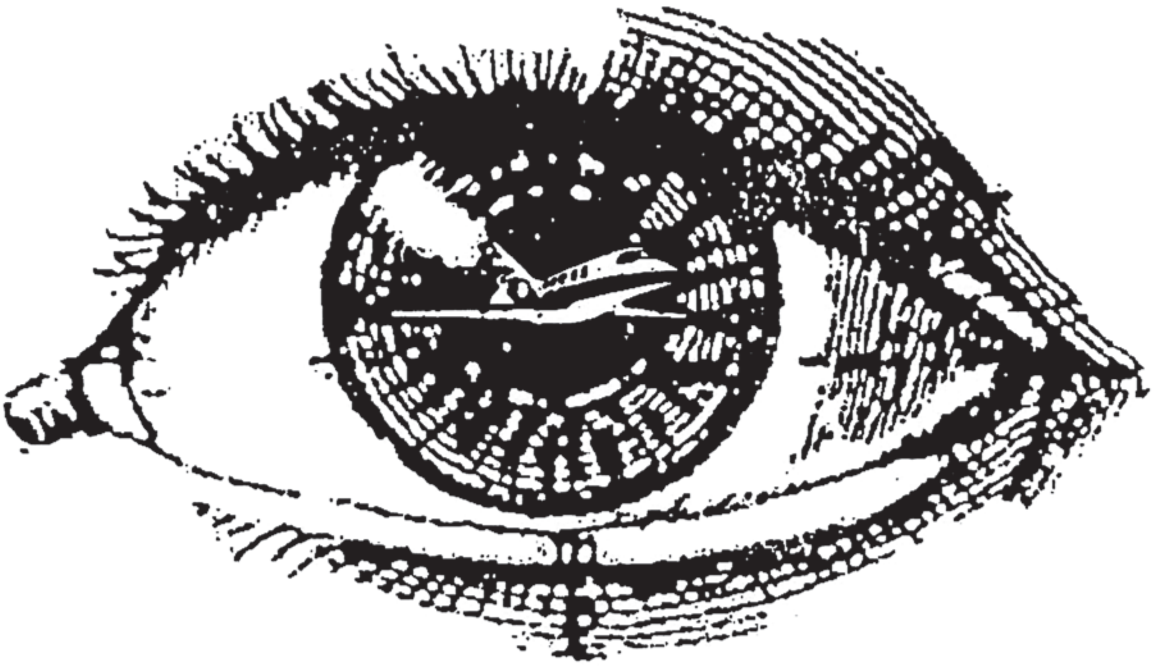
Australian Government
Australian Transport Safety Bureau

Limitations of the See-and-Avoid Principle

Alan Hobbs



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RESEARCH REPORT

Limitations of the See-and-Avoid Principle

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CONTENTS

PREFACE

On the 20th May 1988 at approximately 1609 hours, a Cessna 172 collided with a Piper Tomahawk in the circuit area at Coolangatta, Queensland. The accident, in which four people died, occurred in conditions of good visibility.

This collision and others which occurred in the late 1980s drew attention to the deficiencies of the see-and-avoid concept.

The Coolangatta accident report stated that: 'As a result of this accident, the Bureau of Air Safety Investigation has undertaken to conduct an evaluation and prepare a report on the practicability of the see and be seen (see-and-avoid) principle in controlled and non-controlled airspace.' (BASI report 881/1042).

This report, prepared in response to that undertaking, summarises the research relevant to unalerted see-and-avoid and is intended as a reference document for Civil Aviation Authority (CAA), Industry, and BASI personnel as well as a source of recommendations. The report does not analyse the Australian accident experience.

SUMMARY

The see-and-avoid principle serves a number of important functions in the Australian air traffic system.

However, while it undoubtedly prevents many collisions, the principle is far from reliable. The limitations of the see-and-avoid concept demand attention because increases in air traffic may impose an accelerating level of strain on see-and-avoid and other aspects of the air traffic system.

Numerous limitations, including those of the human visual system, the demands of cockpit tasks, and various physical and environmental conditions combine to make see-and-avoid an uncertain method of traffic separation. This report provides an overview of the major factors which limit the effectiveness of unalerted see-and-avoid.

Cockpit workload and other factors reduce the time that pilots spend in traffic scans. However, even when pilots are looking out/ there is no guarantee that other aircraft will be sighted. Most cockpit windscreen configurations severely limit the view available to the pilot. The available view is frequently interrupted by obstructions such as window-posts which totally obscure some parts of the view and make other areas visible to only one eye. Window-posts, windscreen crazing and dirt can act as 'focaltraps' and cause the pilot to involuntarily focus at a very short distance even when attempting to scan for traffic. Direct glare from the sun and veiling glare reflected from windscreens can effectively mask some areas of the view.

Visual scanning involves moving the eyes in order to bring successive areas of the visual field onto the small area of sharp vision in the centre of the eye. The process is frequently unsystematic and may leave large areas of the field of view unsearched. However, a thorough, systematic search is not a solution as in most cases it would take an impractical amount of time.

The physical limitations of the human eye are such that even the most careful search does not guarantee that traffic will be sighted. A significant proportion of the view may be masked by the blind spot in the eye, the eyes may focus at an inappropriate distance due to the effect of obstructions as outlined above or due to empty field myopia/ in which, in the absence of visual cues/ the eyes focus at a resting distance of around half a metre. An object which is smaller than the eye's acuity threshold is unlikely to be detected and even less likely to be identified as an approaching aircraft.

The pilot's functional visual field contracts under conditions of stress or increased workload. The resulting 'tunnel vision' reduces the chance that an approaching aircraft will be seen in peripheral vision.

The human visual system is better at detecting moving targets than stationary targets, yet in most cases, an aircraft on a collision course appears as a stationary target in the pilot's visual field. The contrast between an aircraft and its background can be significantly reduced by atmospheric effects/ even in conditions of good visibility.

An approaching aircraft/ in many cases/ presents a very small visual angle until a short time before impact. In addition, complex backgrounds such as ground features or clouds hamper the identification of aircraft via a visual effect known as 'contour interaction'. This occurs when background contours interact with the form of the aircraft/ producing a less distinct image.

Even when an approaching aircraft has been sighted/ there is no guarantee that evasive action will be successful. It takes a significant amount of time to recognise and respond to a collision threat and an inappropriate evasive manoeuvre may serve to increase rather than decrease the chance of a collision.

Because of its many limitations/the see-and-avoid concept should not be expected to fulfil a significant role in future air traffic systems.

1 INTRODUCTION

1.1 Role of see-and-avoid

See-and-avoid serves three functions in Australian airspace:

1. Self-separation of aircraft outside controlled airspace
2. As a separation procedure for VFR aircraft in control zones, where the pilot is instructed to 'sight and avoid' or 'sight and follow' another aircraft as outlined in NOTAM C0511989

   This procedure only operates when the pilot can see the traffic and is therefore significantly different to other types of see-and-avoid which may involve unalerted searches for traffic.
3. Last resort separation if other methods fail to prevent a confliction, regardless of the nature of the airspace.

It is important to distinguish between unalerted and alerted see-and-avoid. In alerted see-and-avoid, the pilot of an aircraft in controlled airspace is assisted to sight the traffic and an important back up exists because positive control will be provided if the traffic cannot be sighted. Unalerted see-and-avoid on the other hand, presents a potentially greater safety risk because it relies entirely on the ability of the pilot to sight other aircraft. For these reasons, this report concentrates on unalerted see-and-avoid.

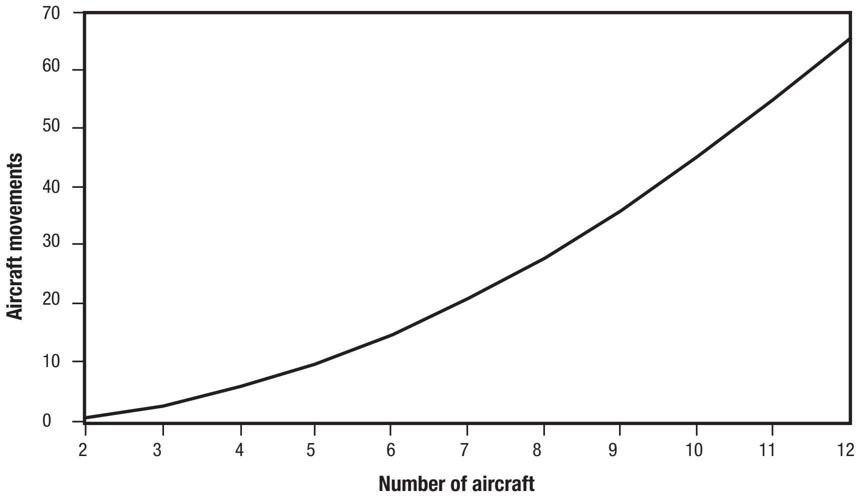
However, many of the problems of unalerted see-and-avoid apply equally to alerted see-and-avoid.

