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13. ABSTRACT

Ten volunteers were exposed to high intensity double pulse light flashes with flash fields subtending 1°, 3°, 5°, 10°, and 15° of visual angle. Flashblindness recovery times for several aircraft instruments were measured for each flash field diameter. Countermeasures including looking around the afterimage and body movement were permitted on some of the trials. Recovery time increased as the adapting flash visual angle was increased from 1° to 15°. Instruments requiring a greater visual acuity to be read had substantially longer recovery times than instruments requiring less. The two countermeasures listed above were found to be helpful in reducing recovery time.

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Effect of Flash Field Size on Flashblindness in an Aircraft Cockpit

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Ten volunteers were exposed to high intensity double pulse light flashes with flash fields subtending 1°, 3°, 5°, 10° and 15° of visual angle. Flashblindness recovery times for several aircraft instruments were measured for each flash field diameter. Countermeasures including looking around the afterimage and body movement were permitted on some of the trials. Recovery time increased as the adapting flash visual angle was increased from 1° to 15°. Instruments requiring a greater visual acuity to be read had substantially longer recovery times than instruments requiring less. The two countermeasures listed above were found to be helpful in reducing recovery time.

THE UNANTICIPATED EXPOSURE of unprotected combat pilots to the high intensity light emitted during a nuclear detonation can produce retinal burns, flashblindness, or both. Retinal burns are permanent lesions of the retina and underlying tissue layers which result from directly viewing extremely high intensity light sources such as nuclear detonations, lasers, and the sun. In contrast, flashblindness is only a temporary visual loss lasting from several seconds to a minute or more. Flashblindness is usually considered to be the greater operational problem since it may be caused not only by direct viewing but also by diffuse reflections of the fireball from clouds, the terrain below, or the aircraft. Hence, the angular subtense and reflectivity of the object or objects viewed at the time of a detonation must be considered in evaluating the flashblindness hazard in any combat situation.

The visual characteristic of flashblindness is the formation of an afterimage which appears in the visual field as a bright area of the same size and shape as the flash field. The veiling luminance of the afterimage prevents an observer from perceiving visual detail in the portion of his visual field which is masked by the afterimage. The afterimage persists for some time but gradually fades as visual function is restored. The elapsed time between flash exposure and when an observer can again distinguish pertinent details of a visual display is called *recovery time.* While an afterimage may persist five minutes or more, recovery times are usually much shorter, for an observer can often distinguish visual detail through an afterimage soon after it begins to fade, especially if the level of ambient illumination is high.

Experimental investigations of flashblindness are numerous. Most have been controlled laboratory studies using trained subjects, Maxwellian-view optical systems, single pulse flashes, and Snellen letters or gratings as recovery targets. While these experiments may be adequate from a scientific viewpoint, they are often less than satisfactory for military planners who must predict flashblindness incapacitation under entirely different circumstances (i.e., free viewing, two-pulse flashes, and aircraft instruments as recovery targets). Nevertheless, laboratory investigations have delineated the variables which affect recovery time. These variables include flash intensity and duration,[7,10,11,12] visual angles subtended by the flash field[3,10,11] and recovery targets,[7,10,11] target luminance,[7,10,11] preflash adaptation,[4,10] pupil diameter[4,12] and retinal locus of the afterimage.[3]

A lesser number of studies have been published concerning flashblindness as it might affect military aircrews. Alder[1,2] and Hamilton[5,6] have done flashblindness experiments in aircraft and aircraft flight simulators. Their studies dealt primarily with loss of aircraft control during flashblindness and differences in recovery times for different aircraft. They did not attempt to replicate any of the parametric laboratory studies concerned with the variables which affect recovery time, nor did they measure recovery time for any instrument except the gyrocompass.

The primary objective of the present study is to determine the effect of flash field size on flashblindness recovery time in an aircraft cockpit for several different flight instruments. This information is needed for two reasons:

1. The findings of similar laboratory studies have been contradictory. Miller[10] has reported that foveal recovery times decrease as the flash field diameter is increased from 2.5° to 10° of visual angle, while Chisum[3] and Miller and White[11] have noted an increase in recovery time as the adapting flash visual angle is increased from ½° to 10°.

