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Keywords

Visual, Perception, Touchdown, Point, During, Simulated, Landing

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Visual Perception of Touchdown Point During Simulated Landing

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Running Head: Perceived touchdown point during landing

Keywords: Visual landing, Optic flow, Heading, Glideslope

Abstract

Experiments examined the accuracy of visual touchdown point perception during oblique descents (1.5°-15°) towards a ground plane consisting of: (i) randomly positioned dots; (ii) a runway outline; or (iii) a grid. Participants judged whether the perceived touchdown point was above/below a probe that appeared at a random position following each display. While judgments were unacceptably imprecise and biased for moving dot and runway displays, accurate and unbiased judgments were found for grid displays. We conclude that optic flow per se does not appear to be sufficient for a pilot to land an airplane and that the systematic errors associated with optic flow under sparse conditions may be responsible for the common occurrence of landing incidents in so-called 'black hole' situations.

The final approach for landing is generally recognized as one of the most critical and demanding stages of flight (e.g. Hartman & Cantrell, 1968; Langewiesche, 1944). Considerable training is required to develop the necessary skills for a visually controlled landing (Gillis, Li, & Baker, 2001). Ideally, the pilot of the plane should follow a constant 3° or 4° glideslope from the start of the descent down to the desired gear touchdown point (which typically lies 1000ft from the runway threshold). In the 1940's and early 1950's, theorists and aviators noted that the *pattern of visual motion* generated by the airplane's descent could be used as a cue for glideslope control. Langeweische (1944) provided one of the earliest descriptions of this potential cue in his classic book on aviating, *Stick and Rudder*:

> "The clue that tells you whether you are going to overshoot or undershoot is this: All objects that move downward, however slightly, are going to be overshot; all objects that move upward, toward the horizon, however slightly, are going to be undershot. And the objects that remain stationary in your field of vision and just grow in apparent size – those are the objects that you will hit" (Langeweische, 1944; pp.285-286).

Gibson (1950; Gibson, Olum, & Rosenblatt, 1955) further developed this concept by mathematically analysing the *optic flow* – or gradient of optical velocities - produced by observer motion. Gibson and his colleagues noted that:

> "during a landing glide, the projection of the ground seems to expand radially from a centre at the intersection of the glide-line with the ground, to reach a maximum

> between that point and the horizon, and again to vanish at the horizon” (Gibson et al, 1955; pp.374-375).

Gibson, Olum and Rosenblatt (1955) demonstrated that the “focus of expansion” (FoE – also called the “focus of radial outflow”) of this optic flow always lies in the direction of self-motion. Because the position of this FoE shifts relative to the environment when the direction of self-motion changes, they argued that it could serve as a “point of aim” to guide or control locomotion. Specifically, they proposed that pilots could regulate and maintain their glideslope during landing by aligning their perceived future touchdown point, based on the FoE, with their desired visual touchdown point on the runway. One benefit of this FoE strategy is that touchdown point perceptions would not depend on the accurate perception of environmental depth or surface orientation (Gibson, 1950, 1966, 1979). This would be advantageous since previous research has shown that observers consistently and systematically misperceive the physical orientation of a runway during simulated approaches – even when dynamic optic flow based information about its inclination is provided by the motion of the runway lights (e.g. Mertens, 1978, 1981; Mertens & Lewis, 1982).

Optic flow (Gibson, 1966, 1979) describes motion as a projection from the environment to a spherical surface centred at the location of the point of observation as this point moves relative to the environment. While Langeweische and Gibson’s strategies for aiming as described above hold true for optic flow, they are incorrect for retinal flow (the motion stimulation which the pilot actually receives on his/her retinas). If the pilot performs pursuit head or eye-movements to track an object in the scene, the FoE of his/her retinal flow will correspond to the direction of fixation, not to the direction of self-motion (Regan & Beverley, 1982). Thus, before he/she can use FoE information to perceive the touchdown point and control his/her glideslope, the pilot must first distinguish the retinal flow due to head- or eye-motion from the retinal flow (or optic flow) due to self-motion. This could be achieved by using either visual information contained in the retinal flow or non-visual, extraretinal information (e.g. retinal flow components due to eye-movement could be estimated from either vestibular information and/or an internal copy of the motor command - see Lappe, Bremmer & van den Berg, 1999 for a review).

Prompted by the above observations, numerous researchers have examined the possibility that the optic flow pattern is sufficient to accurately perceive one's instantaneous heading (direction of self-motion relative to a fixed reference direction). While initial studies appeared to report surprisingly poor heading detection performance (e.g. Johnston, White & Cumming, 1973; Llewellyn, 1971), more recent research by W.H. Warren and his colleagues has demonstrated that visual heading judgments based on optic flow can in fact be highly accurate and unbiased (e.g. Warren, Blackwell & Morris, 1989; Warren & Hannon, 1988, 1990; Warren & Kurtz, 1992; Warren, Morris & Kalish, 1988). The majority of this research examined the accuracy of lateral heading judgments during simulated self-motion parallel to a ground plane surface consisting of randomly positioned dots. Observers in these studies typically viewed the moving dot displays for about 3.7 seconds, after which all motion ceased and a vertical probe line appeared some distance to the left or the right of the simulated heading. The observer's task was to judge whether they had appeared be to moving to the left/right of this probe during the simulation - a two-alternative forced choice (2AFC) paradigm. Consistent with Gibson's hypothesis, lateral heading judgments were found to be very accurate in most of the display speed/density conditions tested (with mean 75%-correct thresholds of around 1.2° of visual angle). Specifically, Warren and his colleagues found that lateral heading judgments remained accurate during slow simulated linear self-motions through sparse simulated environments (e.g. thresholds were still less than 2° for both displays with simulated speeds of 1m/s and displays consisting of only 12 dots) (Warren et al, 1988, 1989). Further, they found that lateral heading judgments not only remained accurate across a range of different simulated environments (e.g. self-motion parallel to a ground plane, towards a vertical plane, or through a 3-D cloud of dots), but they also were quite robust to misperceptions of the environmental layout (Warren et al, 1988).

In summary then, optic flow based lateral heading judgments have been shown to be sufficiently accurate for the perception and control of most terrestrial locomotions (walking, driving, etc.). However, these findings may not generalise to landing an aircraft. The present study thus examines whether optic flow could also play a role in glideslope perception (and hence control) during the final stages of a visual aircraft landing. This requires locating the future touchdown point primarily along a vertical dimension rather than a lateral one and approach at an angle rather than parallel to a surface. These conditions have received comparatively little previous empirical examination. Using a 2AFC paradigm similar to that outlined above, we examine the accuracy of passive vertical touchdown point judgments during oblique angle descents towards a ground plane surface.

Experiment 1: Effect of Surface Texture on Touchdown Point Perception

In this experiment, we examined the accuracy of passive vertical touchdown point detection during oblique descents towards a ground plane consisting of either: (i) 800 randomly positioned dots; (ii) a runway outline; or (iii) a runway outline superimposed on a ground plane of 800 randomly positioned dots. If a visually controlled landing can be done using optic flow cues alone (e.g. by using a FoE strategy) then we should be able to represent this situation perfectly using a schematic display of moving dots (i.e. there should be no difference in the touchdown point detection for the three different surface type conditions). However, Longuet-Higgins (1984) has noted that the pattern of retinal flow generated by an oblique approach towards a planar surface is inherently ambiguous. Consider the situation during a night landing, when only the lights on the ground plane are visible. Longuet-Higgins has shown that in this situation, the pattern of moving lights projected on to the pilot’s retina could be either correctly interpreted as indicating his/her oblique approach towards a horizontal ground plane, or misperceived as his/her pure descent relative to a nearly vertical planar surface. Longuet-Higgins has argued that the latter misinterpretation of the flow field could be a major contributor to the increase in pilot error during night landings. However, he also notes that such a misinterpretation should become untenable after a finite time, because other visual information would lead to its rejection (e.g. texture cues to distance). Thus, we predict that optical changes to specific terrain features - such as the runway outline and markings etc. - might also provide useful information that facilitates landing performance based on optic flow (e.g. Galanis, Jennings, & Beckett, 1998; Lintern & Walker, 1991). In addition to examining the effects of surface type, we also examined: (i) the effects that the simulated starting altitude (30m and 90m) and the simulated glideslope (1.5°-15°) have on the precision and bias in touchdown point detection; and (ii) whether simulated starting altitude and simulated glideslope would interact with surface type to determine performance.

