Estimation of tunneling effect caused by luminance non-uniformity in head-up displays

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Head-up displays (HUDs) enable a pilot to manage aircraft activities by facilitating simultaneous access to the flight instrument data and to the outside scene. However, HUDs can also distract a pilot. This study shows that HUD luminance non-uniformity may force inappropriate distribution of attention between the events shown on HUD symbology and the outside scene because of the resultant differential contrast in the display area. Results of statistical analysis demonstrate considerable effects of HUD image luminance and ambient luminance, as well as their interaction, on the detection of events displayed on an HUD and the outside scene.

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Aircrafts host a multitude of displays such as head-up display (HUD), multifunctional display, standby display unit (SDU), head-mounted display (HMD), and associated systems (e.g., Mission Computer, Laser Designator Payload, etc.) to aid pilot operations. These systems process data from a host of sensors.

HUDs are vital components of aircraft cockpit instrumentation and overlay flight information on the pilot's forward view. HUDs and HMDs reduce stress for the pilot by avoiding adjustments required in the form of continual eye adjustments necessary to cope with varying focus, changing brightness, etc. Given the projection of a HUD image at optical infinity, a pilot need not refocus his eyes while switching his attention between interpreting events embedded in the outside scene and those displayed on the HUD[1−5]. However, a HUD may cause inappropriate attention capture and consequent tunneling (also called cognitive tunneling). Cognitive tunneling is a phenomenon that causes delay in the pilot's response time with respect to event detection, both regarding display symbology and the outside environment because of the existing cognitive load[6]. The reasons of cognitive load may be over engrossment in a scene or too much concentration on the symbology.

The presence and use of a HUD in the cockpit adds to the already complex system. The constant addition of new gadgets to the cockpit may lead to human factor problems, including workload and sensory overload. Achieving situation awareness (SA) for the pilot is the primary preference in the case of aviation. A commonly accepted definition of SA divides it into three distinct levels: Level 1 is the perception of elements in the environment within a volume of time and space, Level 2 is the comprehension of their meaning, and Level 3 is the projection of their status in the near future[7].

In the complex and dynamic aviation environment, information overload, task complexity, and multiple tasks can quickly exceed the aircrew's limited attention capacity. The resulting lack of SA can result in poor decisions, leading to human error[8]. Failure of SA occurs if any of these levels is not achieved, and most commonly, cognitive overload is the reason behind not achieving Level 1 of SA[9].

Among various factors associated with HUD that may cause tunneling are as follows: relative HUD image luminance (IL) and ambient luminance (AL)[10,11]. HUD luminance non-uniformity (NU) is a related parameter and has been discussed in detail. This parameter refers to differential symbologies, images, or outside scene luminance within the display field of the beam combiner. The effects of these three parameters on attention capture and tunneling during HUD use have been experimentally studied and statistically analyzed. This understanding can further help develop an automatic display contrast ratio adjustment methodology to comply with the situation of attention tunneling and a means for reducing it to a minimal possible range.

Attention capture describes the deterioration of responses to outside events due to diverted attention caused by data interpretation from a HUD image. Attention capture also refers to the deterioration of responses to data interpretation from a HUD image caused by diversion of attention in interpreting events embedded in the outside scene. Thus, the cognitive process of selective attention, divided attention, and the associated attention switching are involved. Situations wherein a particular task may capture most of the pilot's attention may arise and lead to filtering out of unattended information/data and missing out some important information[11−13].

During low-visibility conditions, the outside scene is captured as a thermal image by the forward looking infrared (FLIR) camera with flight symbology overlaid on it. Identical color, focal distance of symbology, and the outside captured image can make things very confusing. Luminance and the contrast parameters of a HUD image, relative movement, proximity of the outside objects and changes, and the symbols cause these confusions, which may pose difficulties to the pilots in correlating and understanding the raster and stroke forms of the image at the same time. However, this situation causes problems especially under low-visibility conditions because during day operations, the pilot simultaneously adapts to distant focusing on the HUD and to the outside view with relative ease[5,10,14].

Other probable causes of attention disruption may be misaccommodation and misconvergence (Mandelbaum effect), size misconception, and binocular misalignment. The Mandelbaum effect is observed when far objects are attempted to be viewed through nearer objects. Meanwhile, size perception affects distance judgment and gap acceptance. Binocular misalignment is observed when the visual system cannot combine vertical or horizontal disparity resultant caused by the scan of image distortion. The contrast interference resultant due to contrast variation in the outside scene and the HUD image further adds to the misperception. This factor depends on the degree to which the HUD image covers a given field of view and on the contrast of the HUD image against the background. However, relative movement between the HUD image and the events embedded in the outside scene considerably improves appreciation of the outside events and objects. Overall performance degrades if the HUD image contrast is either very high or very low. Other possible interference source include spatial locations, amount and data format, and limitations in the field of view. These restrictions may further deteriorate the attention optimization[10,15,16].

