THE INTERNATIONAL JOURNAL OF AVIATION PSYCHOLOGY, *17*(1), 91–108

PRACTIONER ARTICLE

HUD With a Velocity (Flight-Path) Vector Reduces Lateral Error During Landing in Restricted Visibility

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The operational community has assumed that using a head-up display (HUD) instead of conventional head-down displays will increase accuracy and safety during approach and landing. The putative mechanism for this increase in safety is that previously demonstrated improvements in lateral and vertical control of the aircraft in flight should carry over to the landing situation. Alternatively, it is possible that, during approach and landing, the HUD might affect the pilot's ability to assimilate outside cues at the decision height, thereby reducing the success ratio for landings using an HUD. This article reports a pair of experiments that test these competing hypotheses. Taking advantage of the opportunity when an air transport operator introduced HUD in an existing aircraft fleet, we were able to use a Boeing 737–700 full-motion simulator flown by commercial airline pilots. We explored the effects of (a) HUD use, (b) ambient visibility, and (c) length of approach lighting on the size and location of the touchdown footprint. We also explored the effects of HUD use on approach success ratio. HUD use reduced the width of the touchdown footprint in all tested visibility and lighting conditions, including visibility below the minimum allowed. HUD

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use had no effect on the length of the touchdown footprint. We could not detect any decrease in approach success rate for HUD approaches. Based on these empirical data, the minimum visibility for approaches using HUDs could be set lower than for approaches without an HUD.

This article reports two experiments designed to assess the impact of commercial airline pilots' use of a head-up display (HUD) on approach and landing performance under reduced runway visual range (RVR) conditions. Our goal is to report experimental work designed to inform the development or revision of regulations on HUD use in low-RVR conditions. We begin by reviewing previous research on HUD use and by describing how ambient RVR affects approach and landing operations. The review motivates a pair of hypotheses regarding the impact of HUD use on the size of the landing footprint and the probability of approach success. We discuss the experiments and their findings in turn with particular emphasis on the mechanisms behind the effects and the practical implications for approach and landing in restricted visibility.

HUD USE IN COMMERCIAL FLIGHT OPERATIONS

The HUD projects computer-generated aircraft flight-path and energy symbols onto a transparent screen in the pilot's primary view. Pilots can concurrently view the HUD symbology and the surrounding world. Commercially available HUDs replicate the information on the pilot's conventional flight instruments, showing aircraft attitude, speed, altitude, and heading, and containing a flight-path symbol showing the aircraft velocity. From the pilot's perspective, these data project onto the outside world. HUDs with this 1:1 relation between the displayed symbols and their real-world referents are called *conformal HUDs.* Thus a conformal HUD with a flight-path symbol can explicitly show the pilot where the aircraft is going relative to the surrounding world. In contrast, a pilot flying with conventional flight instruments must infer the aircraft's flight path from a synthesis of the H-angle (Lintern & Liu, 1991), optical flow (Gibson, 1986), and possibly also the relative perspective gradient (Lintern, 2000).

Comparisons between HUDs and head-down displays in manual flight have found that conformal HUDs use improved track, speed, and altitude maintenance (Lauber, Bray, Harrison, Hemingway, & Scott, 1982; Martin-Emerson & Wickens, 1997). The civil aviation community assumed that these HUD performance advantages over conventional head-down instrumentation could reduce the number of approach and landing incidents and accidents (Flight Safety Foundation, 1991). Specifically, the commercial operational community assumed that HUD use could mitigate two well-documented problems associated with approach and landing: visual approaches to runways without radio navigation aids or with unreliable navigation aids, and the transition from instrument to external visual cues for landing in low visibility (e.g., Newman, 1995).

In this article we focus on pilot performance during landing in low-RVR conditions where transitioning from instrument to external cues for manoeuvring is an issue. The presumed sources for the advantage in flight-tracking performance for the HUD are that it eliminates the need for the pilot to move his or her gaze from head-down instruments to the outside world to look for maneuvering cues (Stuart, McAnally, & Meehan, 2003) and it minimizes scanning requirements (Martin-Emerson & Wickens, 1997). The transition from head down to the outside world requires a change in visual accommodation (e.g., the visual depth of field changes from less than 1 m to infinity). Because conformal HUD symbology is focused at infinity, HUD use eliminates the need for and time demand of visual accommodation, simplifying the pilot's task.

One possible negative effect of HUD in the landing situation is that inserting a glass plate with symbols in front of a pilot may affect his or her ability to visually acquire the approach lights, which is necessary to continue the approach below the decision height. This could be either through attentional capture, also called *cognitive tunneling* (Fischer & Haines, 1980; Weintraub, Haines, & Randle, 1985; Wickens & Long, 1995), or merely by the fact that light transmission through the HUD is not 100%. A commercial HUD will let about 85% to 90% of the incoming light pass through the glass plate. A detrimental effect of HUD use during the landing would then show up as a lower success ratio for HUD than for a conventional flight deck without HUD.