1.2 Potential for mid-air collisions

There have been relatively few mid-air collisions in Australia. However, there are reasons why the mid-air collision potential demands immediate attention.

At a time when aircraft movements are increasing, (Civil Aviation News September 1990) the probability of a mid-air collision in a given airspace grows faster than the traffic growth. One of the factors which determines the probability of a collision is the number of possible collision combinations in a particular airspace. The number of possible collision pairs is given by the formula: $P = N \times (N-l)/2$ where N is the number of aircraft operating in a given airspace. For example, with only two aircraft there is only one possible collision pair, with five aircraft there

FIGURE 1:
Number of possible collisions with increasing air traffic

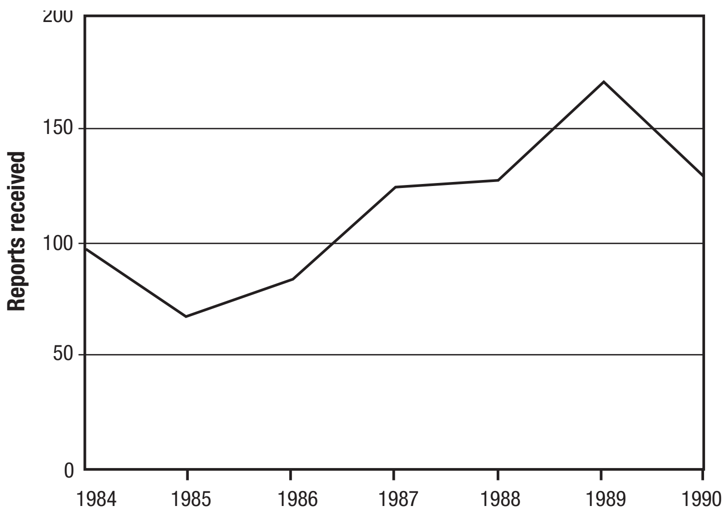


are ten possible pairs and with ten aircraft there are forty five. Figure 1 illustrates the increase in possible collisions which accompanies increasing traffic density.

Fortunately, the frequency of collisions has not increased as steeply as figure 1 would suggest because various safety systems have prevented the full expression of the collision potential. Air traffic services (ATS), flight rules and visual sighting are three such systems. As well as illustrating the increasing stress placed on the air traffic system by traffic growth, figure 1 also implies that the cost of traffic separation may follow an inverse 'economy of scale' rule.

In recent years there have been a number of mid-air collisions in Australia and an increase in reported breakdowns of separation (see figure 2). The actual number of separation breakdowns may be much higher as it is likely that many separation breakdowns are not officially reported.

FIGURE 2:
Breakdowns in separation



(1990 Figures are preliminary)

1.3 See-and-avoid is an important safety system

The see-and-avoid principle is a significant feature of the Australian air traffic system. There is no doubt that safety features such as air traffic services and see-and-avoid prevent many collisions. It has been estimated that without ATS and in the absence of any ability to see-and-avoid there would be thirty four times more mid-air collisions en route and eighty times more mid-airs in terminal areas (Macho1 1979). However, although many collisions are averted by see-and-avoid, the concept is a flawed and unreliable method of collision avoidance.

1.4 See-and-avoid is not 100 per cent reliable

See-and-avoid has been described as a maritime concept originally developed for slow moving ships which is now out of place in an era of high speed aviation (Marthinsen 1989).

There is a growing case against reliance on see-and-avoid. A report released in 1970 concluded that although see-and-avoid was often effective at low closing speeds, it usually failed to avert collisions at higher speeds. It was estimated that see-and-avoid prevents 97 per cent of possible collisions at closing speeds of between 101 and 199 knots but only 47 per cent when the closing speed is greater than 400 knots (Graham and Orr 1970).

A 1975 FAA study concluded that although see-and-avoid was usually effective, the residual collision risk was unacceptable (Graham 1975). Accident investigations here and in the U.S. are increasingly pointing to the limitations of see-and-avoid. The Americans, having recognised the limitations of the concept, are looking to other methods such as the automated airborne collision avoidance system (TCAS) to ensure traffic separation. TCAS equipment carried on board an aircraft will automatically provide information about any nearby transponder-equipped aircraft which pose a collision threat. It is planned that by the mid 1990s all large civil passenger aircraft operating in the U.S. will be fitted with this system.

Perhaps the most damning evidence against see-and-avoid comes from recent trials carried out by John Andrews in the United States which have confirmed that even motivated pilots frequently fail to sight conflicting traffic.

In one of these studies, twenty four general aviation pilots flew a Beech Bonanza on a VFR cross country flight. The pilots believed that they were participating in a study of workload management techniques. In addition to providing various information to a researcher on the progress of the flight, the pilots under study were required to call out any traffic sighted.

The pilots were not aware that their aircraft would be intercepted several times during the test by a Cessna 421 flying a near-collision course. The interceptions occurred when the Bonanza was established in cruise and the pilot's workload was low, however, the Bonanza pilots sighted the traffic on only thirty six out of sixty four encounters - or 56 per cent (Andrews 1977, 1984, 1987).

1.5 Seeing and avoiding involves a number of steps

See-and-avoid can be considered to involve a number of steps. First, and most obviously, the pilot must look outside the aircraft.

Second, the pilot must search the available visual field and detect objects of interest, most likely in peripheral vision.

Next, the object must be looked at directly to be identified as an aircraft. If the aircraft is identified as a collision threat, the pilot must decide what evasive action to take. Finally, the pilotmust make the necessary control movements and allow the aircraft to respond.

Not only does the whole process take valuable time, but human factors at various stages in the process can reduce the chance that a threat aircraft will be seen and successfully evaded. These human factors are- not 'errors' nor are they signs of 'poor airmanship'. They are limitations of the human visual and information processing system which are present to various degrees in all pilots.

This report documents the known limitations of the see-and-avoid concept and outlines some possible solutions.

> **CAIR Report Number 1158**
>
> On return to Parafield via Dublin and the Lane of Entry, I encouraged two Tobagos (or Trindads) travelling north. The first was at my eye level (1500 ft) and on a precise collision course. I waggled my wings and turned on my landing light as he got closer, then descended to 1300 ft and looked up as he went straight overhead. Five minutes later the second aircraft went by, also at 1500 ft. The frightening thing is that I am sure the pilots did not see me, as neither waved his wings in answer, turned on his lights or changed heading or height. Whatever happened to see-and-avoid especially in a Lane of Entry?

2 LIMITATIONS OF SEE-AND-AVOID

2.1 Looking for traffic

Obviously, see-and-avoid can only operate when the pilot is looking outside the cockpit. According to a U.S. study, private pilots on VFR flights spend about 50 per cent of their time in outside traffic scan (Suzler and Skelton 1976).

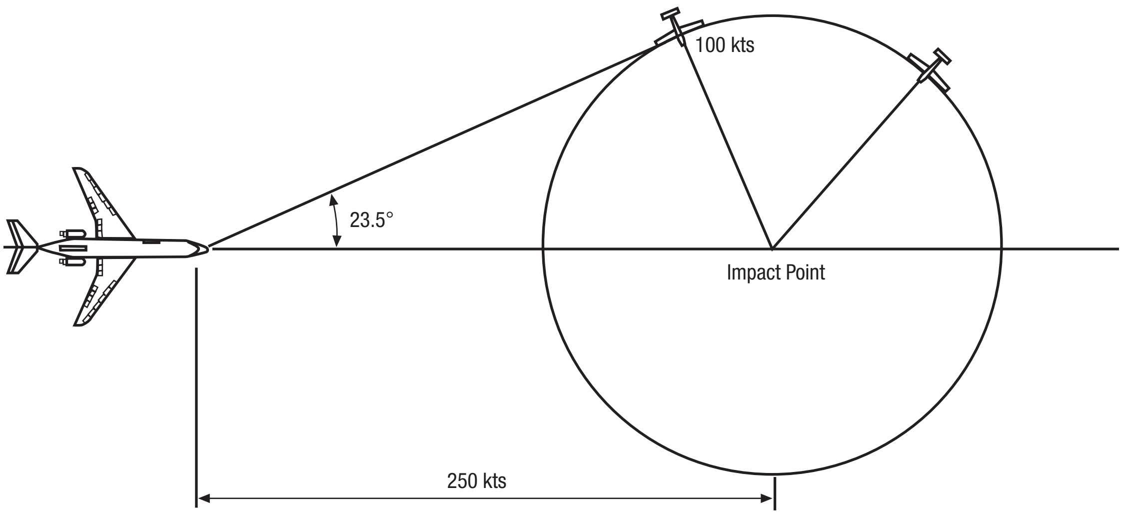
Airline pilots may possibly scan less than this. In the late 1960s it was estimated that American airline pilots spent about 20 per cent of their time in outside scan (Orlady 1969). Although this is an old figure it gives a rough idea of the likely amount of scanning by Australian pilots in the 1990s.

