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Magnitude of Visual Accommodation to a Head-Up Display

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This Head-Up Display (HUD) report
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MAGNITUDE OF VISUAL ACCOMMODATION TO A HEAD-UP DISPLAY*

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The virtual image symbology of head-up displays (HUDs) is presented at optical infinity to the pilot. This design feature is intended to help pilots maintain visual focus distance at optical infinity. However, the accommodation response could be nearer than optical infinity, due to an individual's dark focus response. This experiment measured accommodation responses of two age groups of airline pilots to: (a) static symbology on a HUD, (b) a landing site background at optical infinity, (c) the combination of the HUD symbology and the landing site background, and (d) complete darkness. Magnitude of accommodation to HUD symbology, with and without the background, was not significantly different from an infinity focus response for either age group. The dark-focus response was significantly closer than optical infinity for the younger pilots, but not the older pilots, a finding consistent with previous research. For present purposes, that the younger pilots had an infinity focus with HUD symbology, yet a dark focus closer than infinity, suggests that HUD imagery is a significantly strong stimulus to prevent the accommodation response from becoming myopic.

Head-up displays (HUDs) are designed to assist aircraft pilots by displaying flight-related information. The symbolic information is displayed in virtual images reflected from a semitransparent beam splitter, or combiner glass. Displays are presented superimposed over the pilot's line of sight, as he looks straight ahead through the aircraft windshield (i.e., when flying head-up).

One advantage of HUDs is to reduce the number of head-up and head-down transitions (looking alternatively out the window and at the instrument panel) pilots must make during the landing phase (Haines, Fischer, and Price, 1980; Jenny, Malone, and Schweickert, 1971). Another claimed advantage, based on the fact that HUD's optics present virtual images at optical infinity, is that pilots do not need to change visual focus (accommodation) distance when switching attention from the runway environment (at apparent optical infinity) to the HUD's symbology, or vice versa. Simply stated, this should help eliminate the need to change visual focus from one optical distance to another.

In spite of the optical design, there are reasons to suspect pilots may be unable to maintain an optical infinity focus distance with a HUD. One reason is that the distance the natural resting state of the eye's accommodation system focuses at is relatively close (approximately 2/3 m for college-age students) compared to optical infinity (Leibowitz and Owens, 1978; Simonelli, 1979). In addition, some common lighting conditions result in nearer-than-ideal focus distances (e.g., empty-field myopia). That is, the accommodation response is more near-sighted (myopic) relative to the distance at which the stimulus to accommodation is located. Under these lighting conditions, the magnitude of accommodation is either the same as the dark focus (resting state) response or at an intermediate distance between the dark focus distance and the stimulus distance. The best known of these "anomalous" myopias are night myopia, empty-field myopia, and instrument myopia (Leibowitz and Owens, 1975; Simonelli, 1979). Pilots do experience lighting conditions which can result in night myopia and empty-field myopia. Additionally, HUDs are designed for use during such lighting conditions. The question of interest, then, is whether the HUD symbology is a

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sufficiently strong stimulus to prevent the accommodation response from becoming myopic. That is, will pilots be able to maintain visual focus at or near optical infinity when using a HUD, or will their focus become myopic? A consequence of a myopic response is that the HUD symbology and the runway environment would appear blurred to the pilot. The degree of blur is potentially large because the dark-focus response can be quite far from optical infinity.

A complication of the above is that systematic changes in the magnitude of the dark-focus response occur with changes in age (Leibowitz and Owens, 1978; Simonelli, 1979). Leibowitz and Owens observed a mean dark-focus response of 1.52 diopters* (0.66 m) with a standard deviation of 0.77 diopters (1.30 m) for a group of 220 college students. Simonelli observed that 20-year-olds had a mean dark-focus response near 1.5 diopters (0.67 m), 30-year-olds near 1.0 diopters (1 m), 40-year-olds near 0.5 diopters (2 m), 50-year-olds near 0.3 diopters (3.3 m), and 60-year-olds near -1.0 diopters.

