Modeling of the Human Pilot in Aircraft Landing Control

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Abstract

This paper provides an overview of literature on visual perception for position and motion awareness in general, and focuses on the visual inputs used by human pilots for landing aircraft in particular. General introductions are given on the background of manual aircraft landing and on depth and motion perception. These fields are then brought together in a discussion of visual cues available during aircraft landing. Visual thresholds and visual illusions are discussed and subsequently used to test the likeliness that the cues proposed in literature are actually used by pilots.

Keywords

Visual Cues, Perception, Human Pilot, Manual Control, Visual Flight, Pilot Vision, Aircraft Landing

1. Background

The final phases of aircraft landing are very demanding for the pilot and critical in terms of both time and safety. Notwithstanding the growing capabilities of automated landing control systems, most landings are still performed manually because automated systems impose strict requirements on the aircraft, airport, weather and crew and apart from that pilots prefer being in control and see a good landing as the 'cherry on the cake' after a long and boring cruise flight[1, priv.comm.]. Moreover, pilots will have to keep practicing manual landings to be able to properly supervise the automated system and deal with emergency situations. Finally, research has shown that manual landings generally result in a lower sink rate at touch down [2] which increases passenger comfort. All together, there are many reasons why manual landing control deserves a closer look.

During a manual landing the pilot cannot allot time for reading out all instruments, and therefore must obtain almost all information from the view he has through the cockpit windows. Only occasionally will he be able to cross-check a few parameters, mainly airspeed, altitude and descend rate [3–6][1]. The pilot makes control adjustments to keep a constant 3° descend path ('glide', Fig.1) and to keep the aircraft aligned with the runway using visual information. Also the initiation and execution of the 'flare' maneuver — a slight lifting of the aircraft nose in order to decrease descend rate and to land on the main gear first — are based on visual inputs [7, 8]. The flare has to be performed only a few seconds before touchdown and is critical because a too late or to soft flare will result in a hard landing (which is bad for the landing gear and for passenger comfort) or even a crash, while a too early or too strong flare may lead to 'floating' over the runway (leaving too little runway length for breaking) or even missing the runway at all and going back into the air.

Learning proper landing control is the most difficult and time consuming part of pilot training [7–9], as the student has to develop a mental picture of 'what looks right'. At the same time it is very difficult for instructors to express what was wrong with a landing or approach, or how it should be changed. Even when one knows how to use all visual input effectively, pictures may be deceiving, and even highly experienced pilots are vulnerable to visual illusions (see §4.3).

The goal of this research is to identify which elements in the visual field experienced pilots use to make smooth and soft landings under varying conditions. Such insights can be taught to trainees and analysis of pilots could be helpful to give specific feedback, which is thought to greatly improve learning efficiency [7, 8]. Knowledge of the use of visual cues by pilots can also help finding out why and when optical illusions arise and how pilots can be trained to recognize or avoid them. Apart from applications in training, the uses for this knowledge range from human-machine interaction optimization to improving the effectiveness of flight simulator training.

Although this research project is focussing on large passenger jet aircraft (especially the Boeing 767), most concepts discussed apply to aircraft landing in general and various car driving research is closely related as well [10–17]. To maintain a wide scope, this paper will first discuss some basics of visual depth and motion

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[1] Note that in large jet aircraft altitude and sink rate information can be obtained from the 'Radio Altitude Call-outs', i.e., an automated voice calling '100', '50', '30', '20', '10' at the respective altitudes in feet. The speed at which the calls follow up on each other gives information about the sink rate.

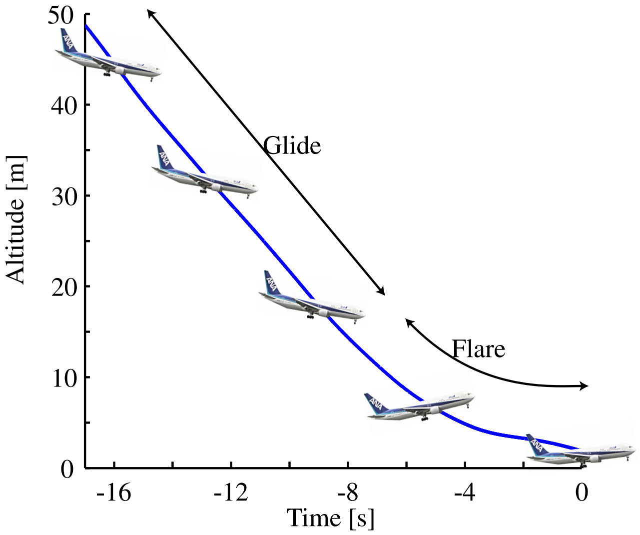

Figure 1: In the final approach to landing, the pilot pitches up to arrest sink rate and land softly on the main gear. This maneuver is called the flare.

perception in sections 2 and 3 respectively. Section 4 will then zoom in on visual cues specific to aircraft landing.

