INSIDE THE PILOT'S MIND: VISUAL INFORMATION USE IN MANUAL AIRCRAFT LANDINGS

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Abstract

We test the hypothesis that experienced airline pilots base their flare timing on the visual cue $\dot{\theta}$, which can be described as 'the speed of the apparent runway widening' or 'the rotational speed of the runway sidelines', in contrast to the 'fixed altitude' and 'time to contact (τ)' hypotheses. We analysed data from 57 landings flown by 5 professional airline pilots in level D certified full flight simulators of Boeing 767-type aircraft to get a better understanding of what the pilot is actually looking at. We focus on the availability and use of visual cues by analysing time histories of aircraft states, visual cues, the pilot's control inputs, and eye-mark recordings of 30 of these landings. We present a statistical analysis of the flare initiation points and a qualitative analysis of the eye-mark data. We conclude that experienced pilots initiate their flares at higher altitudes than the recommended 30 ft (9 m) and clearly depending on the sinkrate, thereby rejecting the fixed altitude hypothesis. The eye-mark recordings give much insight in the pilot's visual cue and instrument use, and suggest pilots use $\dot{\theta}$ rather than time-to-contact to decide their flare initiation.

1 Introduction

1.1 Motivation

More fatal accidents happen in the landing phase than in any other phase of flight, and pilots mention the flare as one of the most difficult landing manoeuvres to learn [1, 2]. The flare is a pitch-up manoeuvre that should be executed a few seconds before touch down, in order to arrest sinkrate and to ensure touching down with the main gear first. Its timely initiation and proper execution are essential to achieve a safe and soft touchdown. Although most training literature mentions the flare should be initiated at 'a certain altitude', various researchers have found that pilots' flare initiation altitudes depend on the sinkrate [e.g., 2–4]. A few hypotheses have been put forward, but no consensus has yet been reached about how pilots decide the timing of their flare initiation.

The outside visual scene provides a wealth of information to pilots during the approach and landing. Whether pilots control the aircraft manually or supervise an auto-landing system, the proper interpretation of visual cues is essential for a safe landing. However, acquiring this skill requires practice through many hours of (expensive) simulator or real flight training. If the importance of the various features in the visual scene is understood better, training of new pilots can be more efficient. Additionally, the development of synthetic or augmented vision displays could benefit from the results of this study, as well as the development of vision based automatic landing systems.

1.2 Outline

We test the hypothesis that experienced airline pilots base the timing of the flare manoeuvre on the visual cue $\dot{\theta}$, which can be described as 'the speed of the apparent runway widening' or 'the rotational speed of the runway sidelines' (Fig. 1). The visual cue $\dot{\theta}$ is a function of altitude and sinkrate, the two parameters considered of main importance to the flare. We will contrast our $\dot{\theta}$ hypothesis with the 'altitude' and the 'time-to-contact' flare initiation hypotheses suggested in training literature and by other researchers.

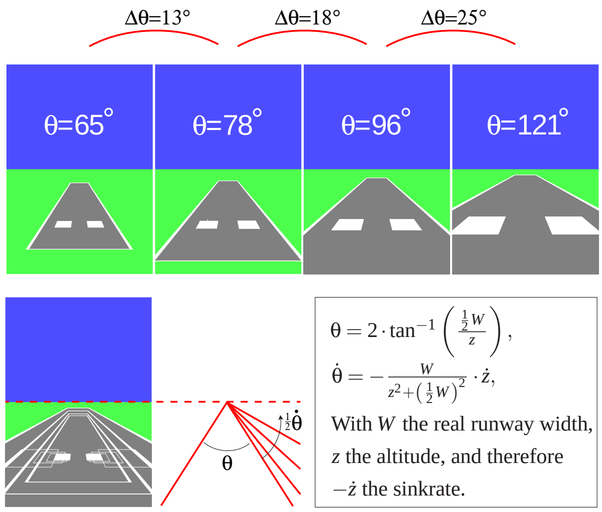

Fig. 1 In a constant velocity descent along a 3° glide path, the pilot will see the image of the runway expanding faster and faster. We define the apparent angle between the runway sidelines θ, and therefore the expansion speed $\dot{\theta}$.