The variations across age groups in the dark-focus response have important implications for the use of HUDs. Any anomalous myopias experienced while using a HUD would be more or less troublesome depending upon the dark-focus response of a given pilot. For example, one would expect few focusing problems for a pilot whose dark focus was very near optical infinity (0 diopters). Conversely, severe focusing problems could exist for a pilot whose dark focus was far from optical infinity (e.g., 2.0 diopters or 0.5 m).

A further reason for questioning whether pilots will be able to maintain focus at optical infinity while using a HUD is the accommodation phenomenon known as the Mandelbaum effect (Owens, 1978).

> ". . .the Mandelbaum effect might be parsimoniously explained as an involuntary focusing preference for objects lying near the observer's characteristic dark focus distance. When confronted with two superimposed stimuli, one at the dark focus and one at some other distance, accommodation would show a bias toward that at the dark focus." (p. 646)

Owens reported that when observers were presented with two competing stimuli, they consistently focused on the stimulus optically nearer their dark-focus distance, even when it was not exactly at the distance corresponding to their dark-focus distance. Additionally, a pane of glass, when placed near a person's dark-focus distance, can serve as a sufficient stimulus for the Mandelbaum effect to occur (Owens, 1979). The consequence for HUDs is that a pilot who has a dark focus near the same distance as the HUD's combiner glass may involuntarily focus at that distance and not be able to maintain an infinity-focus distance. As with the anomalous myopias, the variations across different age groups in the dark-focus response adds complexity to the issue. Any potential focusing problems due to the Mandelbaum effect would be more or less troublesome depending on the pilot's dark focus distance.

It is also important to note that the magnitude of accommodation response is influenced by other factors in addition to the anomalous myopias and the Mandelbaum effect. Indeed, there are both autonomic and willful controls of the accommodation response (Randle, 1975). If the anomalous myopias and/or the Mandelbaum effect control the accommodation response, it is possible that some pilots will experience blurring of the HUD symbology and the landing site. It is also possible that few, if any, pilots would experience such blurring, if their accommodation response were controlled by some other factor, or factors, known to influence accommodation (e.g., volitional control). This investigation aims to measure the amplitude of the accommodation response to HUD symbology and to determine whether or not pilots actually experience any of the blurring effects discussed above.

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PREVIOUS HUD ACCOMMODATION RESEARCH

In an extensive review of HUD research (Jenny et al., 1971), the following statement was made:

> "Even though the whole question of optical errors is of great concern in relation to the HUD, very little investigation has been performed in this area." (p. VII–13)

*A diopter is defined as the reciprocal of the physical distance between the lens and object viewed (measured in m).

Recently, however, one study (Chisum and Morway, 1979) investigated some questions of interest to the present study. Testing one 24-year-old male, they found him able to maintain close to an infinity focus with a HUD. However, the subject's dark-focus response was not reported. Additionally, the brightness of the collimated, external scenes were very low (ranging from 0.023 to 0.067 fL), simulating a relatively dark condition.

CURRENT STUDY

The current study employed airline pilots spanning a relatively wide age range. Their accommodation response was measured continuously to four visual conditions. The hypotheses investigated were that the accommodation response: (a) to the HUD alone, simulating its use in darkness, would not be different from optical infinity; (b) to the HUD with a dim runway background, simulating the use of HUD in dusk, would not be different from optical infinity; (3) to complete darkness, the dark-focus response, would not be different from infinity for older pilots, but it would be different from infinity for younger pilots (specifically, closer to the subject's eye position).

METHOD

Subjects

All 12 subjects were captains, first officers, or flight engineers currently employed by a major commercial airline. Six were in one age group with a mean age of 27 years (25 to 30), and six were in a second age group with a mean age of 44 years (37 to 50). All subjects were emmetropic and had at least 20/20 uncorrected distance acuity. None wore glasses or contact lenses.

Apparatus and Stimuli

The subjects were presented four different visual conditions: (a) a static symbology displayed on a HUD with a dark background, (b) a high-fidelity, 35-mm color photographic aerial slide of a landing environment (back-projected onto a lightly diffused glass screen and viewed through a large-diameter, 0.64-m focal length collimating lens), (c) the combination of the HUD and the 35-mm slide, viewed through the HUD combining glass, and (d) complete darkness, obtained in a light-tight room with black curtains and a black ceiling.

