Apparent Motion of the Runway Sidelines as a Visual Cue to Flare Timing: An Investigation through Full Flight Simulator Experiments

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Abstract

A series of experiments were carried out in Level D certified Full Flight Simulators of Boeing 767-type aircraft to analyse the human pilot's visual information usage and decision making in the final phase of the approach to landing. Based on earlier stages of this research, we hypothesized that the motion of the runway sidelines provides experienced pilots with an important visual cue to time the flare manoeuvre. Four veteran pilots from two different airlines took part in the experiments and additionally one junior pilot (co-pilot rank) was evaluated for comparison. By varying wind conditions and aircraft gross weight, a variety of nominal approach sink rates were achieved, while maintaining the visual scene geometry pertaining to the 3° descent path common in civil aviation. Our results refute the common belief that the flare is initiated at a certain altitude, and our hypothesis compared favourably to the time-to-contact (tau-margin) hypothesis.

Keywords: Visual cues, Airplane landing, Human pilot, Flare control, Perception, Flight simulation, Time-to-contact, Runway shape.

Introduction

Only through extensive training practice, pilots can learn the proper interpretation of visual information during the approach and landing. In this paper we analyze the subconscious control technique experienced pilots have developed over time. Special attention is given to the cues a pilot may use to decide the right moment to initiate the flare, a maneuver critical for the safety and smoothness of a landing.

Contrary to common belief, automated landing systems are not used in most cases. For his positional awareness and decision-making, the pilot heavily relies on the information contained in the out-the-window view, especially in the final phase below 60m (200ft) altitude when there is simply not sufficient time to obtain and integrate all information from the separate cockpit instruments. However, learning to make a proper and robust interpretation of the visual scene is the most difficult and time-consuming part of pilot training [1, 2].

We discuss a comparison of several visual cues that pilots might be using to time the initiation of the flare maneuver. Visual cues are elements or relations between elements in the (simplified) visual scene that convey information about our state (position, orientation, velocity). A daily life example of a visual cue to distance would be "the size of an object", because all things appear smaller at farther distance. Knowledge about which visual cues are used by experienced pilots can help the training of new pilots, who are easily overwhelmed by the richness of the visual scene.

The experiments and analyses we present here follow up on a more general investigation of visual cue use during airplane landing [3], and the interested reader is referred to the thesis by Entzinger [4] for more details and background information.

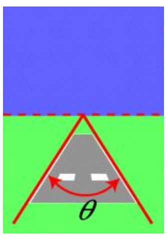
Perception

Cues for Flare Timing

Control of the flare is mainly based on visual inputs [1, 2]. However, the pilots may also use motion information (g-forces) and the automatic radio altitude callouts made by the flight computer to decide on flare initiation and control. The callouts do not only offer the altitude information, but the time between the subsequent callouts also provides the trained pilot with a sense of sink rate.

According to training literature for mid-sized and large jet aircraft such as the Boeing 767 [5], the flare should be commenced when the landing gear reaches a specific height above the ground. Depending on the aircraft type, altitudes of 6 or 9m (20 or 30ft) are generally advised. In our experiment (de)briefings the pilots also noted that they initiate the flare at a certain altitude, typically 9m (30ft).

An important question here would then be how pilots perceive altitude. One option would be the use of the radio altitude (RA) callouts at 50, 30, or 20ft altitude. However, experienced pilots mentioned that they use these callouts merely as a crosscheck and do not rely on them, but use visual cues instead. It is often suggested that “the shape of the runway”, or more specifically, “the apparent angle between the runway sidelines” —which we will call θ— is the most important visual cue to altitude (Fig. 1). The visual cue θ is a nonlinear function of the true runway width and the altitude of the pilot’s eye above the runway, as expressed by Eqn 1. Assuming a just noticeable difference (JND) for angles of 5°, trained pilots should be able to initiate the flare within an altitude band of 1.5m (5ft) around the “ideal flare initiation altitude”.