The time-to-contact (τ) is a state variable that might be perceived visually. It was first suggested by Lee [5] to describe braking behaviour of car dirvers. In the case of an aircraft in the glide phase, τ could be defined as $\tau_z = \frac{z}{\dot{z}} = \frac{\text{altitude}}{\text{sinkrate}}$ or $\tau_x = \frac{x}{\dot{x}} = \frac{\text{ground distance to touchdown point}}{\text{groundspeed}}$. Several landing flare researchers picked it up [e.g., 4, 6] and some used the visual cue variant τ_Ψ, with Ψ the angle subtended by the runway at the aimpoint markers[1][2, 7]. However, the accuracy with which the time-to-contact can be perceived remains a topic of debate in literature.

We analysed data from a total of 57 landings flown by 5 professional airline pilots in level D certified full flight simulators of Boeing 767-type aircraft. The recorded data consists of the main aircraft states (to calculate visual cues in post-processing) and the pilot's control inputs, as well as eye-mark recordings to get a better understanding of what the pilot is actually looking at. A number of parameters were varied in the experiment to validate the flare timing hypothesis over a broad operation range.

[1] i.e., the (visual) angle between the point next to the aimpoint markers on one runway sideline, the pilot's eyes, and the point next to the aimpoint markers on the other runway sideline.

1.3 Visual Attention

In this paper we will especially focus on the question 'where is the pilot looking?' and try to answer the following questions using data obtained with an eye-mark recorder:

- *Are visual cues really so important, or are pilots mainly using the cockpit instruments?* This touches one of the main assumptions in this research, namely that visual cues are important in the final approach and landing.
- *Which instruments are pilots using?* Pilots use instruments to cross-check important visual cues, as well as to obtain information that visual cues cannot provide accurately.
- *How does the instruction to 'use visual cues as much as possible, especially below the Decision Height of 200 ft (61 m)' influence instrument and visual cue use?* By comparing instrument use with and without this instruction, we investigate which instruments are mostly used for cross-checking and which instruments really provide additional information.
- *Does (simulated) motion influence visual cue use?* Pilots mentioned that 'it feels bad/wrong' when they fly the simulator without motion simulation. They also mentioned that their instrument/visual cue use ratio changes.
- *Is visual cue use changing for extreme wind cases?* Pilots commented that the strongest headwind cases in our experiments required atypical settings, so we investigate changes in instrument or visual cue use.

Scan patterns, that is, which combinations of instruments are used and in what order instruments are (cross)checked, were not analysed in detail in this research. Differences between novice and experienced pilots have also not been investigated, as both pilots taking part in the eye-mark experiment were captain pilots. These topics, however, have been extensively studied by airlines and other researchers [e.g., 8–10].

1.4 Organization

After explaining our experiment setup, we present an analysis of the flare initiation points and a qualitative analysis of the eye-mark data. Finally we discuss our findings in the light of comments we obtained from pilot interviews. A more detailed description of the research presented here and related research can be found in the thesis by Entzinger [11].

2 Materials & Methods

2.1 Subjects

Five professional airline pilots participated in our experiments. All are male and are licensed to operate Boeing 767 type aircraft. Three of these pilots fly for All Nippon Airways (ANA), two as captain pilot with about 8300 recorded flight hours and one as a co-pilot with 2700 hours of flight experience. The other two pilots fly for Japan Airlines (JAL) and are both captain pilots, with 9548 and 6677 flight hours. In this paper we will focus on the data obtained from the JAL pilots, because they wore an eye-mark camera during the experiments as explained below. The authors did not directly select the pilots, but requested the collaboration of 'highly experienced' and 'beginner' level pilots from the two airlines.

