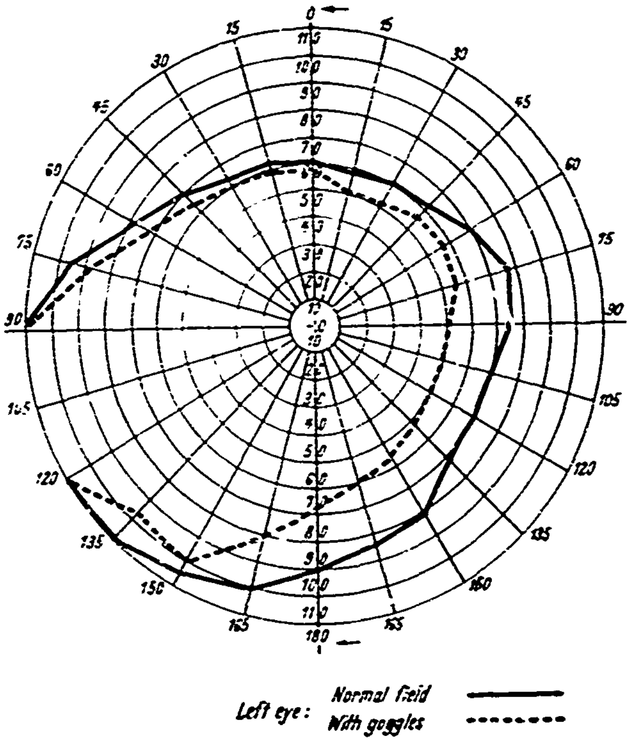

Fig. 63. Restriction of the nasal field by goggles

Discussion—The reason for these changes in the amount of head rotation probably lies in an effort to keep seeing the cursor, or the area of search, binocularly, even when there is a restriction of the visual field on the nasal side. *Fig. 63* shows the visual field for the left eye of a subject wearing Mk. 8 goggles, and also the normal field. It will be seen that although the peripheral field is only slightly reduced, there is a considerable infringement on the nasal side. Obviously, therefore, the wearer, looking to one or other side, must either observe a target monocularly or rotate his head more than normally so as to retain the binocular presentation which he finds more satisfying. The results support the latter view, thus demonstrating the importance of avoiding in the design of eye-protective devices restrictions in the nasal side of the visual field as well as in the periphery.

Appendix G. Construction of the small dot test plate

In a piece of sheet aluminium 40 cm. square, 17 small holes were drilled in a star-shaped pattern. The diameter of each hole was about 1 mm., and the separation between any two holes was about 5 cm. The photographing of this plate, which involved a reduction to 1 12th of the original size, was carried out by the Printing Department of the Royal Aircraft Establishment.

The metal template was illuminated from behind so that the holes appeared as a star-shaped pattern of small light sources. The photographic plate, with the reduced negative image of the pattern of lights, constituted the test plate used in the experiments on accommodation. Several plates were made and rejected before one was obtained which was sufficiently free from visible defects, such as scratches or 'seed' (small bubbles in the glass), in the area of the test.

After exposure and development of the photographic plate, the size of the dots was reduced by immersing the plate in a mild reducer of sodium thiosulphate and potassium ferricyanide. This caused a reduction in the diameter of the dots, whilst the reduction in thickness was so little that afterwards they remained apparently quite black.

The test plate proved easy to handle and keep clean and free from dust. Light surface scratches and smears on the emulsion were invisible to the subject.