Method

Participants

Nine of the 15 observers were undergraduate psychology students at the University of Wollongong who participated in this experiment for course credit. The remaining 6 observers were academics or graduate students. Participants ranged in age from 19 to 34 years. All had 20/20 vision and had successfully completed the landing training phase of Microsoft Flight Simulator 2002® prior to the experiment. The data from 4 additional observers was not included in the analyses either because they were unable to complete this landing training or because they failed to produce clear thresholds for a given condition during initial data screening. Note that: (i) for the initial data screening, 75% correct thresholds were computed for each of the surface type by starting altitude conditions by combining the data across the different glideslopes (for additional details on threshold calculation see the judgment precision section below); (ii) Warren et al (1988, 1991) used a similar screening procedure (which combined data from the different approach angles) to remove equivalent proportions of participants from their lateral heading studies.

Apparatus

Visual landing displays were generated on a Macintosh G4 personal computer and presented on a Sony Trinitron Multiscan G420 monitor (36.5cm H x 27.5 cm V, with a pixel resolution of 1280 H x 1024 V). This screen subtended a visual angle of 40° H x 30° V when viewed binocularly through a cylindrical viewing tube attached to the head-and-chin rest 0.5m distant.

Visual Displays

Displays simulated an oblique descent towards a ground plane surface consisting of either: (i) 800 randomly positioned blue dots (with a mean luminance of 118 cd/m^2 on a black background of 0.2 cd/m^2); (ii) a blue runway outline (simulated dimensions: 200ft wide by 4500ft long); or (iii) both the 800 randomly positioned blue dots and the blue runway outline (see Figure 1). All displays started at a height of either 30m or 90m and simulated a constant angular descent speed of 137km/hr (74 Knots). In the case of dot-only and runway-dot displays, dot placement on the ground plane surface was determined by randomly positioning one dot in each cell of an appropriately sized grid. To avoid a dense clustering of dots at the horizon, the ground plane was truncated at a simulated distance of 2km along the depth axis, creating an apparent horizon either 0.9° or 2.6° below the true horizon for 30m and 90m starting altitudes respectively. Dot size and line thickness remained constant (at 1 pixel) throughout the simulation. As dots disappeared off the bottom and side edges of the screen, they were replaced at a distance of 2km along the depth axis at the same horizontal and vertical coordinates. Each display consisted of 120 frames, which were presented over 2s.

Displays simulated one of ten different glideslopes or path angles to the ground plane surface (1.5°, 3°, 4.5°, 6°, 7.5°, 9°, 10.5°, 12°, 13.5°, 15°), producing ten different simulated touchdown points (the FoE always coincided with an unoccupied location on the screen). These touchdown points always lay within the textured region of the display, except for one special case: When displays simulated a 1.5° glideslope and had a 90m starting altitude, the location of the touchdown point was located just above the textured area. Following each display, a red probe line (1° wide) appeared on the ground plane either above or below the simulated touchdown point by one of the following angular distances: 0.39°, 0.78°, 1.17°, 1.56°, 1.95°, 2.34°, 2.74°, 3.12°, 3.52° or 3.91°.

Task

Displays were blocked by surface type (dot-only, runway-only or runway-dot) and starting altitude (30 or 90m), and these blocks were presented in a random order to each participant over twelve sessions. Participants were told that they would view a series of displays simulating descent in an airplane and that they should always try to look at the point in the display where they were going to touch down. Within each block, participants viewed displays simulating the ten different glideslopes and 20 different probe positions. After display motion ceased, a red horizontal probe line appeared at some distance above or below the simulated touchdown point. The participants then judged whether this probe lay above/below their perceived touchdown point by pressing either the "up" or "down" arrow keys on the keyboard. Participants received 10 practice trials with feedback (a green horizontal probe line was presented at the true/simulated touchdown point for an additional 1s following their response). The remaining test trials were presented without feedback.

Results

Judgment Precision

We calculated the mean absolute touchdown point detection thresholds for each condition by: (i) combining the data from the 'above probe' and 'below probe' simulated touchdown point conditions to calculate the mean percentages of correct responses; (ii**)** then fitting this data with an ogive by performing a z-transformation on these percentages; and (iii) computing a linear regression (see Warren et al, 1991). The absolute visual angle between the simulated touchdown point and the probe (0.39° to 3.9°) where the regression line reached 75% correct was adopted as the threshold. To increase the reliability of estimates (by increasing the number of data points used in the linear regression), these 75% correct thresholds were calculated for the following 3 averaged glideslopes: 1.5°-4.5°, 6°-9°, and 10.5°-15°. We then performed a 3 (surface type) x 2 (starting altitude) x 3 (averaged glideslope) repeated measures analysis of variance (ANOVA) on this threshold data (the results are shown in Table 1). We found a significant main effect of surface type – indicating that touchdown judgments for runway-dot displays (M = 1.6°) were more precise than those for dot-only (M = 2.5°) and runway-only displays (M = 2.8°). The main effect of starting altitude failed to reach significance – however, as the effect size was small (Cohen, 1988), one cannot be certain that a difference of this order was absent. As can be seen from Figure 2a, the precision of observers' touchdown judgments decreased significantly as the glideslope increased from 1.5° to 15° of visual angle for all three different surface types. The interaction between glideslope and surface type was also found to reach significance – indicating that touchdown judgments produced by runway-dot displays were significantly less affected by the simulated glideslope than those made for dot-only or runway-only displays. No other 2- or 3- way interactions were found to reach significance.

Judgment Bias

The data was also examined for evidence of directional bias. We calculated the mean constant errors for each condition by: (i) replotting the percentage 'above' responses as a function of the uncollapsed simulated touchdown point; and (ii) fitting the data with an ogive by performance a z-transformation on these percentages (see Warren et al, 1991). The signed visual angle between the simulated touchdown point and the probe at which the regression line reached 50% 'above' was adopted as the constant touchdown point bias. Constant errors were calculated for the following 3 averaged glideslopes: 1.5°-4.5°, 6°-9°, and 10.5°-15°. We then performed a 3 (surface type) x 2 (starting altitude) x 3 (averaged glideslope) repeated measures ANOVA on these constant errors (the results are shown in Table 2). On average, touchdown judgments were biased upwards by 1.8° of visual angle. The main effects of surface type and starting altitude failed to reach significance, suggesting that: (i) a similar overall upwards bias was evident in runway-dot (M = -1.6°), dot-only (M = -1.7°) and runway-only conditions (M = -2.0°); and (ii) there was no difference in the bias produced by the 30m and 90m starting altitude displays. However, in both cases, the effect sizes for these comparisons were small (Cohen, 1988), so one cannot be certain that differences of this order were absent. Importantly, we found a significant main effect of glideslope. As can be seen from Figure 2b, the overall tendency towards an upwards bias in responding appeared to increase steadily as the glideslope was increased from 1.5° to 15° of visual angle. Participants demonstrated a downward bias when displays simulated glideslopes of less than

3.1°-6.5° (depending on the surface type) and a much larger upward bias when displays simulated larger glideslopes. The interaction between glideslope and surface type was also found to be significant – suggesting that runway-dot displays were less biased than dot-only and runway-only displays at the four largest glideslopes tested (i.e. 10.5° – 15°). No other 2- or 3-way interactions were found to reach significance.

Discussion

Previous research found that *lateral heading detection thresholds* ranged from 1.3° to 1.9° when displays simulated a perpendicular (90°) or nearly perpendicular (78° or 84°) translational approach towards a vertical plane of dots (Warren et al, 1988). However, in the current experiment, we found that *vertical heading detection thresholds* during oblique approaches (1.5°-15°) towards a ground plane of dots were far less precise (with mean thresholds ranging from 2.3° to 2.7°). While similar performance was observed with a runway-outline (thresholds ranging from 2.2° to 3.4°), there was a significant improvement in precision when displays contained both moving dots and a runway outline (thresholds ranging from 1.5° to 1.8°). Vertical heading precision was also found to decrease as the glideslope increased from 1.5° to 15° of visual angle. This appears consistent with previous findings of Crowell and Banks (1993) that lateral heading judgments become less accurate as the eccentricity of the simulated destination point (relative to straight ahead or the centre of the screen) increases.