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2. Recovery targets in almost all flashblindness experiments have been letters, numbers, or gratings requiring a relatively high visual acuity. However, many aircraft instruments require considerably less acuity to be read, particularly those having large pointers or bars. For this reason generalizations of laboratory findings to an aircraft cockpit may not be valid, particularly since Miller[10] has pointed out that the visual angle subtended by the critical detail in a target display is an important variable affecting recovery time.

MATERIALS AND METHODS

Apparatus—The USAF School of Aerospace Medicine's B-47 Flashblindness Orientation-Training (FOT) system shown in Figures 1 and 2 was modified for use as the experimental apparatus. The FOT System consists of a light-tight, instrumented mock-up of the B-47 cockpit with a two pulse high intensity flash source attached.

The first pulse of the adapting flash was provided by a General Electric FT 503 flash tube mounted within an 11½-inch parabolic reflector assembly. The exit aperture of the reflector was completely covered with a circular diffusing plate in order to provide uniform luminance up to 7.5° in all directions from a central fixation cross etched on the plate's front surface. The fixation cross and diffusing plate were continuously illuminated from behind prior to the flash by a type EAK modeling lamp located inside the FT 503. The investigator adjusted the intensity of the modeling lamp until the luminance of the fixation point and diffusing plate, as measured with a direct reading photometer, was .2 mL. Flash field diameter could then be varied by placing, on the front surface of the diffusing plate, templates with circular apertures subtending 1°, 3°, 5°, 10°, or 15° of visual angle at 35 inches, the normal viewing distance.

The peak luminance of the adapting flash delivered by the FT 503 was measured by a procedure briefly outlined below. The output of the photomultiplier (PM) tube of a Gamma Scientific model 700-16 photometric telescope (complete with photopic eye response filter) was connected to the input of a Tektronix type 549 storage oscilloscope. The photometric telescope was aligned to measure the luminance of a 100 mL standard source. The sensitivity of the oscilloscope and the voltage on the telescope's PM tube were adjusted until the investigator observed a full scale deflection of the oscilloscope beam. The telescope was next positioned to measure the peak luminance of the FT 503 diffusing plate. The investigator placed a stack of calibrated neutral density filters in front of the PM tube, flashed the FT 503 several times, and added or subtracted filters as needed until the peak deflection of the stored oscilloscope trace was again full scale. The total optical density (OD) required to reduce the luminance of the FT 503 to 100 mL was 6.2. Since OD = log (1/transmission), the unattenuated luminance of the adapting flash was 1.6×10^8 mL. Flash duration between one-half peak amplitude points was 2 msec.

Five Colortran tungsten-halogen "quartz" lamps positioned in a semicircular arc across the canopy top as shown in Figure 2 provided the second pulse. Activated by the trailing edge of the first pulse, the "quartz" lamps remained on for two seconds and illuminated the B-47 instrument panel with 100 ft-c. These secondary sources did not affect recovery time, however, since they were situated so their filaments were not visible to subjects seated in the FOT device and fixating on the FT 503 reflector's diffusing plate.

The B-47 altimeter, gyrocompass, and airspeed indicator were used as recovery targets in this study. They were illuminated only by the red nighttime cockpit lights normally found in the B-47. The gyrocompass is located in the upper central portion of the instrument

Fig. 1. USAF School of Aerospace Medicine's B-47 Flashblindness Orientation-Training (FOT) Device with canopy raised.

Fig. 2. Interior of B-47 FOT Device showing position of flight instruments and location of flash sources

panel. The compass needle subtends 3.1° × 10′ and it had a mean luminance of .07 mL; the angular subtense of the entire instrument is 7.3°. Located slightly below and to the left of the gyrocompass, the altimeter subtends 4.5°. Its longest hand has an angular subtense of 1.6° × 10′ and had a luminance of .3 mL. The airspeed indicator also subtends 4.5° of visual angle. Located slightly below and to the right of the gyrocompass, the numerals in the central window of the airspeed indicator subtend 20′, although the critical detail of each numeral subtends only 4′. The luminance of the airspeed indicator was .2 mL.

Recovery times for each of the three instruments were measured independently with three electric timers (Industrial Timer Corporation, model SC-100).

Subjects—Five commissioned officers and five enlisted personnel assigned to the Oculo-Thermal Function of the USAF School of Aerospace Medicine volunteered to serve as subjects. Each had a visual acuity of 20/100 or better, correctable to 20/20. All had normal dark adaption curves; none had detectable retinal damage or other eye disease.