$$\theta = 2 \cdot \tan^{-1}\left(\frac{\frac{1}{2}\text{Width}}{\text{Altitude}}\right) \tag{1}$$

$$\dot{\theta} = \frac{\text{Width}}{\text{Altitude}^2 + \left(\frac{1}{2}\text{Width}\right)^2} \cdot \text{Sink rate} \tag{2}$$

Fig. 1: Definition of θ

Some researchers suggested that next to altitude, the sink rate (vertical velocity) plays a role in the actual pilot decisions [e.g., 6] and our previous investigation of visual cues in landing suggested $\dot{\theta}$ —the time derivative of θ— as a possible cue for flare timing [3]. As can be seen from Eqn 2, the visual cue $\dot{\theta}$ integrates altitude and sink rate information. $\dot{\theta}$ would be perceptible if exceeding a threshold of ca. 5°/s.

Another variable that takes both altitude and sink rate into account is the time-to-contact τ, which is a variable derived from optical flow theory. The time-to-contact τ_z can be defined as altitude over sink rate [7], with the note that this is an aircraft state and not a visual cue. In airplane landings, the forward distance and velocity components are much greater than the vertical components. It would therefore be likely that visual time-to-contact estimates are based on distance cues such as the apparent size of the touchdown zone markers, or the apparent runway width at the markers and their respective change rates (e.g. τ_w or the highly similar τ_ψ suggested by Mulder et al. [8]). Since it remains unclear how pilots actually perceive time-to-contact (if at all), perceptual thresholds and JND values are not available yet, but Prowse et al. suggest that time-to-contact estimates may be too inaccurate to be used as a flare timing cue [9].

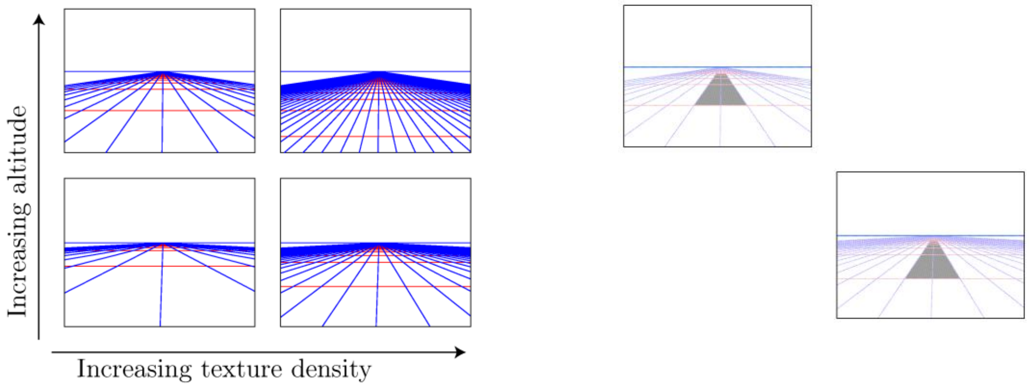
In this paper we will further analyze and compare the three parameters that have been introduced here: altitude (via RA-callouts or visual cues such as θ), the visual cue $\dot{\theta}$, and Time-to-contact τ.

Visual Illusions

When analyzing visual cues, it is important to keep in mind that the pilot may be susceptible to visual illusions. A visual illusion can occur when two different real world states result in the same image. Figure 2 illustrates the "runway width illusion", where a pilot is likely to misperceive a dangerously low altitude for a safe altitude when approaching a narrower than usual runway.

Pilots and training literature often mention the occurrence of visual illusions such as the runway width illusion, and in our interviews pilots said they actively remind themselves when they know they will land on a differently sized runway. In such a case, they pay close attention to secondary cues such as texture detail or RA callouts and perform crosschecks to ensure proper cue interpretation.