APPROACH OPERATIONS IN REDUCED VISIBILITY

The majority of approaches (the segment of flight immediately before touchdown) performed in U.S. and European civil air transport operation are conducted as Category I instrument landing system (ILS) approaches. For a Category I approach the two critical factors when making the decision of whether to land are the decision height and the RVR. Decision height refers to the aircraft's vertical distance above the runway threshold where the pilot must make the decision to land or make a go-around. The pilot must be able to see at least some of the approach or runway lights at the decision height. The approach lights will then guide the pilot to the runway.

The RVR is a measure of horizontal visibility defined by the length of visible approach and runway lights in the ambient atmospheric conditions. If the RVR is too low the pilot will not be able to see any of the approach lights at the decision height and must make a go-around. Although the resulting missed approach is part of normal operations (and formal procedures), it adds an undesired additional risk (International Civil Aviation Organization [ICAO], 1993).

The approach light lengths differ from runway to runway. Geographical constraints sometimes make the standard full length of 720 m (Full Facilities) impossible to achieve. Fewer approach lights means less guidance and later contact with the approach lights during the approach. Consequently the length of the approach lights is reflected in existing regulations. For example, to commence a Category I ILS approach to a runway equipped with a 720 m length of approach lights, the RVR measured at the runway must not be less than 550 m (Federal Aviation Administration [FAA], 2002; Joint Aviation Authorities [JAA], 2004b). This RVR is expected to allow the pilot to see a visual segment of the ground that contains enough of the runway approach lights to judge the aircraft's lateral position, cross-track velocity, and position in roll when the aircraft is at decision height. This condition is sketched in Figure 1. The same condition viewed from the pilot's position in cockpit is sketched in Figure 2. The figure depicts how the visible row of Full Facility (720 m) approach lights appear from under the aircraft's nose and stretch forward toward the runway until they are obscured by the limited visibility. In Figure 3 we have sketched the pilot's view of the same approach lights length in lower than standard (450 m) RVR. Here the shorter ground visual segment is seen as fewer approach lights are available for guidance toward the runway.

For shorter approach light lengths there is less guidance. In Figure 4 we have sketched what the pilot sees at decision heights for approach lights with 420 m length in standard (700 m) RVR. In Figure 5 the pilot view of the same approach lights is shown in lower than standard (550 m) RVR. In all of these approach light

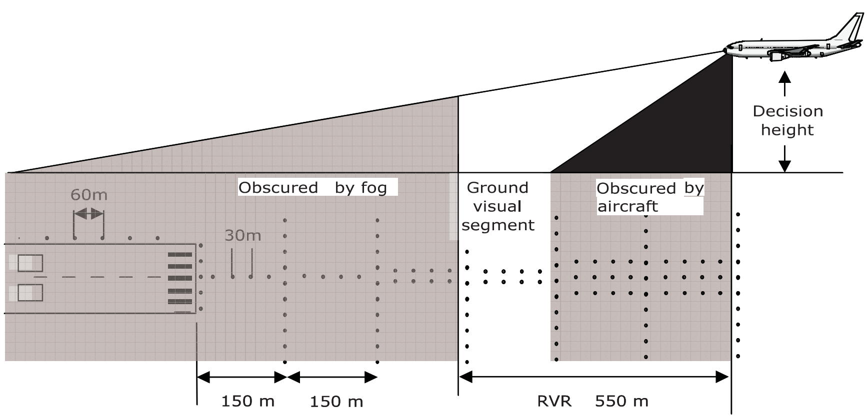

FIGURE 1 The visual segment as seen from the aircraft from the decision height at a given runway visual range.

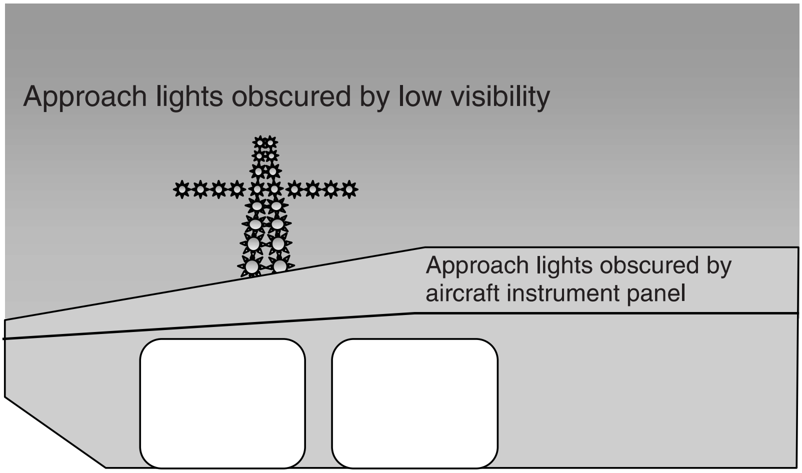

FIGURE 2 The visual segment as seen through the left cockpit window in a B–737 at decision height when flying in over a Full Approach Lights System (at least 720 m length) in standard 550 m runway visual range.