The time spent scanning for traffic is likely to vary with traffic density and the pilot's assessment of the collision risk. In addition, factors such as cockpit workload and the ATS environment can influence traffic scanning.

2.1.1 Workload

Many tasks require the pilot to direct attention inside the aircraft. Cockpit workload is likely to be high near airports where traffic is most dense and where an outside scan is particularly crucial. Most of these cockpit tasks are essential, however some of the workload is less critical and could be performed at other times. It is a common complaint of pilots that air traffic services frequently impose unnecessary tasks in terminal areas.

FIGURE 3:
Illustration showing two aircraft converging upon an impact point at different points



From Marthinsen 1989

In the case illustrated, two aircraft are converging upon an impact point at different speeds. The jet is travelling two and a half times faster then the light aircraft and at any time prior to the collision, will be two and a half times further away from the collision point than the light aircraft. one result of this is that the faster aircraft will always have a slower aircraft in front of it.

At all times leading up to the collision, any slow aircraft with which the jet may collide will appear at a point relatively close to the centre of the jet's windscreen. From the slower aircraft pilot's of view, however, the jet can approach from any angle, even from a part of the sky not visible in the windscreen.

2.1.2 Crew numbers and workload

The widespread introduction of flight deck automation has meant that modem airliners are now frequently flown by only two crew-members. However, automation has not reduced the need for pilots to be vigilant for other air traffic and compared to twenty years ago, the average airliner now has fewer crew looking for more traffic. It has been suggested, sometimes as part of industrial campaigns, that two-crew aircraft have been involved in a disproportionate number of mid-air collisions (Marthinsen 1989). However, it is doubtful that any firm evidence would support this view.

2.1.3 Glass cockpits and workload

A recent survey (Weiner 1989) suggests that pilots of advanced 'glass cockpit' airliners are spending more time 'heads down', particularly at low altitudes as they interact with the flight management computers which were introduced to reduce workload. Yet there are reasons why in some circumstances, the pilot of a fast airliner has a better chance of detecting a conflicting slow aircraft than vice versa (see figure 3).

2.1.4 Diffusion of responsibility

Diffusion of responsibility occurs when responsibility for action is divided between several individuals with the result that each assumes that somebody else is taking the necessary action. Diffusion of responsibility has been a factor in a number of serious aviation accidents, for example the 1972 accident involving an LlOll in the Florida Everglades.

A frequent criticism of the see-and-avoid principle is that pilots flying in controlled airspace relax their traffic scans in the assumption that Air Traffic Control (ATC) will ensure separation. Yet as the Australian experience shows, mid-air collisions and near collisions can and do occur in controlled airspace. An analysis of U.S. Near Mid-Air Collisions (NMACs) showed that the great majority of reported NMACs occurred in controlled airspace (Right Safety Digest December 1989).

Diffusion of responsibility has been suggested as a contributing factor in a number of overseas midair collisions, for example the collision of a Cessna 340A and a North American SNJ-4N at Orlando Florida May 1 1987 (NTSB Report 88/02). Pilot complacency when under air traffic control was also identified as a problem by a 1980 NASA report (Billings, Grayson, Hetch and Curry 1980).

At present, there is no reliable information on the amount of scanning done by Australian pilots in controlled airspace and outside controlled airspace.

2.2 Visual search

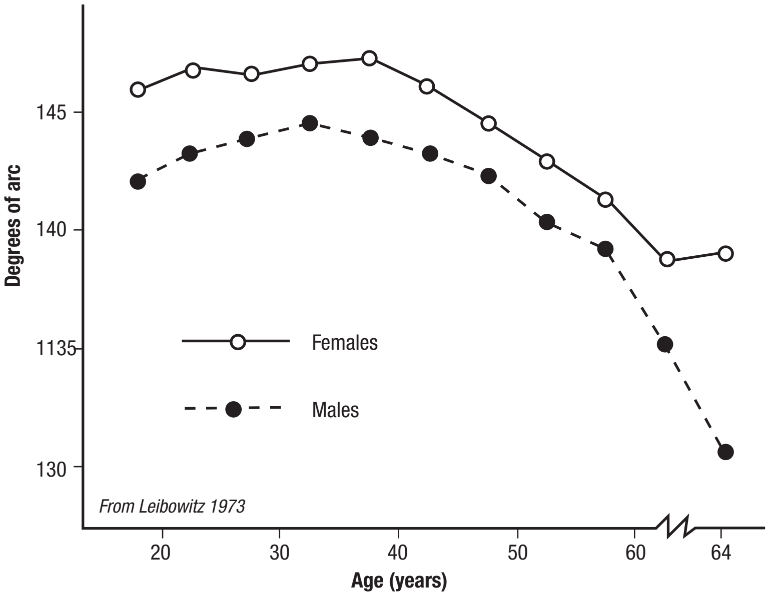
The average person has a field of vision of around 190 degrees, although field of vision varies from person to person and is generally greater for females than males (Leibowitz 1973). The field of vision begins to contract after about age 35.

In males, this reduction accelerates markedly after 55 years of age (see figure 4).

A number of transient physical and psychological conditions can cause the effective field of vision to contract even further. These will be discussed at a later point.

The quality of vision varies across the visual field, largely in accord with the distribution on the retina of the two types of light sensitive cells, rods and cones. Cones provide sharp vision and colour perception in daylight illumination and are concentrated at the fovea, the central part of

FIGURE 4:
Right eye visual field for males and females

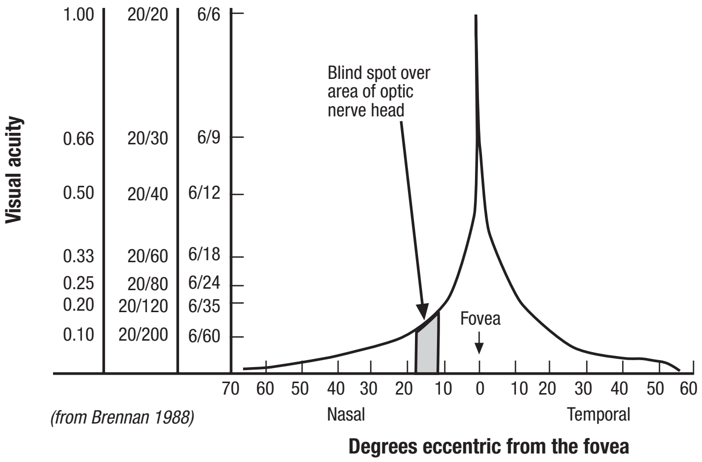


the retina on which an object appears if it is looked at directly. Rods are situated on the remainder of the retina surrounding the fovea on an area known as the peripheral retina. Although rods provide a black and white image of the visual field, they continue to operate at low light levels when the cones have ceased to function.

Vision can be considered to consist of two distinct systems, peripheral and foveal vision. Some important differences between the two systems are that colour perception and the detection of slow movement are best at the fovea, while detection of rapid movement is best in the periphery. In daylight, acuity (sharpness of vision) is greatest at the fovea, but with low light levels such as twilight, acuity is fairly equal across the whole retina. At night, acuity is greatest in the peripheral retina.

As figure 5 shows, acuity in daylight is dramatically reduced away from the direct line of sight, therefore a pilot must look at or near a target to have a good chance of detecting it.

FIGURE 5:
Variation of visual acuity



The variation of visual acuity (expressed in decimal, British and USA notation) at retinal sites eccentric to the fovea. The acuity at 5 degrees eccentric to the fovea is only one-quarter that at the fovea.

Peripheral and foveal vision each perform different functions in the search process. An object will generally be first detected in peripheral vision but must be fixated on the fovea before identification can occur.

Searching for traffic involves moving the point of gaze about the field of view so that successive areas of the scene fall onto the high-acuity area of the retina.

The eye movements in a traffic search occur in rapid jerks called saccades interposed with brief rests called fixations. We only see during the fixations, being effectively 'blind' during the saccades. It is not possible to move the eyes smoothly across a view unless a moving object is being tracked.

A number of factors can limit the effectiveness of visual searches.

2.3 Obstructions and available field of view

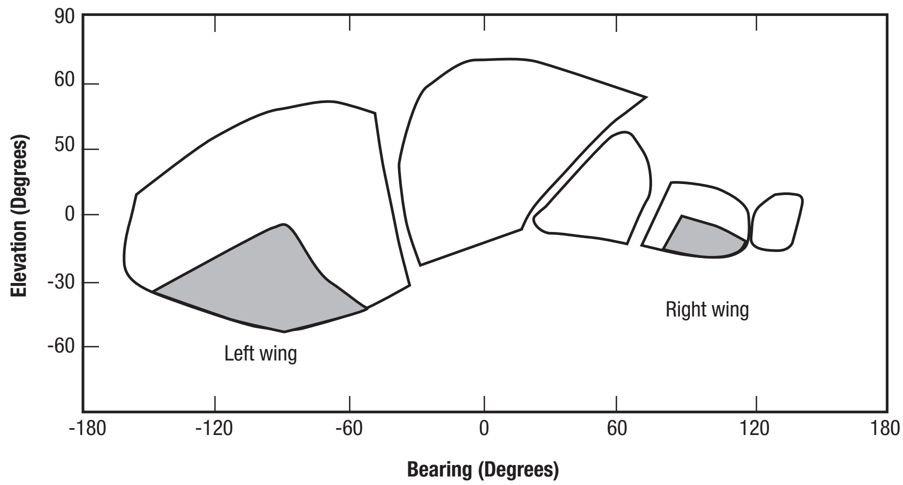
2.3.1 Cockpit visibility

Most aircraft cockpits severely limit the field of view available to the pilot. Figure 6 illustrates the limited cockpit visibility from a typical general aviation aircraft which because of its relatively slow speed, can be approached from any direction by a faster aircraft (figure 3). Visibility is most restricted on the side of the aircraft furthest away from the pilot and consequently, aircraft approaching from the right will pose a particular threat to a pilot in the left seat.