Since both the visual cues θ and $\dot{\theta}$ contain the "actual runway width" component (cf. Eqns 1 & 2), both these visual cues may give rise to a runway width illusion experienced by pilots. Time-to-contact cues, on the other hand, do not depend on the actual runway width, and will therefore not excite the runway width illusion.



(a) Altitude vs. texture density: angles between longitudinal ground lines get sharper with decreasing distance between the ground lines, and with increasing altitude.

(b) The shape of a wide runway seen from high altitude is indistinguishable from that of a narrow runway seen from low altitude. This may lead to the `runway width illusion'.

Fig. 2: The effect of altitude and actual size on perception.

Ways to Perceive $\dot{\theta}$

The possible use of the visual cue $\dot{\theta}$ was a recent finding from our research, and several pilots and researchers have asked us how one could actually perceive this cue. Although our research and experiments focus on theoretical analysis of the cue, correlation of several visual cues with the pilot control inputs, and statistical analyses, we provide a few ideas here of how $\dot{\theta}$ could be perceived. This is in the first place important to establish perception thresholds (if the cue is below threshold, we can be sure pilots do not use it), but it also offers a starting point for base-line perceptual research, which could in turn lead to more effective augmented or synthetic vision displays.

Both in literature and in our interviews, pilots often mentioned that runways sidelines (or runway shape/perspective in general) provide important visual cues for the landing [e.g. 1, 2]. This indicates that they probably observe the runway outline closely. It is therefore likely that $\dot{\theta}$ will also be perceived, although this information is of course not necessarily being used.

Figure 3 presents four fundamentally different ways in which pilots may perceive $\dot{\theta}$, and of course a combination of these may be used as well. In case 1, the pilot focuses on the runway sideline and observes $\dot{\theta}$ as a rotation of a single line. Because the pilot focuses on the sideline, the line will be projected on the fovea —the most acute part of the retina— and the threshold for rotary line motion is about 2.5°/s. In case 2, the pilot looks at the end of the runway or at the horizon and observes $\dot{\theta}$ as the speed at which the angle between the sidelines grows. The threshold is about 5°/s. A third possibility is that the looming of the runway is observed. The visible area of the runway is closely related to the angle θ and the looming is closely related to $\dot{\theta}$. The last possibility we suggest here is that the pilot recognizes, probably unconsciously, the upward optical flow of the runway sideline in the far periphery of his visual field.

With these four cases, we showed several possible ways to observe the visual cue $\dot{\theta}$ and for two of these cases we were able to provide visibility threshold values. We will leave the question of which perception method(s) pilots actually use, for further psychophysical and neuropsychological research. Experiments with large structured surfaces and wide fields of view (at least horizontally) are needed to establish or confirm the perceptual thresholds for each suggested case.