Procedure—Each volunteer served once in each of the ten experimental conditions (see Table I). The order in which these 10 conditions were presented was independently determined for each subject from a table of random numbers. A preliminary study showed that the altimeter, gyrocompass, and airspeed indicator could be sequentially read as indicated in Table I without biasing the data.

The visual angles subtended by the adapting flash in conditions 1-3 were 1°, 3°, and 5°, respectively. Subjects were requested to identify as quickly as possible clockwise or counterclockwise movement of the altimeter hands (ALT) and the number—10, 20, 30, 40, 60, 70, 80, or 90—appearing in the central window of the airspeed indicator (ASI). In conditions 4-6 the adapting flash visual angles remained the same but subjects were required only to read the course heading—N, NE, E, SE, S, SW, W, or NW—indicated by the gyrocompass (GC). In conditions 7 and 9 the flash field subtended 10°; it subtended 15° in conditions 8 and 10. In these last four conditions the altimeter was read first, followed by the gyrocompass, and finally the airspeed indicator.

Limited countermeasures including looking around the afterimage and moving slightly forward were permitted except in conditions 9 and 10. In these two conditions subjects were required to remain in a fixed position and read their instruments through the decaying afterimage. Turning up cockpit lighting and excessive forward movement were prohibited in all conditions.

Prior to each exposure the subject dark adapted for two minutes while seated in the B-47 cockpit. From a console outside the cockpit the investigator set the three target instruments to their assigned readings for that trial as determined from a table of random numbers. At the conclusion of the adaptation period the fixation and instrument lights were turned on and the subject was instructed to take up fixation. The subject signaled his readiness for the adapting flash by depressing a hand-held switch. The investigator then presented the flash within two seconds, and the subject began verbally reading the target instruments in the proper sequence as quickly as he could. As soon as a

TABLE I. EXPERIMENTAL CONDITIONS

Condition	Adapting Flash Visual Angle	Instrument Reading Sequence	Countermeasures Permitted
1	1°	ALT, ASI	Yes
2	3°	ALT, ASI	Yes
3	5°	ALT, ASI	Yes
4	1°	GC	Yes
5	3°	GC	Yes
6	5°	GC	Yes
7	10°	ALT, GC, ASI	Yes
8	15°	ALT, GC, ASI	Yes
9	10°	ALT, GC, ASI	No
10	15°	ALT, GC, ASI	No

ALT—altimeter; GC—gyrocompass; ASI—airspeed indicator

TABLE II. MEAN RECOVERY TIMES IN SECONDS AND THEIR STANDARD DEVIATIONS

		Adapting Flash Visual Angle						
		1°	3°	5°	10°	15°	10°LT	15°LT
Altimeter	$\bar{X}$	1.71	2.06	3.25	4.26	6.79	18.94	25.59
	S.D.	1.57	2.81	3.21	2.87	3.02	9.41	12.39
Gyro-compass	$\bar{X}$	2.29	2.59	3.79	13.18	20.60	37.31	48.27
	S.D.	2.62	2.35	2.64	11.64	14.88	14.98	29.07
Airspeed Indicator	$\bar{X}$	3.98	17.12	32.85	39.42	44.29	48.98	66.47
	S.D.	2.69	9.94	10.96	15.42	14.12	19.30	27.74

LT—Subjects were required to read the cockpit instruments through the afterimage. No countermeasures were permitted.

TABLE III. ANALYSIS OF VARIANCE SUMMARY

Source	d.f.	M.Sq.	e.t.	F	P
		ALTIMETER			
Flash Field Diameter (FFD)	4	1.291	FFD × Ss	7.550	< .01
Subjects (Ss)	9	.526			
FFD × Ss	36	.171			
		GYROCOMPASS			
FFD	4	10.846	FFD × Ss	21.576	< .01
Ss	9	2.166			
FFD × Ss	36	.486			
		AIRSPEED INDICATOR			
FFD	4	23.596	FFD × Ss	40.473	< .01
Ss	9	2.349			
FFD × Ss	36	.583			

A square root transformation of the data was performed prior to analysis.