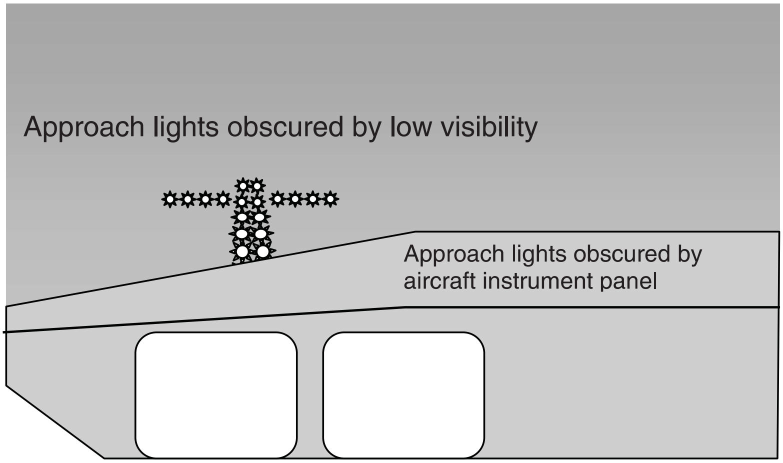

FIGURE 3 The visual segment as seen through the left cockpit window in a B–737 at decision height when flying in over a Full Approach Lights System (at least 720 m length) in lower than standard 450 m runway visual range.

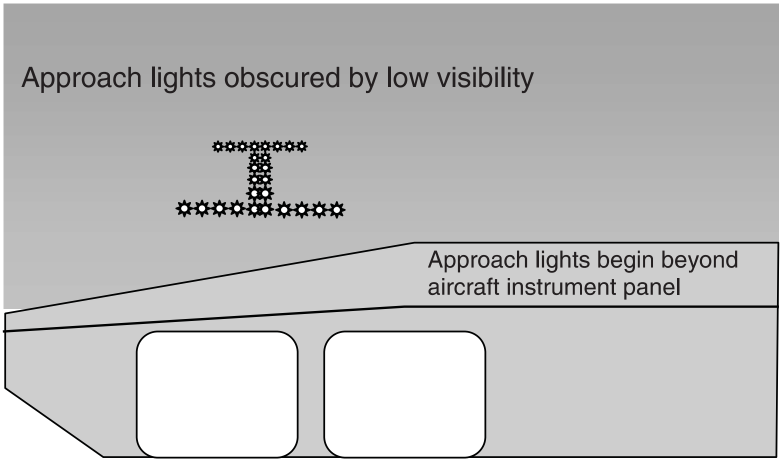

FIGURE 4 The visual segment seen through the left cockpit window in a B–737 at decision height when flying in over an Intermediate Approach Lights facility (450 m length) in standard 700 m runway visual range.

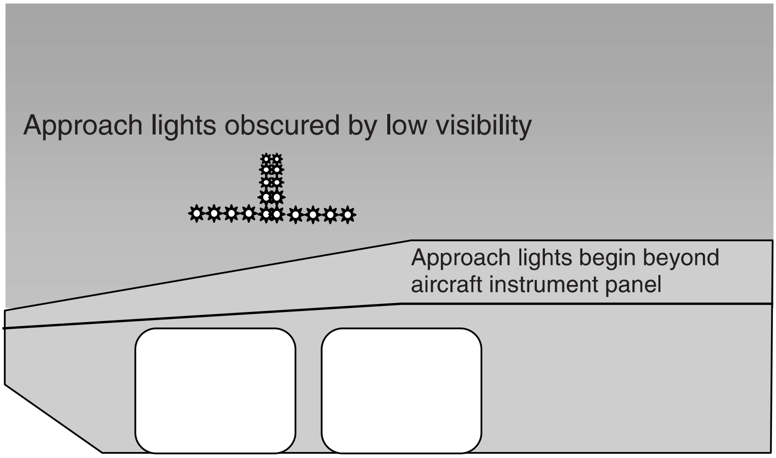

FIGURE 5 The visual segment seen through the left cockpit window in a B–737 at decision height when flying in over an Intermediate Approach Lights facility (450 m length) in lower than standard 550 m runway visual range.

lengths–RVR combinations the pilot does not see the runway threshold at decision height. Only later as the aircraft comes closer to the runway threshold can the pilot see and aim the aircraft at the designated touchdown point, normally 305 m down the runway. Apart from the obvious effect that the approach lights will come in view later with lower RVR, other effects of shorter approach lights lengths could also come into play. If runway length has been shown to influence the perceived descent path (Lintern & Walker, 1991) it is also possible that a reduced length of approach lights can have similar effects, adding a source of uncertainty to the vertical control of the aircraft.