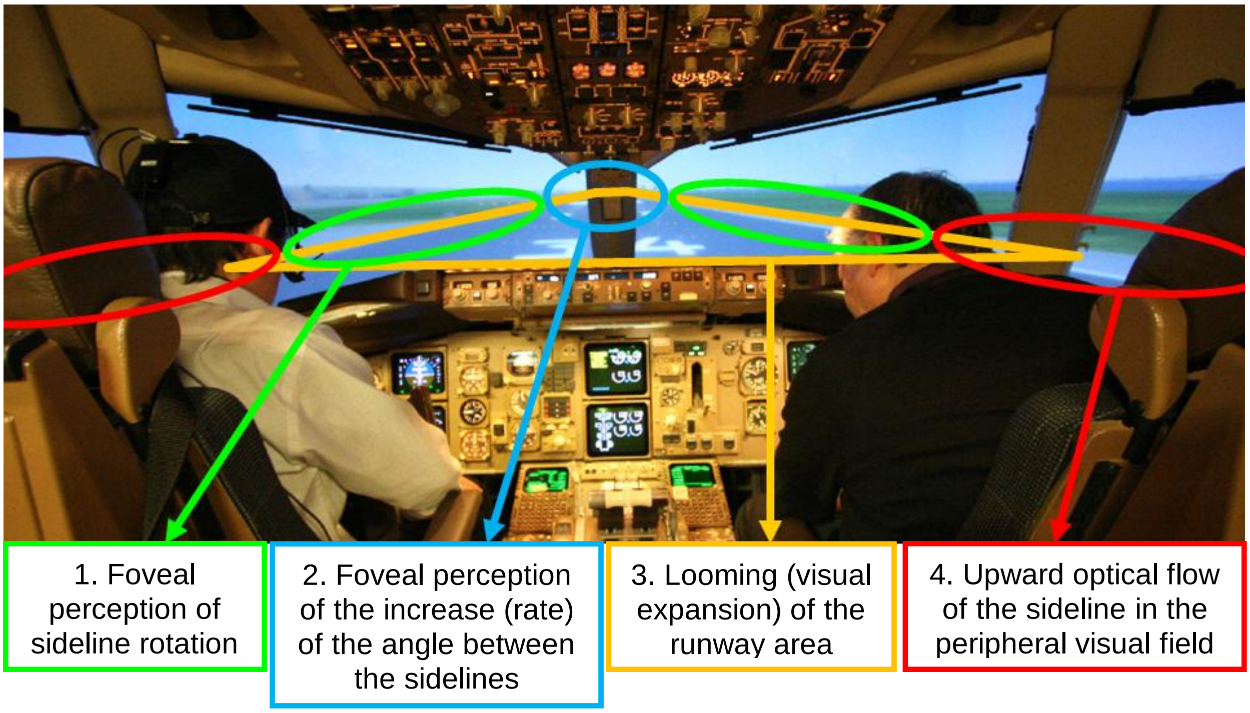


Fig. 3: Four ways to perceive $\dot{\theta}$

Experiments

We investigate the hypothesis that airline pilots base their flare initiation timing on the visual cue $\dot{\theta}$: the rate at which the angle between the runway sidelines increases. We test this hypothesis against several alternative flare timing methods suggested in literature, particularly the "specific altitude", and the "time-to-contact" hypotheses.

Materials & Methods

A series of experiments were carried out in Level D certified Full Flight Training Simulators of Boeing 767-type aircraft. Certified captain and junior pilots of All Nippon Airways (ANA) and Japan Airlines (JAL) flew several approaches under various conditions, and we analyzed correlations between their control column inputs and a number of visual cues and aircraft states.

The four captain pilots who took part in our dedicated experiments had 6677~9548 hours of flight experience, with an average of 8221 hours. The junior pilot had 2700 hours flight experience. Additional comparable data were available from earlier experiments, obtained from captain pilot NHC, who had 8340 hours flight experience.

Pilots manually landed the simulated aircraft under different wind and loading conditions. As shown in Tab. 1, this leads to a variation of nominal sink rate, which has a profound effect on the visual cues under investigation. Using this method —rather than a change of glide slope angle for instance—, we can maintain the other visual cues pertaining to the 3° approach path typical flown by airline pilots.

The limited availability of the simulators generally allowed only a few repetitions under each condition. The pilots seemed to see the strongest wind conditions as a challenge. We chose the wind speeds within or on the normal operation limits, so the approaches may be difficult, but are not impossible. The large airspeed additions in the strongest headwind cases required a low pitch attitude, which pilots JLA and JLB explicitly noted to be atypical. This lower pitch attitude in the strongest headwind approaches could require an earlier or stronger flare than usual, to make sure that the pitch attitude at touchdown is high enough to land on the main gear first. Data and results from the strongest headwind should therefore be interpreted with caution.

Time histories of various aircraft states, as well as the pilots' control inputs were digitally recorded during the simulator experiments. Visual cue information was recalculated from the aircraft states and the known scene geometry in post-processing. Additionally, we used an eye-marking system in several of the experiments to record the pilot's gaze direction and blinking.