A HUD can function in three modes, namely, pure stroke mode of symbology (day mode), pure raster mode (night or low light conditions), and stroke-in-raster vertical flyback (night or low light conditions). As long as the luminance of an aircraft HUD image is kept appropriately between 1 and 7500 cd/m^2, a reasonable contrast can be obtained for ambient lighting ranging from twilight to bright sunny conditions. A display contrast of 1.2 is the minimum needed to barely view the HUD display[1,2,5].

Few defining factors influence the visibility of a HUD image and the outside scene on and through the HUD, respectively. These factors include HUD IL (symbology or FLIR raster video) and the outside world view reflected/seen from/through the combiners, diffused sunlight and skylight passing from combiners that mix with the HUD image and reduce feature contrast, and sunlight and skylight reflected from the outer glass, causing shine that further reduces the contrast. The range of contrast ratio required for maximizing HUD benefits is an optimum tradeoff between high and low contrasts[1,2,5,15,17,18].

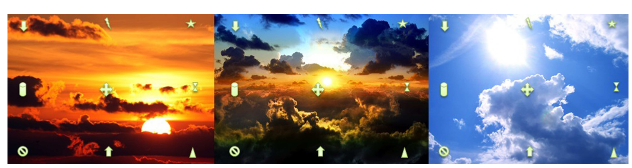
HUD limitation in the form of HUD luminance NU can affect the dynamic contrast ratio through and within the display field. This limitation may be contributed by the inherent NU of CRT, excess rise and fall times of the video and blanking signals, faulty folding mirror coating that bends the CRT image toward the combiners, faulty combiner coating that causes non-uniform, as well as wavelength variable reflections and transmission, along with the inappropriate overlap of primary and secondary combiners. The specification of HUD luminance is generally "luminance variations in nearby locations within the monocular field of view should not be more than +/− 35%," which may be too high for actual usage. Optical parameters in relation to HUD such as IL, accommodation, vergence, and contrast within the instantaneous and total field of view must be uniform across the entire field[5,18].

The experimental study used HUD system in a simulated environment. The simulated environment consisted of: varying outside scene and HUD image, varying AL, differential contrast, as well as, luminance on and through combiners to examine how participants would respond to events displayed on HUD image and the outside scene. The prime hypothesis was based on splitting of pilot's attention on HUD and the outside events depending on these conditions.

The experimental setup consisted of an HUD unit mounted on a cockpit mockup, signal simulator, overhead projector interfaced to the ambient environment simulation computer, and a bright light source capable of simulating AL of more than 50 000 cd/m^2 along with a light diffuser and a TV monitor. The experimental setup is shown in Fig. 1.

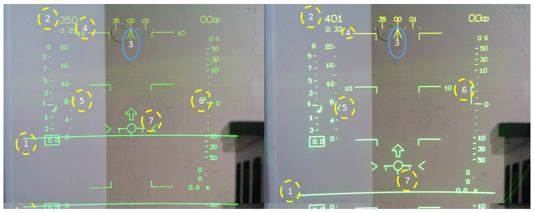
AL during the simulation was varied in three ranges: high AL (10000–30000 cd/m^2), mid AL (1000–5000 cd/m^2), and low AL (50–500 cd/m^2). AL was varied using a floodlight in the room, and luminance of the light was measured using a Pritchard photometer (part of the experimental setup). The dot in the photometer eyepiece (aperture of the photometer set at 2') was focused on the desired point to measure luminance at that same point. Furthermore, AL measurements were made at a particular point, say "O," by blanking the HUD image. IL was adjusted to 17 fixed levels through software control. To measure IL, the photometer was focused again on a point, say "O," with symbol luminance set at the desired level. The intention was to understand the response of the participants to events on the HUD image and on the outside scene when attention was modulated through the above discussion on luminance parameters. The outside scene (Fig. 2) was simulated using a projector coupled with a computer, whereas a HUD image (symbology) was generated using a HUD signal simulator. The participants were asked to give their judgment by looking through the HUD from a distance of 450 mm, which is generally the distance at which the pilot sits away from the HUD unit. Hence, the symbology overlapped on the outside scene simulated the exact HUD conditions.

