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Effects of scenery, lighting, glideslope and experience on timing the landing flare

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Abstract

This study examined 3 visual strategies for timing the initiation of the landing flare based on perceptions of either: (i) a critical height above ground level; (ii) a critical runway width angle (Y); or (iii) a critical time-to-contact (TTC) with the runway. Visual displays simulated landing approaches with trial-to-trial variations in glideslope, lighting, and scene detail. Twenty-four participants (8 private pilots, 8 student pilots and 8 non-pilots) were instructed to initiate the flare when they perceived that their TTC with the runway (30 m wide by 840 m long) had reached a critical value of 2 seconds. Our results demonstrated a significant effect of flight experience on flare timing accuracy and dominance of the height-based strategy over the runway-width-angle and TTC-based strategies.

Keywords

Effects, scenery, lighting, glideslope, experience, timing, landing, flare

Disciplines

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Running head: VISUAL TIMING OF THE LANDING FLARE

Effects of Scenery, Lighting, Glideslope and Experience on Timing the Landing Flare

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Abstract

This study examined 3 visual strategies for timing the initiation of the landing flare based on perceptions of either: (i) a critical height above ground level; (ii) a critical runway width angle (Ψ); or (iii) a critical time-to-contact (TTC) with the runway. Visual displays simulated landing approaches with trial-to-trial variations in glideslope, lighting, and scene detail. Twenty-four participants (8 private pilots, 8 student pilots and 8 non-pilots) were instructed to initiate the flare when they perceived that their TTC with the runway (30 m wide by 840 m long) had reached a critical value of 2 seconds. Our results demonstrated a significant effect of flight experience on flare timing accuracy and dominance of the height-based strategy over the runway-width-angle and TTC-based strategies.

Effects of Scenery, Lighting, Glideslope and

Experience on Timing the Landing Flare

To obtain a safe, smooth landing, pilots of fixed-wing aircraft must reduce their descent rate during the final stages of the landing approach (Grosz et al., 1995; Mulder, Pleijsant, van der Vaart, & van Wieringen, 2000). This is achieved by performing the *landing flare manoeuvre*. While the flare is often regarded as a continuous manoeuvre, it actually has two distinct phases: flare initiation (or ‘leveloff’) followed by ‘roundout’ (Benbassat, Willams & Abramson, 2005). Below we describe the situation facing a pilot landing a general aviation aircraft (e.g., a Cessna 152). First, it is essential that the pilot make a well-timed decision to initiate the flare. During this initial leveloff phase, the pilot typically sets the throttle to idle and simultaneously transitions the aircraft from a nose-down approach attitude to straight and level flight (by pulling backwards on the yoke or control wheel). Then during the roundout phase, the pilot continues to adjust the aircraft so as to reach the desired (nose-high) landing attitude and descent rate at touchdown (Benbassat et al., 2005; Langewiesche, 1972). If performed correctly, the flare manoeuvre should reduce the aircraft’s descent rate to acceptable levels {e.g., from around 3 m/s (591 ft/min) during the glide to 1 m/s (197 ft/min) or less on touchdown – Grosz et al., 1995} so that it settles gently on the main landing gear.

The landing flare is considered one of the most technically demanding aspects of piloting. Both novice and expert pilots consistently rate the landing flare as one of the most difficult flight manoeuvres (Benbassat & Abramson, 2002b). It has been conservatively estimated that 18% of all landing accidents in the USA between 1995 and 2000 were due to problems with the landing flare (Benbassat & Abramson, 2002b;

Benbassat et al., 2005). In one questionnare study by Benbassat and Abramson (2002b), 87% of the 134 US pilots sampled indicated that they used visual cues to time the initiation of the flare. However, no consensus emerged as to which specific visual cues were required for a successful flare. A more recent study by Benbassat et al. (2005) examined the landing flare in finer detail. They had novice, intermediate and expert pilots rate the perceived difficulty of the leveloff and roundout phases of the flare. Suprisingly, many of the pilots were unclear as to the distinction between these two phases (including the experts). When definitions were provided, their participants were found to rate both leveloff ("determining the aircraft height and beginning of the flare" pp. 193) and roundout ("increasing the angle of attack by raising the nose of the aircraft after the leveloff" pp. 193) as equally difficult.

The goal of the present study was to examine the visual cues that pilots could use to accurately time the initiation of the landing flare (i.e., leveloff). Accurate timing of the leveloff phase is crucial. If flare initiation is too late, then the aircraft will eventually make hard contact with the runway. If it is too early, then the aircraft may level out at too high an altitude, which is also problematic because: (i) it increases the likelihood of long landings and runway overruns; and (ii) any further reduction in airspeed may cause the aircraft to stall and drop with excessive velocity (Grosz et al., 1995). While leveloff timing errors can be compensated for (to a degree) during roundout, it is clear from self-reports and questionnaire studies that accurate flare timing is an essential skill for pilots to acquire and retain.

Three possible visual strategies for timing the initiation of the landing flare have been identified in the literature. First, pilots could initiate the landing flare when they perceive that they are at a critical height above ground level (AGL). The critical height AGL for the flare depends on several factors. For example, the critical flare height might be 3 to 9 m (10 to 20 ft) AGL for a small or light (i.e., general aviation) aircraft compared to 24 m (80 ft) AGL for a larger transport aircraft (Benbassat & Abramson, 2002b; Benbassat et al., 2005; Langewiesche, 1972). In principle, the pilot's perception of height in this situation could be based on a variety of visual cues including stereopsis (binocular disparity), size (familiar and relative size), horizon (height in the visual field), motion (motion parallax and optic flow), texture gradients (linear perspective and compression gradients), etc (Allison, Gillam & Vecellio, 2007; Benbassat & Abramson, 2002b; Benbassat, Abramson, & Williams, 2002; Cutting & Vishton, 1995; Langewiesche, 1972; Riordan, 1974). Importantly, scene depths, heights and ground slant are often misperceived in entry-level flight simulators (which utilise binocular viewing of 3-D displays on near 2-D screens without collimation - Pierce & Geri, 1998; Roscoe, 1979). Thus, if accurate flare timing requires veridical perceptions of scene layout (including height AGL), then systematic errors might occur when using such simulators.

As a second strategy, pilots could initiate the landing flare when the visual angle (Ψ) formed between the left and right edges of the runway at the aiming line reaches a critical value (see Figure 1). The aiming line is a hypothetical line that lies at right angles to the runway alignment and passes through the pilot's aimpoint (Mulder et al., 2000). Because this strategy is based only on a visual angle, it should allow accurate flare timing performance even when scene depths, heights and slants are misperceived (e.g., during night landings or when using entry-level simulators). However, this strategy should produce serious errors (at least initially) when applied to unfamiliar runways (e.g., if one used a critical Ψ angle value appropriate for a familiar, narrow runway, this would produce an early flare when landing on an unfamiliar wide runway; see Mertens, 1981; Mertens & Lewis, 1982).

Finally, pilots could initiate the landing flare when their perceived time-to-contact (TTC) with the runway reaches a critical value (Grosz et al., 1995; Lee, 1980; Mulder et al., 2000). TTC during landing is defined as “the time remaining to the moment that the wheels make contact with the runway if no pilot action is taken” (Mulder et al., 2000, p. 294). However, since the aircraft’s wheels are not visible, TTC is probably perceived by the pilot as the time remaining for him/her to make contact with the runway. This TTC could be perceived indirectly (e.g., McLeod & Ross, 1983), either by dividing the pilot’s perceived distance to the aimpoint by the perceived approach velocity, or by dividing the pilot’s perceived height above ground by his/her perceived descent rate. However, since human perceptions of absolute distance and absolute velocity can be highly error prone (e.g., Schiff, Oldak, & Shah, 1992; Scialfa, Guzy, Leibowitz & Garvey, 1991; Sidaway, Fairweather, Sekiya & McNitt-Gray, 1996), some theorists have argued that TTC must be perceived directly (i.e., without first estimating speed and distance). One possibility is that TTC is calculated directly via the following ratio (known as *optic tau* – see Lee, 1976; 1980):

$$\text{Tau} \approx \theta/(d\theta/dt) \qquad [1]$$

One commonly studied TTC scenario is the perpendicular approach, where the observer moves along a straight line towards a frontoparallel surface, which in turn generates a global pattern of optic flow. In such situations, the optical expansion is isotropic (see Figure 2A) and the θ term in this equation can be defined in several different ways, resulting in useful local and global tau-based information about TTC. Consider the situation facing an automobile driver approaching a truck stopped at a set of traffic lights. In the case of global tau, θ would be defined as the instantaneous visual angle between the moving observer's aimpoint (which coincides with the focus of expansion of the global optic flow) and any other visible point lying on the truck (Lee, 1980; Tresilian, 1991). In the case of local tau type 1, θ would be defined as the instantaneous angular distance between any two visible points on the rear of the truck (e.g., its left and right brake lights - Tresilian, 1991); and (iii) in the case of local tau type 2, θ would be defined as the angular distance between the optical boundaries of the truck (e.g., its left and right sides - Lee, 1976; Tresilian, 1991). In all three cases, dθ/dt refers to the instantaneous rate of change in these angular distances over time. In this perpendicular approach situation, both local and global tau would provide accurate estimates of TTC that could in principle be used to safely approach and stop behind the truck[1].