The HUD employed was a flat-plate combiner with a 12.7-cm (5-in.) diameter exit lens manufactured by Kaiser Electronics, Santa Clara, California. The symbology was projected onto the combining glass, which allows a total horizontal field of view of 20° and has a reference eye position of 23 in. from the exit lens. The symbology employed (see fig. 1) approximated a simple Cartesian coordinate system, with evenly spaced horizontal and vertical grid marks, and a large zero in the upper-left quadrant. This zero overlayed the runway shown in the 35-mm slide when the HUD and slide were used in combination. All imagery was static and produced by a P1 phosphor (green). The typical luminance of any portion of the symbology, as measured with a Prichard photometer, was 7 fL.

The 35-mm color slide was an aerial photograph of a runway, approximately centered in the slide and surrounding environment, taken during an approach to the runway. The vertical and horizontal fields of view were approximately 7.5° and 11.25° in visual angle, respectively. The mean luminance of the slide was 0.2 fL. The image from the slide was back-projected onto a 3-ft×3-ft diffusing glass screen, placed approximately 2.29 m from the subjects' reference eye position. The image was viewed through a collimating lens (0.46-m high and 0.53-m wide), placed between the eye position and the screen. The lens distance from the screen was equal to the 0.64-m focal length of the lens. Thus, the lens served to collimate the image of the color slide. That is, when viewed from the reference eye position, the landing site appeared to be at optical infinity (as measured with a dioptometer).

All measurements of the subjects' accommodation responses were obtained with the optometer of an SRI Dual-Purkinje-Image Eyetracker (see fig. 2). This instrument is described elsewhere (Crane and Steele, 1978). The eyetracker and optometer employ infrared light sources. The outputs from the instruments were recorded continuously on a Beckman Instruments Type R Dynagraph Direct Writing Recorder.