2.3.2 Obstructions

Obstructions to vision can include window-posts, windscreen bug splatter, sunvisors, wings and front seat occupants. The instrument panel itself may obstruct vision if the pilot's head is significantly lower than the standard eye position specified by the aircraft designers. The effects of obstructions on vision are in most cases self-evident. However there are some less obvious forms of visual interference.

FIGURE 6:
Limited cockpit visibility from a typical general aviation aircraft



In response to the Zagreb mid-air collision of 1976, Stanley Roscoe investigated the effects of cabin window-posts on the visibility of contrails (Roscoe and Hull 1982). Two significant effects were described:

First, an obstruction wider than the distance between the eyes will not only mask some of the view completely, but will result in certain areas of the outside world being visible to only one eye. A target which falls within such a region of monocular visibility is less likely to be detected than a similar target visible to both eyes.

A second undesirable effect of a window-post or similar obstruction is that it can act as a focal trap for the eyes, drawing the point of focus inwards, resulting not only in blurred vision but distorted size and distance perception. This effect is dealt with in more detail in a later section.

The findings of Roscoe and Hull have recently been replicated by Chong and Triggs (1989).

CAIR Report Number 1034

While on downwind, a PA28 joined the circuit on a distorted crosswind in such a position that he should have joined behind us, but instead he turned early and flew a closed downwind leg, we moved out and slowed down to give separation, my student then continued a normal circuit. Meanwhile the PA28 extended his downwind to the extend that when he was on a long final, we were once again on a collision course, we manoeuvred behind him. Even though the circuit was irregular the main concern is that the instructor was resting his head on his hand, with his elbow on the window sill, probably blocking his student's vision.

While they and us were on a parallel downwind legs I had a good view of the instructor's head. There is no way the instructor would have seen our C150. In fact I wonder if they saw us at all?

In my opinion, any occupant of the right seat should be instructed by the pilot to keep a look out , particularly in the circuit area. it is not the first time I have seen instructors joining a circuit do a number of touch and go's and disappear into the wild blue yonder without as much as lifting the head from its rest.

2.3.3 Glare

Glare occurs when unwanted light enters the eye. Glare can come directly from the light source or can take the form of veiling glare, reflected from crazing or dirt on the windscreen.

Direct glare is a particular problem when it occurs close to the target object such as when an aircraft appears near the sun. It has been claimed that glare which is half as intense as the general illumination can produce a 42 per cent reduction in visual effectiveness when it is 40 degrees from the line of sight.

When the glare source is 5 degrees from the line of sight, visual effectiveness is reduced by 84 per cent (Hawkins 1987). In general, older pilots will be more sensitive to glare.

2.4 Limitations of visual scan

2.4.1 A traffic scan takes time

The individual eye movements associated with visual search take a small but significant amount of time.

At most, the eyes can make about three fixations per second (White 1964) however, when scanning a complex scene pilots will typically spend more time on each fixation.

FAA Advisory Circular 90-48 C recommends scanning the entire visual field outside the cockpit with eye movements of ten degrees or less to ensure detection of conflicting traffic. The FAA estimates that around one second is required at each fixation. So to scan an area 180 degrees horizontal and thirty degrees vertical could take fifty four fixations at one second each = 54 seconds. Not only is this an impracticable task for most pilots, but the scene would have changed before the pilot had finished the scan.

Harris (1979) presents even more pessimistic hypothetical calculations. He estimates that under certain conditions, the search of an area 180 degrees by thirty degrees would require 2700 individual fixations and take around fifteen minutes!

2.4.2 Scan coverage

Visual scans tend to be unsystematic, with some areas of the visual field receiving close attention while other areas are neglected. An observer looking for a target is unlikely to scan the scene in a systematic grid fashion (Snyder 1973). Areas of sky near the edges of windscreens are generally scanned less than the sky in the centre (White 1964) and saccades may be too large, leaving large areas of unsearched space between fixation points.

2.5 Limitations of vision

2.5.1 Blind spot

The eye has an inbuilt blind-spot at the point where the optic nerve exits the eyeball. Under normal conditions of binocular vision the blind spot is not a problem as the area of the visual field falling on the blind spot of one eye will still be visible to the other eye. However, if the view from one eye is obstructed (for example by a window post), then objects in the blind spot of the remaining eye will be invisible. Bearing in mind that an aircraft on a collision course appears stationary in the visual field, the blind spot could potentially mask a conflicting aircraft.

The blind spot covers a visual angle of 7.5 degrees vertical and 5 degrees horizontal (Westheimer 1986).

At a distance of around 40 centimetres the obscured region is about the size of a twenty cent coin.

The obscured area expands to around 18 metres in diameter at a distance of 200 metres, enough to obscure a small plane.

The blind spot in the eye must be considered as a potential, albeit unlikely accident factor. It should be a particular concern in cases where vision is severely limited by obstructions such as window-posts, wings or visors.

2.5.2 Threshold for acuity

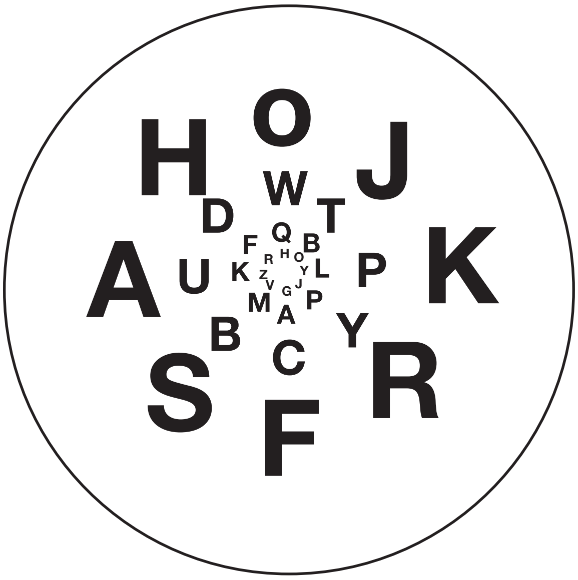
There are times when an approaching aircraft will be too small to be seen because it is below the eye's threshold of acuity.

The limits of vision as defined by eye charts are of little assistance in the real world where targets frequently appear in the comer of the eye and where acuity can be reduced by factors such as vibration, fatigue and hypoxia (Welford 1976, Yoder and Moser 1976). Certain types of sunglasses can also significantly reduce acuity (Dully 1990).

There have been attempts to specify how large the retinal image of an aircraft must be before it is identifiable as an aircraft. For example, the NTSB report into a mid-air collision at Salt Lake City suggested a threshold of twelve minutes of arc whereas a figure of between twenty four and thirty six minutes of arc has been suggested as a realistic threshold in sub-optimal conditions.

Unfortunately it is not possible to state how large a target must be before it becomes visible to a pilot with normal vision because visual acuity varies dramatically across the retina. Figure 7 illustrates how poor vision can be away from the direct line of sight.

FIGURE 7:
Chart showing how visual acuity varies across the retina



All the letters in the chart should be equally readable when the centre of the chart is fixated (Anstis 1986). It must be remembered that in most cases, an aircraft will be first noticed in peripheral vision.

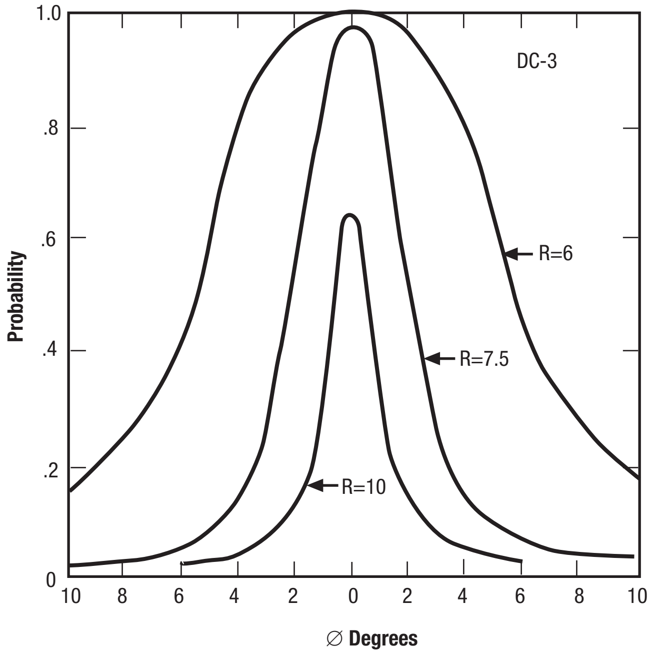
An effective way to visualise the performance of the eye in a visual detection task is with a visual detection lobe such as figure 8 which shows the probability of detecting a DC3 at various ranges and at various degrees away from the line of sight (Harris 1973). The figure illustrates that the probability of detection decreases sharply as the aircraft appears further away from the direct line of sight.