THE ISSUE OF RVR AND HUD USE

Large commercial airlines such as American Airlines, All Nippon Airways, Delta, Scandinavian Airlines, and Southwest Airlines are introducing HUDs to the flight deck at an increasing rate, making the effect of HUD use on touchdown performance an operationally relevant question. Generalizing from earlier research (Martin-Emerson & Wickens, 1997), HUD use with conformal symbology should improve tracking performance during approach and landing in restricted visibility. Showing the instantaneous flight path should improve the pilot's ability to control the aircraft velocity in relation to the real world below decision height and this, in turn, should reduce the variance of the touchdown point. However, the landing situation is different from cruise or approach when the pilots can concentrate on the HUD symbology at the expense of outside cues. During landing the pilots have to concurrently process both outside cues and HUD cues to get any benefit from the HUD. The operational benefit from a reduction in touchdown variability could be that regulations would allow approach operations using HUD in lower than standard RVR conditions. The current operating minima were not set bearing HUD operations in mind and may be too restrictive for operations using HUD, a fact that the existing legislative text acknowledges (JAA, 2004b). However, setting RVR for approach too low will ultimately reduce approach success rate. In low RVR with very few external cues available at decision height, there is a risk that the pilots will focus their attention on the HUD symbology to the extent that they might not perceive the few visible approach lights at decision height. Pilots who do not pick up the outside cues may thereby initiate a go-around when the approach actually could have been continued, an outcome that is not desirable from an operational standpoint. Squeezed between operational pressure for lower minima for the HUD's presumed advantage and possible negative effects of the HUD, regulators are being pressed to generate rules that are insufficiently grounded in research.

In light of the increasing use of HUDs in commercial aviation and the paucity of the existing knowledge base, we studied whether the established improvement in tracking performance when using an HUD would be reflected in the landing as a smaller touchdown footprint on the runway in standard and lower than standard RVR conditions. We sought to ascertain and quantify whether the HUD-related advantages for flight-path tracking during cruise established by earlier research is carried over to the landing when the pilot has to concurrently process HUD symbology and outside cues. Data exist for certification trials for HUDs currently used in civil aviation. However, those certification trials were aimed at showing HUD performance in a low-visibility mode with guidance down to and including the landing flare, where there was no need for external visual cues at all (JAA, 2004a). Such data do not export well to touchdown performance using HUD in Category I flight operations where obstacle clearance below the decision height is maintained by visual maneuvering. We know of no other studies with commercial pilots in high-fidelity simulations that have tested whether HUD use is associated with performance advantages related to landing in restricted visibility operations predicated on visual cues for maneuvering. We were given the opportunity when a European Air transport carrier installed HUDs in an existing fleet of Boeing 737 (B–737–NG) aircraft. In connection with the normal training program we were able to compare pilot performance during approach and landing when using an HUD and when using conventional head-down instrumentation.

As there is less guidance with shorter approach lights we investigated the effect of HUD on touchdown performance for two different approach lights conditions as defined in the European regulations: Full Approach Light facilities (≥ 720 m) and Intermediate Approach Light facilities (420 to 719 m; JAA, 2004b). See Table 1 for the RVR and approach light lengths in the two experiments. In the first experiment, we assessed HUD use in visibilities at and below the required minimum RVR at simulated facilities with a system of approach lights of full length (900 m). In the second experiment, we assessed HUD use with visibilities at and below the required minimum RVR at simulated facilities with a system of approach lights of intermediate length (420 m). We predicted that the HUD would reduce the size of

TABLE 1
RVR Standards for Facilities With Full and Intermediate Systems of Approach Lights

Experiment 1 With Full Facilities[a]		*Experiment 2 With Intermediate Facilities*[b]	
Low RVR	*Standard RVR*	*Low RVR*	*Standard RVR*
450 m	550 m	550 to 600 m	700 m

Note. RVR = runway visual range.
[a]900 m. [b]420 m.

the footprint both longitudinally and laterally and that an HUD in itself would not reduce the approach success rate at the RVRs used in the experiments.

EXPERIMENT 1

Method

Forty-eight pilots from a major European airline volunteered to participate. All were qualified to fly the B–737–700 aircraft and had completed their HUD training for the operator. The HUD training sessions consisted of 1 day of theory and two simulator sessions of 4 hr duration each. Experience on the B–737–700 varied from 50 hr to more than 1,000 hr. There is every reason to believe that these participants are representative of the population of commercial pilots to whom regulators need the data to generalize.