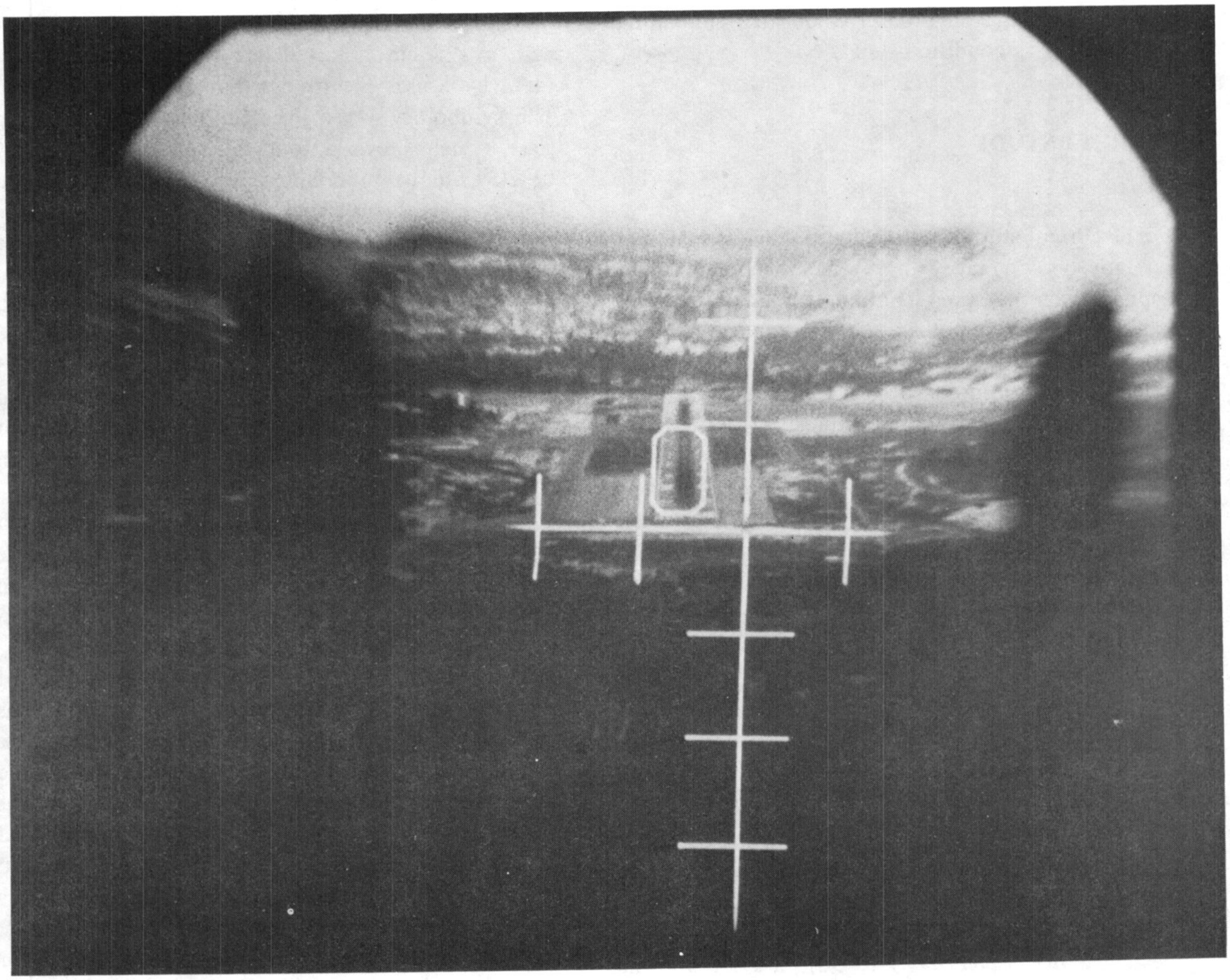

Figure 1.– HUD symbology superimposed over external scene.