2.5.3 Accommodation

Accommodation is the process of focussing on an object. Whereas a camera is focussed by moving the lens, the human eye is brought into focus by muscle movements which change the shape of the eye's lens.

A young person will typically require about one second to accommodate to a stimulus (Westheimer 1986), however the speed and degree of accommodation decreases with age. The average pilot probably takes several seconds to accommodate to a distant object. Shifting the focus of the eyes, like all muscular processes can be affected by fatigue.

FIGURE 8:
Detecting a DC3 aircraft at various ranges and at various degrees away from the line of sight



2.5.4 Empty field myopia

In the absence of visual cues, the eye will focus at a relatively short distance. In the dark the eye focuses at around 50 cm. In an empty field such as blue sky, the eye will focus at around 56 cm (Roscoe and Hull 1982). This effect is known as empty field myopia and can reduce the chance of identifying a distant object.

Because the natural focus point (or dark focus) is around half a metre away, it requires an effort to focus at greater distances, particularly in the absence of visual cues. However, the ability to accommodate to greater distances can be improved by training (Roscoe and Couchman 1987).

2.5.5 Focal traps

The presence of objects close to the eye's dark focus can result in a phenomenon known as the Mandelbaum effect, in which the eye is involuntarily 'trapped' at its dark focus, making it difficult to see distant objects. Window-posts and dirty windscreens are particularly likely to produce the Mandelbaum effect.

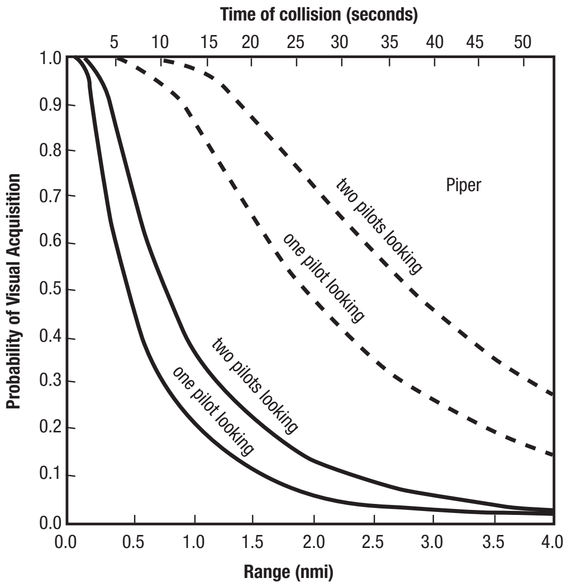
2.6 Psychological limitations

2.6.1 Alerted search versus unalerted search

A traffic search in the absence of traffic information is less likely to be successful than a search where traffic information has been provided because knowing where to look greatly increases the chance of sighting the traffic (Edwards and Harris 1972). Field trials conducted by John Andrews found that in the absence of a traffic alert, the probability of a pilot sighting a threat aircraft is generally low until a short time before impact. Traffic alerts were found to increase search effectiveness by a factor of eight. A traffic alert from ATS or from a radio listening watch is likely to be similarly effective (Andrews 1977, Andrews 1984, Andrews 1987).

A mathematical model of visual acquisition developed by Andrews was applied by the NTSB to the Cerritos collision between a DC9 and a Piper PA28. Figure 9 shows the estimated probability that the pilots in one aircraft could have seen the other aircraft before the collision.

FIGURE 9:
Estimated probability of visual acquisition



2.6.2 Visual field narrowing

An observer's functional field of vision can vary significantly from one circumstance to another (e.g. Leibowitz 1973, Baddeley 1972, Mackworth 1965). For example, although a comfortable and alert pilot may be able to easily detect objects in the 'comer of the eye', the imposition of a moderate workload, fatigue or stress will induce 'tunnel vision'. It is as though busy pilots are unknowingly wearing blinkers.

Visual field narrowing has also been observed under conditions of hypoxia and adverse thermal conditions (Leibowitz 1973). However, in aviation, cockpit workload is likely to be the most common cause of visual field narrowing.

CAIR Report Number 1037

I was tracking north along the coast at 1000 ft, flying NOSAR no details. I was looking down at houses below when a shout from a passenger alerted me to an on-coming C172 or C182 on a collision course.

The other aircraft was tracking coastal on a southerly heading at the same height. We both banked sharply right and probably passed with less than fifty metres between us. had we not sighted each other, a collision of some sort would have been a certainty. The passenger claims he heard the engine noise of the other aircraft as it shot past. Lack of vigilance on my part certainly contributed.

2.6.3 Cockpit workload and visual field narrowing

The limited mental processing capacity of the human operator can present problems when there is a requirement to fully attend to two sources of information at the same time. An additional task such as radio work, performed during a traffic scan can reduce the effectiveness of the search, even to the extent of reducing the pilot's eye movements and effectively narrowing the field of view.

A number of researchers have shown that peripheral stimuli are more difficult to detect when attention is focussed on a central task (e.g. Leibowitz and Apelle 1969, Gasson and Peters 1965) or an auditory task (e.g. Webster and Haslerud 1964).

Experiments conducted at NASA indicated that a concurrent task could reduce pilot eye movements by up to 60 per cent. The most difficult secondary tasks resulted in the greatest restriction of eye movements (Randle and Malmstrom 1982).

Talking, mental calculation and even daydreaming can all occupy mental processing capacity and reduce the effective field of vision.

2.7 Target Characteristics

2.7.1 Contrast with background

In determining visibility, the colour of an aircraft is less important than the contrast of the aircraft with its background. Contrast is the difference between the brightness of a target and the brightness of its background and is one of the major determinants of detectability (Andrews 1977, Duntley 1964). The paint scheme which will maximise the contrast of the aircraft with its background depends of course, upon the luminance of the background. A dark aircraft will be seen best against a light background, such as bright sky, while a light coloured aircraft will be most conspicuous against a dull background such as a forest.

2.7.2 Atmospheric effects

Contrast is reduced when the small particles in haze or fog scatter light. Not only is some light scattered away from the observer but some light from the aircraft is scattered so that it appears to originate from the background, while light from the background is scattered onto the eye's image of the aircraft.

Even in conditions of good visibility, contrast can still be severely reduced (Harris 1979).

Figure 10 graphs the amount of contrast reduction when visibility is five nautical miles. The graph illustrates that even at distances less than five miles, contrast can be greatly reduced.

2.7.3 Aircraft paint schemes

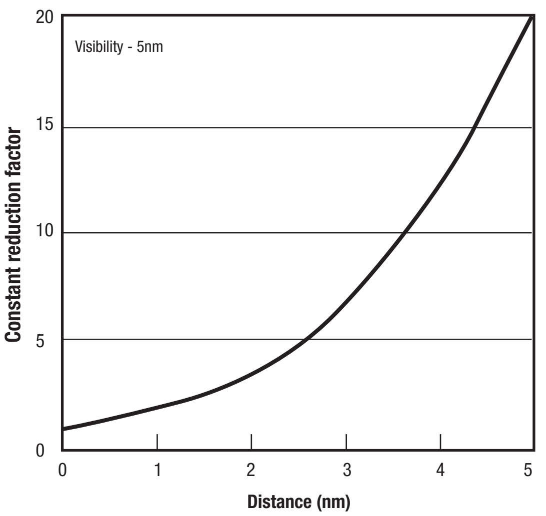
From time to time, fluorescent paint has been suggested as a solution to the contrast problem (Federman and Siege1 1973). However, several trials have concluded that fluorescent painted aircraft are not easier to detect than aircraft painted in nonfluorescent colours (Graham 1989).

Trials of aircraft detection carried out in 1961 indicated that in 80 per cent of first detections, the aircraft was darker than its background (Graham 1989). Thus a major problem with bright or fluorescent aircraft is that against a typical, light background, the increased luminance of the aircraft would only serve to reduce contrast.