2.2 Flight Simulator

The flight simulators used are level D certified full flight training simulators operated at ANA and JAL for regular pilot training (Fig. 2). Analogue data was discretised and captured at a rate of 30 Hz in the ANA simulator, while floating point data was captured at 10 Hz in the JAL simulator. The ANA simulator has a field of view of 150°, while the JAL simulator's field of view is 200° wide. Other minor differences between the two simulators and the virtual world scenes used are considered to be insignificant for the results presented here. Both are extremely high fidelity simulators with 3 visual channels and 6 degrees of freedom motion simulation.

All landings were made on 3000×60 m runways equipped with a PAPI[2]. Automated radio altitude (RA) call-outs were available to the pilots at 100, 50, 30, 20, and 10 ft (30, 15, 9, 6, 3 m) height of the main gear above the runway.

Fig. 2 Outside and inside of ANA's Boeing 767-300 simulator

2.3 Experiment Design

Training literature and pilots generally state that the flare should be commenced at a certain altitude, while several researchers found the sinkrate also influenced flare timing. The visual cue $\dot{\theta}$ proposed in the hypothesis under examination integrates altitude and sinkrate information in a unique way, and if our hypothesis holds, pilots will initiate the flare at a the same value of $\dot{\theta}$, even when the approach sinkrate is varied.

Therefore, we designed an experiment where the pilots have to land under different sinkrate conditions. Rather than changing the approach glideslope to achieve this —as is commonly done in similar experiments—, we decided to vary head/tail wind conditions and aircraft weight. We did so because the professional airline pilots in our experiment are used to the 3° glide path and any change would create an unnatural situation and therefore not provide reliable results.

[2] PAPI = Precision Approach Path Indicator, a series of lights providing glideslope information. It is installed on the ground next to the runway, close to the aimpoint markers.

Approaches typically started 3.7 km (2 NM) from the touch down zone, with the aircraft trimmed, and on the 3° glide path. Aircraft gross weight was varied between 100.000∼145.000 kg and wind speeds between 20 m/s head and 10 m/s tail wind (-40 kt ∼20 kt) to obtain nominal sinkrates of around 3.1 m/s, 3.8 m/s, 4.15 m/s and 4.4 m/s. Although all parameters are within or on the official operation limits of the Boeing 767-300, some pilots noted the strongest headwind cases would require an unusually low pitch during the approach, requiring a somewhat higher altitude flare to assure landing on the main gear rather than on the nose gear first. Strong headwind cases are therefore analysed separately.

2.4 Eye-mark Experiments

Captain pilots JLB and JLA were asked to wear an eye-mark camera (Fig. 3) to track their point of gaze during the simulated approaches. We used a lightweight cap-type unit with one small camera for each eye to record movements of the subject's pupils and a third camera to capture the scene the pilot is looking at. In post-processing, the data of both eye cameras were analysed and a marker indicating the point the pilot is looking at was overlayed on the scene camera's image. Classification of the gaze locations was done manually.

When asked, the pilots said that the system did not hinder them in any way, and their visual field was unobstructed. Initially, the tiny cameras capturing the eye movements (situated a little in front of and below the eyes) drew their attention from time to time, but they got used to their presence quickly. The pilots were allowed to move their heads during the experiments. The eye-mark system was set up, calibrated, and operated throughout the experiments by an expert of the manufacturer.

Eye-mark data were captured at 60 Hz and identified with the Purkinje and pupil centre methods by the bundled software. Software also automatically detected blinking. Final video data was obtained at a rate of 30 Hz and with a resolution of 0.1° of visual angle. The system was calibrated to capture the flight instruments accurately. Since professional flight simulators have collimated displays for the outside scene, a significant vertical offset exists between the actual and detected gaze position when the pilot looks outside. We calculated the theoretical value of this offset, and used it for the classification and interpretation of the eye-mark data for outside visual cues. There is no horizontal offset, since the midpoint between the left and right eye gaze positions is used.