Appendix H. Cine-film record of changes in size of the third Purkinje-Sanson image on focussing from a near to a distant stimulus

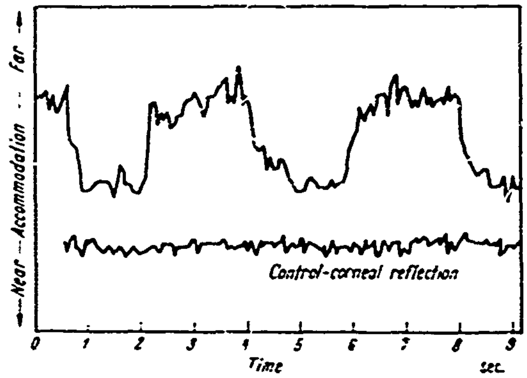

Fig. 64. The accommodation changes on looking alternately from near to far (cine-film

The first Purkinje-Sanson image—the reflection from the anterior surface of the cornea—was employed as a control. It thus gives an indication of the amount of scatter in readings which is attributable to difficulties in making measurements.

Appendix I. Analysis of Questionnaires

Ratio	*No stimulus distance (in.)*	*Age*	*High altitude sorties*	*Fighter hours*	*Total hours*	*1939 to 1946*	*Uncorrected far point (in.)*
1·11	18	36	30	806	3100	–	6·5
1·11	18	34	500	—	2700	–	7·0
1·11	18	26	3	—	260		5·5
1·2	15	21	63	294	590		5
1·25	16	23	6	72	350		7·5
1·25	16	29	116	900	1700	–	7·0
1·25	16	20	15	120	400		10
1·29	14	30	10	—	3500		6
1·33	12	25	—	—	1650		5·5
1·43	14	27	4	—	500		6
1·43	14	28	30	—	412		5
1·5	12	21	22	194	536		5
1·5	16	31	—	135	212		5
1·5	10	29	60	425	1090		4·5
1·5	16	26	110	860	1480		9·5
1·6	10	21	—	—	600		2
1·6	15	30	90	—	2400		6
1·67	12	27	12	—	450		5·5
1·67	12	26	110	191	550		9·5
1·67	9	24	75	346	667		5·5
1·67	12	27	100	640	1425		5
1·71	14	24	3	70	1501		4
1·8	10	20	23	152	450		5
1·8	10	37	12	250	3500	–	6
1·83	8	28	70	740	1200		6
1·88	8	39	55	—	4150	–	3
2·0	6	22	—	—	400		2
2·0	12	24	—	—	1200		6
2·0	12	29	15	200	1300	–	8
2·0	12	28	71	675	1078		7·5
2·0	8	26	124	633	1365		1
2·0	10	20	18	86	393		5

Appendix I. Analysis of Questionnaires (continued)

Ratio	*No stimulus distance (in.)*	*Age*	*High altitude sorties*	*Fighter hours*	*Total hours*	*1939 to 1946*	*Uncorrected for point (in.)*
2·0	10	31	95	907	2050		4
2·0	12	29	160	160	3000		3·5
2·0	12	21	—	100	300		7
2·0	12	21	—	—	350		6·5
2·0	10	22	100	—	675		8
2·18	11	28	30	250	1400		11
2·18	11	31	—	—	1100	–	10
2·25	8	42	22	95	1900	–	5
2·33	6	21	—	—	650		3·5
2·5	6	24	5	51	440		5·5
2·5	8	25	81	—	630		3·5
2·57	7	30	70	—	2875	–	7
2·57	7	29	150	800	1700		2·5
2·67	6	26	250	297	1370		2
2·67	6	22	38	206	518		2·5
2·67	6	30	50	760	1917	–	5·5
2·67	4·5	31	—	—	2050	–	4·5
2·86	7	19	—	—	160		6
2·86	7	25	5	42	407		5·5
3·0	6	28	140	500	1500		7·5
3·0	5	20	3	52	326		2·5
3·0	6	22	14	160	430		6·5
3·2	5	20	25	204	530		3
3·43	7	29	—	—	3813	–	6
3·56	4·5	29	60	480	1720		5·5
3·56	4·5	29	—	—	2400		4
4·0	4·5	31	10	150	3100	–	5
4·0	5	22	5	69	352		7·5
4·0	4	21	50	350	600		4·5
4·0	5	21	—	—	650		11·5
4·0	5	20	60	—	470		6·5

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(F.P.R.C.: Flying Personnel Research Committee of Air Ministry)

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