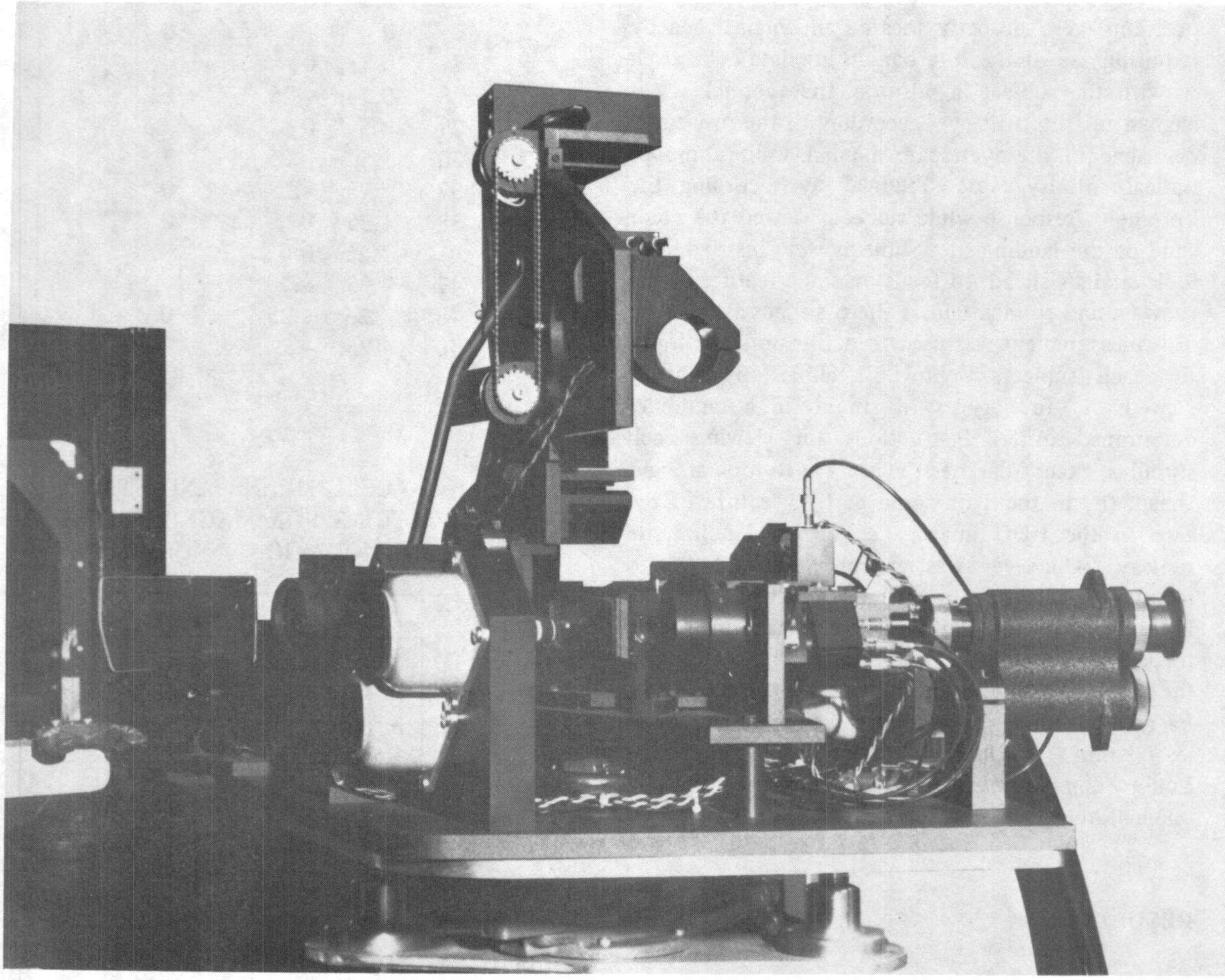

Figure 2.– Infrared Dual-Purkinje-Image eyetracker/optometer system.

Procedure

Upon arrival at Ames Research Center, subjects were shown the equipment to be used and given a general description of the research objectives. Each subject made a bite bar, which was mounted to a support frame next to the eyetracker. Their head positions were properly located and maintained by requiring use of the bite bar during data collection.

With the subject in position, the eyetracker was aligned for the right eye, according to the procedure described in the eyetracker manual. Calibrations of optical infinity were obtained by recording the optometer response while subjects viewed the color slide of the landing site. Subjects were instructed to look straight ahead, to focus on some feature of the runway, and to maintain as sharp a focus as possible. This measurement was used to define optical infinity for each subject. Following calibration, subjects viewed the four types of stimuli in a randomly determined order. Instructions for viewing each stimulus, except darkness, were: (a) to look straight ahead, (b) to focus on some part or feature of the zero in the HUD imagery or on the landing site runway (whichever was appropriate), and (c) to maintain the feature in as sharp a focus as possible. For the darkness condition, subjects were instructed to look straight ahead, but to relax the focusing of the eye, since there was nothing visible to focus upon. Each accommodation response was recorded for at least 1 min. Total time from the beginning of calibration to completion of data collection was typically one-half hour.

TABLE 1.– MAGNITUDE OF ACCOMMODATION RESPONSE OF INDIVIDUAL SUBJECTS IN DIOPTERS

Subject	Age	Dark	HUD	HUD with background	Infinity
1	25	0.5	0	0	0
2	25	0	-.5	0	
5	27	0	0	0	
6	28	0	.25	.25	
4	29	.5	0	.5	
3	30	1.5	.25	0	
7	37	.25	-.25	0	
8	38	1.25	0	0	
9	41	.25	0	.5	
11	47	-.25	-.5	-.25	
10	48	.25	.25	0	
12	50	-.25	-.5	.5	

TABLE 2.– CELL MEANS AND STANDARD DEVIATIONS FOR MAGNITUDE OF ACCOMMODATION IN DIOPTERS

Types of stimulus	Age			
	27 years		44 years	
	Mean	Standard deviation	Mean	Standard deviation
Dark	0.42	0.58	0.25	0.55
HUD	-.08	.26	-.17	.30
HUD with background	.13	.21	.13	.31
Infinity	.00	.00	.00	.00

RESULTS

The main hypotheses of the study were examined, with planned comparisons using magnitude of accommodation as the dependent variable. Table 1 gives the magnitude of the accommodation response for each subject to each stimulus.