Apparatus. We used a CAE B–737–700 training simulator with aircraft aerodynamics and visual angles valid for B–737–700 to collect data. This six-axis full-motion simulator is approved for low-visibility operations down to an RVR of 200 m. The simulator's visual system had a field of vision of 180°/40° with a focal distance greater than 10 m.

The head-down instrumentation was a B–737–700 instrument panel in primary flight display (PFD) configuration with flight director guidance. This instrumentation was available in both the with-HUD and the no-HUD conditions. The HUD installed in the simulator was a Rockwell-Collins Flight Dynamics HGS–4000® (Head-up Guidance System), certified for low-visibility operations down to and including an RVR of 200 m. The HUD symbology and functionality used in the experiment met the production-line standard specification for the instrument meterological conditions (IMC) mode used when conducting Category I ILS and nonprecision approaches (see Figure 6). This mode was deliberately chosen to improve the external validity on the form of operational usability of the study. In normal operations, the vast majority of ILSs are only approved for Category I operations. The HUD provided conformal display of flight path (velocity) and flight-path guidance. The flight path was displayed as a circle with slanted wings. Flight-path guidance was displayed in the form of a ring inside the flight-path symbol. Flight-path guidance was not available in the conventional head-down instrumentation.

The radio navigation facilities simulated in the study conformed to the ICAO (1996) standard for ILS radio navigation aids for Category I approaches transmitting a radio beam for both vertical and lateral reference. The integrity of the transmitted beam is guaranteed to keep the aircraft within allowable airspace, safe from

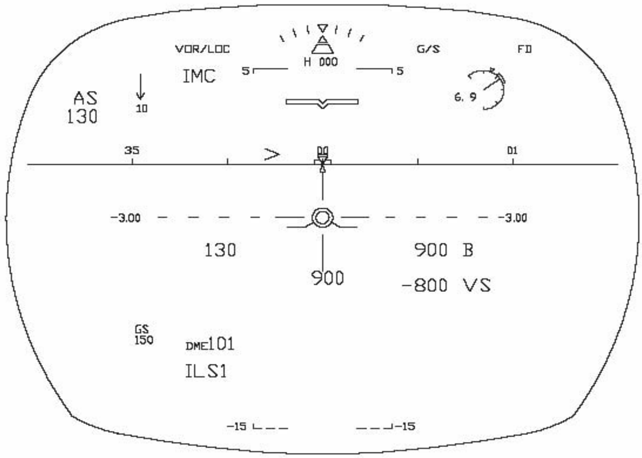

FIGURE 6 The HUD symbology of the instrument meterological conditions (IMC) mode used during the approaches in Experiments 1 and 2. Courtesy of Rockwell-Collins Flight Dynamics. Reprinted with permission.

obstacles down to 200 ft height, corresponding to lowest allowable decision height. Approaches in Experiment 1 were flown to a simulated runway with a system of approach lights 900 m in length. This length falls within the full facilities system category of European aviation regulation (JAA, 2004b).

Design. The design used was a two-factor experiment with repeated measures on HUD use (HUD, no-HUD). The between-subject factor was RVR at two levels, the standard minimum RVR (550 m) for full facilities system and lower than standard RVR (450 m). Each participant flew one approach with HUD and one approach without HUD to a runway with a full system (900 m) of approach lights. The order of HUD use was counterbalanced across participants to control for potential order and carryover effects. This design enables us to assess whether and HUD performance advantages in standard RVR carry over into lower than standard RVR conditions.

Procedure. Each pilot manually flew two approaches using standard operating procedures of the airline. The scenarios started as a 6 nm final to the runway in lower than standard or standard RVR in a simulated 10 kt left crosswind. In the with-HUD condition, the pilots kept the aircraft on lateral and vertical by following the flight-path guidance ring with the flight-path symbol on the HUD. At 50 ft above the runway threshold, the guidance cue was automatically removed and the pilots performed the landing flare using external visual cues in conjunction with the HUD flight-path symbol. The HGS–4000® IMC mode incorporating automatic removal of the guidance cue was deliberately chosen to ensure that the pilots could not attend solely to the HUD symbology in the with-HUD conditions.

In the no-HUD condition the pilots kept the aircraft on lateral and vertical track by following the flight director bar guidance. At decision height they continued the approach and landing using the external cues only.

All approaches were recorded to determine approach success. Approach and landing plots for approaches ending with a landing were printed using the aircraft's center of gravity as the reference to determine the size of the touchdown footprint.