Fig. 3 NAC's EMR-9 eye-mark recorder (*left*; photo by NAC, reproduced with permission) and the pilot wearing it (*right*)

3 Main Results

3.1 Flare Altitude and Sinkrate

From pilot interviews and training literature we know that B767 pilots think they (should) initiate the flare 30 ft (9 m) above the runway. However, only the one novice pilot in our experiments showed such behaviour. All veteran pilots except pilot NHD initiated their flares at considerably higher altitudes (11–15 m on average), and clearly depending on the sinkrate (Fig. 4). This is consistent with the findings of Heffley et al. [3] regarding veteran pilots' flare initiation. We also noted that pilots generally make a 'pre-flare' at an even higher altitude of 15–20 m.

Most of the flare initiations made under the strong headwind conditions do not seem to follow the trend we find in the other data points. This is probably due to the boundary condition on the pitch angle at touchdown. The pilot has to initiate the flare at a higher altitude to be able to pitch-up sufficiently to land on the main gear first, as foreseen by the pilots (§2.3). Since this is a boundary case on an aircraft state, no visual

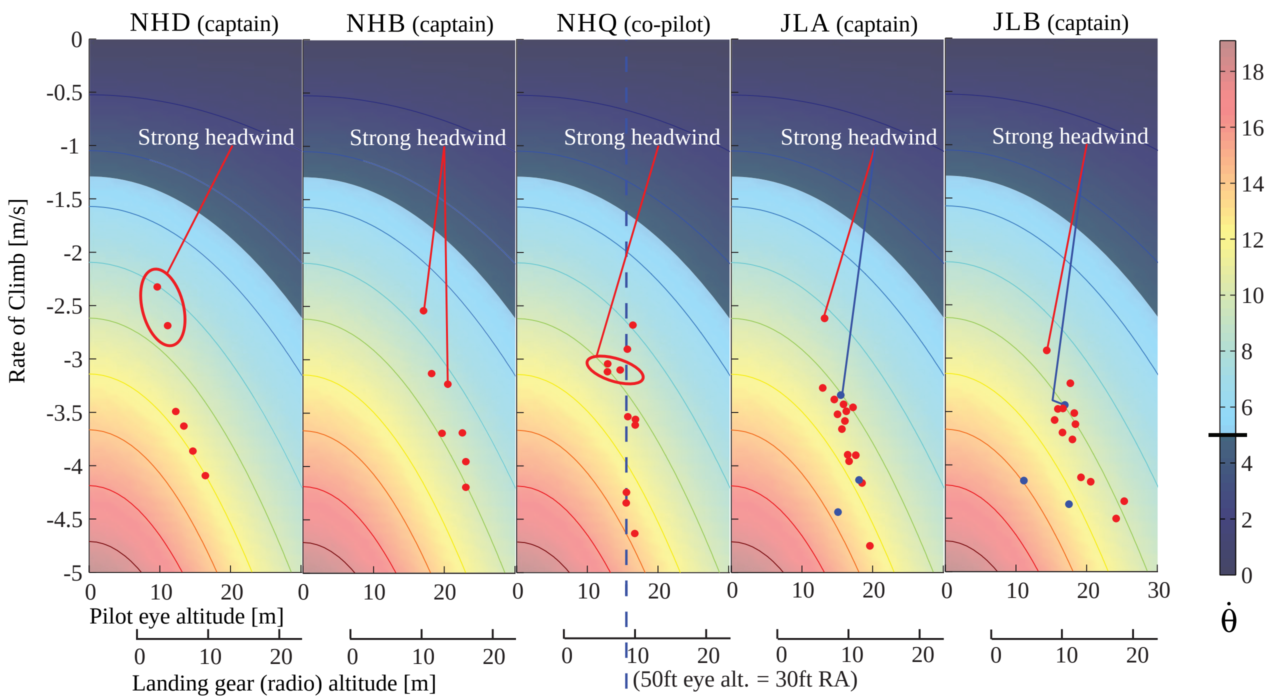

Fig. 4 Flare initiation altitude and sinkrate for each landing approach (dots). The shade of the background indicates the value of $\dot{\theta}$, with the dark blue upper-right area the sub-threshold values. The blue dots for JLA and JLB indicate the flare initiations without motion simulation.

flare initiation theory can be expected to model this behaviour.