Fig. 1. Experimental setup.



(a) (b) (c)

Fig. 2. Outside scene.



(a) (b)

Fig. 3. HUD image field.

The outside and HUD image event variations required participants to frequently alter their attention between the events on the HUD image/symbology and the outside scene. The differential contrast across and through the HUD image area caused by combined luminance NU was expected to cause delayed or missed detection of events. Moreover, the differential contrast varied depending on the existing contrast ratio on that particular field area. The correct adjustment of HUD IL is necessary in achieving appropriate contrast ratio (CR)[1], which is defined as

$$\text{CR} = (\text{Symbol Brightness}) \div (\text{Symbol Brightness} + \text{Ambient Brightness}).$$

The HUD image field was divided into zones covering the entire field. Coating on the combiner glasses caused differential transmission and reflection from the participants.

The experiments were carried out with the participation of 20 people including an equal number of males and females in the age group of 22 to 28 years. The experiment was conducted over all three ranges of AL with IL varying through its 17 levels and 4 levels of NU for each range. The aim was to study tunneling effect under high outside luminance (sunny day), medium outside luminance (normal cloudy day), and low outside luminance (twilight) conditions. The participants were required to report on two event changes. First is a report on any noticed change in designated areas on the HUD image field. Second is a report on any noticed change in the outside scene. The changes in the image field, namely, 1) horizon line, 2) airspeed, 3) heading scale, 4) Mach number, 5) angle of attack, 6) vertical velocity, and 7) instantaneous velocity vector were marked with numbers in Fig. 3. In the outside scenery, different symbols (including up arrow, down arrow, quad arrow, cylindrical shape, etc.) kept appearing and disappearing to check user awareness about the outside scenery, as shown in Fig. 2.

Automatic luminance control was disabled to conduct the experiments at the desired contrast settings and ensure that all participants experienced uniform test conditions. The participants were first asked to participate in the training session on the setup to acquaint them with the experimentation. The effect of fatigue factor on the final result was removed by carrying out experiments at forenoon and afternoon time. The participants were asked to answer a questionnaire to judge their responses in detecting event changes. They were also asked to respond to questions during every experimental setting of the outside-scene image displayed on the HUD and seen through combiners. Each participant was required to answer questions for the same setting, and two sets of readings were recorded. The questions were asked during the time when the participant was looking through the HUD and focusing on the scene and symbology. A total of 16 event changes (nine in the outside scene and seven on the symbology page, as depicted in Figs. 2 and 3) were asked to be identified in a single run. Score point "1" was awarded for every correct identification of the event changes, and a "0" was awarded for a miss. Scores for HUD event detection and outside event detection were individually recorded. The average scores of each participant for both set of readings were computed and subsequently recorded. The individual average scores of all participants for both HUD event detection and outside event detection were taken as the average for each instance (e.g., event detection percentage for HUD and outside scene at an AL value of 30 000 cd/m^2, IL value of 100 cd/m^2, and luminance NU level of 1:1.3 averaged for all participant scores). This final average score was used as the percentage observation value for the corresponding instance (operation variable values).

The contrast ratio was varied at different locations on the combiner display area in the experiment due to two factors: (i) ambient lighting prevailing through that particular location of the combiner, and (ii) luminance of the symbology or image at that location varying because of luminance NU. After data collection and mathematical analysis, data interpretation was performed as described below.

The collected data was extensive and divided into three broad ranges with respect to AL level (high, mid, and low). Within each range of AL, readings were collected for 17 levels of IL and 4 levels of NU for a selected AL value (e.g., in the case of high AL, for an AL of level 30000 cd/m^2, readings for 17 levels of IL at 4 levels of NU were taken). The readings were taken at regular intervals in every range to ensure the representation of all ambient conditions. Contrast ratio as defined above was simultaneously calculated for all instances.

Variation in contrast ratio as observed over the beam combiner is as follows:

(i) High AL for all 17 levels of IL: a) NU 1:1 (**1.003–1.8**), b) NU 1:1.15 (**1.002–1.695**), c) NU 1:1.30 (**1.002–1.615**), and d) NU 1:1.45 (**1.0023–1.55172**).

(ii) Mid AL for all 17 levels of IL: a) NU 1:1 (**1.02–9**), b) NU 1:1.15 (**1.017–7.956**), c) NU 1:1.30 (**1.015–7.153**), and d) NU 1:1.45 (**1.013–6.517**).