Importantly, Mulder et al. (2000) have argued that the local and global tau cues described above, are not appropriate for estimating TTC during an aircraft landing. These slanted landing approaches (along a straight line and towards a rectangular runway lying on a horizontal ground plane) generate asymmetrical patterns of optical expansion (see Figure 2B). In this specific case, Mulder et al. showed that the tau equation only accurately specifies the TTC during landing when it is based on optical expansion which occurs along the aiming line. From Figure 2B, we can see that TTC estimates based on the optical expansion of points lying above the aiming line should result in TTC underestimation (due to their slower rate of expansion), whereas TTC estimates based on optical expansion of points lying below the aiming line should lead to TTC overestimation (due to their faster rate of expansion). Mulder et al. derived a ‘restricted’ tau cue specifically for this landing situation, which was identical to the global tau cue described above, with one exception: it was based on the optical expansion between *the aimpoint* and *any other point lying on the aiming line*. However, accurate estimates of TTC could in principle be provided in this situation by the optical expansion between *any two points lying on the aiming line*. This ‘restricted’ local tau type 1 cue could be based on the expansion either between the two points where the aiming line intersects with the left and right edges of the runway, or between two points lying on the aiming line outside the runway boundaries, etc. Importantly, perceptions of TTC based on restricted global or restricted local tau cues should improve when additional ground texture is provided along the aiming line, as this would enable multiple estimates of TTC.

The available evidence for the use of the three flare timing strategies outlined above is inconclusive. Consistent with the critical perceived height strategy for flare timing, flight instructors and instruction manuals typically suggest that the flare should be initiated when the pilot judges that the plane has reached the appropriate height above the runway (e.g., Benbassat et al., 2005; Thom, 1994). Interestingly, actual aircraft landings performed under monocular viewing conditions have been found to be as accurate as those performed under binocular viewing conditions (e.g., Grosslight, Fletcher, Masterton & Hagen, 1978; Lewis & Krier, 1969; Lewis, Blakeley, Masters & McMurty, 1973). Thus, if a perceived critical height strategy is involved in timing the flare, it appears that monocularly available height information must be sufficient for the successful execution/completion of this task (see also Benbassat & Abramson, 2002a).

Grosz et al. (1995) found little support for any of the three above-mentioned strategies in their flight simulator study, where three jet transport pilots actively controlled 126 simulated landings from a distance of 5 km from the runway to touchdown. Contrary to their predictions, they found that pilots did not initiate their flares at either a constant height above the runway, or a constant time before touchdown. They explained the failure of the above theories to account for flare timing performance by proposing that the experienced pilots in their study primarily "wanted to make contact with the runway at a specific point" (Grosz et al., 1995, pp. 119). They suggested that future studies should constrain the response task in order to test these different strategies in terms of more relevant criteria (e.g., reducing the descent rate on touchdown to safe levels).

In more recent research, Mulder et al. (2000) found mixed support for the proposals that flare timing is based on perceived runway width angle (Ψ) and perceived TTC based on tau. In their simulation study, non-pilot (as opposed to pilot) participants viewed schematic landing displays and simply pressed the space bar on the computer's keyboard when they perceived that they should initiate an idealised pre-programmed flare. Interestingly, Mulder and his colleagues found that flare timing strategies appeared to change from being based on perceived runway width angle when only a runway outline was provided, to being based on perceived TTC when additional texture was provided along the aiming line. This suggested that as the visual information about TTC became more reliable, flare timing responses were predominantly based on the perceptions of critical TTC.

The Experiment

The current study was aimed at examining these three visual strategies, each of which could in principle be used to accurately time the initiation of the landing flare. We hoped to avoid some of the possible problems in the earlier Grosz et al. (1995) study, where the participant's extensive flight experience and the active nature of the glideslope control task may have complicated the flare error data (which would have consisted of components due to both initiation and control error). Instead we chose to focus exclusively on the initiation phase of the flare, which we examined using a passive flare timing task combined with performance feedback. The actual TTC at the start of each landing simulation varied from trial-to-trial. Participants were instructed to watch the simulation and only initiate a landing flare when they perceived that their TTC with the runway had reached 2 s (the critical TTC for all of the conditions tested in this experiment). Unlike the Mulder et al. (2000) study, we tested not only non-pilots, but also student pilots and private pilots. The aim of testing these three groups of participants was to determine whether the different levels of flight experience had any influence on either their choice of flare timing strategy or their response accuracy using our highly constrained experimental task.

Prior to the experiment, participants in each of the three flight experience groups were trained extensively to recognise the critical 2 s time interval. During the simulated landing approaches in the subsequent experimental trials, they pressed a mouse button to indicate that they perceived that the critical time had arrived to initiate the flare. Participants were then told whether they had flared too early or too late and by how many seconds, which should have allowed them to identify the critical TTC for this specific landing scenario (Gagnon, Fleury, & Bard 1988; Tresilian, 1995).

We examined flare timing performance: (i) for 3° and 6° glideslope approaches; (ii) with both day and night lighting conditions; and (iii) with or without 3-D buildings present. While the actual TTC at the start of the trial depended on the simulated glideslope, the critical TTC was always 2 s and the critical runway width angle was always 23.5° for both of the glideslope conditions tested. However, the critical heights AGL were different for the 3° (3.8 m) and 6° (7.5 m) glideslopes. Thus, if participants used either a tau-based critical TTC or a critical runway width angle strategy, they should show no glideslope effects on their flare timing. However, if they used either a non-tau based critical TTC strategy or a critical perceived height strategy, their data should display significant glideslope effects on flare timing - which might be more marked during night lighting conditions without 3-D buildings, because less depth/distance information would be available. Our predictions in terms of the other display manipulations (day versus night lighting and buildings versus no buildings) were as follows. If participants were using a critical runway width angle strategy then we would expect that their performance would not be significantly altered by either manipulation, since the runway outline on which it was based was always visible. Conversely, if accurate perception of the scene layout (including height AGL) was important, then displays which have day lighting and contain 3-D buildings should produce more accurate and consistent flare performance. However, according to Mulder et al. (2000), similar effects might also be found if participants used a critical TTC strategy, because adding day lighting and 3-D buildings would increase the amount of texture along the aiming line, and would therefore provide more visual information for TTC (based on restricted tau).

Method

Participants

Twenty-four males were paid for their participation in this study. Sixteen of these participants had flight experience and were recruited from NSWAir and the Australian Aerial Patrol Flight School located at Albion Park, New South Wales. There were eight student pilots, who had a mean age of 25.6 years (with a standard deviation of 6.9 years) and had accrued 23 flight hours on average (SD = 17.8). There were also eight private pilots with mean age of 38.4 years (with a standard deviation of 11.7 years) who had accrued 217 flight hours on average (SD = 63.8). The remaining eight participants were non-pilots - psychology graduate/undergraduate students at the University of Wollongong (mean age 24.8 years with a standard deviation of 6.5 years). All of the non-pilots, student pilots and private pilots in our study had normal or corrected-to-normal vision.