From a comparison between the novice and a veteran pilot who flew the same set of landing approaches, we noticed that the veteran pilot's control after flare initiation was smoother and of lower amplitude, which may be related to his more advanced flare timing skill. More details about the statistical analysis of landing data and the comparison between the novice and veteran pilot can be found in an earlier publication by the authors [12].

3.2 Eye-mark Results

Figure 5 shows the visual attention breakdown for both pilots averaged over all recorded landings. We distinguish between above and below 200 ft (61 m), which is the 'Decision Height' or 'Minimum Descent Altitude' where the pilot has to decide to continue or abort a manual landing based on the visibility conditions. The left charts show that during the early glide phase (above 200 ft) the pilots check many different instruments. The main focus is on the attitude indicator (i.e., the artificial horizon at the centre of the flight director display[3]), while airspeed and to a lesser degree glideslope also get quite some attention. Fixations on the attitude display are typically long, with brief but frequent checks of airspeed and glideslope. Pilots spend over 70% of their time watching the flight instruments, and thus less than 30% looking at the outside scene during this phase.

Pilots start looking outside well before crossing the runway threshold and thus also well before the flare initiation. The middle and rightmost charts in Fig. 5 show that the attention pattern just before the flare initiation and generally below 200 ft altitude are very similar to that above 200 ft, although the variation in instruments checked is lower and the total time of instrument use is drastically decreased, reflecting that pilots mostly look outside.

[3]Flight Director (FD): Integrated cockpit instrument display providing an artificial horizon, attitude, glideslope, altitude and airspeed information.

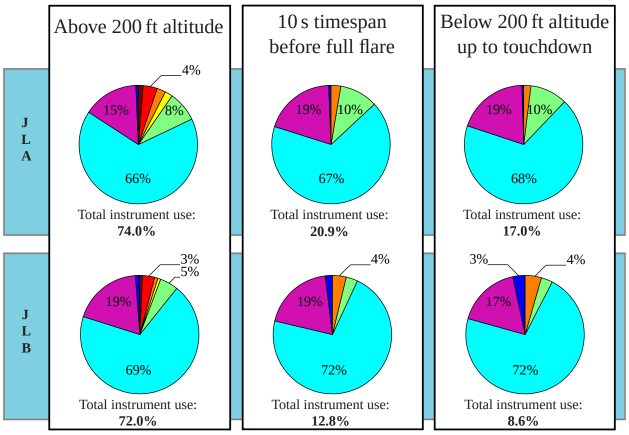

Fig. 5 Overall instrument use per pilot. Total instrument use is high and diverse above 200 ft, and limited below 200 ft. Usage ‘10s before flare’ is very similar to ‘below 200 ft’.

When looking outside above 200 ft, pilots mostly look at the runway threshold or the aimpoint markers. Below 200 ft, they look at the far end of the runway or the horizon.[4] It is also interesting to mention that between the full-flare initiation and the main gear touchdown, pilots never blinked. From the pre-flare to main gear touchdown, they blinked only once in only 3 of the 30 recorded landings.

The results confirmed that not the cockpit instruments, but visual cues in the outside scene are the main information source for the pilot just before and during the flare phase. They also confirm that the Boeing 767 pilots mainly use (inner loop) pitch control to maintain a stable glide path, and check the glideslope indicator very quickly, but frequently. Airspeed is watched closely, probably because it is difficult to accurately perceive airspeed through visual cues or optical flow, especially in a simulator, which has relatively little ground texture. The importance of airspeed, attitude and glideslope information confirms findings from literature [e.g., 8, 13].