(iii) Low AL for all 17 levels of IL: a) NU 1:1(**1.1–161**), b) NU 1:1.15 (**1.086–140.130**), c) NU 1:1.30 (**1.076–124.076**), and d) NU 1:1.45 (**1.068–111.3448**).

The large amount of data collected and related statistical analysis can help elucidate the dependency of attention tunneling on the contributing factors and could also be used in the future for training neural networks for automatic adjustments. Literature provides proofs that the statistical reduction of the problem is an efficient solution for handling NU correction problems[19]. This direction of study would be taken up by the authors later on.

After data collection, statistical analysis was conducted using the MATLAB platform. Paired t-test was performed to check if significant differences existed in the event detection percentages for both cases, i.e., event detection on HUD image/symbology and outside scene. Paired t-test was performed on two data vectors. In this study, two vectors (event detection on HUD image and outside scene) are presented. Thus, a paired t-test was performed with the null hypothesis that data in the vectors HUD image and the outside scene event detection are independent random samples from normal distribution with equal means (no significant difference between the two) against the alternative that the means are not equal (the two vectors significantly differ from each other).

The paired t-test results show that $h = 1$ for all three ranges of AL and for all three ranges of luminance NU (resulting in differential contrast across the display field), indicating that the null hypothesis is rejected in both groups. The p values calculated for the data are as follows:

(i) High AL for all 17 levels of IL: a) NU 1:1 ($\boldsymbol{p = 2.4777 \times 10^{-24}}$), b) NU 1:1.15 ($\boldsymbol{p = 2.5254 \times 10^{-25}}$), c) NU 1:1.30 ($\boldsymbol{p = 5.7617 \times 10^{-26}}$), and d) NU 1:1.45 ($\boldsymbol{p = 1.7001 \times 10^{-26}}$).

(ii) Mid AL for all 17 levels of IL: a) NU 1:1 ($\boldsymbol{p = 0.0046}$), b) NU 1:1.15 ($\boldsymbol{p = 0.0109}$), c) NU 1:1.30 ($\boldsymbol{p = 0.0251}$), and d) NU 1:1.45 ($\boldsymbol{p = 0.0455}$).

(iii) Low AL for all 17 levels of IL: a) NU 1:1($\boldsymbol{p = 2.2923 \times 10^{-14}}$), b) NU 1:1.15 ($\boldsymbol{p = 1.4890 \times 10^{-15}}$), c) NU 1:1.30 ($\boldsymbol{p = 8.5354 \times 10^{-17}}$), and d) NU 1:1.45 ($\boldsymbol{p = 5.7107 \times 10^{-18}}$).

All p values lie below the significance level of 0.05, indicating that the means significantly differ for event detection observed on the HUD image and outside scene.

These results establish indicate a difference in the level of event detection on the HUD image and outside scene. However, the question on the significance of such difference and whether it depends only on variables (the varying AL, the varying HUD IL, the luminance NU, or all three factors) remains. ANOVA was used to verify these assumptions.

Three-way ANOVA was performed for all three ranges of AL, corresponding IL, and luminance NU for event detection on both HUD image and the outside scene. In the ANOVA summary table, the meanings of abbreviations are as follows: SS = sum of squares; df = degree of freedom; MS = mean square; $f = f$ value; p value = probability or level of significance (rejection of the null hypothesis when $p < 0.05$); f_{crit} = critical f value (rejection of null hypothesis when test statistic < critical value, i.e., $f < f_{crit}$). Error MS was used to obtain the f values for both factors. The null hypotheses could be stated as follows:

- H_{oA}: No difference exists in the percentage of event detection due to different AL.
- H_{oB}: No difference exists in the percentage of event detection due to different HUD IL.
- H_{oc}: No difference exists in the percentage of event detection due to luminance NU.
- H_{0AB}: No interaction of varying AL and HUD IL exists in causing significant difference in the percentage of event detection.
- H_{0AC}: No interaction of varying AL and NU of luminance exists in causing significant difference in the percentage of event detection.
- H_{0BC}: No interaction of varying HUD IL and NU of luminance exists in causing a significant difference in the percentage of event detection.
- H_{0ABC}: No interaction of varying AL, HUD IL, and luminance NU exists in causing a significant difference in the percentage of event detection.

When the first ANOVA was attempted with three-way interactions and type-3 sums-of-squares, all terms were marked by #. Thus, estimating the three-way interaction effects is impossible, and inclusion of the three-way interaction term in the model makes the fit singular. Also, the p value found for the three-way interaction term is much higher than 0.05.