2. Visual Depth Perception

For proper control of our movements, spatial awareness is indispensable. Therefore, visual depth perception lies on the basis of research into human guidance and control of vehicular movement. As the term 'depth' may be confusing, I will define it here losely as a relative or unscaled distance between objects in the radial direction from the observer. When I talk about the distance between an observer (aircraft pilot) and the ground surface, I will refer to it as 'altitude' rather than 'depth'. Although strictly speaking depth can not be observed (only objects located in depth can), I will still use depth as was it perceived information. Only when this depth is (mentally) transformed into an (estimated) absolute measure like meters or feet, I will use the term distance (in any direction) or altitude (vertical).

The topic of visual depth perception is so general and of such scientific significance that many publications are available, and many authors choose their own classification and scope. Palmer [18] provides a very detailed and complete work with a wealth of references for those who want to dig deeper into certain phenomenae. Cutting and Vishton [19] (alt. [20]) and Ogle [21] are also suggested for further reading as they provide good overviews and detailed descriptions of the various visual cues to depth.

2.1. Monocular Depth Perception

Monocular or 'pictorial' depth information can be extracted using one eye only, as opposed to binocular or 'stereoscopic' information (§2.2), which can only be extracted from the difference in the information of both eyes. The monocular depth cues are (see also fig.2):

- **Perspective**
  - **Linear perspective** (*Geometric perspective; Relative size; Texture density; Size of the retinal image)*[2] describes the fact that farther objects appear smaller in the retinal projection. This makes for instance parallel rails of a railroad track seem to converge at the horizon and creates a gradient in the level of textural detail we can distinguish. This is a particularly powerful cue if a wide depth range is viewed.
  - **Height in the visual field** (*Relative height)* is the notion that, generally, objects positioned closer to the horizon are further away.

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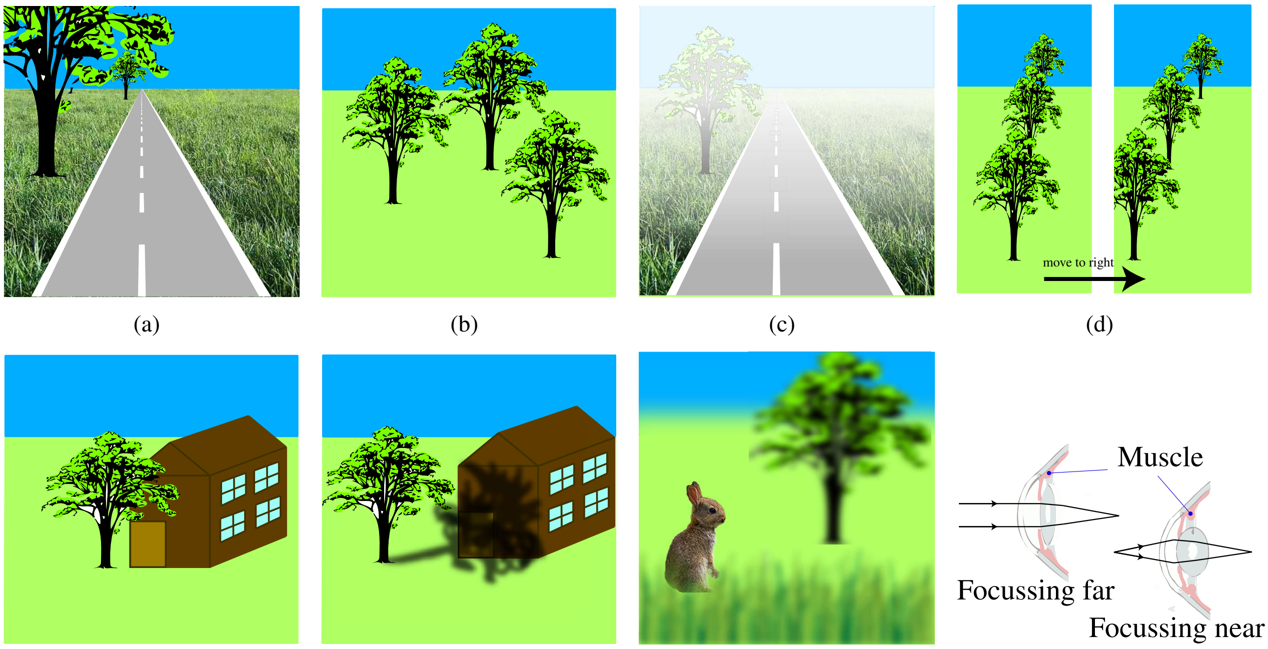
[2] The italic terms in brackets are alternative names given to the cue