The finding that pilots fixate at the aimpoint markers when the look outside above 200 ft suggests that the H-distance and the focus of expansion of the optical flow are important in the glide phase. Since pilots fixate at the far runway end or horizon when looking outside below 200 ft—which they do almost all the time—, it is unlikely that they use visual cues related to the aimpoint markers, such as the visual time-to-contact cue τ_Ψ. Furthermore, it implies that pilots probably do not perceive $\dot{\theta}$ through the rotation of a single sideline, but would perceive the increase of the angle between the two sidelines foveally and/or through the upward optical flow in the visual periphery.

3.2.1 *Strong Wind Cases*

Figure 6 shows how instrument use changes for the strong headwind case (case F) and the strong tailwind case (case G) for the part of the approach below 200 ft altitude. Above 200 ft no clear differences were found. Only 2 datasets were available per case per pilot for cases F and G, and one of each was collected without motion simulation.

There are clear increases in the time spent checking the instruments. For the headwind case F, both pilots clearly spend less time checking airspeed, and more time on the glideslope indicator. Captain JLB also did not (cross)check the altitude and roll indicators any more. Instrument use in tailwind case G is clearly higher than average, but the percent division of attention over the instruments is very similar to the overall average, although captain JLA checks the glideslope indicator much more.

It can be concluded that, especially for captain JLB, the behaviour in the strong headwind case was atypical, as was to be expected.

3.2.2 *‘Normal’ versus ‘Visual’*

Since our major research is on visual cue use in the landing, we normally tell pilots that they can use the flight director (FD) display in the beginning, but that they should ‘fly on visual’ (i.e., mainly observing the out-the-window scene) as soon as they feel confident, and especially below 300∼200 ft altitude. To understand how this changes the pilot’s behaviour, we compare ‘normal’ flight —where the pilot can use instruments as much as he likes— with ‘visual’ flight, where

[4] The far end of the runway and the horizon are very close, and indistinguishable in the eye-mark data.

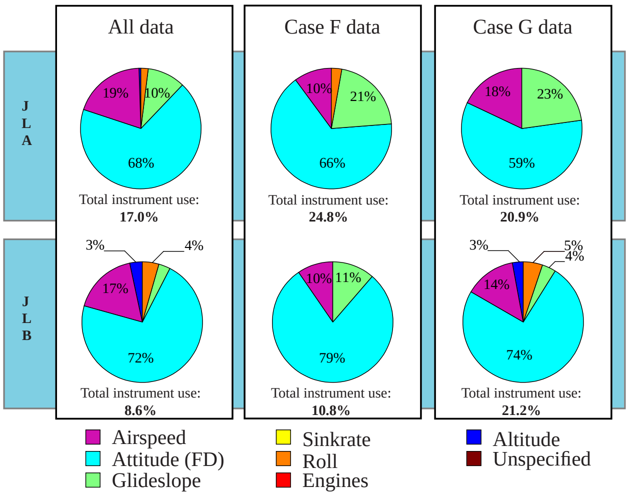

Fig. 6 Comparison of visual attention for strong wind cases. Average over all recorded data below 200ft altitude up to the main gear touchdown.

the pilot is asked to minimize instrument use. The upper four pie charts in Fig. 7 show the results.

First it should be noticed that instrument use above and below 200 ft drops drastically from about 90 and 15% respectively, to 30 and 4% respectively when the pilot is asked to fly on visual.

Above 200 ft, the longest fixations were on the flight director for the normal case, with regular short checks of airspeed and glideslope. In the visual case, the main fixations were outside on the aimpoint markers, with regular short checks of the PAPI, and checks of instruments that provide information hard to obtain from visual cues, such as airspeed and sinkrate.

Below 200 ft, the total time spent checking the airspeed indicator remains almost unchanged, but its importance relative to other cockpit instrument increased tremendously when the pilots were asked to fly on visual. The glideslope indicator was also checked more in the 'visual' cases. The relative increase of importance of these instruments was mostly at the cost of time spent observing the attitude display.