Results

Approach success rate. Each of the 48 pilots attempted two approaches. Thirty-seven made two successful landings, one with HUD and one without. Three made go-arounds in both conditions. Two pilots landed with the HUD and made go-arounds without the HUD; six landed without the HUD and made go-arounds with the HUD.

The McNemar change test is the appropriate statistical procedure for testing the null hypothesis that pilots were equally likely to (a) land with the HUD and go-around without it, and (b) land without the HUD and go-around with it (Siegel & Castellan, 1988). Because the observed test statistic, calculated from the values given earlier (2 and 6), is 1.125 and is less than the criterion, $\chi^2(.05, 1) = 3.84$, we cannot reject the null hypothesis. Accordingly we infer that HUD use had no impact on approach success rate.

Touchdown performance. As noted previously, 11 of the 48 pilots conducted one or two go-arounds. The simulator failed to capture the location of the landing footprint for another 7 pilots. As a result the data set for comparing the touchdown footprints across the HUD and no-HUD conditions consists of 30 pairs of approaches. Of these 30, 15 were flown using the HUD in the first approach and 15 using the conventional head-down instruments (no-HUD) in the first approach; 15 were flown in standard RVR (550 m) conditions and 15 in lower than standard RVR conditions (450 m).

Lateral touchdown performance was measured as the absolute lateral deviation from the runway centerline at touchdown. The data for the main effect of HUD use are shown in Figure 7. Landings were closer to the centerline when pilots used the HUD. The two-factors repeated-measures analysis of variance (ANOVA) revealed a strong effect for HUD use on the lateral component of the touchdown footprint, $F(1, 28) = 9.05$, $p < .006$, $\eta^2 = .12$ indicating a power of .80 at $\alpha = .05$. The main effects for RVR and order of HUD condition were not significant. There was, however, a marginally significant interaction between HUD use and the order

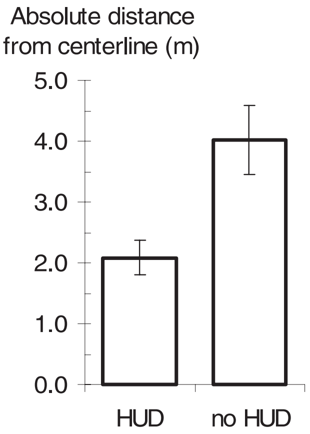

FIGURE 7 Graph showing the main effect for HUD use and the order of its use on the lateral size of the touchdown footprint at simulated facilities with a full system (900 m) of approach lights, Experiment 1.

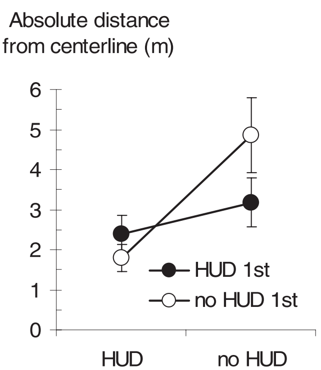

FIGURE 8 Graph showing the interaction of HUD use and the order of its use on the lateral size of the touchdown footprint at simulated facilities with a full system (900 m) of approach lights, Experiment 1.

of HUD use, $F(1, 28) = 3.31$, $p < .08$. As shown in Figure 8, both the group that used the HUD on their first approach (HUD first) and the group that used the HUD on their second approach (no HUD first) landed nearer the centerline when they used the HUD. Thus there is a strong hint of asymmetric transfer in HUD use on the lateral size of the footprint. Pilots appear to benefit from previous exposure to the HUD.

Tests for the equality of variance across conditions of HUD use require the samples to be independent, a condition violated by the repeated-measures design. Were the samples independent, the difference in the observed variances in the lateral touchdown footprint would be significant at $\alpha = .10$ with lower variability when landing with the HUD.

Longitudinal touchdown performance was measured as the distance from the runway threshold at touchdown. Contrary to expectations and in contrast with the results for lateral performance, the analysis of variance revealed that the effect of HUD use was not significant. Neither the between-subject main effect of RVR nor its interaction with HUD use was significant. Thus there is no indication of asymmetric transfer in HUD use on the size of the longitudinal footprint.

EXPERIMENT 2

Method

The method, procedure, and design used in the second experiment were identical to those used in the first experiment with the few exceptions discussed here. The different criteria for standard RVR across facility types preclude collapsing and analyzing the data as a single experiment.

Participants. Forty-five pilots from the same major European airline volunteered to participate. None of the volunteers had participated in Experiment 1. All were qualified to fly the B–737–700 aircraft and had completed their HUD training for the operator. Experience on the B–737–700 varied from more than 50 hr to more than 1,000 hr.

Simulated ground facilities. Approaches in Experiment 2 were flown to simulations of a runway with 420 m of approach lights. This length falls within the intermediate facilities category of approach lights as defined by European aviation regulations (JAA, 2004b).