Planned comparisons with the cell means for the age by type of stimulus interaction, shown in table 2, tested the main hypotheses of the experiment. To give a more complete picture of the pattern of performance, results from the two-way analysis of variance, on which the planned comparisons are based, are also reported (see table 3). The two-way analysis of variance (Dixon and Brown, 1977) included age as a between-subjects factor and type of stimulus as a within-subjects factor. The age factor had two levels: a group with a mean age of 27 and a group with a mean age of 44. The type of stimulus factor had four levels: a 35-mm slide of a landing site collimated to optical infinity, a head-up display, a head-up display with the landing site background, and darkness. The responses to these conditions will be referred to as infinity, HUD, HUD with background, and dark responses, respectively. Table 3 gives the analysis of variance summary. Comparison of the

TABLE 3.– ANALYSIS OF VARIANCE OF MAGNITUDE OF ACCOMMODATION RESPONSE

Source	Degrees of freedom	Sum of squares	Mean square	F test	Probability
Age (A)	1	0.05	0.05	0.36	0.56, N.S.
Error	10	1.31	.13		
Stimulus (S)	3	1.38	.46	4.07	.02
$A \times S$	3	.06	.02	.17	.92, N.S.
Error	30	3.38	.11		

four stimuli, using data from both age groups, was made to determine if the HUD focus response was more similar to the dark-focus response or to the infinity-focus response. The comparisons revealed that the dark response was significantly different (i.e., closer from the subjects' eye position) than either the HUD response or the infinity response – $F(1,40) = 11.54$, $p < 0.01$, and $F(1,40) = 6.12$, $p < 0.05$, respectively. However, the dark response was not significantly different from the HUD-with-background response – $F(1,40) = 2.29$ (NS). Additionally, the infinity response was not significantly different from either the HUD response or the HUD-with-background response – $F(1,40) = 0.85$ (NS) and $F(1,40) = 0.92$ (NS), respectively. Thus, the HUD and the HUD-with-background responses are not different from the infinity response, even though the dark response is different from, that is, closer than, the infinity response.

To test for age effects, planned comparisons between the four types of visual stimuli were performed with the data from each age group separately. For the younger group, the comparisons revealed that dark responses were significantly different (i.e., closer) from either the HUD response or the infinity response – $F(1,40) = 6.82$, $p < 0.05$, and $F(1,40) = 4.81$, $p < 0.05$, respectively. However, the dark response was not significantly different from the HUD-with-background response – $F(1,40) = 2.29$ (NS). Additionally, the infinity response was not significantly different from either the HUD response or the HUD-with-background response – $F(1,40) = 0.17$ (NS) and $F(1,40) = 0.46$ (NS), respectively. Thus, the pattern of results for the younger group is the same as observed for the combined groups.

For the older group, comparisons revealed that the dark response was significantly different (i.e., closer) from only the HUD response – $F(1,40) = 4.81$, $p < 0.05$. The dark response was not significantly different from the HUD-with-background response or the infinity response – $F(1,40) = 0.39$ (NS) and $F(1,40) = 1.70$ (NS), respectively. Additionally, the infinity response was not significantly different from either the HUD response or the HUD-with-background response – $F(1,40) = 0.79$ (NS) and $F(1,40) = 0.46$ (NS), respectively. Thus, the pattern for the older group is the same as observed for the younger and combined groups, except that the dark response is not significantly different from the infinity response. Thus, an age effect is observed for the dark response, but not for any responses involving the HUD. Specifically, the younger group, but not the older group, has a dark response that is significantly closer than the infinity response.

DISCUSSION

The magnitude of the accommodation response to the HUD alone, and HUD with background, for the combined and separate age groups, was not different from an infinity focus. From this finding alone, one cannot conclude that the HUD symbology is a sufficiently strong stimulus to accommodation to prevent a myopic response due to the anomalous myopias or the Mandelbaum effect. However, such a conclusion can be drawn for pilots whose focus with the HUD is not different from infinity and whose dark focus response is different from infinity. The two age groups combined and the younger group did have dark focus responses that were different from an infinity focus. However, this difference was not observed for the older group. The difference in findings for the two groups is consistent with the age-related changes in the dark-focus response reported by Simonelli (1979). The important point for present purposes is that the younger group did have dark-focus responses different from an infinity focus, yet their HUD and HUD-with-background responses were not different from an infinity focus. Thus, one may conclude that the HUD symbology is a sufficiently strong stimulus to prevent the accommodation response from becoming myopic.