Another important difference between our findings and those of Warren, Morris and Kalish (1988) was that on average an upwards touchdown bias was found for all three surface type displays, ranging from 1.6° to 2.0° of visual angle. It appears that participants tended to underestimate the angle of the descent for the majority of the simulated glideslopes and as a result overestimated the perceived distance of their simulated touchdown points. However, this touchdown bias was also systematically related to the simulated glideslope. Specifically, a downwards bias was found for the smallest simulated glideslopes (consistent with an overestimation of perceived glideslope), no bias was found for glideslopes around 3.1°-6.5°, and upwards bias was found for larger glideslopes (consistent with an underestimation of the perceived glideslope). Overall, as the glideslope increased the so did the likelihood that the perceived touchdown point would be shifted upwards. Previous research by Warren and Kurtz (1992) and D’Avossa and Kersten (1996), which found that (lateral and/or vertical) heading estimates were systematically underestimated during simulated linear self-motion through a 3-D cloud of dots, are partially consistent with this finding. While these previous findings were interpreted as indicating a bias towards either the point of fixation or the centre of the screen, this interpretation was not appropriate for the current findings because: (i) no stationary fixation point was provided; and (ii) a systematic overestimation (away from the centre of the screen) was found for the two smallest glideslopes (1.5° and 3°).

If a 2° upwards bias in future touchdown point perception at a height of 90m was maintained throughout the descent, this would shift the location of an aircraft’s final touchdown a distance of 685m beyond the desired touchdown point {i.e. it would consume an extra 15% of the longest runway in the US (4.9km)}. There were several possible explanations for the imprecise and biased touchdown point estimates found in the current experiment. First, it is possible that visual heading judgments (both lateral and vertical) are less precise and more biased when the angle formed between the simulated motion path and the visible reference surface is small. Second, it is possible that vertical heading judgments are less precise and more biased than horizontal heading judgments. Consistent with this notion, D’Avossa and Kersten (1996) found that vertical heading errors were significantly larger and more variable than horizontal heading errors (in three out of the five participants they tested) during simulated self-acceleration through a 3-D cloud of dots. Third, it is possible that accurate vertical, as opposed to lateral, heading judgments require additional information about the location of the true horizon, which was not available in the present displays (these produced an apparent horizon which was either 0.9° or 2.6° below the true horizon and only provided implicit information about the location of the true horizon). The first two possible explanations of the above findings are examined in the following experiment – where the heading judgments during lateral simulated approaches towards a wall are compared to heading judgments made during vertical simulated approaches towards a ground plane.

Experiment 2: Touchdown Point Perception During Lateral and Vertical Oblique Approaches

This control experiment compared the vertical touchdown judgments produced by the dot-only displays used in Experiment 1 to the lateral point of impact judgments produced by the same displays when they were rotated 90° about the roll axis. The latter rotated displays simulated lateral oblique approaches (1.5° – 15°) towards a vertical planar surface of randomly positioned dots - the participants then had to judge whether a vertical probe line lay to the left/right of their perceived point of impact on the wall. If vertical touchdown point judgments tend to be less precise and more biased than lateral touchdown point judgments (e.g. D’Avossa & Kersten, 1996), then we should expect to find superior performance for simulated lateral approaches. Conversely, if visual touchdown point judgments are less precise and more biased when the angle between the motion path and the reference surface is small, then performance should be equally poor for both the lateral and vertical oblique approaches simulated in this experiment. This experiment also examined whether the simulated glideslope (1.5°-15°) would affect touchdown judgments in a similar fashion for vertical and lateral approaches.

Method

Participants

Thirteen of the 15 observers from the first experiment agreed to subsequently participate in Experiment 2 for course credit.

Visual Displays

Displays simulated either: (i) a vertical oblique approach towards a ground plane surface of 800 randomly positioned dots (located 30m below the observer at the start of the simulation); or (ii) a lateral oblique approach towards a vertical planar surface consisting of 800 randomly positioned dots (this wall was parallel to the participant’s mid-saggital plane and located 30m to the participant’s right at the start of the simulation). Both the ground plane and wall were truncated at a simulated distance of 2km along the depth axis. Lateral and vertical approach displays simulated ten different glideslopes (1.5°-15°) towards the wall or ground plane surface (respectively). Following each lateral approach display, a red probe line (1° high) appeared on the wall at a distance of 0.39°- 3.9° to the left/right of the simulated aimpoint. Following each vertical approach display, a red probe line (1° wide) appeared on the ground at a distance of 0.39°- 3.9° above/below the simulated aimpoint.

Task

Displays were blocked by approach type (lateral or vertical approach) and these blocks were presented in a random order to each participant over four sessions. Following simulated lateral approaches, participants judged whether a vertical probe line lay to the left/right of their perceived point of impact on the wall by pressing the “left” or “right” arrow keys.

Following simulated vertical approaches, the participant's task was identical to that in Experiment 1.

Results

Judgment Precision

We performed a 2 (approach type) x 3 (averaged glideslope) repeated measures ANOVA on the threshold data (the results are shown in Table 3). The main effect of approach type failed to reach significance – indicating that the 75%-correct thresholds for lateral approaches (M = 2.1°) were not significantly different to those found for vertical approaches (M = 2.5°); however, approach type had a small to medium effect size (Cohen, 1988). As can be seen from Figure 3a, touchdown judgments became significantly less precise as the glideslope increased from 1.5° to 15° of visual angle. However, the interaction between glideslope and approach type was not found to reach significance – despite having a medium effect size (Cohen, 1988). Thus, it appears that the simulated oblique glideslopes used in this experiment had similar effects on the precision of lateral and vertical touchdown point judgments.

Judgment Bias

We also performed a 2 (approach type) x 3 (averaged glideslope) repeated measures ANOVA on the constant error data (the results are shown in Table 4). The (leftwards) bias for lateral point of impact judgments during simulated translation (M = -0.4°) was not found to be significantly different to the (upwards) bias found vertical point of touchdown judgments during simulated descent (M = -1.1°). However, the effect size for this comparison was small (Cohen, 1988), so one cannot be certain that a difference of this order was absent. As can be seen from figure 3b, the tendency towards an upwards bias in responding increased significantly as the glideslope increased from 1.5° to 15° of visual angle. Importantly, the interaction between approach type and glideslope was also found to be significant – indicating that the effects of the simulated glideslope on judgment bias were weaker during simulated lateral approaches than they were during simulated vertical approaches.

Discussion

Both lateral and vertical heading judgments were found to be similarly imprecise during simulated oblique approaches towards a (vertical or horizonal) planar surface. While previous research has shown that vertical heading errors are generally larger and more variable than lateral heading errors (D'Avossa & Kersten, 1996), the poor performance found in Experiments 1 and 2 cannot be explained by this anisotropy. Rather, it appears that both lateral and vertical heading judgments were more imprecise during oblique approaches towards a planar surface than the equivalent judgments made during simulated translation parallel to a planar surface.

The overall upwards bias found for vertical approaches and the overall leftwards bias found for lateral approaches, meant that the bias towards the centre of the screen tended to be greater than the bias away from the centre of the screen. However, these findings were inconsistent with the proposal that there was a general shift of the perceived touchdown point towards the centre of the screen, because a systematic bias away from the centre of the screen was still found for the three smallest glideslopes (1.5°-4.5°).

Interestingly, the effect of the simulated glideslope on touchdown bias appeared to be significantly greater for vertical approaches than for lateral approaches. In both Experiments 1 and 2, the increase in upwards bias during vertical approaches with greater simulated glideslopes might have been due a number of factors, such as: (i) the shorter simulated timesto-contact for displays with larger simulated glideslopes; (ii) the greater sink rates (or vertical velocities) in displays with larger simulated glideslopes; (iii) the increased eccentricity of the simulated touchdown point from the centre of the screen; and (iv) participants systematically misperceiving the orientation of the ground plane surface. This last possibility assumes that perceived surface orientation plays a role in touchdown point perception. If this was the case, then the finding that glideslope effects on bias were reduced for lateral heading judgments might indicate that participants' slant percepts (perceived orientation of the surface relative to the vertical axis) were more consistent with the simulation than their inclination percepts (perceived orientation of the surface relative to the horizonal axis). Such a situation might arise if participants were more tolerant to the misleading effects of a false horizon for the wall surface than they were to the misleading effects of the false horizon for the ground plane (since ground surfaces typically extend further than wall surfaces and thus the horizon may be more significant in processing their orientation).