Table 1: Example of cases we considered in the experiments. Note how the aircraft gross weight and wind conditions influence the rate of climb (ROC). The calculations are based on the recommendations in the B767 manuals [5]. We assumed a 3° glideslope to calculate the ROC.

	A	B	C	D	E	F	G
Weight (1000kg)	120	145	145	120	127	120	145
Weight (1000lbs)	265	320	320	265	280	265	320
VREF (kt)	135	148.5	148.5	135	136.5	135	148.5
Wind condition	calm	calm	head	tail	calm	head	tail
Wind speed (kt)	0	0	17	14	0	30	10
Addition (kt)	5	5	8.5	5	5	15	5
Target AirSpeed (kt)	140	153.5	157	140	141.5	150	153.5
Ground speed (kt)	140	153.5	140	154	141.5	120	163.5
Ground speed (m/s)	72	79	72	79	73	62	84
ROC (m/s)	−3.77	−4.14	−3.77	−4.15	−3.81	−3.24	−4.41

We briefed the pilots about the purpose of the experiments and shortly explained the hypothesis under investigation. We also told the pilots that the study considers their `natural' behavior, and they were requested to land the simulator `like they would normally land an aircraft'. As the focus of this research is on the visual approach, we told pilots that they could use the flight director (a cockpit instrument) in the beginning, but to use visual cues as much as possible, and especially below an altitude of around 61m (200ft, the "Decision Height").

Results

Before pilots really flare, they generally pull the control column shortly and slightly to evaluate the aircraft response, we will call this the "pre-flare". The "full flare" then is the actual flare, where the pilot pulls the column in order to achieve the desired increase of pitch attitude and decrease of sink rate.

Table 2 gives a statistical overview of the flare initiation altitudes. The standard deviations and minimum and maximum altitudes show a wider range than would be expected based on the JND for altitude (based on the visual cue θ). Additionally, it is remarkable that most captain pilots initiate even the full flares at altitudes clearly higher than the 9.1m (30ft) radio altitude recommended in literature. Heffley et al. [6, p104] made these same two observations from his data and concluded that there was clearly no nominal flare altitude. Only junior pilot NHQ consistently initiated his full-flares around the officially recommended altitude.

Figure 4 shows the relation between eye altitude, sink rate, and $\dot{\theta}$ at the full-flare initiation per pilot. The graphs clearly show that the value of $\dot{\theta}$ is always well above the perception threshold at flare initiation. Additionally it visualizes a common research finding which often remains unstated in training literature or pilot comments, namely that experienced pilots flare at a higher altitude (i.e., `earlier') in case of higher sink rates. The strongest headwind cases are explicitly indicated, because the pitch angles before the flare initiation were as small as 0~1°, and significantly lower than in the other approaches, as expected by the pilots. These cases may therefore not be representative of `normal' landing control.