Consequently, two-way ANOVA was conducted. Here, the p value for AL is <0.05, and $f > f_{crit}$, so the hypothesis that no difference exists in the percentage of event detection due to different AL can be rejected. The p value for HUD IL is also <0.05, and $f > f_{\text{crit}}$; hence, the hypothesis that no difference exists in the percentage of event detection due to different HUD IL can also be rejected. The p value for interaction is also <0.05; thus, the null hypothesis H_{0AB} is also rejected, meaning that their interaction is a significant factor contributing to the response "event detection." Similar trends could be seen from the ANOVA summary tables for the other combinations, i.e., H_{0A}, H_{0B}, H_{0C}, H_{0BC}, and H_{0AC}. The results obtained were presented in the ANOVA summary tables (Tables 1 to 6).

Table 1. Results of ANOVA Performed on Event Detection from HUD Image when AL is High

Source	AL	IL	NU	AL*IL
SS	3174.7	7214.8	522.8	693.9
df	2	16	3	32
MS	1587.34	450.93	174.26	21.68
f	1305.28	370.8	143.3	17.83
Prob > f	0	0	0	0
Source	**AL*NU**	**IL*NU**	**Error**	**Total**
SS	15.8	110.3	116.7	12005.6
df	6	48	96	203
MS	2.64	2.3	1.22	
f	2.17	1.89		
Prob > f	0.0526	0.0042		

Table 2. Results of ANOVA Performed on Event Detection from HUD Image when AL is in Mid-range

Source	AL	IL	NU	AL*IL
SS	8594	2331.8	524	648.3
df	2	16	3	32
MS	4297	1457.18	174.68	20.26
f	6600.2	2238.22	268.31	31.12
Prob > f	0	0	0	0
Source	**AL*NU**	**IL*NU**	**Error**	**Total**
SS	27.2	55.3	62.5	33226.2
df	6	48	96	203
MS	4.53	1.15	0.65	
f	6.95	1.77		
Prob > f	0	0.0091		

From the Table 1, following results can be deduced: AL, HUD IL, and luminance NU have a significant main effect on event detection from HUD image during high AL conditions. Interaction effects of (i) AL and HUD IL and (ii) HUD IL and luminance NU, have a significant effect on event detection from HUD image during high AL conditions. Interaction effect of AL and luminance NU have an insignificant effect on HUD event detection during high AL conditions.

From the Table 2, following results can be deduced: AL, HUD IL, and luminance NU have significant main effect on event detection from HUD image during medium AL conditions. Interaction effects of (i) AL and HUD IL, (ii) HUD IL and luminance NU, and (iii) AL and luminance NU, have a significant effect on event detection from HUD image during medium AL conditions.

Table 3. Results of ANOVA Performed on Event Detection from HUD Image when AL is Low

Source	**AL**	**IL**	**NU**	**AL*IL**
SS	1375.8	19486.6	96	2518.6
df	2	17	3	34
MS	687.9	1146.27	32.01	74.08
f	975.8	1625.15	45.39	105.02
Prob $> f$	0	0	0	0
AL*IL	**AL*NU**	**IL*NU**	**Error**	**Total**
SS	15.2	162.6	71.9	23764.9
df	6	51	102	215
MS	2.53	3.19	0.71	
f	3.59	4.52		
Prob $> f$	0.0029	0		

From the Table 3, following results can be deduced: AL, HUD IL, and luminance NU have a significant main effect on event detection from HUD image during low AL conditions. Interaction effects of (i) AL and HUD IL, (ii) HUD IL and luminance NU, and (iii) AL and luminance NU, have a significant effect on event detection from HUD image during low AL conditions.

Table 4. Results of ANOVA Performed on Event Detection from Outside Ccene when AL is High

Source	**AL**	**IL**	**NU**	**AL*IL**
SS	117.855	146.683	498.349	64.844
df	2	16	3	32
MS	58.927	9.168	166.116	2.026
f	1827.57	284.33	5151.92	62.85
Prob $> f$	0	0	0	0
Source	**AL*NU**	**IL*NU**	**Error**	**Total**
SS	0.047	0.574	3.095	841.039
df	6	48	96	203
MS	0.008	0.012	0.032	
f	0.25	0.37		
Prob $> f$	0.9601	0.9999		

From the Table 4, following results can be deduced: AL, HUD IL, and luminance NU have a significant main effect on outside event detection during high AL conditions. Interaction effect of AL and HUD IL has a significant effect on outside event detection during high AL conditions. Interaction effects of (i) HUD IL and luminance NU and (ii) AL and luminance NU have an insignificant effect on outside event detection during high AL conditions.