In summary, particularly poor contrast between an aircraft and its background can be expected when:

- A light coloured aircraft appears against a light background
- A dark aircraft appears against a dark background
- The background luminance is low
- Atmospheric haze is present

FIGURE 10:
Contrast reduction with distance



(adapted from Harris 1979)

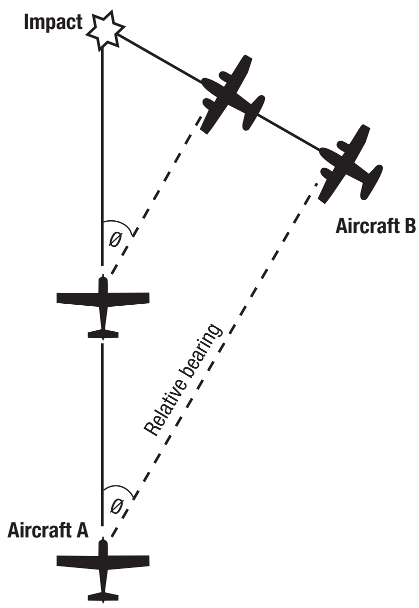
2.7.4 Lack of relative motion on collision course

The human visual system is particularly attuned to detecting movement but is less effective at detecting stationary objects. Unfortunately, because of the geometry of collision flightpaths, an aircraft on a collision course will usually appear to be a stationary object in the pilot's visual field.

If two aircraft are converging on a point of impact on straight flightpaths at constant speeds, then the bearings of each aircraft from the other will remain constant up to the point of collision (see figure 11).

From each pilot's point of view, the converging aircraft will grow in size while remaining fixed at a particular point in his or her windscreen.

FIGURE 11:
Lack of relative motion on collision course



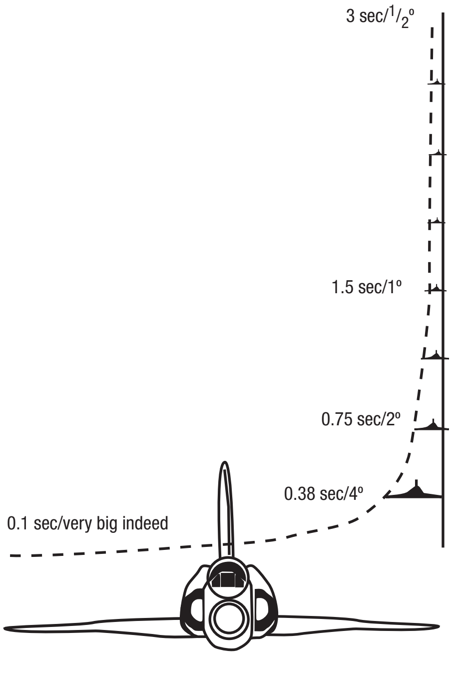
2.7.5 An approaching aircraft presents a small visual angle

An approaching high speed aircraft will present a small visual angle until a short time before impact. The following diagram illustrates the case of a GA aircraft approaching a military jet where the closing speed is 600 knots.

Not all situations will be this severe, first because only about one quarter of encounters are likely to be head-on (Flight Safety Digest 1989) and second because many encounters involve slower aircraft.

Given the limitations to visual acuity, the small visual angle of an approaching aircraft may make it impossible for a pilot to detect the aircraft in time to take evasive action. Furthermore, if only the fuselage is used to calculate the visual angle presented by an approaching aircraft, i.e. wings are considered to be invisible, then the aircraft must approach even closer before it presents a target of a detectable size (S teenblik 1988).

FIGURE 12:
Time to impact and angular size of oncoming aircraft



(from Aviation Safety Digest 1986)

2.7.6 Effects of complex backgrounds

Much of the information on human vision has come from laboratory studies using eye charts or figures set against clear 'uncluttered' backgrounds. Yet a pilot looking out for traffic has a much more difficult task because aircraft usually appear against complex backgrounds of clouds or terrain.

It is likely that an aircraft will be noticed first in peripheral vision but only identified when fixated on the fovea. In such a situation, peripheral vision will pick up objects everywhere, some of which may be conflicting aircraft.

The pilot is faced with the complex task of extracting the figure of an aircraft from its background. In other words, the pilot must detect the contour between the aircraft and background.

Contours are very important to the visual system. The eye is particularly attuned to detecting borders between objects and in the absence of contours, the visual system rapidly loses efficiency.

A finding of great importance to the visual detection of aircraft is that target identification is hampered by the close proximity of other objects (Wolford & Chambers 1984). A major cause of this interference is 'contour interaction' in which the outline of a target interacts with the contours present in the background or in neighbouring objects. Camouflage works of course, because it breaks-up contours and increases contour interaction. Contour interaction is most likely to be a problem at lower altitudes, where aircraft appear against complex backgrounds.

Contour interaction occurs in both foveal and peripheral vision but is a more serious problem in peripheral vision (Bouma 1970, Jacobs 1979). Harris (1979) has highlighted the problem of contour interaction in aviation. Figures 13 and 14 illustrate the possible consequences of contour interaction on the received image of an aircraft.

FIGURE 13:
The effect of background contours on aircraft recognition with no background

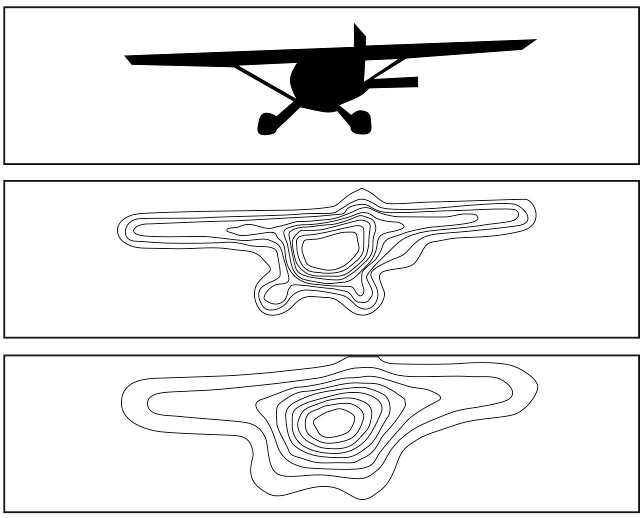
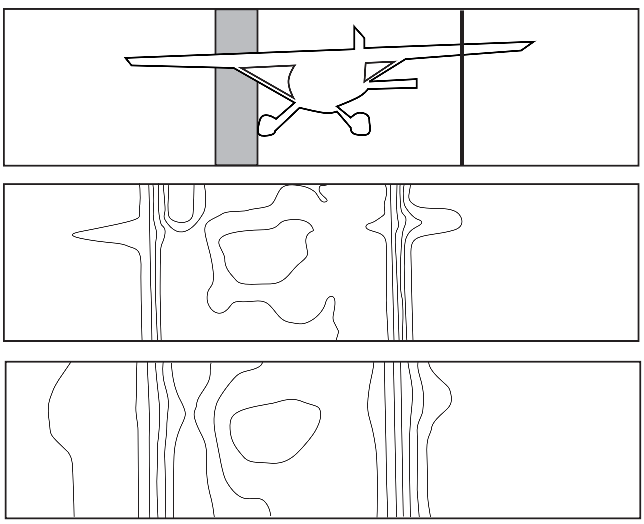


FIGURE 14:
The effect of background contours on aircraft recognition with background contours



(from Harris 1979)

2.8 Anti-Collision Lighting

2.8.1 Effectiveness of lights

There have been frequent suggestions that the fitting of white strobe lights to aircraft can help prevent collisions in daylight. At various times BAS1 and the NTSB have each recommended the fitting of white strobe anticollision lights.

Unfortunately, the available evidence does not support the use of lights in daylight conditions. The visibility of a light largely depends on the luminance of the background and typical daylight illumination is generally sufficient to overwhelm even powerful strobes. Some typical figures of background luminance are:

Table 1:
Luminance of common backgrounds

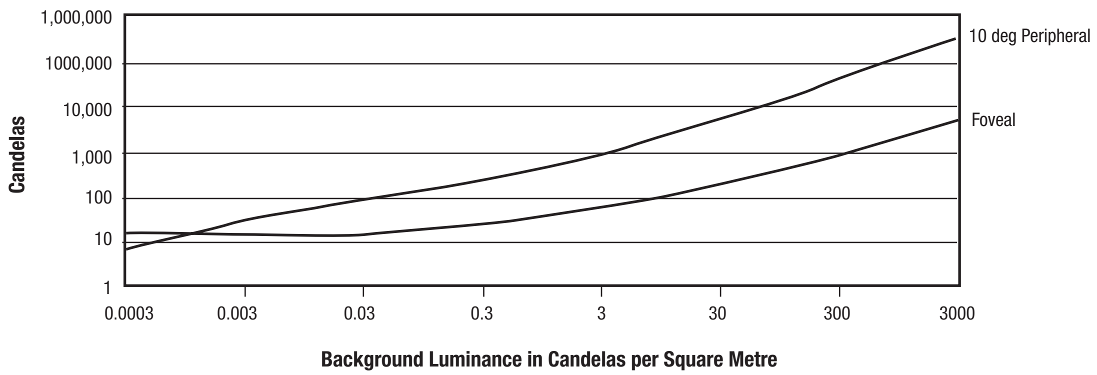
Background	*Candelas* per Square Metre*
Sky	
Clear day	3000.00
Overcast day	300.00
Very dark day	30.00
Twilight	3.00
Clear moonlit night	0.03
Ground	
Snow, full sunlight	16000.00
On sunny day	300.00
On overcast day (approx.)	30.00 to 100.00

(From IES Lighting Handbook, page 325)

* *A candela is approximately equal to a candlepower*

In theory, to be visible at three nautical miles on a very dark day, a strobe light must have an effective intensity of around 5000 candelas (see figure 15). In full daylight, the strobe must have an effective intensity greater than 100,000 candelas (Harris 1987). Most existing aircraft strobes have effective intensities of between 100 and 400 candelas.