(a) (b) (c) (d)

(e) (f) (g) (h)

Figure 2: Monocular depth cues: (a) ***Linear perspective*** *makes parallel lines seem to converge at the horizon, makes closer objects appear larger and causes gradients in texture (b) The* ***height in the visual field*** *makes the middle tree seem farthes and the right tree closest (c)* ***Aerial perspective*** *makes distant objects (d)* ***Parallax*** *makes closer objects move faster through the visual field when changing the viewpoint (e)* ***Occlusion*** *makes clear that the tree is in front of the house' facade (f) The* ***shadow*** *makes clear that the tree is in front of the house' facade (g) When focussing on the rabbit,* ***blurring of the image*** *shows that both the grass and the tree are at different depths (h) Focussing requires the change of muscles in the eye. The muscle tension, called* ***accommodation****, can be a cue to depth.*

- **Aerial perspective**
  is the effect that farther objects have less sharp outlines, less distinct textures and less saturated colors due to water vapor, dust and smoke particles in the air. Aerial perspective only provides a coarse cue for large depth differences, and only works under the assumption that the transparency is more or less homogeneous.
- **Parallax** (*Motion parallax; Motion perspective)*
  is the change of the relative position of objects due to a (small) change in position, also phrased as "near objects move faster than far objects". This can be illustrated by making your 2 index fingers, one at arm-length and the other at half-arm-length, overlap with a distant object while looking with one eye. When moving your head left-right while focusing on the distant object, you see the nearer finger move faster (and further) than the other one. Parallax is a strong depth cue.

- **Occlusion** (*Interposition; Overlay)*
  means that closer objects can (partly) conceal farther objects. Occlusion is an ordinal cue and can thus only reveal depth but does not carry any distance information.

- **Light/Shade/Shadow**
  Brightness, cast shadows and attached shadows give detailed cues about layout and object shape.

- **Blurring of the image**
  occurs in parts of the visual field which are not in focus. Objects further away from the focal point will be more blurred.

- **Accommodation**
  is the state (muscle tension) of the lens focusing mechanism of the eye. Accommodation is actually not a visual cue, but a proprioceptive vision cue.

2.2. Binocular Depth Perception

Binocular depth information is obtained through a coupling the brain makes between the information from both our eyes. References and an in-depth discussion of binocular cues, their limitations and implications for aircraft landing can be found in a previous publication by the author [22]. The binocular depth cues are

- **Stereopsis** (*Disparity*)
  is depth perception based on the minute differences between the two retinal images resulting from the slightly different viewpoint of each eye. Stereopsis is clearly illustrated by the red/green pictures which are to be viewed with special glasses. The practical limit of stereopsis should be expected to be 20–65m and it is very unlikely to be a cue of significant importance beyond 100m.
- **Vergence** (*Convergence*)
  is the simultaneous movement of the pupils of the eyes toward or away from one another during focusing. Feedback on the eye positions (muscle tension) provides some depth information, but it is only effective within a few meters range. Like Accommodation, vergence is actually not a visual cue, but a proprioceptive vision cue.

Due to its limited range of practical use, stereopsis can generally be ignored as a cue for landing, except for small aircraft or helicopters and in case of severely degenerated monocular cues such as when landing at unknown airfields, at night or in bad weather.

3. Three Models of Visual Ego-Motion Perception

Although of course related by nature, three conceptually different approaches can be found in visual motion perception research. The first is ‘optical flow’, which regards the combined flow of all points in the visual scene (§3.1). The second approach hangs somewhere in between ‘optical flow’ and ‘visual cues’ and is the τ or Time-to-Contact (TTC) hypothesis (§3.2). The last approach focuses on specific ‘visual cues’, where motion perception is thought to be derived from the movement in the retinal image of some characteristic points in the visual scene (§3.3).