Design. Once again, the design was a two-factor experiment with repeated measures on one factor, HUD use. Each participant flew one approach with HUD and one approach without HUD to a runway with a system of approach lights of 420 m length. The between-subject variable was RVR at two levels, a standard minimum RVR (700 m) for intermediate facilities and a lower than standard minimum RVR (550 m to 600 m).

Results

Approach success rate. Each of the 45 pilots attempted two approaches. Thirty-two made two successful landings, one with HUD and one without. Four pilots made go-arounds in both conditions. Three pilots landed with the HUD and made go-arounds without the HUD; six pilots landed without the HUD and made go-arounds with the HUD. Once again we used the McNemar change test to test the null hypothesis that pilots were equally likely to (a) land with the HUD and go-around without it, and (b) land without the HUD and go-around with it. Because the observed test statistic, calculated from the values given previously (3 and 6) is 0.44 and is less than the criterion, $\chi^2(.05, 1) = 3.84$, we infer that HUD use had no impact on approach success rate.

Touchdown performance. As noted earlier, 13 of the 45 pilots conducted one or two go-arounds. The simulator failed to capture the location of the landing footprint for another 4 pilots. As a result, the data set for comparing the touchdown footprints across the HUD and no-HUD conditions consists of 28 pairs of approaches. Of these 28 pairs of approaches, 9 were flown using the HUD in the first approach and 19 using the conventional head-down instruments (no-HUD) in the first approach; 14 were flown in standard RVR (700 m) conditions and 14 in lower than standard RVR conditions. The opportunistic nature of data collection precluded balancing the order of HUD use.

The main effect for HUD use, shown in Figure 9, is the only factor in the two-factor repeated-measures ANOVA to achieve statistical significance. As in Experiment 1, the effect for HUD use on the lateral component of the touchdown footprint is strong, $F(1, 26) = 14.9$, $p < .001$, $\eta^2 = .10$, indicating a power greater than .70. Once again, landings were closer to the centerline when pilots used the HUD. Because participant order was not fully counterbalanced, it is not possible to assess the potential for asymmetric transfer effects. As in Experiment 1, there was no significant effect for HUD use or RVR on the longitudinal component of the touchdown footprint. Once again, the difference in the observed variances across conditions of HUD use would be significant at $\alpha = .10$ if the data sets were independent.

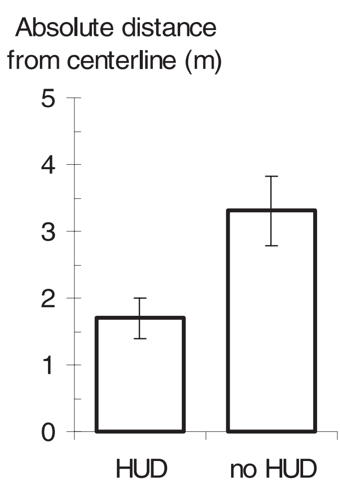

FIGURE 9 Graph showing the main effect of HUD use on the lateral size of the touchdown footprint at simulated facilities with an intermediate system (420 m) of approach lights, Experiment 2.

DISCUSSION

There are three findings. First, HUD use per se did not influence the pilots' decision to land or go-around at the decision height. The lack of an effect of HUD suggests that the additional information in the HUD did not distract the pilots' attention or interfere with their decision making during the most critical portion of the approach and landing sequence. Second, HUD use significantly reduced the size of the lateral component of the touchdown footprint for all RVR conditions. We cannot ascertain exactly where this effect resided. As the control condition was the standard instrumentation of the B–737–NG, we can only say that inserting an HUD with the properties that the tested HUD had, will give this effect. Arguably it can be said that the difference between the HUD and the no-HUD conditions lay in the presence of a conformal flight-path vector in the pilots' primary field of view during the landing. Third, in contrast to its effect on the lateral component of the touchdown footprint, it appears that the HUD did not influence the size of the longitudinal footprint. The first two findings conform to our hypotheses. Here we reexamine our hypotheses about the impact of HUD use on the touchdown footprint and offer an explanation for its differential impact on the lateral and longitudinal components.

Experience engenders automaticity. For commercial pilots, hours of practice and numerous repetitions make touchdowns at standard facilities in good weather relatively routine. Nevertheless, the ubiquitous and ever-varying direction and velocity of wind is likely to preclude the development of true automaticity at touchdown. Crosswinds introduce an element of uncertainty regarding drift (the shift in lateral location of the aircraft relative to the runway's centerline). For the pilot to detect drift the visual ground segment needs to be long enough to determine the aircraft's movement over the ground. That means that to detect drift at all, a noticeable lateral displacement must take place and not all of this displacement can be corrected before touchdown. Such exogenous uncertainty is likely to have conditioned pilots (and regulators) to tolerate a certain amount of variance in the lateral touchdown footprint.