FIGURE 15:
Required effective intensity in cadelas



(from Harris 1987)

Field trials have generally confirmed the ineffectiveness of strobes in daylight. The following U.S. military trials are outlined in a US Air Force report (Schmidlapp 1977).

1. In 1958 the USAF Air Training Command conducted flight tests to compare strobe anti-collision lights with rotating beacons. It was concluded that in daylight conditions, no lighting system could be expected to prevent collisions.
2. Further tests in 1958 at the U.S. Air Force's Wright-Patterson Base again found that strobe lights were ineffective in daylight.
3. A major U.S. Army study was conducted in 1970 in which observers on a hilltop were required to sight approaching helicopters equipped either with strobes of 1800, 2300 or 3300 effective candela or a standard red rotating beacon. It was found that none of the lights were effective against a background of daytime sky, however strobes were helpful when the aircraft was viewed against the ground.
4. U.S. Air Force tests in 1976 found extremely poor performance of strobe lights on aircraft. In all cases, the aircraft was sighted before the strobe. In addition, it was found that after two years service on aircraft, strobe lights were about half as intense as expected.
5. Extensive trials in 1977 by the US Air Force Aeronautical Systems Division used strobes fitted on a tower and observers at various distances and viewing angles. The results indicated that in daylight, even a strobe of 36000 candelas was not particularly conspicuous. However, strobes were more visible when the background illumination was less than 30 candelas per square metre, equivalent to a very dark day.

FAA studies have also concluded that there is no support for the use of strobes in daylight. A 1989 FAA study of the effectiveness of see-and-avoid concluded that 'Aircraft colours or lights play no significant role in first directing a pilot's attention to the other aircraft during daytime' (Graham 1989).

An earlier FAA study considered that there was 'little hope that lights can be made bright enough to be of any practical value in daylight' (Rowland and Silver 1972). A major FAA review of the aircraft exterior lighting literature concluded that 'During daytime, the brightest practical light is less conspicuous than the aircraft, unless there is low luminescence of background ...' (Burnstein and Fisher 1977).

In conclusion, while strobes are not likely to be helpful against bright sky backgrounds, they may make aircraft more visible against terrain or in conditions of low light.

2.8.2 Use of red lights

Until 1985, the then Australian Air Navigation Regulation 181 required aircraft to display a red flashing anticollision light. After 1985, the requirement was changed to allow either a red or white light or both.

The use of red warning lights in transport has a long history. Red lights have been used in maritime applications since the days of sail and red became the standard colour for danger on railways. An 1841 convention of British railwaymen decided that white should represent safety, red danger and green caution (Gerathewohl, Morris and Sirkis 1970).

It is likely that the widespread use of red as a warning colour in aviation has come about more because of common practice than any particular advantages of that colour.

2.8.3 White lights superior to red

There are reasons why red is not the best colour for warning lights. Humans are relatively insensitive to red (Leibowitz 1988) particularly in the periphery (Knowles-Middleton and Wyszecki 1960).

About 2 per cent of males suffer from protan colour vision deficiency and are less sensitive to red light than people with normal vision. A protan is likely to perceive a red light as either dark brown, dark green or dark grey (Clarke undated).

Any colour involving a filter over the bulb reduces the intensity of the light and field trials have shown that intensity is the main variable affecting the conspicuity of warning lights (Connors 1975). Given a fixed electrical input, the highest intensities are achieved with an unfiltered white lamu. In a comparison of commercially available warning lights, white strobes were found to be the most conspicuous (Howett 1979).

If an aircraft does carry an anticollision light, then it should be an unfiltered white light rather than a red light.

Caire Report Number 1133

I was given clearance by MC TWR to track 1000 coastal and report abeam the airfield. While I was concentrating on looking at airfield to give my position report, I saw another aircraft straight ahead. Fortunately, I was able to make a sharp left turn to avoid a collision. The plane approached out of nowhere and my forward vision was only relaxed for thirty seconds. I was given no warning of this plane by ATC and was complying with instructions. I don't know if the plane was doing circuits at MC or was transiting the zone.

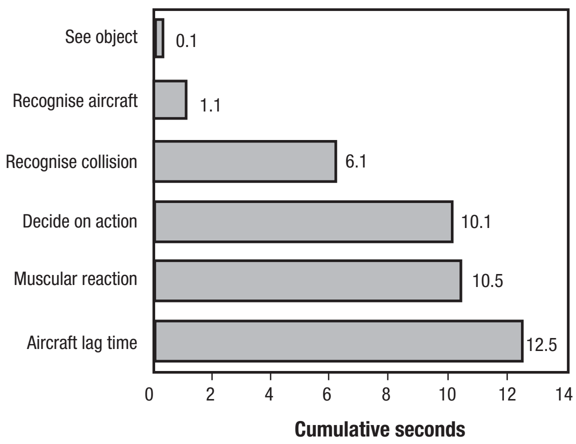
3 EVASIVE ACTION

The previous pages have dealt with the 'see' phase of see-and-avoid. However, it should not be assumed that successful avoiding action is guaranteed once a threat aircraft has been sighted.

3.1 Time required to recognise threat and take evasive action

FAA advisory circular 90-48-C provides military-derived data on the time required for a pilot to recognise an approaching aircraft and execute an evasive manoeuvre. The calculations do not include search times but assume that the target has been detected. The total time to recognise an approaching aircraft, recognise a collision course, decide on action, execute the control movement and allow the aircraft to respond is estimated to be around 12.5 seconds (see figure 16).

FIGURE 16:
Time to react to collision threat from FAA advisory circular

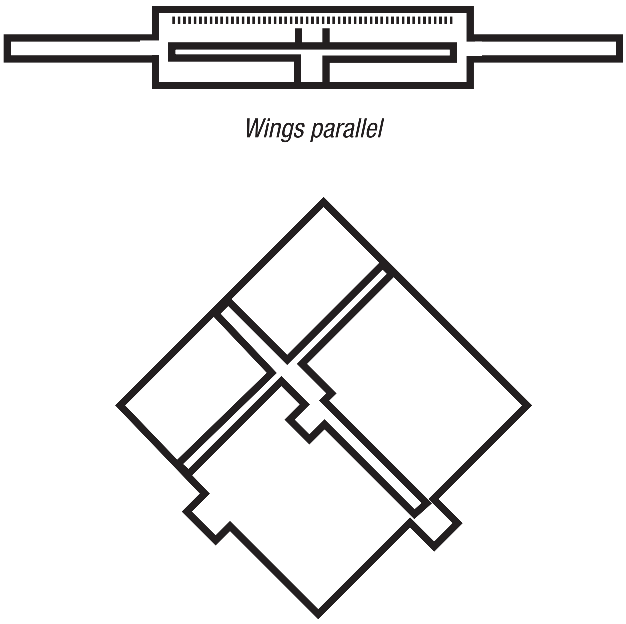


Therefore to have a good chance of avoiding a collision, a conflicting aircraft must be detected at least 12.5 seconds prior to the time of impact. However, as individuals differ in their response time, the reaction time for older or less experienced pilots is likely to be greater than 12.5 seconds.

3.2 Evasive manoeuvre may increase collision risk

James Harris in his paper *Avoid, the unanalysed partner of see* focuses attention on the 'avoid' side of seeing and avoiding (Harris 1983). He stresses that an incorrect evasive manoeuvre may cause rather than prevent a collision. For example, in a head-on encounter, a bank may increase the risk of a collision. Figure 17 illustrates this. In the top diagram, two (stylised) high-wing aircraft are approaching head-on with wings parallel. There is a limited number of ways in which the aircraft can collide if they maintain a wings-level attitude, and the area in which the two aircraft can contact or the 'collision cross-section' is relatively small. However, if the pilots bank shortly before impact, as in the lower diagram, so that the aircraft approach each other with wings perpendicular, then there is a much larger collision cross section and consequently, a higher probability of a collision. This is not to suggest that banks are always inappropriate evasive manoeuvres, but that in some cases, evasive action can be unsuccessful or even counterproductive. At least one foreign airline accident has been attributed to an unnecessary evasive manoeuvre (Civil Aeronautics Board 1966).