There are two other characteristics of the visual accommodation system that can influence interpretation of magnitude of accommodation responses to a HUD: depth of focus of the human eye, and speed or rate at which one can change the accommodation response from one distance to another.

The eye, like any optical system, can only be sharply focused for one viewing distance at a time. There is, however, a depth of focus through which an object can be moved, while the eye is focused at some fixed distance, without resulting in any noticeable reduction in the image sharpness of the object. This is because humans are not capable of detecting the most minute amount of defocus, or reduction in image sharpness. Rather, a certain amount of defocus must occur before it can be detected. Consequently, when one is focused at some fixed distance, an object may move anywhere within some range of distances (centered in terms of diopters around the fixed focus distance) and maintain equivalent apparent image sharpness to the observer. Thus, one need not be accommodated exactly at optical infinity in order to see the HUD symbology as clearly as possible. As long as the distance to which one is accommodated is within the depth of focus, for a fixed focus at infinity, the symbology can be seen as clearly as possible.

The range of the depth of focus is directly dependent upon the observers ability to detect reductions in image contrast (due to blurring) and inversely dependent upon pupil diameter and visual acuity. In Green, Powers and Banks (Depth of Focus, Eyesize, and Visual Acuity; Vision Research, in press) details of calculating the depth of focus using the above relation are found. However, the depth of focus for adults to intermediate and high-acuity infomation seldom exceeds a quarter of a diopter, according to these authors.

In the event that a pilot is not focused at optical infinity or within the depth of focus while viewing a HUD, it would be useful to know how long it would take to change focus distance from that distance to optical infinity, or at least within the depth of focus. This information can be approximated from studies on the speed or velocity at which one can change accommodation distance. Although no studies on the speed of accommodation with a HUD exist, there are some studies on the speed of accommodation with other types of visual stimuli. One may refer to a recent paper for references to most of this research work (Tucker and Charman, 1979). Tucker and Charman and others have found the speed of accommodation to depend on several factors (e.g., the direction in which the accommodative change occurs). However, they do report an overall mean speed of accommodation of 2.2 diopters/sec. This value appears reasonable when compared with the results of others, although somewhat lower than is typically found. For example, Randle and Murphy (1974) obtained an overall mean that was approximately twice as great. Presently, there is insufficient research on the speed of accommodation to make any detailed judgments about the speed of accommodation one can expect from observers while using a HUD.

CONCLUSIONS

The data obtained from this experiment allow one to conclude that the HUD symbology is a sufficiently strong stimulus to accommodation to prevent the accommodation response from becoming myopic with a simple fixation and focus task and static imagery.

Additionally, it is not necessary to focus exactly at the optical distance of the HUD symbology (infinity), because it can be seen with no reduction of clarity anywhere within the observer's depth of field.

Lastly, when one is focused outside the depth of focus, it is possible to change accommodation distance reasonably rapidly (approximately 2 to 5 diopters/sec) to bring an object in focus. It is not known, however, what rate of change applies when HUD symbology is the visual stimulus.

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15. Supplementary Notes

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16. Abstract

The virtual image symbology of head-up displays (HUDs) is presented at optical infinity to the pilot. This design feature is intended to help pilots maintain visual focus distance at optical infinity. However, the accommodation response could be nearer than optical infinity, due to an individual's dark focus response. This experiment measured accommodation responses of two age groups of airline pilots to: (a) static symbology on a HUD, (b) a landing site background at optical infinity, (c) the combination of the HUD symbology and the landing site background, and (d) complete darkness. Magnitude of accommodation to HUD symbology, with and without the background, was not significantly different from an infinity focus response for either age group. The dark-focus response was significantly closer than optical infinity for the younger pilots, but not the older pilots, a finding consistent with previous research. For present purposes, that the younger pilots had an infinity focus with HUD symbology, yet a dark focus closer than infinity, suggests that HUD imagery is a significantly strong stimulus to prevent the accommodation response from becoming myopic.

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