Experiment 3: Effect of Simulated Distance on Touchdown Point Perception

In Experiments 1 and 2, dot motion displays – both with and without runway outlines - always simulated a distance of 2km. These displays produced an apparent horizon, which at the beginning of the display was either 0.9° or 2.6° below the true horizon and gradually moved up the observer's visual field during the simulated descent. As a result, there was only implicit information about the location of the true horizon (its location was specified by the motion perspective of the optic flow). The current experiment examined whether increasing the distance simulated by displays from 2km to 20km and providing an explicit horizon line would reduce the errors and bias in vertical touchdown point judgments. Specifically, it was predicted that these two manipulations would reduce glideslope effects on vertical touchdown point judgments by providing additional information about the true orientation of the ground plane.

Method

Participants

Fourteen naïve observers participated in this experiment – they were undergraduate psychology students who met the selection criteria outlined for Experiment 1. The data from 3 additional observers was not included in the analyses because they failed to successfully complete the landing training or they failed to produce a clear threshold in one or more of the distance type by starting altitude conditions.

Visual Displays

The 2km implicit horizon displays were similar to the dot-only displays used in Experiment 1 - they simulated ten different glideslopes towards a ground plane (1.5°-15°) consisting of only 160 randomly positioned blue dots. Explicit horizon displays were identical to these implicit horizon displays, with the only exceptions being that: (i) an explicit horizon line (also blue) was added at the observer's eyeheight; (ii) the distance simulated by the display was increased from 2km to 20km; and (iii) the total number of dots was increased to 1600 dots to keep the local display density constant. The 2km implicit horizon and the 20km explicit horizon displays were tested at both starting altitudes (30 and 90m).

Task

Displays were blocked by distance type (2km implicit horizon or 20km explicit horizon) and starting altitude (30 or 90m), and these blocks were presented in a random order to each participant over eight sessions. As in Experiment 1, following the simulated vertical approaches, participants judged whether a horizontal probe line lay above/below their perceived point of impact on the ground plane by pressing the "up" or "down" arrow keys.

Results

Judgment Precision

We performed a 2 (distance type) x 2 (starting altitude) x 3 (averaged glideslope) repeated measures ANOVA on this threshold data (the results are shown in Table 5). The main effects of distance type and starting altitude failed to reach significance for the 75% correct threshold data. However, in both cases the effect size was small (Cohen, 1988), so one cannot be certain that differences of this order were absent. Consistent with the findings of experiments 1 and 2, we found a significant main effect of glideslope, which indicated that the precision of touchdown judgments decreased steadily as the simulated glideslope increased (see Figure 4a). Importantly, the interaction between distance type and glideslope was also found to be significant – which indicated that as the glideslope increased above 10.5°, touchdown judgments produced by 20km explicit horizon displays were more precise than those produced by 2km implicit horizon displays. No other 2- or 3- way interactions were found to reach significance.

Judgment Bias

We performed a 2 (distance type) x 2 (starting altitude) x 3 (averaged glideslope) repeated measures ANOVA on the constant error data (the results are shown in Table 6). We found a significant main effect of distance type - vertical touchdown point judgments for 20km explicit horizon displays (M = -0.1°) were significantly less biased than those for 2km implicit horizon displays (M = -1.7°). We also found a significant main effect of glideslope and a significant interaction between distance type and glideslope. As can be seen from Figure 4b, while judgment bias was highly dependent on the simulated glideslope for both 2km and 20km displays, the relationship between bias and glideslope was significantly weaker for the 20km explicit horizon displays. There was also a significant interaction between altitude and glideslope in this experiment – which was interpreted as indicating that the downwards bias for the three smallest glidslopes (1.5°-4.5°) was significantly greater when the starting altitude was 300ft as opposed to 100ft (mean bias was similar for both starting altitudes when displays simulated larger glideslopes, i.e. 6°-15°). No other 2- or 3-way interactions were found to reach significance.

Discussion

In Experiment 1, we found that adding an explicit runway outline to moving dot displays significantly increased the precision and reduced the bias of touchdown point judgments during 10.5°-15° glideslopes. In a similar fashion, in this experiment, we found that increasing the simulated display distance from 2km to 20km and providing an explicit horizon line also increased the precision and reduced the bias of touchdown point judgments during 10.5°-15° glideslopes. In 2km dot-only displays, the horizon was only specified implicitly and the angular difference between the true horizon and the apparent horizon ranged from 0.9° to 2.6° at the start of the display. Conversely, in 20km dot-only displays, the location of the true horizon was idenitified by an explicit horizon line and the angular difference between this horizon and the furthest dot in the display was only 0.1°or 0.2°. Thus, the similarity of the findings of these two experiments suggests that both manipulations (i.e. providing an explicit runway outline to dot motion displays and increasing the simulated distance of dot motion displays) improved touchdown point perceptions by providing additional information about the true orientation of the ground plane. Also consistent with the notion that the large errors found in Experiments 1-3 were due to misperceptions of the ground plane's inclination, during debriefing, all 14 participants confirmed that the 20km explicit horizon displays appeared to be much more like a ground plane receding in depth than the 2km implicit horizon displays. A number of these participants (4 of the 14) also spontaneously reported an apparent warping of surface in the foreground of the ground plane during the descent, which was particularly salient for 2km displays with larger glideslopes and lower starting altitudes.

Why did reducing the starting altitude reduce the bias in touchdown point judgments for the three smallest glideslopes (1.5°-4.5°) examined in this experiment? The observed interaction between starting altitude and glideslope was likely to have been due to the lower density dot-motion displays used in this Experiment (8 dots/km^2 as opposed to 40 dots/km^2 used in Experiment 1). Unlike previous experiments, judgments were found to be significantly less biased for the 30m (compared to the 90m) starting height, when the touchdown point was near the horizon (i.e. glideslopes of 1.5°-4.5°). As a dot's simulated distance along the depth axis increased, its display motion decreased until it appeared stationary or almost stationary around the horizon. However, as the observer's simulated altitude decreased the dot motion increased across the display – so that dots which had appeared stationary/near stationary at 90m, moved visibly at 30m. The current finding suggests that sparser displays used in Experiment 3 had too few noticeably moving dots near the simulated touchdown point when the starting height was 90m. Thus, this starting altitude by glideslope interaction can be interpreted as evidence of a motion density effect on touchdown point perception.

Experiment 4: Touchdown Point Perception During Approach to a Grid Covered Ground Plane

One possible explanation for the divergent findings of Experiments 1-3 was that visual touchdown point perception was not only based on information provided by the optical velocity field (such as the FoE), but also on information provided by its first order spatial derivatives. Using vector analysis, Koenderink and van Doorn (1976) showed that any small region of a instantaneous velocity field can be decomposed into four basic components: (i) a translation; (ii) an isotropic expansion or contraction; (iii) a rigid rotation; and (iv) a pure shear (an expansion in one direction and a contraction in the orthogonal direction). They defined *div* as the rate of expansion, *curl* as the rate of rotation and *def* as the rate of shear of the flow in the neighbourhood of a visual direction.

In principle, participants in the current experiments could also have used the point of maximum of divergence (div_{max}) in the visual flow to perceive their touchdown point (Koenderink, 1986; Koenderink & van Doorn, 1976, 1981). If the observer travels at an oblique angle to the ground plane, div_{max} will always lie in a direction that bisects the angle between the glideslope and the surface normal. Thus, he/she would first need to correctly perceive the orientation of the ground plane in order to determine the location of his/her touchdown point from the point of div_{max} {def could be used to estimate the orientation of the surface patch}. While previous research suggests that div_{max} alone can not account for heading perception (e.g. Warren et al, 1988), it is possible that this information contributes to heading percepts in difficult situations (e.g. oblique approaches of 1.5°-15° towards a ground plane surface). Consistent with this notion, Grigo and Lappe (1999) found that during simulated oblique approaches towards a planar surface covered with randomly positioned dots (at 10° or 20°), heading judgments were consistently biased towards the location of the div_{max}.