These results confirm the idea that airspeed is probably difficult to accurately estimate from visual cues, while attitude cues are very salient. It also shows that it may be difficult to accurately perceive the glide path from visual cues only,

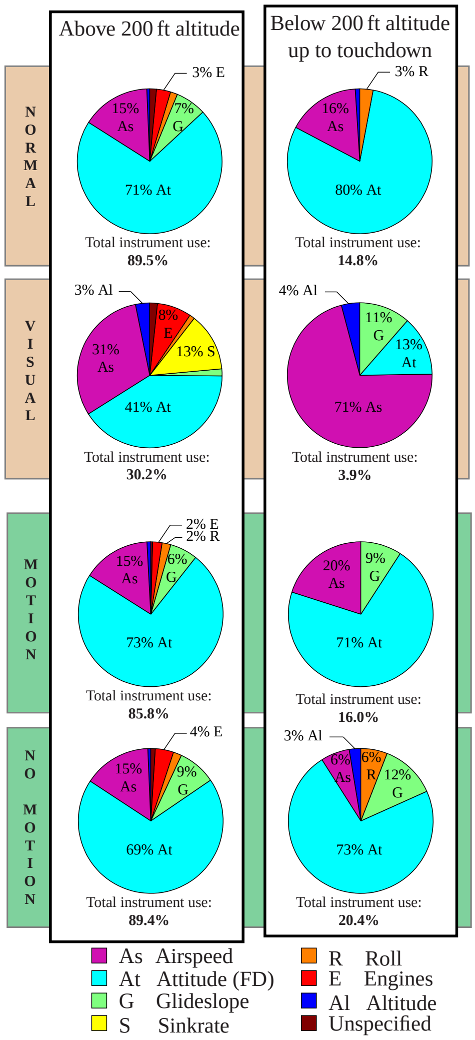

Fig. 7 Eye-tracking results: 'normal' vs. 'visual' & the influence of motion simulation.

or at least that the pilot feels the responsibility to cross-check it regularly, using either the PAPI or the cockpit instruments. The clear use of the PAPI indicates that the presence of a PAPI cannot be ignored when analysing visual cues during the glide, at least not for airliner approaches.

It should be stressed that the pilots constantly looked outside short before and during the flare, regardless of whether they were flying 'normal' or 'visual' cases.

3.2.3 'Motion' versus 'No Motion'

In discussions, the pilots admitted there is a difference between simulated motion and the motion of a real aircraft, noting that the missing g-forces in the simulator forced them to make more use of the cockpit instruments for their judgements, leaving less time to observe the outside view. When motion simulation is turned off entirely, the reliance on instruments increases even further, they said.

A few researchers previously studied this issue. Zaal et al. [14] also found that pilots make more use of visual cues from optical flow if motion simulation is present. Comstock [15] found that mean fixation times on instruments decreased in simulated Boeing 737 landing approaches when motion simulation was present, and concluded that *"motion serves an alerting function, providing a "cue" or "clue" to the pilot that "something happened"."*

The lower part of Fig. 7 shows a comparison of instrument use between presence and absence of motion simulation. As expected, the use of instruments is slightly higher in the 'no motion' case, both above and below 200 ft altitude. Especially the glideslope indicator receives more attention, and below 200 ft altitude pilots check altitude and roll only when motion is absent. The lesser attention to the airspeed indicator below 200 ft in the no motion case is remarkable. It could be that the pilot has little time left over for extra (cross-)checks due to the increased workload, or it might be an artefact of the small sample size of only 3 landings.

3.3 Pilot Opinions

In the experiment (de)briefings and discussions, we asked pilots which cues they think are important for the approach and landing.

Pilots seemed a bit sceptical about the proposed cue $\dot{\theta}$ at first, because they felt that they use altitude as a main cue to flare initiation timing. However, when asked how they then perceive altitude information, they found it very difficult to describe what they see or what they look for (note that altitude itself is an aircraft state, not a cue, and that pilots rarely look at the altimeter). Only when asked directly and specifically to indicate the importance of several suggested factors, pilots could give some clear answers.