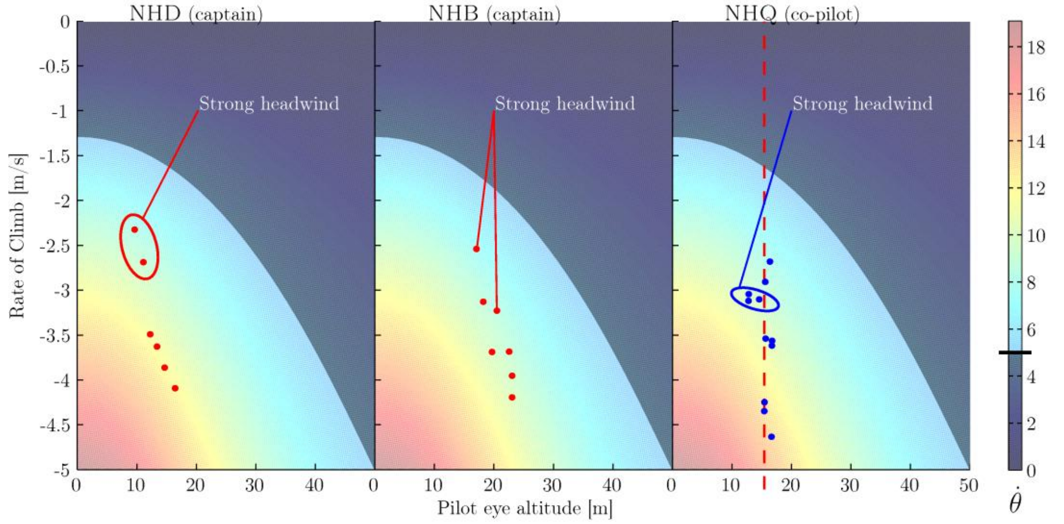
Captain pilot NHB and co-pilot NHQ flew the same landing approach cases and could therefore be compared directly. We will not go into detail here, but a statistical analysis showed that the main aircraft states and visual cues before the flare initiation and at touchdown were not significantly different between both pilots. The chosen moment of flare initiation, on the other hand, varied significantly in virtually all parameters. Time histories of the control inputs were also very different between pilots: the co-pilot's control was of clearly higher frequency and amplitude.

Table 2: Flare initiation altitudes from simulator experiments (radio altitude in meters).

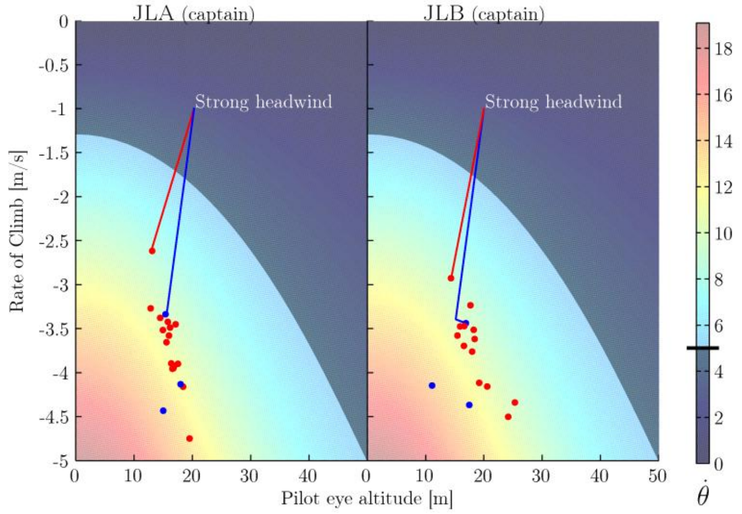
		← Pre-Flare initiation →				← Full-Flare initiation →			
Aircraft	Pilot	Mean	St.Dev.	Min	Max	Mean	St.Dev	Min	Max
MuPal[(1)]	A	16.9	3.3	11.4	21.9	12.7	3.3	9.9	19.7
	B	18.3	6.7	11.7	28.2	11.1	3.2	7.7	16.9
Boeing 767	NHB	19.2	3.9	12.2	23.1	14.4	2.6	10.8	17.2
	NHC	20.2	4.9	12.8	26.6	14.4	2.7	11.0	20.8
	NHD	12.0	1.3	10.3	13.0	6.5	2.4	3.4	10.0
	NHQ[(2)]	15.9	4.6	7.6	23.6	9.2	1.4	6.5	10.8
	JLA	14.6	2.7	10.0	19.9	10.4	1.8	7.2	14.1
	JLB	19.5	7.2	11.4	41.5	11.8	3.6	5.0	19.9

(1) Data available from previous experiments with the MuPal-α, a Dornier 228-200 turboprop aircraft owned by the Japanese Aerospace Exploration Agency (JAXA).

(2) Junior pilot, that is, having "co-pilot" rank, rather than "captain".