TABLE IV. SUMMARY OF t-TESTS FOR 10° AND 15° FLASH FIELDS

Instrument	Comparison	t (one-tail test, 9d.f.)	P
Altimeter	10° vs 10° LT	-6.163	< .01
	15° vs 15° LT	-6.096	< .01
Gyrocompass	10° vs 10° LT	-5.866	< .01
	15° vs 15 °LT	-7.854	< .01
Airspeed Indicator	10° vs 10° LT	-2.228	< .05
	15° vs 15° LT	-3.937	< .01

target instrument was correctly read, the investigator immediately stopped the timer corresponding to that instrument. A correction factor of 4.25 seconds—2 seconds for flash duration plus 2.25 seconds for mean instrument reading time in the absence of a flash—was subtracted from the elapsed times indicated on each of the timers before the data were recorded. If the subject made an incorrect response, the data were discarded and the trial rerun at a later time. Subjects were given three days convalescence between flashes.

All subjects were given sequential instrument reading practice and several preliminary flashblindness trials with different flash field diameters. These preliminary sessions enabled them to become familiar with flashblindness countermeasures which were permitted.

RESULTS

Table II shows the mean recovery times and standard deviations of the ten subjects for each of the 21 instrument-flash field size treatments. *LT* refers to treatments in which subjects were required to *look through* the afterimage and were not permitted to use countermeasures. The mean recovery times for all treatments in which countermeasures were permitted are graphically presented in Figure 3. Figure 4 shows the mean recovery times of the 10° and 15° treatments. Since the variances increased with an increase in mean level, a transformation of the data was required before an analysis of variance could be validly performed. A square root transformation was used and the transformed data of the 15 treatments whose means are shown in Figure 3 were then analyzed in three Lindquist treatments x subjects analyses of variance.[8] For all three instruments recovery time was found to increase significantly as the visual angle subtended by the source was increased ($F = 7.550$, $F = 21.576$, $F = 40.473$, $P < .01$). Recovery times were greatest for the airspeed indicator and least for the altimeter. The analysis of variance summary table is presented in Table III.

Figure 4 shows the magnitude of reduction in recovery time attributable to looking around the afterimage and moving slightly forward. These countermeasures decreased mean altimeter recovery time by about 17 seconds or 75%. Mean gyrocompass recovery time was reduced by 25 seconds or 60%, and airspeed indicator recovery time was reduced by 16 seconds or 25%.

Six paired observation t-tests were done to determine the significance of the difference between 10° and 10° LT means and between 15° and 15° LT means for each target instrument. Table IV shows the results of these tests. In all cases the mean recovery times for LT treatments were significantly longer than for those of corresponding treatments in which countermeasures were permitted.

DISCUSSION

The function relating flashblindness recovery time and adapting flash visual angle for 20′ numerals of the airspeed indicator (luminance .2 mL) is similar in shape to those found by Miller and White[11] for 19′ Snellen letters (luminance 9.5 mL and 38 mL) and by Chisum[3] for a .33 acuity grating (luminance .4-8.3 mL). In this

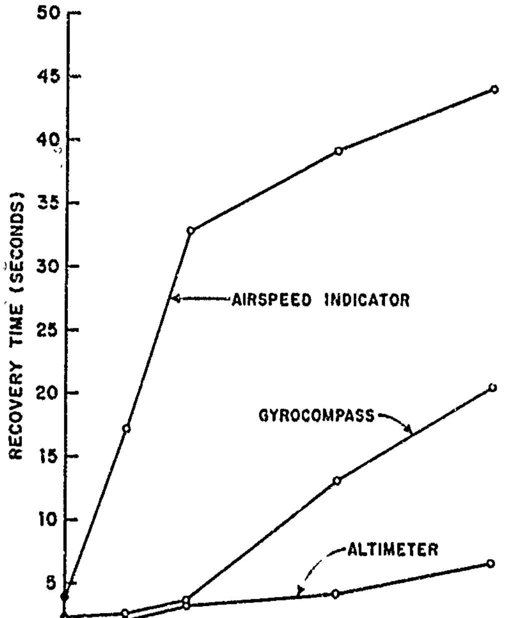

Fig. 3. Flashblindness recovery time as a function of adapting flash visual angle for three primary flight instruments.