FIGURE 17:
Collision cross-sections



Wings parallel

Wings perpendicular

4 CONCLUSIONS

The see-and-avoid principle in the absence of traffic alerts is subject to serious limitations. It is likely that the historically small number of mid-air collisions has been in a large part due to low traffic density and chance as much as the successful operation of see-and-avoid.

Unalerted see-and-avoid has a limited place as a last resort means of traffic separation at low closing speeds but is not sufficiently reliable to warrant a greater role in the air traffic system. BASI considers that see-and-avoid is completely unsuitable as a primary traffic separation method for scheduled services.

Many of the limitations of see-and-avoid are associated with physical limits to human perception, however there is some scope to improve the effectiveness of see-and-avoid in other areas.

Although strobes cannot increase the visibility of an aircraft against bright sky, it is likely that high intensity white strobes would increase the conspicuity of aircraft against a dark sky or ground. There is no evidence that low intensity red rotating beacons are effective as anticollision lights in daytime.

Pilots and ATS personnel should be made aware of the limitations of the see-and-avoid procedure, particularly the psychological factors which can reduce a pilot's effective visual field. Pilots may be trained to scan more effectively and to accommodate to an appropriate distance when searching for traffic. Simply ensuring that the windscreen is clean and uncrazed will greatly increase the chance of sighting traffic.

There are important questions about the operation of see-and-avoid which can be answered by future BASI research. These include the question of how frequently Australian pilots scan for traffic and whether they scan significantly less in controlled airspace due to an over-reliance on ATS. The traffic scan training received by student pilots should be assessed. The visibility from aircraft should also be examined, with particular reference to windows and cabin obstructions.

The most effective response to the many flaws of see-and-avoid is to minimise the reliance on see-and-avoid in Australian airspace.

5 RECOMMENDATIONS

The following recommendations were issued as part of the BASI Research Report - 'Limitations of the See-and-Avoid Principle', 1991. At the time of the issue of that report the six recommendations were not assigned formal recommendation numbers. To facilitate publication of the recommendations and the responses to them, they have been entered into the OASIS database. As a result, the recommendation numbers assigned to them do not reflect the actual recommendation issue date.

Recommendation R20040015

The CAA should take into account the limitations of see-and-avoid when planning and managing airspace and should ensure that unalerted see-and-avoid is never the sole means of separation for aircraft providing scheduled services.

Note: The Recommendation was issued to the [then] Civil Aviation Authority (CAA) in 1991 and in 2001 the ATSB and CASA agreed that the word 'never' had been overtaken by the Australian Risk Management Standard.

CAA response received 29 April 1998

Firstly, we will be using our existing cost benefit formula (which is based on the proven FAA Formula) to mandate Class D airspace where traffic densities require.

CASA also proposes a complete package to address this important issue. Unfortunately, unalerted see and avoid can not be eliminated entirely, as even if primary and secondary radar, Class A airspace, mandatory radio, TCAS and transponders were deployed, there can always be a time, because of human factors or technical breakdown, that unalerted see and avoid becomes the primary means of separation.

The CASA proposal is to do everything we can, while still allocating the safety dollars effectively, to reduce the chance of unalerted see and avoid being the primary means of separation, whilst at the same time educating pilots on how they can improve their scan to improve the effectiveness of both alerted and unalerted see and avoid.

In relation to our package to improve the availability of alerted see and avoid, we have proposed to the airlines that in future, all airports serviced by scheduled services of over 10 passengers must have third party confirmation that the radio is on frequency. This will reduce the chance of an airline/aircraft being on the wrong frequency or the speaker is being deselected. We are also encouraging the fitment of Aerodrome Frequency Response Units which will operate 24 hours per day and reduce the chance of unalerted see and avoid. We are proposing to increase the number of recommended calls at non-tower aerodromes to seven, following the USA procedure. This will greatly assist alerted see and avoid.

In order to reduce the necessity to rely on see and avoid, we will be training VFR pilots to remain clear of areas of IFR traffic density, such as IFR air routes or IFR approach paths. These will be marked on maps in future. In relation to IFR aircraft, we will be training pilots to follow a recommendation to fly .1 nm to the right of track when flying on a marked air route between navigational aids or reporting points when the airway is used for two-way traffic.

In places where a tower is not cost effective and that have RPT services of over 10 passengers, we will have mandatory procedures in relation to alerting.

ATSB classification: OPEN

Further CAA response received 12 November 2001

At our meeting on November 3, I undertook to follow up CASA's response to the outstanding recommendations contained in the 1991 BASI research report on the *Limitations of See-and-Avoid*. As you would be aware, most of the recommendations - including those concerning TCAS and the education initiatives - have been implemented and continue to provide positive safety outcomes for Australian aviation.

In respect of the remaining recommendations, CASA provides the following response.

> 'The CAA should take into account the limitations of see-and-avoid when planning and managing airspace....'

CASA agrees that the limitations of see-and-avoid should be taken into account when planning and managing airspace. Where traffic densities are such that see-and-avoid does not provide the required level of safety, CASA will require Class D or a higher level of airspace.

> ....and should ensure that unalerted see-an-avoid is never the sole means of separation for aircraft providing scheduled services.'

CASA understands the intent of this recommendation but does not agree with its absolute form. The wording of the recommendation reflected its time and was prior to the 1995 Standards Australia AS/NZS4360 Risk Management Standard. CASA also understands that the use of the absolute 'never' is not consistent with current ATSB practice.

To accept the absolute form of the recommendation would require the allocation of Class D or higher airspace wherever scheduled services operate. This would result in an allocation of resources that is not commensurate with risk.

ICAO Class E and G airspace specifically has no radio requirement for VFR aircraft. ICAO has introduced both of these classifications with the full knowledge of the limitations of see-and-avoid. ICAO makes no recommendation in relation to scheduled services not operating in these airspace classifications.

Overly discounting the effectiveness of see-and-avoid and devising unique procedures has itself led to unintended consequences that are unresolved. Pilots may scan significantly less and become over reliant on radio alerting through a concept known as diffusion of responsibility. The BASI report RP/93/01 (December 1993) and the continuing incident reports that are being filed listing near misses in mandatory radio Class E and G airspace may support this concern. CASA believes that radio alerting is only effective when the alerting area is small with readily identifiable reporting points so that the alert is specific.

ATSB classification: CLOSED-ACCEPTED

Recommendation R20040016

In light of the serious limitations of the see-and-avoid concept, the CAA should continue to closely monitor the implementation of TCAS in the US and should consider the system for Australia.

Note: The Recommendation was issued to the [then] Civil Aviation Authority (CAA) in 1991.

CAA response received 28 April 1998

Agreed and will be introduced where cost effective.

ATSB classification: CLOSED-ACCEPTED

Recommendation R20040017

The CAA should ensure that pilots are trained in effective traffic scans.

Note: The Recommendation was issued to the [then] Civil Aviation Authority (CAA) in 1991.

CASA response received 29 April 1998

Agreed and CASA will continue to emphasise that see-and-avoid is a key factor in collision avoidance and pilots should be vigilant.

ATSB classification: CLOSED-ACCEPTED

Recommendation R20040018

The CAA should require white strobes rather than red rotating beacons to assist visbility when the aircraft appears against dark backgrounds.

Note: The Recommendation was issued to the [then] Civil Aviation Authority (CAA) in 1991.

CASA response received 29 April 1998

CASA feels that rotating beacons and strobe lights should be used whenever an aircraft is airborne or is taking off, landing, or taxying or being towed (including temporarily stopped while being towed) on an active runway. Pilots are not always able to assess when the display of these lights is effective, so CASA recommends their use on every flight.

ATSB classification: OPEN

Further CASA response received 12 November 2001

CASA does not accept this recommendation. Whilst it is acknowledged that there are some circumstances in which visibility would be enhanced by the use of white strobe lights in place of red rotating beacons there would only be a marginal reduction in the level of risk when taken in the total context of collision avoidance strategies. CASA would not be able to sustain with industry, the argument for such equipage on a demonstrable cost benefit basis.

ATSB classification: CLOSED-ACCEPTED

Recommendation R20040019

The CAA should ensure that pilots are aware of the physiological and psychological limitations of the visual system.

Note: The Recommendation was issued to the [then] Civil Aviation Authority (CAA) in 1991.

CASA response received 29 April 1998

CASA agrees with both the above recommendations. However CASA believes that the limitations have been promoted to the extent that benefits of the visual system may have become seriously discounted. As a consequence, CASA will continue to emphasise the requirement to be vigilant.

ATSB classification: CLOSED-ACCEPTED

Recommendation R20040020

Pilots should recognise that they cannot rely entirely on vision to avoid collisions. Consequently, they should attempt to obtain all available traffic information, whether from Air Traffic Services or a listening watch, to enable them to conduct a directed traffic search.

CASA response received 29 April 1998

CASA agrees with both the above recommendations. However CASA believes that the limitations have been promoted to the extent that benefits of the visual system may have become seriously discounted. As a consequence, CASA will continue to emphasise the requirement to be vigilant.

ATSB classification: CLOSED-ACCEPTED

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