Materials & Apparatus

Displays were generated by a Macintosh G5 personal computer and presented on a Samsung Trinitron SyncMaster monitor (37 cm wide x 27.5 cm high, with a pixel resolution of 1280 x 1024 and an 85 Hz refresh rate). A chin rest was used to align the participant's eye level with the simulated location of the display's true (implicit) horizon – this chin rest was located 45 cm in front of the 44.7° wide x 34.0° high display. A follow-up questionnaire was given to student and private pilots to examine their perceptions of the landing flare – the items of which were taken from an earlier survey study by Benbassat and Abramson (2002b). In this questionnaire, pilot participants rated the perceived difficulty of the landing flare compared to nine other standard flight manoeuvres (“steep turns”, “takeoff roll”, “holding altitude”, “climbing”, “descending”, “taxiing”, “coordinated turns”, “forward slip” and “landing roll”). They were also asked whether they relied on visual or other information (“instrument readings”, “gut reaction”, “sense of balance”, “other”) to initiate the landing flare. If participants responded that they used “vision” to initiate the flare, they were asked to indicate which of the following was the most important cue or information for flare timing (“shape of the runway” “runway markings”, “angle with the runway”, “horizon”, “familiar objects”, “motion parallax”, “descent rate”, or “other” cues). Finally, they were also asked to indicate the factors that they felt were responsible for their current successful landing flares (“pattern practice”, “natural ability”, “sheer luck”, “aviation books”, “my instructor”, “other”).

Visual displays

Computer-generated displays simulated fixed-wing aircraft landing approaches under day or night lighting conditions (approach velocity was held constant in all cases at 130 km/hr or 70 KIAS). Each approach simulated either a 3º or 6º glideslope (producing a descent rate of either 1.9 m/s = 374 ft/min or 3.8 m/s = 748 ft/min), starting 30 m AGL and then progressing towards the rectangular red aimpoint marker lying on the runway. On 3° approaches the actual TTC with this aimpoint marker was 15.87 s at the start of the trial, whereas on 6° approaches the actual TTC at the start of the trial was 7.96 s. The location of this aimpoint marker varied randomly from trial-to-trial, ranging 100 m to 250 m from the start of the runway (starting distance was adjusted accordingly). The runway was 30 m (or 100 ft) wide by 840 m (or 2755 ft) long, and was lined by 15 white lights placed in intervals of 60 m along each of the two long runway edges. Unlike other scene features in the display, there was no local change in the image size of either the runway lights or the red aimpoint marker during the simulated approach. Both the aimpoint and the runway rested on a 1000 m (or 3281 ft) wide by 2000 m (or 6562 ft) deep flat ground plane. In half of the trials in this experiment, five buildings were placed in random locations on the left of the runway and five buildings were placed in random locations on the right of the runway (see Figure 3B). Buildings ranged in height from 1 to 10 storeys (3 to 30 m. Typical aircraft hangars are approximately 6 m high), and in width from 24 to 48 m. During night lighting conditions, only the red aimpoint marker, the white runway lights and the 3-D texture-mapped buildings (when present) were visible. During day lighting conditions, the detailed textures of the runway tarmac and the surrounding ground plane surface were also visible (see Figure 3A). In these day lighting conditions, the most distant parts of the ground plane were obscured by a simulated fog – the goal being to reduce the strength of the false visible horizon produced by the ground's finite dimensions. Specifically, at the beginning of the display this was located 0.86º below the true horizon and moved up the participant's visual field as the viewpoint changed during the simulated descent.

Procedure

Each participant went through three training phases prior to the main experiment. In the first training phase, participants were shown demonstration programs simulating an idealised preprogrammed flare, which was automatically initiated when the TTC with the ground (based on the constant velocity glide at 130 km/hr) reached 2 s. Thus, for a 3° approach the flare was initiated 13.87 s after display onset, whereas for a 6° approach the flare was initiated 5.96 s after display onset. After the flare had been initiated, the manoeuvre itself had an exponential trajectory and lasted 6 s (for the flare equation - see Mulder et al., 2000, pp. 303). During each demonstration, participants were shown a real-time readout of both the simulated TTC and the simulated height AGL. In the second training phase, participants were simply required to time a 2 s interval. No landing display was presented. Only the following instructions were displayed on the monitor: "*Press the space bar then the mouse button 2 s later*". After each 2 s time interval was produced, written feedback was displayed on the monitor indicating the accuracy of the participants estimate ("*too early*" or "*too late by … seconds*"). Participants had to produce this 2 s time interval a minimum of 10 times. In order to proceed onto the next training phase, participants had to produce an estimation error smaller than 0.5 seconds on 5 consecutive training trials. In the third and final training phase, participants were exposed to both the computer generated landing displays and the flare timing task used in the main experiment. Each participant ran one full block of 40 practice trials. The details of this final training phase and the main experiment are described below.

In the main experiment, displays were blocked by scene type: 2 blocks used displays which contained no 3-D buildings (only the runway and the ground plane, the latter was visible only in day lighting conditions – see Figure 3A), whereas the remaining 2 blocks used displays which each contained ten visible 3-D buildings. Each of these blocks consisted of 40 trials simulating both 3º and 6º approaches during either night and day lighting conditions. Four participants in each group (non-pilot, student pilot or private pilot) were randomly allocated to practice trial displays with 3-D buildings and 4 were randomly allocated to practice trial displays without 3-D buildings. They were instructed that they always need to initiate the flare when they perceived that they were 2 s from touchdown. Participants started a trial by pressing the spacebar on the keyboard and then later initiated the flare by pressing the mouse button. In order to produce 0 s timing error, participants needed to initiate their flares when the TTC with the aimpoint was 2 s, which corresponded to a critical runway width angle (Ψ) of 23.5° or a critical distance to the aimpoint of 72 m (regardless of the angle of the linear approach). However, if participants were using a critical height strategy, they needed to initiate their flare when they were at a height of 3.8 m AGL during 3° approaches or 7.5 m AGL during 6° approaches (as the descent rate was higher in the latter condition). The display froze after each flare initiation and participants were immediately provided with written feedback on the display monitor about their flare initiation performance ("*too early*" or "*too late by … seconds*" – see Figure 1). After completing 40 practice trials, participants then ran the 4 experimental blocks (all with performance feedback) in a random order. There were 20 replications of each scene by lighting by glideslope condition combination per participant. The experimental software was written so that data were only recorded for trials for which the frame rate remained above 60 Hz ("bad trials" were automatically retested later in the experiment). On completion of the main experiment, participants performed 10 more runs on the Two second time interval estimation task without performance feedback. The goal of this retest was to check whether there were group differences in the ability to time a 2 s interval (as opposed to a 2 s TTC). When this task was completed, the non-pilot participants were dismissed from the study. Student and private pilots were however still required to complete the landing flare questionnaire.

Results

Landing Flare Questionnaire Data

The results of our survey on 16 Australian aviators were found to closely replicate those of the Benbassat and Abramson (2002b) study, carried out on a much larger sample of 134 US aviators. Consistent with the earlier study: (i) all but one of our 16 pilot participants rated the landing flare as the most difficult of the 10 standard flight manoeuvres (compared to steep turns, takeoff roll, holding altitude, climbing, descending, taxiing, coordinated turns, forward slip and the landing roll) and indicated that practice was the major contributing factor to recent successful flares; and (ii) all 16 pilot participants indicated that they used vision to initiate the landing flare (two of the private pilots and 2 student pilots chose gut reaction when given the opportunity to choose a second option). Consistent again with the findings of the Benbassat and Abramson (2002b) study, little consensus emerged as to which specific visual cues were reported to be necessary for a successful landing. When given the opportunity to choose more than one item, multiple items were chosen by all of our pilot participants (see Figure 4). For example, some chose runway based cues: “angle with the runway”, “end of the runway”, and “shape of the runway”, “runway markings”. Others chose traditional monocular distance cues, such as “motion parallax”, “relative size”, “texture gradient”, “familiar size”, and “horizon” (note that “shape of the runway” is also a monocular distance cue). Possibly due to the priming inherent in the experimental instructions and training, one of the student pilots included "time-to-contact" under the "other" option. Table 1 clearly illustrates the similarity of the current visual cue ratings to those of the Benbassat and Abramson (2002b) study, which in turn suggests that these visual cues are given similar emphasis during US and Australian flight training. However, these survey results should still be interpreted with some caution since pilots might not be conscious or aware of the visual cues that they actually use to time the flare, and even if they are, they might still have difficulty expressing (or verbalizing) how this task is carried out.

Two-second Time Interval Estimation Error Data

Before running the analyses on the data obtained in the experimental conditions, we checked for any group (non-pilot, student pilot and private pilot) differences in estimating a 2 s time interval (as opposed to a 2 s TTC). We performed a Between-groups ANOVA on this 2 s time interval estimation data. The main effect of group type failed to reach significance ($F_{2,21} = 1.01$, $p > .05$, Cohen's $f = 0.31$), indicating that non-pilots, student pilots, and private pilots produced similar errors when attempting to estimate a 2 s time interval.