As the landing of aircraft is a very specific task and the visual scene (airport, runway, etc.) is very typical, mostly the visual cue approach is followed, supplemented by the TTC hypothesis for investigation of timing tasks. Occasionally the optical flow theory is used directly, for instance when evaluating the effect of different levels of textural detail in flight simulators, or in studies regarding the accuracy of heading detection.[23–26].

3.1. Optical Flow

Optical flow[3] is the logical extension of (motion) parallax (see §2.1) to all points in the scene. Although noted earlier by others [29], Gibson [30–33] was the first to study the concept of optical flow extensively in the 1950s and became a leader in optical flow research.

3.1.1. Formulation

Gibson et al. [32] noted that the regular definition of motion parallax (§2.1) holds for a sideways movement of the observer with respect to the scene, but is not trivial in case of forward movement. They extended the description of apparent relative motions of near and far objects due to movements of the observer to a full description of the space around the observer (regardless of the area the observer can actually perceive). Optical flow and retinal flow are related, but the latter has superimposed flows due to head and eye movements[4].

Optical flow can be visualised by drawing motion vectors for a number of points around the observer (see fig.3). The flow pattern generally gives information about the direction of motion and can also carry information about the layout and shape of objects [35]. When extracting the optical flow from an image sequence (video) the flow field is generally identified in terms of (local) divergence, curl and deformation (these are the first-order differential invariants, see also fig.4) [27, 36]. Any flow pattern can be captured by a combination of these basic patterns and the uniform unidirectional flow pattern.

Applications of the optical flow formulation can be found in computer vision (artificial intelligence) [35, 37], cognitive neuroscience modeling [38, 39] and more fundamental research connecting these practical and theoretical fields [40].

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[3] Optical flow is also referred to as “motion perspective”, “differential perspective”[27] or “Streamer effect” (at lower altitude ground texture ‘flows’ faster [28]).

[4] Macuga et al. [34] have even shown optical flow can be sensed without retinal flow, which has important implications for neuro-vision models.

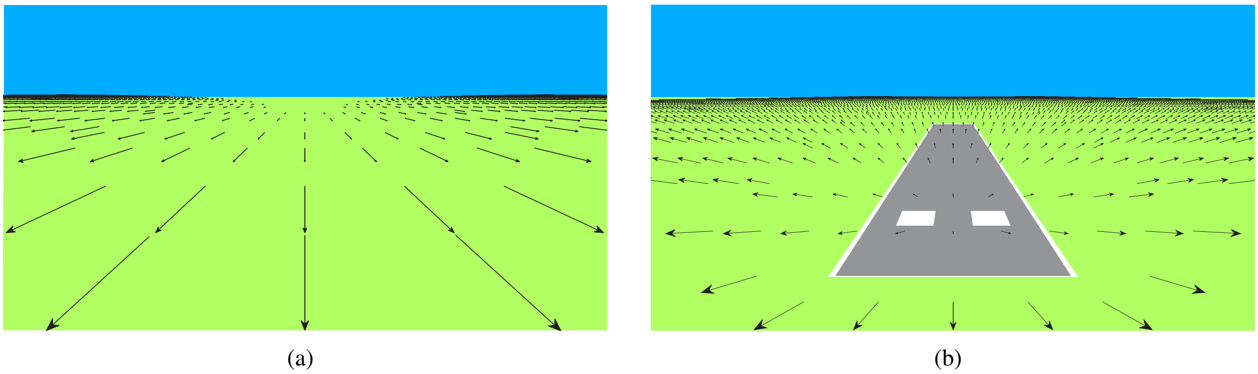
(a) (b)

Figure 3: Examples of optical flow fields: (a) optical flow field in case of level and straight motion, (b) optical flow field in case of a 3° glide slope aiming at the aimpoint markers.

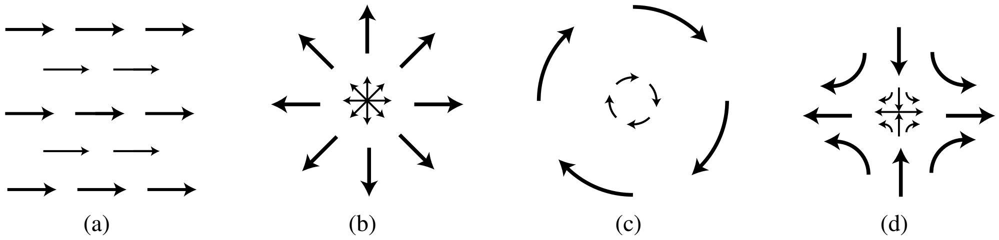
(a) (b) (c) (d)

Figure 4: The four basic descriptors of optical flow: (a) Pure translation, (b) Divergence, (c) Curl and (d) Deformation. (b)–(d) are the first-order differential invariants.