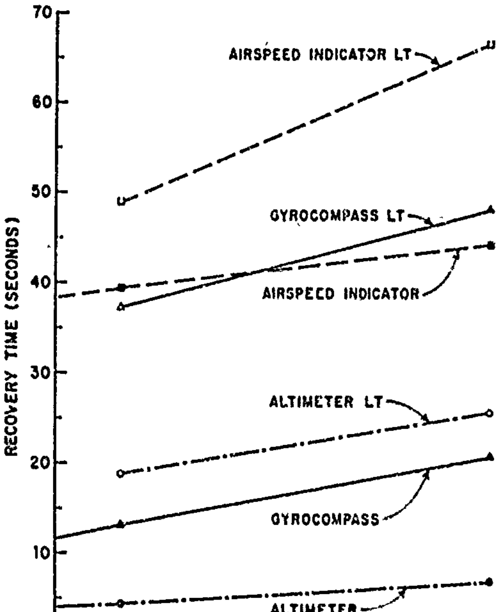

Fig. 4. Flashblindness recovery times for 10° and 15° flash field diameters as a function of use or non-use (LT) of counter measures for three aircraft instruments.

study recovery time for the 20′ numerals of the airspeed indicator increased as the visual angle of the source was increased from 1° to 15°, but the rate of increase was more rapid from 1° to 5° than from 5° to 15°. However, the slope transition point of the curves in the Miller and White[11] and Chisum[3] studies, which were done in Maxwellian view, is 2° rather than 5°.

The function relating recovery time and angular subtense of the source for the airspeed indicator numerals is dissimilar, however, to the one found by Miller[10] for 20′ Snellen letters (luminance .07 mL). She found recovery time decreased as the visual angle subtended by the source was increased from 2.5° to 10°.

The large differences in recovery times between the airspeed indicator and the other two instruments probably reflect the involvement of different underlying visual processes. Numerals of the airspeed indicator with a luminance of .2 mL and critical detail subtending 4′ cannot be recognized at distances greater than about 2.5° from the line of fixation,[9] indicating they are seen with foveal and parafoveal elements. On the other hand, the critical detail of the gyrocompass and altimeter (i.e., width of the needle or hands) subtends 10′. These two instruments can be read by peripheral mechanisms at retinal eccentricities—distances from the center of the fovea—of 7½° and greater.[9] Hence, an observer could read the altimeter and gyrocompass by looking around the afterimage for all flash fields used in this experiment. The altimeter was easier to read relative to the gyrocompass because it was brighter and was moving.

A general function can be promulgated which relates recovery time to adapting flash visual angle and which has three components or segments. The slope of the first is essentially zero. It extends from 0° to 5° for the gyrocompass and from 0° to 10° or 15° for the altimeter. Recovery targets can be read almost immediately around the afterimage for all flash fields within the first segment's range.

The slope of the second segment is positive and the function fairly steep. As the angular subtense of the source is increased within the range of this component, an observer encounters increasing difficulty in reading an instrument by looking around the afterimage. The second component extends from 1° to 5° for the airspeed indicator and from 5° to 15° for the gyrocompass.

The slope of the third component is less than the slope of the second and eventually becomes zero. For flash fields of the third segment recovery time can be reduced very little, if any, by looking around the afterimage, because the visual receptors at these retinal loci are not capable of resolving the critical detail of the recovery target. The third component for the airspeed indicator extends from 5° to 15° and greater. It begins beyond 15° for the gyrocompass and altimeter.

The differences in recovery times between the LT and non-LT treatments shown in Figure 4 may now be explained. This difference of 26 seconds for the gyrocompass and 17 seconds for the altimeter may be attributed mostly to subjects looking around the afterimage in the non-LT treatments, since both instruments could easily be read around a 10° or 15° afterimage at the original distance.[9] The 16-second difference for the airspeed indicator probably was due to subjects moving forward, since all subjects reported it was extremely difficult, if not impossible, to read the airspeed indicator at the original distance around an afterimage subtending 10° or greater; some did not even attempt to do it. The "moving forward" hypothesis is also supported by Miller's[10] data. She found LT recovery time for Snellen letters decreases rapidly as the angular subtense of their critical detail is increased. Her data would predict a 10-15-second reduction in airspeed indicator recovery time for a subject who looked *through the afterimage* but moved forward in the cockpit about 15 inches.

Moving forward, while found to be an effective countermeasure, may not be advisable in some operational situations nor possible in some aircraft. In these cases the mean recovery times for an instrument requiring the same visual acuity as the airspeed indicator may be slightly greater (for sources subtending 10° or more) than would be predicted from the data in Figure 3.

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