Flare Timing Error Data

A split-plot ANOVA was then performed on the mean flare timing error data. Group type (non-pilot, student pilot or private pilot) was again the between subjects factor and there were three within subjects factors: scenery type (buildings or no buildings), glideslope type (3º or 6º), and lighting type (day or night). The results and statistics are shown in Table 2. We found a significant main effect of glideslope on flare timing errors.

As can be seen in Figure 5, participants tended to initiate the flare too early (i.e., before 2 s TTC) for 3º glideslope conditions and too late (i.e., after 2 s TTC) for 6º glideslope conditions. While we did not find a significant main effect of group type, we did find a significant interaction between group type and glideslope. From Figure 5, it can also be seen that all 3 types of participant (non-pilots, student pilots and private pilots) displayed the same tendencies to flare too early on 3º approaches and too late on 6° approaches. However, these biases were markedly larger for the non-pilots compared to the student and private pilots.

We also found a significant main effect of scene type on flare timing errors, indicating that visual displays which contained 3-D buildings produced less flare timing error than those without buildings (see Figure 6). While the main effect of lighting did not reach significance, we did find a significant interaction between scene type and lighting type. We interpreted this finding as indicating that the presence of 3-D buildings in the display reduced flare timing error more during simulated night lighting conditions than during simulated day lighting conditions (see Figure 6). No other main effects or interactions reached significance.

Runway Width Angle (Ψ) at Flare

A 3 (Group type) x 2 (Scene type) x 2 (Lighting type) x 2 (Glideslope type) split-plot ANOVA was also performed on the mean runway width angle Ψ at flare data. The results and statistics are shown in Table 3. We found a significant main effect of glideslope on the runway width angle at flare. While the critical runway width angle was 23.5º for both of the glideslope conditions tested, participants were found to initiate the flare at smaller

Ψ angles for 3º approaches (21.4º ± 9.5º) and larger Ψ angles for 6º approaches (27.5º ± 9.6º). While the main effect of group type on runway width angle at flare was not significant, the interaction between group type and glideslope was significant. From Figure 7 we can see that the biasing effect of glideslope on the runway width angle at flare was greater for the non-pilots than for the student or private pilots.

Interestingly, we also found a significant main effect of lighting on runway width angle at flare, which was not evident in the flare timing data. Specifically, the mean Ψ angle at flare was 22.91° ± 6.75° during day simulations compared to 26.01° ± 12.29° during night simulations. This demonstrates that the actual Ψ angle chosen at flare was closer to the ideal Ψ angle at flare (of 23.5°) during day lighting conditions. Unlike the flare timing error data, neither the main effect of scene type, nor the interaction between scene type and lighting type reached significance for the runway width angle data. However, it should be noted that while TTC at flare and runway width angle at flare were highly related in this experiment, their relationship was non-linear, which could account for the observed differences between these two data sets. No other main effects or interactions reached significance.

Height AGL at flare

A 3 (Group) x 2 (Scene type) x 2 (Lighting type) x 2 (Glideslope type) split-plot ANOVA was also performed on the mean height AGL at flare data. The results and statistics are shown in Table 4. We found a significant main effect of glideslope type on the height AGL at flare. As can be seen from Figure 8, non-pilots, student pilots and private pilots correctly initiated their flares at lower heights AGL for 3º glideslopes (M =

4.76 m; S.D. = 2.08 m) and at higher heights AGL for 6° glideslope conditions (M = 6.96 m; S.D. = 1.96 m). While we did not find a significant main effect of group type, we did find a significant interaction between group type and glideslope. From Figure 8, it can also be seen that the flare heights selected by student pilots (4.2 ± 1.1 m for 3° glideslopes; 7.1 ± 1.8 m for 6° glideslopes) and private pilots (4.6 ± 1.7 m for 3°; 7.3 ± 1.9 m for 6°) were much closer to the actual critical heights for our ideal flares (3.8 m for 3°; 7.5 m for 6°) than those selected by the non-pilots (5.3 ± 2.8 m for 3°; 6.4 ± 2.1 m for 6°).

While the main effects of lighting type and scene type did not reach significance, we did find a significant interaction between scene type and lighting. The presence of 3-D buildings in the display was found to reduce the height AGL at flare more for night simulations than for day simulations. This general reduction in flare heights improved task performance in 3° glideslope conditions (as flare heights without buildings tended to be greater than the critical value of 3.8 m), but not for 6° glideslope conditions (as flare heights without buildings tended to be less than the critical value of 7.5 m). No other main effects or interactions reached significance.

Discussion

Our study examined three different visual strategies that could be used to time the initiation of the landing flare, based on either a perceived *critical TTC* with the runway, a perceived *critical runway width angle,* or a perceived *critical height AGL*. Exclusive use of the critical runway width angle strategy should have led to accurate performance in all conditions tested, since the runway outline was always available. However, contrary to this prediction, we found that the display lighting and building manipulations significantly influenced flare timing performance. Flare timing accuracy was found to improve when landing simulations contained 3-D buildings. However, the effects that these buildings had on performance depended on the display lighting: adding 3-D buildings to night lighting displays had a greater effect on flare timing performance than adding 3-D buildings to day lighting conditions. While these scene effects were generally consistent with the tau-based TTC strategy, where according to Mulder et al. (2000) performance should improve when ground texture is added along the aiming line, they were also consistent with the use of a perceived height/distance strategy. Importantly, the runway width angle and tau-based TTC strategies both predicted that glideslope manipulations in the current experiment should have little effect on flare timing judgments because both the critical TTC (2 s) and the critical runway width angle (23.5°) were identical for the two glideslope conditions tested (3° and 6°). Contrary to these predictions, all of our participants were found to flare too early during simulated 3° approaches and too late during simulated 6° approaches. Since only the critical height AGL was altered by the simulated glideslope in this experiment (critical values were 3.8 m for 3° approaches and 7.5 m for 6° approaches), the observed glideslope biases suggested that perception/misperception of height AGL influenced task performance. That is, the results were most consistent with participants using a flare timing strategy based on either a critical perceived height or on an indirectly (i.e., not *tau* based) perceived critical TTC (e.g., the latter could be calculated by dividing the perceived height AGL by the perceived descent rate).

While all 3 types of participant flared too early/high during simulated 3° approaches and too late/low during simulated 6° approaches, these biases were significantly smaller for student and private pilots than for the non-pilots. One possible explanation for this finding might be that the non-pilots were simply less motivated to perform well than our student pilots and private pilots. Contrary to this notion, all three groups of participants were found to perform with similar levels of accuracy in the simple 2 s time interval estimation control task. However, the flare timing task was more challenging than this time interval estimation task, potentially involving multiple perceptions (of runway width angle, height AGL, as well as TTC) and requiring the selection and calibration of successful strategies. Also, unlike our non-pilot participants, the pilots would have been aware of the serious consequences of incorrectly timing the landing flare. Thus, it is possible that differences in motivation might have been more evident with the flare timing task.

A far more likely (and interesting) explanation for the pilot performance advantage was that these results reflected the group differences in flight experience. As we noted in the introduction, our student and private pilot participants should have been primed to use a perceived critical height strategy due to their flight training and real world flight experience (where, unlike the situation in our simulation experiments, they would have typically been exposed to a full complement of depth/distance cues upon landing). Thus, they should have been able to quickly identify and calibrate this successful flare timing strategy and then use it exclusively from that point onwards. Consistent with this notion, in an earlier flight simulation experiment, Grosz et al. (1995) found evidence that their highly trained commercial pilot participants were heavily biased towards initiating the flare at a particular height.

Our non-pilots appeared to have much more difficulty identifying a successful flare timing strategy. We found that the flare heights chosen by non-pilots during 3° (5.32 ± 2.87 m) and 6° approaches (6.46 ± 2.05 m) were actually closer to the *mean of two the critical flare heights* (i.e., 5.65 m) than to their respective critical values (of 3.8 m and 7.5 m). That is, their flare initiation performance demonstrated a strong a central tendency bias (e.g., Slack, 1953). This non-pilot performance contrasted markedly with the student and private pilot performance, where the flare heights chosen during 3° (4.29 ± 1.15 m; 4.67 ± 1.69 m) and 6° approaches (7.09 ± 1.87 m; 7.34 ± 1.85 m) were much closer to their respective critical flare heights than to the mean of these two values. Thus, it appears that the non-pilots were significantly more likely to develop a flawed flare timing strategy in which they initiated their flares at approximately the same height AGL for both glideslope conditions.