(a) Flare initiation points of ANA captains NHD (8290 flight hours) and NHB (8370 flight hours), and ANA co-pilot NHQ (2700 flight hours). Note that co-pilot NHQ initiates most of his flares at 15m = 50 ft eye altitude = 30 ft radio altitude.



(b) Flare initiation points of JAL captains JLA (9548 flight hours) and JLB (6677 flight hours). The blue dots represent approaches without motion simulation here.

Fig. 4: Comparison of pilot eye-altitude, sink rate and $\dot{\theta}$ at flare initiation. The shade of the background indicates the value of $\dot{\theta}$, blue for low values and red for high values. The dark shaded area indicates $\dot{\theta}$ <5°/s and thus below the perceptual threshold value.

First, we show a comparison of possible flare cues based on the coefficient of variation (CV), which equals the standard deviation divided by the mean. This is a dimensionless inequality measure, which can be used to compare variables that are measured on ratio scales. If a variable (state/cue) has a low CV, it means that the pilot flares at a relatively constant value of that variable. If a pilot uses a specific cue to time his flare initiation, it can be assumed that the pilot can perceive that cue accurately (i.e., the just noticeable difference of this cue is small), and that the variance of his response to the cue is low. Cues with a low CV are therefore more likely to be actually used by the pilot.

Table 3 shows a comparison of the CV for the possible flare initiation cues per pilot. The lowest values are highlighted. This shows that generally the time-to-contact τ_z and visual cue $\dot{\theta}$ have the lowest CV. Especially when we leave out the exceptional headwind cases, $\dot{\theta}$

has a consistently low CV, except for junior pilot NHQ. The CV of the visual time-to-contact cue τ_w is consistently high.

The second analysis we present here is a comparison of fitting errors for the altitude, time-to-contact, and $\dot{\theta}$. We hypothesized that the full-flare is initiated at a constant value of a certain variable. Therefore, the mean value (over all approaches and per pilot) of each of the variables is used to predict the altitude and/or sink rate at flare initiation. For a constant altitude flare initiation, obviously, no sink rate can be determined. For $\dot{\theta}$ sometimes no altitude can be determined, since due to the function's properties, imaginary numbers result. Therefore, `altitude' and `time-to-contact' are compared based on altitude estimates and `$\dot{\theta}$' and `time-to-contact' will be compared based on sink rate estimates. Table 4 shows the results of an Analysis of variance (ANOVA) of the fitting errors per pilot.

Table 3: CV at the full flare initiation. The lowest values for each pilot are highlighted.

			NHB	NHC	NHD	NHQ	JLA	JLB
Based on all data	States	Altitude	0.180	0.189	0.361	0.156	0.169	0.301
		τ_z	0.081	0.125	0.067	0.175	0.083	0.150
	Visual	$\dot{\theta}$	0.105	0.109	0.159	0.170	0.100	0.114
		τ_ω	0.177	0.215	0.179	0.162	0.138	0.131
Except strongest headwind case	States	Altitude	0.163	0.189	0.249	0.066	0.163	0.307
		τ_z	0.054	0.125	0.056	0.203	0.078	0.161
	Visual	$\dot{\theta}$	0.060	0.109	0.024	0.188	0.081	0.112
		τ_w	0.117	0.215	0.129	0.169	0.141	0.138

Table 4: Analysis of mean square errors (MSE) of altitude, τ_z and $\dot{\theta}$ fitting. Differences with 20% or better significance are highlighted. ROC (rate of climb) is the negative of sink rate.