Captain pilots estimated that visual altitude and sinkrate cues made up at least 70∼80% of the information for flare initiation and control. They also acknowledged the importance of the runway sidelines and a wide field of view. The automated altitude call-outs are of secondary importance, but useful as a cross-check. They said landing is not more difficult when call-outs are missing.

Co-pilots mentioned that the call-outs are very important to them. When asked, they felt that especially the time between the call-outs — providing sinkrate information— was important, although they also use the altitude information itself. Especially when the call-outs were missing by surprise, they found it increasingly difficult to land the aircraft.

In their whole description of the approach phase, pilots seem to be 'altitude-driven', with comments like *"from about 200 ft altitude, look outside"*, and *"at 50 ft, check longitudinal position along the runway with respect to the runway threshold"*. Most pilots also believe they initiate the flare at *"a certain altitude"*, although they generally cannot quantify this altitude. They say that they may flare *"a little early or late"* depending on the sinkrate, although they could not explain how they then make this decision. This justifies our visual cue research, because explaining which cues are crucial is important for a more efficient training of new pilots.

Two explanations for the pilots' belief that they start the flare at a constant altitude are suggested here. First, pilots may have been 'brainwashed' by (training) literature, since it always mentions altitude as the main factor. Automatic landing systems start flaring at a fixed altitude as well. Early in their career, pilots may actually use altitude, as some training manuals suggest novice pilots to flare at the automated 30 ft altitude call-out for convenience. As it is very difficult —if not impossible— to word the perception-action systems learned through extensive experience, pilots might resort to this 'learned' explanation.

Another explanation is that pilots may have developed a different conception of 'altitude'. Instead of seeing altitude as a linear distance measure, they might see it as a 'safety margin'. In this case, it would be natural to integrate sinkrate into altitude, as high sinkrate is a threat constantly decreasing the safety margin. After all, near zero altitude with near zero sinkrate is safe, but near zero altitude with high sinkrate means a crash.

4 Conclusion

We presented the results from flight simulator experiments on the visual cues used for flare timing. The experiments were set up to compare the suggested $\dot{\theta}$-based flare initiation with the altitude and τ hypotheses. The first results already showed that veteran pilots generally initiate the flare at an altitude considerably higher than the recommended 30 ft, and clearly depending on sinkrate. As this is in line with the findings from other researchers, the fixed-altitude flare hypothesis can be rejected.

One of the many results of the eye-mark analysis is that pilots particularly keep using the airspeed instruments when asked to minimize instrument use and to focus on the outside visual cues ('visual' case). The pilots also cross-checked other factors which are critical or cannot easily or accurately be derived from outside visual cues, such as the sinkrate and glideslope.

In the 'normal' case, the longest fixations were on the flight director display. In the 'visual' case and above 200 ft, the pilots mainly looked at the aimpoint markers, with regular short checks of the PAPI and a few instruments. Below 200 ft the pilot's attention is mostly at the end of the runway or the horizon. These results are confirmed by the pilot comments. This means that it is unlikely that pilots use τ_Ψ as visual cues for flare timing, because this cue requires the pilot to focus on the aimpoint markers. However, it cannot be ruled out that there is another way to perceive the time-to-contact from the optical flow in the visual scene.

Another interesting finding was that the pilots do not blink between the flare initiation and the touchdown, which highlights the importance of visual information in this critical phase of the landing. Switching off the motion simulation results in a slight increase in the use of flight instruments, in particular the glideslope indicator.

The analysis of flare initiation points, control style, and pilot eye fixations, in combination with the knowledge obtained from pilot interviews and literature, leads us to believe that experienced pilots have developed a sophisticated way of timing the initiation of the flare manoeuvre whereby they make use of the speed of the apparent runway widening, $\dot{\theta}$.

For further research, it would be interesting to compare real landings with simulator landings and see if pilots use different visual cues or instruments. In that case, real landings should be flown first, so that initial conditions can be accurately mimicked in simulation. A challenge here would be the fact that not only the fidelity of the visual simulation, but also the motion simulation would influence the outcomes.

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