Since div can be extracted from any locally continuous velocity field, this spatial derivative information about the location of the touchdown point should have been available in the dot-only displays used in Experiments 1-3 (which contained either 160 or 800 moving dots). However, as was pointed out above, a pilot would first need to correctly perceive the orientation of the ground plane, before he/she could determine the location of his/her touchdown point from the point of div_{max}. It is possible then that the erroneous touchdown judgments found in the 2km dot-only and runway-only displays were the result of participants misperceiving the orientation of the ground plane. According to this div_{max} account, touchdown point estimates were imprecise and biased in these conditions, because they were based on percepts of surface inclination which were themselves highly variable and biased (by the apparent horizon and glideslope). Touchdown point estimates became more precise and less biased when: (i) an explicit runway outline was added to 2km dot motion displays (Experiment 1); and (ii) the simulated distance of dot motion displays was increased (Experiment 3). According to this div_{max} account, these improvements in touchdown point accuracy were produced because both manipulations provided additional information about the (true/simulated) orientation of the ground plane surface (i.e. producing more precise and less biased perceptions of surface inclination).

If div_{max} does play a significant role in touchdown point perception then we would predict that performance should improve when displays simulate an oblique descent towards a *grid covered ground plane*. A grid covered ground plane would provide optimal information about surface inclination (e.g. Perrone, 1984). Based on the above arguments, the additional information in these grid displays should increase the precision and reduce the bias of touchdown point judgments. Contrary to this prediction, Llewellyn (1971) found no difference in heading accuracy when visual displays simulated perpendicular approaches towards frontal surfaces covered with either randomly positioned dots or with a grid. However, these findings do not necessarily discount the above proposal, because this study: (i) did not compare performance with grid and dot displays during simulated oblique approaches; (ii) produced large heading errors for both types of display (ranging from 4° to 7° of visual angle); and (iii) only reported unsigned mean errors.

Method

Participants

All fourteen of the observers from Experiment 3 subsequently participated in this experiment. Two additional naïve participants were recruited using the selection criteria from Experiment 1.

Visual Displays

Grid displays simulated descent (glideslopes ranging from 1.5°-15°) towards a ground plane covered by a square grid consisting of 20 horizontal and 20 vertical lines – each blue line had a luminance of 118cd/m^2 (the average luminance of the background was 0.2cd/m^2). The dot-only displays were identical to those used in the first experiment - simulating descent (glideslopes ranging from 1.5°-15°) towards a ground plane surface consisting of 800 randomly positioned blue dots. In both cases, the simulated display distance was only 2km and no explicit horizon line was provided. All displays started at a height of either 30 or 90m and simulated a constant angular descent speed of 137km/hr.

Task

Displays were blocked by surface type (grid or dot) and starting altitude (30 or 90m), and these blocks were presented in a random order to each participant over eight sessions. As in the previous experiment, the participant’s task was to judged whether a horizontal probe line lay above/below their perceived point of impact on the ground plane by pressing the “up” or “down” arrow keys.

Results

Judgment Precision

We performed a 2 (surface type) x 2 (starting altitude) x 3 (averaged glideslope) repeated measures analysis of variance (ANOVA) on the touchdown point detection thresholds (the results are shown in Table 7). We found a significant main effect of surface type, which indicated that the vertical touchdown judgments produced by grid displays (M = 1.3°) were significantly more precise than those produced by dot-only displays (M = 2.3°). While there was a significant overall effect of glideslope on touchdown thresholds, there was also a significant interaction between glideslope and surface type – indicating that touchdown judgments produced by grid displays were less affected by the simulated glideslope than those produced by dot displays (see Figure 5a). Consistent with the findings of Experiments 1 and 3, the main effect of starting altitude failed to reach significance – however, the effect size was small (Cohen, 1988). The remaining 2- and 3-way interactions also failed to reach significance.

Judgment Bias

We performed a 2 (surface type) x 2 (starting altitude) x 3 (averaged glideslope) repeated measures ANOVA on the constant errors (the results are shown in Table 8). We found a significant main effect of surface type, indicating that grid displays (M = -0.2°) produced significantly less biased vertical touchdown judgments than dot-only displays (M = -1.5°). While there was a significant overall effect of glideslope on touchdown bias, there was also a significant 2-way interaction between glideslope and surface type – indicating that simulated glideslope had less affect on the touchdown bias for grid displays compared to dot displays (see Figure 5b). Consistent with the findings of Experiments 1 and 3, the main effect of starting altitude failed to reach significance – however, the effect size was small (Cohen, 1988). The remaining 2- and 3-way interactions also failed to reach significance.

Discussion

Vertical touchdown point judgments for grid displays were found to be more precise and less biased than those for the dot-only displays – despite the fact that both the grid and dot displays simulated a distance of only 2km and contained no explicit horizon line. These results are clearly consistent with the div_{max} hypothesis. Judgments were more precise and less biased for grid displays, suggesting that the orientation of the ground plane surface was perceived more accurately for grid displays than for dot-only displays. Consistent with this notion, after being shown grid and dot-only displays simulating 15° glideslopes during their debriefing, all fourteen of the participants confirmed that the grid displays appeared to be much more like a ground plane receding in depth than the dot-only displays. Upon further questioning, they also reported that the dot-only displays appeared to be much more inclined than the grid displays.

General Discussion

Warren and colleagues (1988) have argued that lateral heading point accuracies on the order of 1.2° "indicate that optical flow can provide an adequate basis for the control of locomotion and other visually guided behaviour" (pp. 659). While we do no dispute this claim as it pertains to self-motions parallel to a ground plane of randomly positioned dots, the findings of the current study clearly demonstrate that optic flow is not sufficient for the visual control of oblique descents towards a ground plane of randomly positioned dots. However, rather than dismissing the influence of optic flow on pilot behaviour, the large, systematic touchdown point errors found for dot-motion and runway outline displays suggest that erroneous perceptions based on optic flow contribute significantly to pilot error in reduced visibility conditions.

In Experiment 1, visual conditions were similar to those in ‘black hole’ or night landing situations - there was little visible ground texture (only 800 dots or a runway outline truncated at a simulated distance of 2km) and no explicit horizon cues. We found that touchdown point judgments based on either dot-motion or runway-outline displays contained large systematic errors. The (overall) upwards bias evident in these touchdown errors appeared highly consistent with common pilot errors during actual night landings. Mertens and Lewis (1982) have previously noted that there is “a general tendency for pilots to fly lower approaches at night in ‘black hole’ conditions, in which only the edge and end lights of an unfamiliar runway are available for vertical guidance during the approach” (pp. 463). Such a situation could easily arise if pilots consistently perceived their touchdown point to be higher in the visual field during their final approach and as a result lowered their flight path.

However, in Experiments 1, 3 and 4 it was shown that the variability and (overall) upward bias in touchdown errors could be substantially reduced by either: (i) adding an explicit runway outline to dot-only displays; (ii) increasing the distance simulated by dot-motion displays (from 2km to 20km and adding an explicit horizon line); or (iii) covering the ground plane with a grid pattern. These visual conditions in all three types of display were more similar to the available information provided during landings on an extended ground surface in daylight – which are significantly less likely to lead to landing incidents (Hartman & Cantrell, 1968).

One of the most interesting and unexpected findings of this study was that both the size and direction of the bias in participant’s touchdown point judgments appeared to be systematically related to the simulated glideslope for all of the dot motion and runway displays tested. This relationship between touchdown bias and glideslope was negligible for grid displays. However, for the remainder of the displays tested: (i) small glideslopes (simulated touchdown points near the horizon) were overestimated, leading to a “downward” bias; and (ii) glideslopes larger than 3.1°-6.5° (simulated touchdown points substantially below the horizon) were underestimated, leading to an “upwards” bias. These effects of glideslope on touchdown bias were highly consistent with the findings of an earlier landing simulation study by Mertens (1981). In this experiment, participants had to estimate the glideslope represented by a *static view* of an inclined runway model (simulated glideslopes ranged from 0.9° to 10.7° and were represented by rotating this model by different amounts about its pitch axis). Mertens found that while simulated approach angles of less than 3° were overestimated (consistent with a downwards bias in our study), simulated approach angles of greater than 3.5° were underestimated (consistent with an upwards bias in our study). The similarity of these *static perceptions of runway inclination* to the current *dynamic perceptions of touchdown point location*, suggests that the touchdown bias observed in our 2km dot-motion or runway outline displays was caused by participants misperceiving the inclination of the ground plane. Such a conclusion is clearly inconsistent with a pure FoE account of touchdown point perception, which maintains that touchdown judgments are based solely on direct perceptions and hence should be unaffected by misperceptions of the 3-D layout.