Research has shown that observers tend to respond earlier in TTC and collision control tasks when the speed of closure is slower (e.g., McLeod & Ross, 1983; Schiff, et al., 1992; Smith, Flach, Dittman & Stanard, 2001). Because both the starting height AGL (30m) and the approach velocity (130 km/hr) were held constant in the current experiment, the descent rate (or the vertical speed of closure with the ground) varied significantly with the glideslope (1.9 m/s for 3° approaches and 3.8 m/s for 6° approaches). This glideslope-based difference in descent rate could potentially explain the finding that non-pilots flared much earlier than they should have in 3° conditions (by on average 0.8 s compared to 0.4 s for pilots) and later than they should have in 6°

conditions (by on average 0.3 s compared to 0.1 s for pilots). If one ignored the presence of the two different approach angles (which participants were informed both had a critical TTC of 2 s), such a central tendency bias would have actually been reinforced by the performance feedback ("too early" or "too late") provided across different trials.

Why then did the perceived *critical height strategy* dominate pilot flare timing responses in the current experiment? In the earlier flare timing study, Mulder et al. (2000) found that non-pilot participants changed from using a critical runway width angle strategy to using the critical TTC strategy when additional texture was added to their landing displays. They concluded that their non-pilots became more likely to adopt the critical TTC strategy as optic tau information became more reliable. Analysis of the landing displays used in the current experiment suggests that pilots (and possibly non-pilots to a lesser extent) might have been more likely to adopt the critical perceived height strategy because the optical splay angles formed by the left and right sides of the runway provided a reliable cue to height AGL for all of the conditions tested (Flach, Hagen, & Larish, 1992; Flach, Warren, Garness, Kelly, & Stanard, 1997). Optical splay angle (S) can be defined as follows:

$$S = \tan^{-1} (Y_g/Z) \quad [2]$$

Where Y_g is the lateral displacement of the left or right edge from the runway centre-line and Z is the height AGL of the observer. Since we used a 30 m wide by 840 m long runway for every landing simulation, runway splay angle information was directly related (in a non-linear fashion) to height AGL and this information was available during both day and night lighting conditions (in the case of the latter via the runway lights). Importantly, this runway splay angle cue is different to the runway width angle (ψ) cue outlined in the introduction. While the former strategy would require participants to flare at different critical splay angles for each of the two approach angles (75.8° during 3° approaches and 63.4° during 6° approaches), the latter strategy would require participants to always flare when the angular width of the runway at the aimpoint reached 23.5°. Figure 9 shows the splay angle at flare data, which reveals very similar patterns of non-pilot, student pilot and private pilot performance to those in height AGL at flare data. However, it is important to note that if we had used a variety of runways, each with different dimensions, this splay angle cue would have become less reliable, which might have forced participants to search for other flare initiation strategies (e.g., based on either other depth cues, a perceived critical TTC based on optic tau, a perceived critical angular width of the runway, or some other property of the dynamic visual display).

The lighting and scene effects observed in the flare timing data suggest that our pilot participants were actually responding to a perceived critical height AGL, not simply a perceived critical splay angle. That is, optical splay angle appeared to be one of many cues that contributed to the overall percept of a critical height AGL. Longuet-Higgins (1984) has previously noted that the scene layout information provided by visual motion of the runway lights is inherently ambiguous during an aircraft landing at night. This *optic flow* can either be correctly interpreted as indicating an oblique approach towards a horizontal ground plane, or misperceived as pure descent relative to a nearly vertical planar surface. Consistent with his analysis, many of our participants spontaneously reported strong illusions of both runway inclination and scene depth during night lighting conditions without buildings. So it seems likely that adding 3-D buildings to our night lighting displays improved flare timing performance because they helped disambiguate the optic flow information about self-motion and the orientation of the runway and/or ground plane. However, it is notable that night lighting displays with 3-D buildings produced more accurate flare timing performance than day lighting displays (both with and without 3-D buildings). It is possible that the higher than expected level of performance error found during day lighting was due to the false visible horizon formed in these conditions (located 0.86º below the true horizon at the beginning of the display). According to this argument, misleading information from the visible horizon biased participant perceptions of environmental distance and ground plane orientation during day lighting conditions (even when accurate information was provided by adding 3-D buildings to the displays); and these misperceptions of the environmental layout led to flare timing errors (e.g., participants might have flared too early when displayed distances were perceived to be smaller than were being simulated).

In conclusion, the findings of our flight simulation study demonstrate that perceived height can play an important role in timing the initiation of the landing flare. In this experiment, pilot, and to a lesser extent non-pilot, flare timing performance were best explained by participant perceptions of height AGL. There was no support for the use of the angular width of the runway at the aimpoint. The findings were also clearly contrary to proposals that pilot timing and control of the landing flare could be based solely on direct perceptions of TTC via optic tau (e.g., Jump & Padfield, 2006; Padfield, Lee & Bradley, 2003). Despite the strong support found in this study for the use of a height strategy, it is important to note that both the current landing simulations and the experimental task were highly constrained (in comparison to situations faced during actual landings). Based on previous findings, it is unlikely that a single cue or strategy can account for landing flare performance (DeLucia, Kaiser, Bush, Meyer, & Sweet, 2003; Grosz et al., 1995; Hancock & Manser, 1997; Mulder et al., 2000; Smith et al., 2001; Tresilian et al., 2004). It seems more likely that this perceived critical height based strategy dominated over TTC and other strategies in the current experiment, because the optical splay angle formed by the fixed runway in our displays provided a reliable cue to height AGL in all conditions tested. Even so, it is worth noting that our pilot participants were more readily able to identify and adopt this height based strategy than the non-pilots, which suggests that they were likely to employ such a strategy during actual flight. Thus, with the above qualifications in mind, the current findings provide a validation of current pilot training in the use of critical height AGL as an important cue for initiating the landing flare.

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Footnotes

[1]These estimates would actually indicate the time it would take for the driver (as opposed to the front of the car) to reach the truck if the current speed was maintained. Thus, there is an assumption that the driver is able (e.g., from his/her prior experience with the vehicle) to adjust these TTC estimates to take into account the size of the car's hood (see Tresilian, 1991).

Table 1

Five Most Commonly Selected Visual Cues

Catergories of Visual Cues	**Current Study**	**Benbassat & Abramson (2002)**
Horizon & End of Runway	37.5 %	26.0 %
Runway Shape & Markings	22.5 %	18.9 %
Angle with Runway	15 %	4.1 %
Familiar Objects	7.5 %	9.5 %

Table 2

Analysis of Variance for TTC at Flare

Source and comparison	df	MSE	F	Cohen's *f*
Group (3)	2,21	0.44	1.37	0.36
Glideslope (2)	1,21	0.53	40.47**	1.39
Lighting (2)	1,21	0.20	4.19	0.45
Scene (2)	1,21	0.17	4.79*	0.48
Group x Glideslope	2,21	0.53	4.29*	0.64
Group x Lighting	2,21	0.20	0.39	0.19
Group x Scene	2,21	0.17	0.33	0.18
Glideslope x lighting	1,21	0.05	2.17	0.32
Glideslope x Scene	1,21	0.11	2.11	0.32
Lighting x Scene	1,21	0.04	4.62*	0.47
Group x Glideslope x Lighting	2,21	0.05	0.21	0.14
Group x Glideslope x Scene	2,21	0.11	1.34	0.36
Group x Lighting x Scene	2,21	0.04	1.72	0.41
Scene x Glideslope x Lighting	1,21	0.04	0.04	0.04
Group x Scene x Glideslope x Lighting	2,21	0.04	0.35	0.18

* $p < .05$. ** $p < .01$.

Table 3

Analysis of Variance for Runway Width Angle at Flare

Source and comparison	df	MSE	F	Cohen's *f*
Group (3)	2,21	76.45	0.09	0.09
Glideslope (2)	1,21	37.94	48.04**	1.51
Lighting (2)	1,21	68.06	6.76*	0.57
Scene (2)	1,21	14.72	1.53	0.27
Group x Glideslope	2,21	37.94	5.03*	0.69
Group x Lighting	2,21	68.06	0.64	0.25
Group x Scene	2,21	14.72	0.02	0.03
Glideslope x lighting	1,21	9.86	0.91	0.21
Glideslope x Scene	1,21	19.17	1.74	0.29
Lighting x Scene	1,21	6.40	3.75	0.42
Group x Glideslope x Lighting	2,21	9.86	0.51	0.22
Group x Glideslope x Scene	2,21	19.17	0.63	0.25
Group x Lighting x Scene	2,21	6.40	0.33	0.18
Scene x Glideslope x Lighting	1,21	10.90	0.27	0.11
Group x Scene x Glideslope x Lighting	2,21	10.90	0.50	0.22

* $p < .05$. ** $p < .01$.