Table 5. Results of ANOVA Performed on Event Detection from outside Scene when AL is in Mid-range

Source	**AL**	**IL**	**NU**	**AL*IL**
SS	7902.8	5028.9	1629.2	4603.8
df	2	16	3	32
MS	3951.38	314.3	543.07	143.87
f	79822.4	6349.28	10970.7	2906.31
Prob $> f$	0	0	0	0
Source	**AL*NU**	**IL*NU**	**Error**	**Total**
SS	8.2	5.2	4.8	19182.7
df	6	48	96	203
MS	1.36	0.11	0.05	
f	27.47	2.18		
Prob $> f$	0	0.0006		

From the Table 5, following results can be deduced: AL, HUD IL, and luminance NU have a significant main effect on outside event detection during medium AL conditions. Interaction effects of (i) AL and HUD IL, (ii) AL & luminance NU, and (iii) HUD IL & luminance NU have a significant effect on outside event detection during medium AL conditions.

Table 6. Results of ANOVA Performed on Event Detection from outside Scene when AL is Low

Source	**AL**	**IL**	**NU**	**AL*IL**
SS	50186.5	78887.1	1088.2	7787.4
df	2	17	3	34
MS	25093.3	4640.4	362.7	229
f	16197.3	29942.9	2340.66	1477.92
Prob $> f$	2.54E-01	2.03E-01	7.19E+0	4.71E-01
Source	**AL*NU**	**IL*NU**	**Error**	**Total**
SS	89.4	143.1	5.8	139097
df	6	51	102	215
MS	14.9	2.8	0.2	
f	96.14	18.11		
Prob $> f$	1.05E+0	2.78E+00		

From the Table 6, following results can be deduced: AL, HUD IL, and luminance NU have a significant main effect on outside event detection during low AL conditions. Interaction effects of (i) AL and HUD IL, (ii) AL and luminance NU, and (iii) HUD IL and luminance NU have a significant effect on outside event detection during low AL conditions.

Therefore, the above discussion indicates that HUD can lead to attention capture and tunneling if the relative HUD IL and AL are not optimized with respect to each other.

The paired *t*-test results establish the fact that a difference exists in the level of event detection on the HUD image and outside scene. ANOVA was performed to verify the significant dependence on all contributing factors. The *p* value found through ANOVA shows that a significant effect on the percentage of event detection due to AL and HUD IL individually. The statistical results confirm the dependency of attention tunneling concept on the image contrast. This dependency could also be accordingly inferred through calculated contrast ratio scores.

The response of the participants to the events displayed on the HUD image appearing on those HUDs is observed to be inferior when the display area is <1.4. When the contrast ratio is kept at <1.4, the percentage for event detection on the HUD image varies from 47% to 70%, whereas event detection in the outside scene ranges from 98% to 94%. Across these areas, the outside scene event detection is much better. Considering luminance NU, contrast ratios can be more than 1.4 in certain areas and less than 1.4 in others.

In cases where the contrast ratio on the display area is between 1.4 and 5, the percentage for event detection on the HUD image varies between 70% and 95%, whereas for event detection in the outside scene, the values range from 94% to 86%. The response of participants to the events displayed on the HUD image is found to be very good. However, across these areas of HUD, the outside scene event detection deteriorates with respect to the previous case. Here, the variation in contrast ratio due to luminance NU causes less significant variation in event detection.

In case of the contrast ratio being more than 5, the percentage for event detection on the HUD image varies from 95% to 99%, whereas for event detection in the outside scene, the values range within 86% to 11%. Wherever the contrast ratio on the display area is >5, the response of the participants to the events displayed on the HUD image appearing in high contrast areas is excellent. Through such areas, the outside scene is poor for obvious reasons of attention tunneling. For contrast ratios beyond 7, the effect of luminance NU on the detection of events on the HUD image and outside scene is reduced. In such cases, event detection shows significant dependence on the AL, HUD IL, and contrast ratio. By contrast, less significant dependence is observed on the luminance NU. Overall, our results elucidate the individual and combined effects of AL, IL, and luminance NU on the attention tunneling occurring during the use of HUD. This study produces a substantial amount of data and understanding toward the development of an automatic display contrast ratio adjustment methodology to minimize the effects of attention tunneling during flights while using HUDs.

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