One possible explanation of the current results is based on the assumption that participants were using div_{max} information to supplement FoE information about the location of their perceived touchdown point (Koenderink & van Doorn, 1976, 1981). During an oblique descent towards the ground plane, div_{max} always lies in a direction that bisects the angle between the glideslope and the normal to the ground plane. Thus, a pilot would first need to correctly perceive the orientation of the ground plane in order to perceive the location of his/her instantaneous touchdown point from the point of div_{max}. According to the div_{max}

account of the current findings, the different glideslopes and the presence of apparent horizons in 2km dot-only and runway-only displays caused participants to misperceive the orientation of the ground plane. This misperception was likely to have been exacerbated by the presence of stereoscopic, vergence and accommodation based information which conflicted with the information provided by optic flow (as they do in many flight simulators), indicating that the display was a vertical plane of dots or a vertical outline rather than a ground plane of dots or a runway outline receding in depth. Thus, only displays where optic flow information about simulated orientation of the ground plane was compelling (e.g. 20km dot motion displays with an explicit horizon line) or enhanced by explicit gradients of perspective and compression texture (e.g. 2km grid and runway-dot displays) were found to produce less biased or unbiased touchdown point judgments.

An important qualification of the present research is that participants did not have active control over their simulated glideslope. The participant's task in each of the experiments was simply to passively determine whether they were heading above or below a probe which appeared on the last frame of the display. Since these passive touchdown point judgments were shown to be rather error prone in the current experiments, it seems likely that active control situations would allow for more accurate and less biased perceptions of both the touchdown point and the glideslope. For example, Llewellyn (1971) has suggested that active guidance of self-motion towards a target object could be achieved by continuously adjusting the glide path to cancel drift motions of the target. Consistent with this proposal, he showed that the drift motions of a single target object could be detected and cancelled quite accurately. However, while target drift cancellation might be a more likely candidate for accurate glideslope control than the FoE, this cue would also be complicated by the presence of eye-movements, which often act to stabilize target drift. Thus, as with the FoE strategy, the target drift cancellation strategy could only be successful after the effects of the eye-motion had been removed from the retinal flow.

In conclusion, while optic flow information in moving-dot displays does not appear to be sufficient for a pilot to land an airplane, the systematic errors in perceived future touchdown location produced by these motion cues may be responsible for the common occurrence of landing difficulties in so-called ‘black hole’ situations. Given the relative accuracy of day landings, increased accident rates for night landings suggest that when available, pilots use a range of visual cues to safely control their glideslope and only a subset of these visual cues are available during night landings. The current findings of comparatively more accurate and unbiased touchdown point perceptions during richer visual displays are taken as evidence supporting this proposal.

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Table 1

Mean Heading Threshold Analysis of Variance for Experiment 1

Source and comparison	df	MS	F	Cohen's *f*
Surface	2	31.08	4.86*	0.20
Participants x Surface	28	6.4		
Altitude	1	28.6	3.04	0.10
Participants x Altitude	14	9.4		
Glideslope	2	140.8	25.70**	0.45
Participants x Glideslope	28	5.5		
Surface x Altitude	2	5.9	1.12	0.10
Participants x Surface x Altitude	28	5.3		
Surface x Glideslope	4	17.8	4.3**	0.22
Participants x Surface x Glideslope	56	4.1		
Altitude x Glideslope	2	26.1	2.7	0.15
Participants x Altitude x Glideslope	28	9.4		
Surface x Altitude x Glideslope	4	15.3	2.9	0.22
Participants x Surface x Altitude x Glideslope	56	5.3		

* p < .05 ** p < .01

Table 2

Mean Heading Bias Analysis of Variance for Experiment 1

Source and comparison	df	MS	F	Cohen's *f*
Surface	2	5.04	0.32	0.05
Participants x Surface	28	15.54		
Altitude	1	17.07	1.07	0.03
Participants x Altitude	14	15.98		
Glideslope	2	1030.91	32.17**	0.60
Participants x Glideslope	28	32.04		
Surface x Altitude	2	16.25	0.62	0.08
Participants x Surface x Altitude	28	26.04		
Surface x Glideslope	4	85.25	4.98**	0.27
Participants x Surface x Glideslope	56	17.13		
Altitude x Glideslope	2	35.21	1.10	0.09
Participants x Altitude x Glideslope	28	31.91		
Surface x Altitude x Glideslope	4	21.11	1.47	0.13
Participants x Surface x Altitude x Glideslope	56	14.40		

* p < .05 ** p < .01

Table 3

Mean Heading Threshold Analysis of Variance for Experiment 2

Source and comparison	df	MS	F	Cohen's *f*
Approach	1	4.83	2.55	0.22
Participants x Approach	13	24.67		
Glideslope	2	20.98	12.23**	0.43
Participants x Glideslope	26	22.30		
Approach x Glideslope	2	7.61	2.33	0.26
Participants x Approach x Glideslope	26	42.42		

* p < .05 ** p < .01

Table 4

Mean Heading Bias Analysis of Variance for Experiment 2

Source and comparison	df	MS	F	Cohen's *f*
Approach	1	7.81	0.31	0.17
Participants x Approach	13	7.14		
Glideslope	2	133.91	42.98**	0.97
Participants x Glideslope	26	3.12		
Approach x Glideslope	2	14.81	5.69**	0.32
Participants x Approach x Glideslope	26	2.6		

* p < .05 ** p < .01

Table 5

Mean Heading Threshold Analysis of Variance for Experiment 3

Source and comparison	*df*	*MS*	*F*	Cohen's *f*
Distance	1	13.87	2.76	0.18
Participants x Distance	13	5.02		
Altitude	1	0.41	0.21	0.04
Participants x Altitude	13	1.98		
Glideslope	2	106.52	26.38**	0.68
Participants x Glideslope	26	4.04		
Distance x Altitude	1	1.02	0.44	0.03
Participants x Distance x Altitude	13	2.32		
Distance x Glideslope	2	16.18	3.9*	0.29
Participants x Distance x Glideslope	26	4.15		
Altitude x Glideslope	2	0.50	0.30	0.02
Participants x Altitude x Glideslope	26	1.70		
Distance x Altitude x Glideslope	2	3.05	1.79	0.08
Participants x Distance x Altitude x Glideslope	26	1.70		

* p < .05 ** p < .01

Table 6

Mean Heading Bias Analysis of Variance for Experiment 3

Source and comparison	df	MS	F	Cohen's *f*
Distance	1	105.90	18.55**	0.42
Participants x Distance	13	5.71		
Altitude	1	8.63	2.16	0.09
Participants x Altitude	13	4.00		
Glideslope	2	885.50	216.40**	1.64
Participants x Glideslope	26	4.09		
Distance x Altitude	1	0.84	0.26	0.02
Participants x Distance x Altitude	13	3.20		
Distance x Glideslope	2	33.76	6.39*	0.33
Participants x Distance x Glideslope	26	5.28		
Altitude x Glideslope	2	8.92	5.42*	0.18
Participants x Altitude x Glideslope	26	1.65		
Distance x Altitude x Glideslope	2	2.97	1.48	0.09
Participants x Distance x Altitude x Glideslope	26	2.01		