Table 4

Analysis of Variance for Height AGL at Flare

Source and comparison	df	MSE	F	Cohen's *f*
Group (3)	2,21	2.15	0.74	0.27
Glideslope (2)	1,21	2.83	82.73**	1.99
Lighting (2)	1,21	1.43	3.59	0.41
Scene (2)	1,21	1.01	4.31	0.45
Group x Glideslope	2,21	2.83	4.80*	0.68
Group x Lighting	2,21	1.43	0.5	0.22
Group x Scene	2,21	1.01	0.09	0.10
Glideslope x lighting	1,21	0.42	0.04	0.04
Glideslope x Scene	1,21	0.58	0.42	0.14
Lighting x Scene	1,21	0.32	4.80*	0.48
Group x Glideslope x Lighting	2,21	0.42	0.63	0.25
Group x Glideslope x Scene	2,21	0.58	1.28	0.35
Group Lighting x Scene	2,21	0.32	1.48	0.37
Scene x Glideslope x Lighting	1,21	0.31	0.25	0.11
Group Scene x Glideslope x Lighting	2,21	0.31	0.09	0.22

* $p < .05$. ** $p < .01$.

Figure Captions

Figure 1. This figure provides a graphical representation of: (i) the (explicit) aimpoint (A) which was identified by a rectangular marker in all visual displays; (ii) the (implicit) aiming line that lies at right angles to the runway and passes through the aimpoint. This figure also illustrates the several features which might be important for timing the flare. First, the separation LR forms the angle ψ at the observer's eye (i.e., the angular width of the runway along the aiming line). Second, the angular separations LA and RA both form the angle θ at the observer's eye. This figure also illustrates how the lexical feedback on the accuracy of flare timing was provided in the current study.

Figure 2. Figure 2A shows the isotropic pattern of optical expansion produced during perpendicular approach along a straight line towards a frontoparallel surface. This is represented as a purely vertical approach – with the camera pointed straight down - towards the rectangular runway lying on the horizontal ground plane and surrounded by 3-D buildings. Conversely, Figure 2B shows the asymmetric pattern of optic expansion produced by a 6° slanted landing approach in the same environment. Each figure was created by taking two pictures at different stages of the descent and then superimposing them. An explicit aimpoint marker is visible in each figure, located at the centre of the runway. White arrows indicate the change in position of selected runway lights from one snapshot to the next. In Figure 2A, the rate of optical expansion is the same for lights which lie above and below the aimpoint. In Figure 2B, the rate of optical expansion is clearly greater for nearer lights which lie below the aimpoint than for farther lights which lie above this point.

Figure 3. Examples of the day lighting stimuli (no buildings and buildings) used in this experiment. The size of explicit aimpoint has been increased to aid in the viewing of these images.

Figure 4. Cues employed during the landing flare as rated by private and student pilots.

Figure 5. Effects of group type (non-pilot, student pilot or private pilot) and glideslope (3° or 6°) on flare timing error (s). A negative flare timing error means that the participant responded before the actual time-to-contact (TTC) reached 2 s. Error bars represent the standard error of the mean.

Figure 6. Effects of scene type (no buildings or buildings) and lighting type (day or night) on flare timing error (s). A negative flare timing error means that the participant responded before the actual TTC reached 2 s. Error bars represent the standard error of the mean.

Figure 7. Effects of group type (non-pilot, student pilot or private pilot) and glideslope (3° or 6°) on the visual runway width angle (Ψ) at flare initiation. The appropriate runway width angle for a critical 2 s TTC was 23.5°. Error bars represent the standard error of the mean.

Figure 8. Effects of group type (non-pilot, student pilot or private pilot) and glideslope (3° or 6°) on the height above ground level (AGL) at flare initiation. The two critical heights for a 2 s TTC were 3.8 m for a 3° approach and 7.5 m for a 6° approach. Error bars represent the standard error of the mean.

Figure 9. Effects of glideslope (3° or 6°) on the runway splay angle at flare initiation. The two critical splay angles for a 2 s TTC were 75.8° for a 3° approach and 63.4° for a 6° approach. Error bars represent the standard error of the mean.