The HUD largely eliminates uncertainty about drift. The addition of a conformal flight-path vector projected over the runway provides instantaneous feedback about aircraft drift and actual flight path. The additional information enables precise control of the flight path during approach and landing and reduces the variance in lateral displacement practically to nil.

Control of the longitudinal component of the touchdown footprint is largely an effect of how pilots handle the aircraft's energy (operationally manifested as sink rate) in the final seconds before landing. The pilot uses information provided by the optic flow from the looming runway to control the aircraft's energy (Lee, 1974). It is important to note that pilots of large commercial air transport aircraft are also aided by radio altimeter callouts that count down from 50 ft to 0 ft (runway contact) in 10-ft decrements. The initiation of the landing flare has been shown to be a function of time to contact (Mulder, Pleijsant, van der Vaart, & van Wieringen, 2000). A small change in the timing of a landing flare at the nominal glide slope of 3° results in large longitudinal differences. The HUD mode used in the experiments provided no flare guidance and no additional information that could be used to guide the pilots when to initiate the landing flare. So, if the pilots are relying more on timing of a flare maneuver than on velocity cues from the HUD to initiate the flare, it is easy to understand why we failed to detect any effect of the tested HUD with a flight-path symbol on longitudinal touchdown performance. It remains to be seen whether similar results are found for HUD modes with flare guidance, and which visual representations are actually most effective in prompting pilots to reduce sink rate at the optimal height above the runway.

APPLICATION

The effect of the tested HUD use on landing performance was to reduce the lateral size of the touchdown footprint. This effect was seen in both standard and lower than standard RVR conditions. Left crosswind is known by operators to produce landings on the leeward side. This leeward displacement may not be critical when visibility is restricted by fog but can be crucial when visibility is restricted by rain or snow in strong crosswind conditions. Carriers that operate in higher latitudes (with more snow and inclement weather) are aware of the danger of misaligning the aircraft's velocity with the runway, especially during night when a combination of sideways-drifting precipitation and landing lights may produce an illusion of sideways movement. Some operators specifically recommend their pilots to switch the landing light off in such situations (SAS, 2005). The message that an aircraft equipped with a HUD showing a flight-path vector is likely to reduce the tendency of drifting with the wind during landing compared to the standard instrumentation condition is important for carriers that routinely operate in these weather conditions.

The absence of a detectable influence on the approach success rate in the HUD condition is also operationally important. European and U.S. authorities are currently working on a set of harmonized aerodrome operating minima. These minima are expected to allow a lower than standard minimum RVR to commence approach for HUD-equipped aircraft (JAA, 2004c). The effects of HUD use on landing performance were seen in standard and lower than standard RVR conditions in both Experiments 1 and 2. This study carries a clear and important operational implication: Based on empirical performance data, the minimum RVR for approaches using HUD with flight-path symbology could be set lower than for approaches without an HUD while still maintaining a similar or even smaller touchdown footprint.

CONCLUSIONS

Data from the experiments reported here show that HUD with a conformal velocity symbol (flight path) improved lateral touchdown performance, likely because the conformal flight-path vector in conjunction with the visual ground segment makes it easier for pilots to determine and correct for aircraft drift. We did not find an effect of HUD use on longitudinal touchdown performance, probably because the pilots flared the aircraft using a time-to-contact strategy, rather than using the flight-path vector available in the HUD modes studied here. The beneficial effects of HUD use on landing performance were seen in both in standard and lower than standard RVR conditions in both experiments, which implies that the minimum RVR for approaches using an HUD could be set lower than for approaches without an HUD. Finally, we did not find any detrimental effect of HUD use on approach success rate.

These results could be critical in supporting regulatory decision making about the visibility required to commence an approach using an HUD-equipped aircraft. In fact, it is precisely this type of systematic empirical data that is often lacking as a basis for developing well-informed regulations, in Europe as well as the United States. We believe that empirical results like these should be a critical ingredient in safety regulators' rule writing for (the application of) new technology in commercial aircraft operations. When it comes to HUDs, the need for informed regulation of HUD use is already pressing, and will only increase as HUD use proliferates. The relevance of the findings here could even support the expansion of such targeted empirical studies, for example, to Category II conditions, or to refine them to find, for example, the lowest acceptable RVR using HUDs.

ACKNOWLEDGMENTS

We thank Staffan Carlsson and Zacharias Soudah for assistance in data collection, Jan-Olof Ehk for statistical advice, and the pilots who volunteered their time and skill. Rockwell-Collins Flight Dynamics Company provided simulator time to conduct the experiment.

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Manuscript First Received: September 2005