* p < .05 ** p < .01

Table 7

Mean Heading Threshold Analysis of Variance for Experiment 4

Source and comparison	*df*	*MS*	*F*	Cohen’s *f*
Surface	1	45.62	21.17**	0.37
Participants x Surface	15	2.16		
Altitude	1	0.40	0.26	0.06
Participants x Altitude	15	1.50		
Glideslope	2	44.07	16.40**	0.51
Participants x Glideslope	30	2.69		
Surface x Altitude	1	0.01	0.00	0.03
Participants x Surface x Altitude	15	1.64		
Surface x Glideslope	2	38.65	16.20**	0.48
Participants x Surface x Glideslope	30	2.39		
Altitude x Glideslope	2	0.48	0.37	0.03
Participants x Altitude x Glideslope	30	1.29		
Surface x Altitude x Glideslope	2	1.70	1.13	0.13
Participants x Surface x Altitude x Glideslope	30	1.50		

* p < .05 ** p < .01

Table 8

Mean Heading Bias Analysis of Variance for Experiment 4

Source and comparison	df	MS	F	Cohen's *f*
Surface	1	80.51	10.57**	0.31
Participants x Surface	15	114.27		
Altitude	1	1.47	0.38	0.07
Participants x Altitude	15	58.49		
Glideslope	2	871.24	89.32**	0.94
Participants x Glideslope	30	146.32		
Surface x Altitude	1	6.62	2.26	0.11
Participants x Surface x Altitude	15	43.97		
Surface x Glideslope	2	300.28	25.57**	0.57
Participants x Surface x Glideslope	30	176.15		
Altitude x Glideslope	2	2.67	0.43	0.04
Participants x Altitude x Glideslope	30	93.29		
Surface x Altitude x Glideslope	2	4.99	0.87	.10
Participants x Surface x Altitude x Glideslope	30	86.31		

* p < .05 ** p < .01

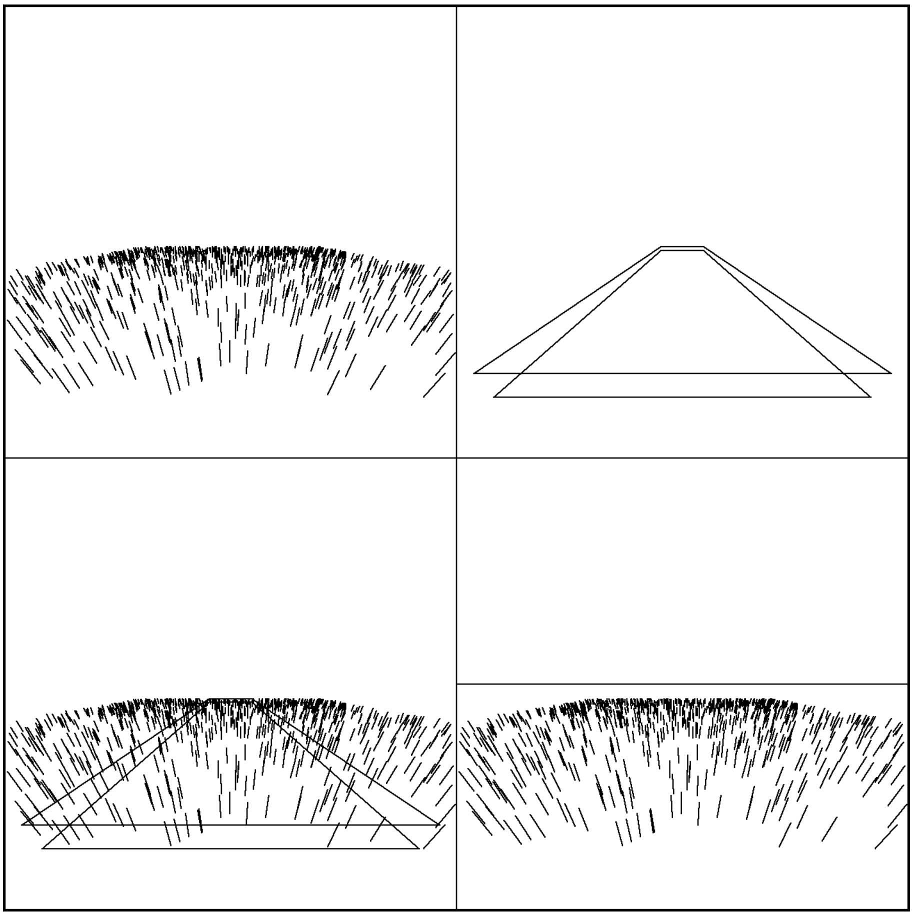

Figure 1.

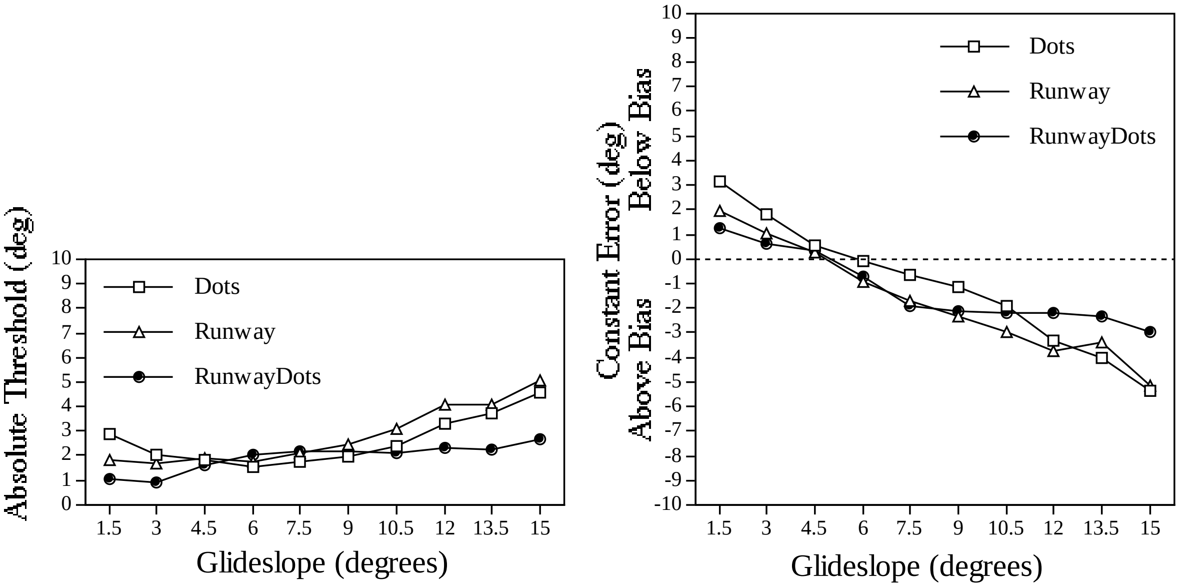
Absolute Threshold (deg)
10
9
8
7
6
5
4
3
2
1
0
Dots
Runway
RunwayDots
1.5
3
4.5
6
7.5
9
10.5
12
13.5
15
Glideslope (degrees)
Constant Error (deg)
Below Bias
Above Bias
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
Dots
Runway
RunwayDots
1.5
3
4.5
6
7.5
9
10.5
12
13.5
15
Glideslope (degrees)

Figure 2

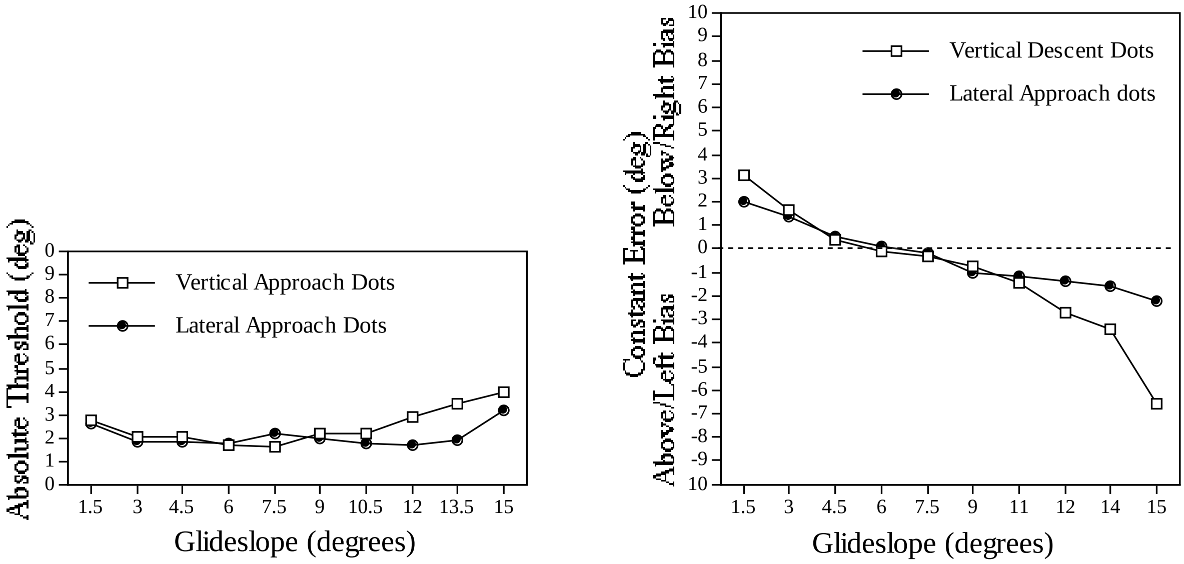
Absolute Threshold (deg)
0
9
8
7
6
5
4
3
2
1
0
Vertical Approach Dots
Lateral Approach Dots
1.5
3
4.5
6
7.5
9
10.5
12
13.5
15
Glideslope (degrees)
Constant Error (deg)
Below/Right Bias
Above/Left Bias
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
10
Vertical Descent Dots
Lateral Approach dots
1.5
3
4.5
6
7.5
9
11
12
14
15
Glideslope (degrees)