Figure 1

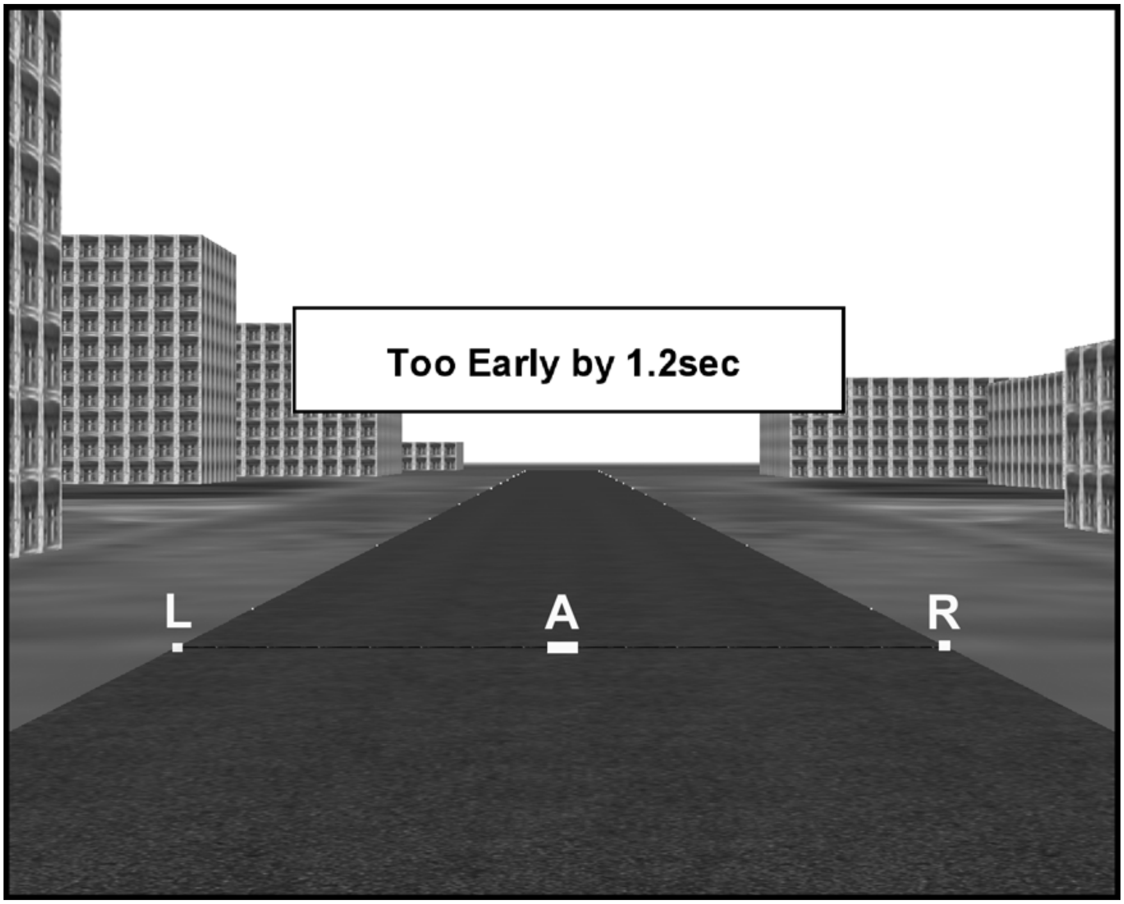


Figure 2

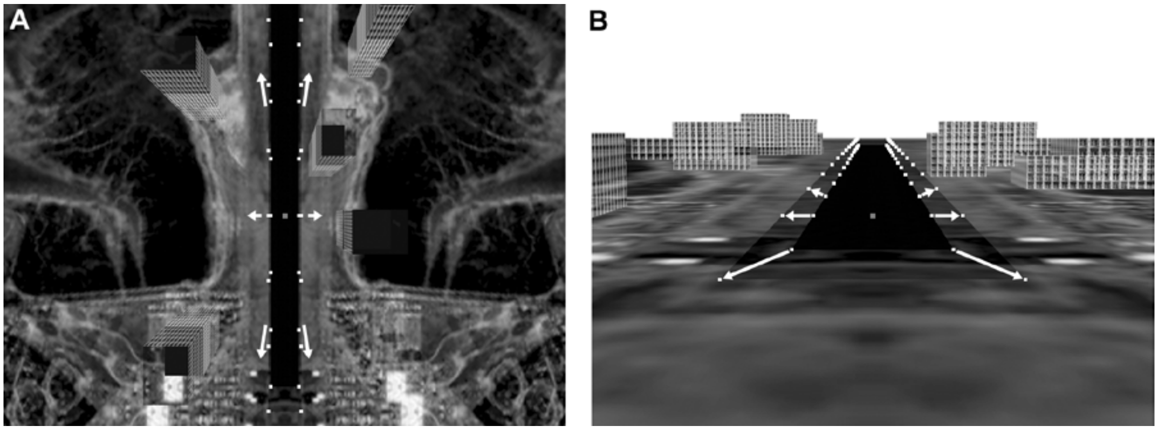


Figure 3

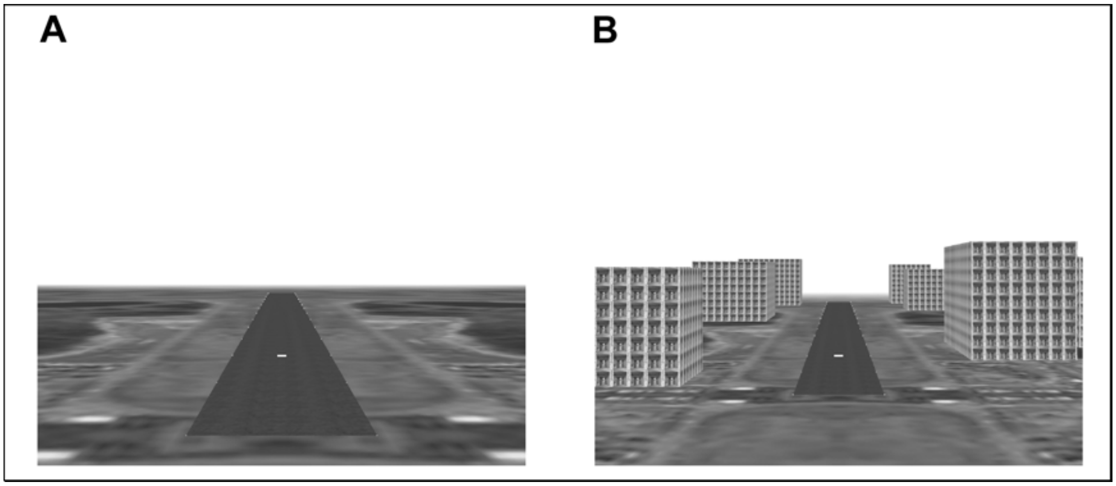
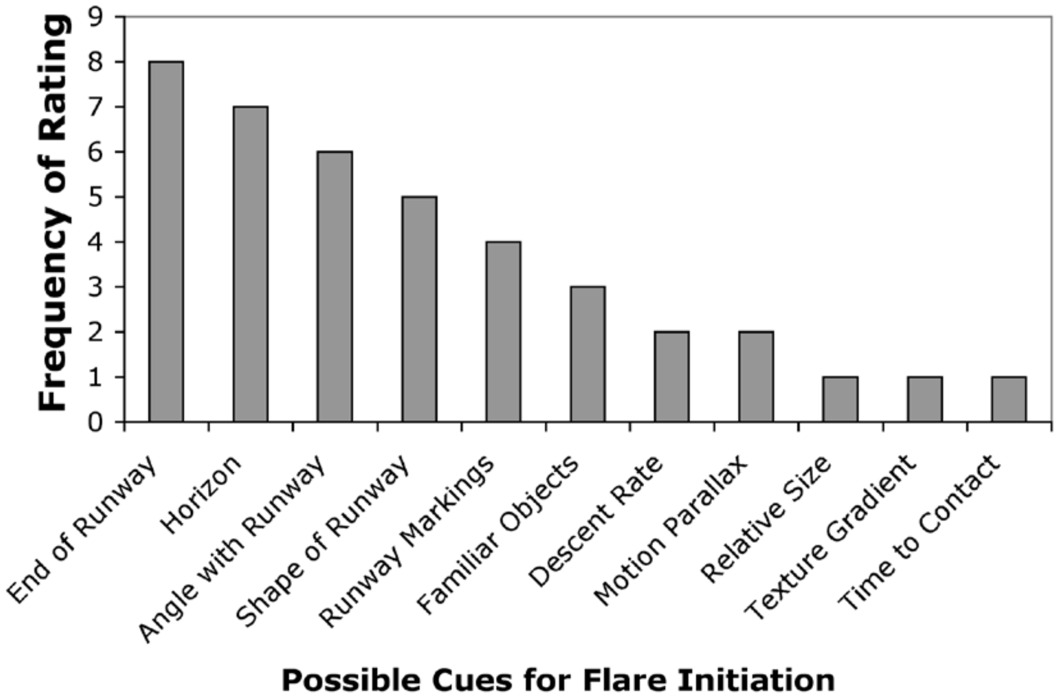


Figure 4


Frequency of Rating
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Horizon
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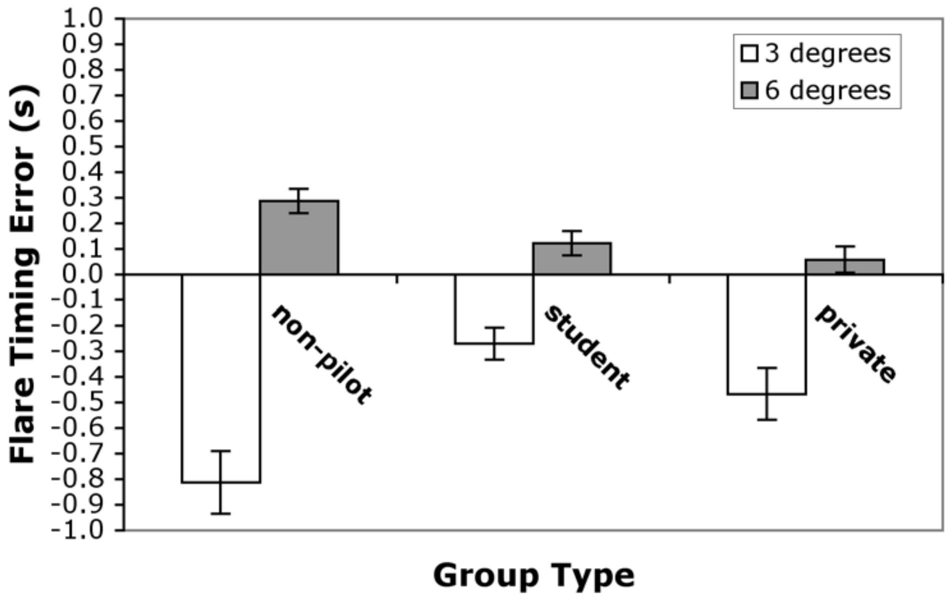
Shape of Runway
Runway Markings
Familiar Objects
Descent Rate
Motion Parallax
Relative Size
Texture Gradient
Time to Contact
Possible Cues for Flare Initiation

Figure 5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0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1.0
Flare Timing Error (s)
3 degrees
6 degrees
non-pilot
student
private
Group Type