Pilot	Altitude MSE	Alt (τz) MSE	Best fit	ANOVA p-value	ROC($\dot{\theta}$) MSE	ROC(τz) MSE	Best fit	ANOVA p-value
All experiments								
NHB	6.3	3.0	τ_z	0.20	0.11	0.07	-	0.55
NHC	7.1	6.5	-	0.89	0.11	0.14	-	0.70
NHD	6.3	0.8	τ_z	0.06	0.16	0.04	τ_z	0.06
NHQ	2.4	6.1	Alt.	0.16	0.26	0.25	-	0.96
JLA	2.7	1.8	-	0.50	0.13	0.09	-	0.65
JLB	11.0	8.0	-	0.65	0.15	0.36	-	0.33
Only cases with motion simulation, and without the strongest headwind cases								
NHB	4.8	1.5	τ_z	0.15	0.04	0.04	-	0.96
NHC	7.1	6.5	-	0.89	0.11	0.14	-	0.70
NHD	2.9	0.9	τ_z	0.18	0.00	0.05	$\dot{\theta}$	0.03
NHQ	0.4	8.6	Alt.	0.02	0.34	0.34	-	1.00
JLA	2.4	0.8	τ_z	0.13	0.06	0.04	-	0.53
JLB	8.8	2.8	τ_z	0.14	0.04	0.11	$\dot{\theta}$	0.15

The analysis shows that the captain pilots are more likely to base their flare initiation on the time-to-contact τ_z than on altitude, while there is generally no statistically significant preference for either τ_z or $\dot{\theta}$. The reason that differences almost never reach 5% significance can be found both in the similarity of the cues, and in the natural variability of human control. The visual time-to-contact cue τ_W was analyzed as well, but it never provided a significantly better fit than the other parameters, and the τ_W-fits were typically significantly worse.

Discussion

The experiment setup was successful in creating a variety of sink rates through the different wind and loading cases, in combination with the natural variability of human control. The control in the strongest headwind cases may not have been representative of typical manual control, as a boundary condition on minimum pitch attitude at touchdown was reached.

A statistical analysis of the landing data supported our $\dot{\theta}$-based flare initiation hypothesis for captain pilots. Only co-pilot NHQ seems to flare consistently at the same eye height of 15m, which means the main landing gear is about 9m (30ft) above the ground. It is interesting to note that there is an automated voice callout of the (radio) altitude at 30ft, and that co-pilots mentioned in the debriefings that these callouts are important for deciding their control actions, while captains said that they only use it as a cue for crosschecking.

An investigation of psychophysical aspects, such as cue salience and visual illusions, as well as discussions with pilots and results from the eye-marking experiments strengthened the belief that experienced pilots base their flare initiation timing on the visual cue $\dot{\theta}$, rather than on the time-to-contact or altitude. It remains unclear through which visual cues the state τ_z could be perceived, and with what accuracy. The visual cue τ_W suggested in literature appears to be too sensitive to variations in forward speed to be practical as a flare timing cue. From the pilot interviews and eye-marking data, we additionally found that pilots mainly observe the far end of the runway or the horizon when below the decision height of 60m, and not the aimpoint markers on the runway (as required for observing τ_W).

Finally, we found that the junior pilot's higher control frequency and amplitude may help him to make up for his less sophisticated flare timing, and achieve a touchdown performance similar to that of a captain pilot. However, large control inputs are generally undesired in close proximity to the ground.

Conclusion

It has long been known that the runway sidelines provide important visual cues. However, the discovery that not just the instantaneous angle between the sidelines (θ, an altitude cue), but also their motion ($\dot{\theta}$, for flare timing) is important, is an original finding of this research. With this knowledge, pilot training and evaluation can be focused at training the proper perception and interpretation of this cue. Learning a more sophisticated flare timing method can take away the need for relatively aggressive control in the final stage of the landing.

Knowledge about pilots' visual cue use can also help to make the right trade-offs between simulator scene realism and computational power, and it may help to explain and raise the awareness of visual illusions. Additionally, analysis of visual cue use and control decision-making would be interesting in the light of the recent suggestion by Ebbatson et al. to include not only the flight path, but also control style in pilot performance evaluation [10, 11].

We believe both training efficiency and flight safety will benefit from this insight in pilot control technique.

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