Figure 3.

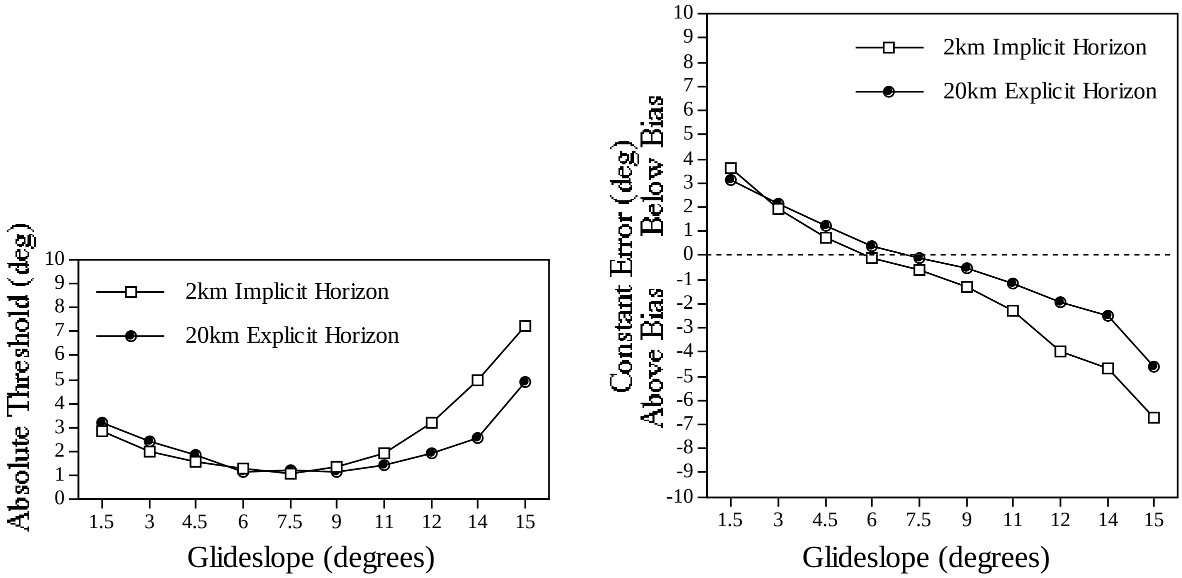
Absolute Threshold (deg)
10
9
8
7
6
5
4
3
2
1
0
2km Implicit Horizon
20km Explicit Horizon
1.5
3
4.5
6
7.5
9
11
12
14
15
Glideslope (degrees)
Constant Error (deg)
Below Bias
Above Bias
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
2km Implicit Horizon
20km Explicit Horizon
1.5
3
4.5
6
7.5
9
11
12
14
15
Glideslope (degrees)

Figure 4.

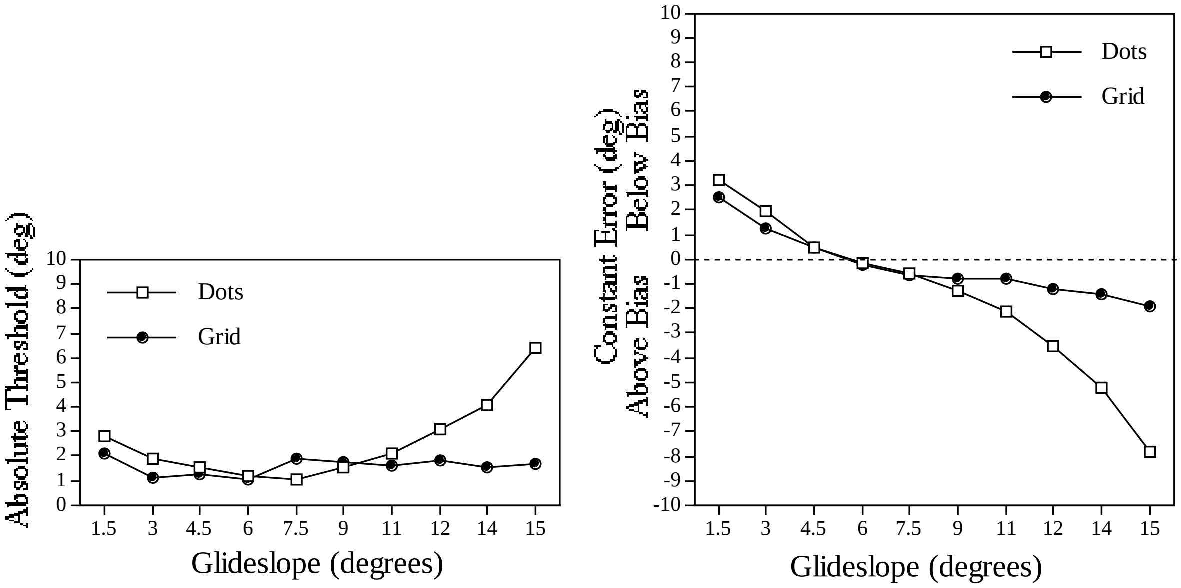
Absolute Threshold (deg)
10
9
8
7
6
5
4
3
2
1
0
Dots
Grid
1.5 3 4.5 6 7.5 9 11 12 14 15
Glideslope (degrees)
Constant Error (deg)
Below Bias
Above Bias
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
Dots
Grid
1.5 3 4.5 6 7.5 9 11 12 14 15
Glideslope (degrees)

Figure 5.

Figure Captions

Figure 1. Velocity-field representations of the visual displays used in experiment 1. All of the above diagrams simulate a 15° glideslope, starting from an initial altitude of 30m. The top-left diagram represents the pattern of optical velocities produced by a dot-only display. The top-right diagram shows the change in the shape of runway outline over the same time interval. The bottom-left diagram shows both the optic flow and runway cues available in combined displays. The bottom-right diagram is provided for observation purposes – it demonstrates the angular deviation between the true horizon and the apparent/visible horizon formed by the dots.

Figure 2. Effects of the simulated glideslope on touchdown detection thresholds and signed constant errors for the 3 different surface type displays (dot-only, runway-only and runway-dot). These mean thresholds and constant errors were calculated for each of the 10 different glideslopes by averaging the data across the 15 participants.

Figure 3. Effects of the simulated glideslope on absolute touchdown detection thresholds and signed constant errors for the lateral and vertical approach displays (both conditions were simulated using dot motion only). These mean thresholds and constant errors were calculated for each of the 10 different glideslopes by averaging the data across the 13 participants.

Figure 4. Effects of the simulated glideslope on absolute touchdown detection thresholds and signed constant errors for the 3 different surface type displays. These mean thresholds and constant errors were calculated for each of the 10 different glideslopes by averaging the data across the 14 participants.

Figure 5. Effects of the simulated glideslope on absolute touchdown point detection thresholds and signed constant errors for dot and grid surface type displays. These mean thresholds and constant errors were calculated for each of the 10 different glideslopes by averaging the data across the 16 participants.