Figure 6

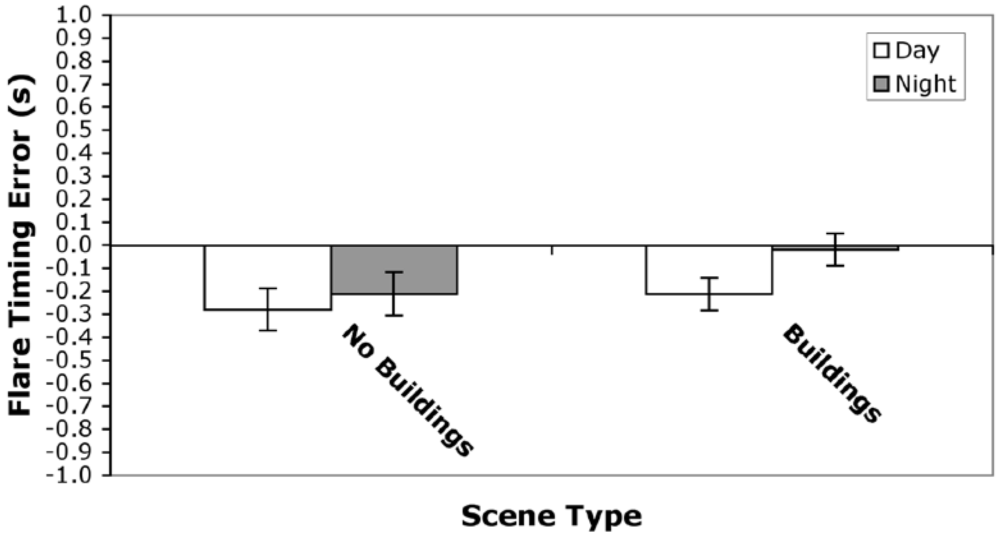
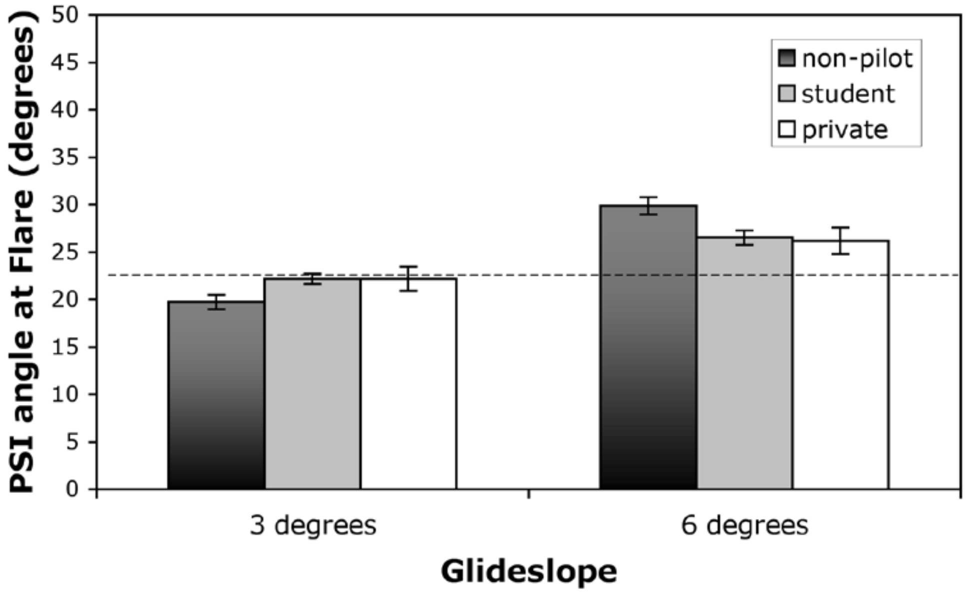

1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1.0
Flare Timing Error (s)
Day
Night
No Buildings
Buildings
Scene Type

Figure 7



50
45
40
35
30
25
20
15
10
5
0
PSI angle at Flare (degrees)
non-pilot
student
private
3 degrees
6 degrees
Glideslope

Figure 8

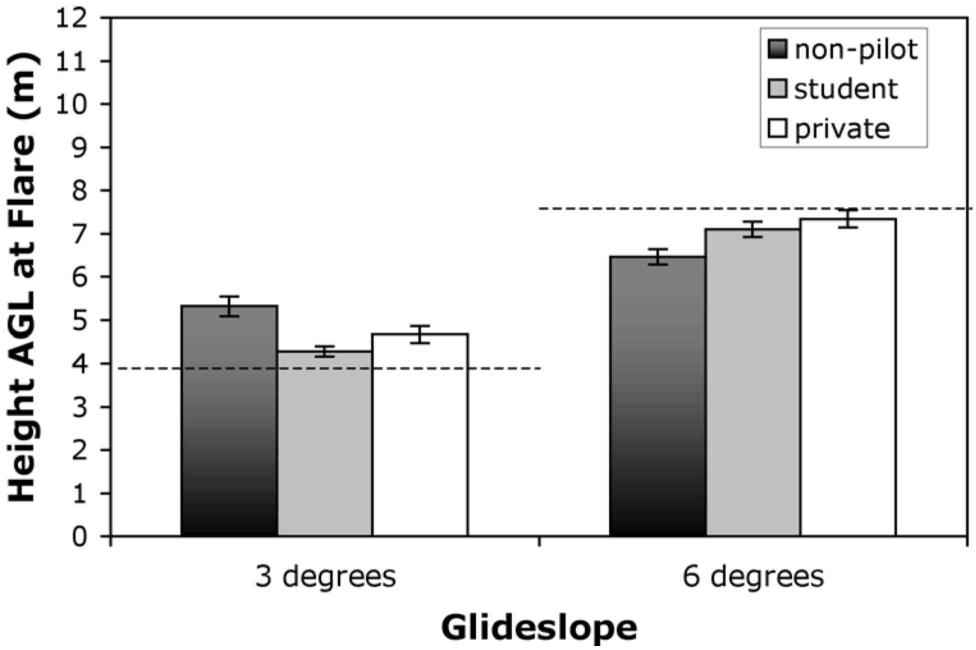
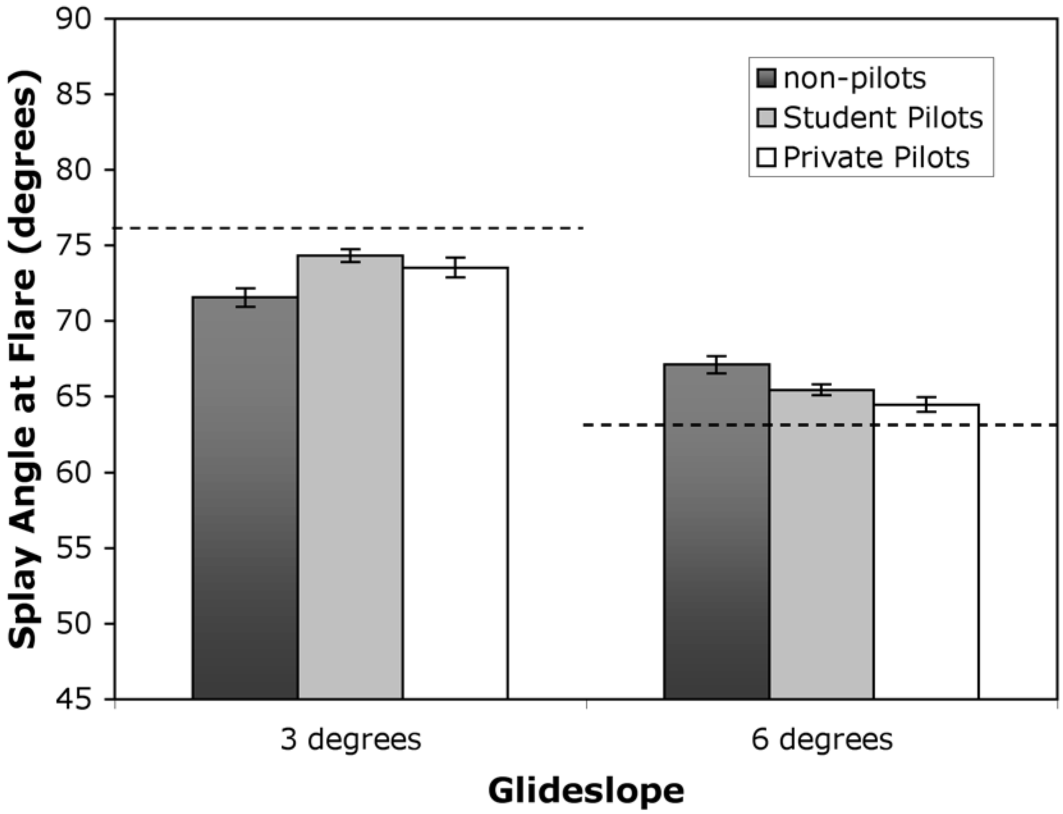

12
11
10
9
8
7
6
5
4
3
2
1
0
Height AGL at Flare (m)
non-pilot
student
private
3 degrees
6 degrees
Glideslope

Figure 9


90
85
80
75
70
65
60
55
50
45
Splay Angle at Flare (degrees)
non-pilots
Student Pilots
Private Pilots
3 degrees
6 degrees
Glideslope