3.1.2. Findings

Probably the most important insight given by the optical flow formulation is that the 'focus of expansion' (i.e., the stationary point in the flow field) indicates the current direction the observer is moving in. This notion can be used in vehicular control by steering the vehicle until the aiming point and the focus of expansion coincide [3, 10, 11, 23, 24, 28, 41–44]. However, Gordon [10] raised some questions regarding the usefulness of optical flow as posed by Gibson. In his car driving research, he finds that the curved rather than linear motion paths complicate matters considerably and that the focus of expansion is often difficult to perceive against the smooth sky background.

Other laboratory experiments have confirmed that optical flow alone would give a too inaccurate estimation of the direction of movement for most control tasks [45, 46]. It is however recognised that, in a natural scene containing some more structured elements and perspective cues, optical flow could provide accurate directional and speed information [11, 45, 46] (see also §4.2.4).

Apart from the 'focus of expansion' cue to heading, optical flow contributes to the perception of self-motion especially through peripheral vision. Unlike specific visual cues, which need foveal attention to be perceived properly, optical flow especially works in the outer area of the field of view (FOV) [39, 47, 48].

Several sources mention the importance of a wide FOV for speed [48] and attitude [49] perception in general and for aircraft landing in specific [22, 50, 51]. Also here, the FOV is found to be especially important for proper determination of the aircraft attitude [52 vol.2,§3.4.5.1.5] and control of the resulting sink rate [priv.comm.]. This leads to the suggestion that optical flow is generally used by pilots as a visual cue.

3.1.3. Binocular equivalent

The binocular equivalent of optical flow would be the stereo-motion cues ('dynamic stereopsis'). This is a relatively new research field considering the difference between the velocity fields of the retinae. As binocular cues are considered to be of minor importance in jet aircraft landing (§2.2), and since applied and experimental data in this direction is still scarce, I will confine to refer the interested reader to Regan et al. [53], Rokers et al. [54] and Morgan and Castet [55] as a starting point for deeper investigation.

3.2. τ-hypothesis and Time-to-Contact (TTC)

The τ-hypothesis or the idea that our movements are guided by time-to-contact perception was formulated by Lee [13, 56] —a student of Gibson's— in the 1970's.

3.2.1. Formulation

Although derived from the optical flow theory, the τ-hypothesis focuses on a single object ('obstacle') or even a single pair of points, and finds the time to contact with the object directly from the rate of dilation of the object in the retinal image (assuming constant speeds and a stationary scene)[5]. τ can be expressed numerically as

$$\begin{aligned}\tau &= \frac{\text{(angular separation of any two image points of the obstacle)}}{\text{(rate of separation of the image points)}} \\ &= \frac{x}{\dot{x}} = \frac{\text{gap}}{\text{closure rate}} = \frac{\text{distance}}{\text{speed}} = \frac{\text{altitude}}{\text{descend rate}} = \ldots\end{aligned} \tag{1}$$

"However, that does not imply that sensing tau requires sensing the size of the motion gap and its rate of closure. By analogy, though linear acceleration is numerically equal to the second time derivative of distance, it is sensed directly, without sensing distance or time [...]. Likewise tau could be sensed directly by virtue of physical laws." [57].

In the field of perception research this statement is quite controversial. Hoffmann [58] found that the perception of τ is learned, rather than innate. Many others pose that τ is not directly perceived, but that time-to-contact information is derived from other cues [59], in particular from separate perceptions of distance and speed [51, 60].

Other criticism on the τ-hypothesis originates from the fact that the hypothesis only holds for small visual angles (objects) [13] but motion of small objects (or objects large distances) can hardly be perceived (Motion camouflage) [14] and for small objects at close distance binocular cues would provide abundant and more accurate information [61, 62].

3.2.2. Findings

Time-to-contact was found to guide movements ranging from animal behaviour [63], to ball catching [64] and aircraft operations [65, 66], although some question whether these findings are really a result of visual feedback or a side-effect of smooth motion control[67].

Studies considering road traffic generally find high biases and standard deviations in the time-to-contact perceived by drivers, leading to dangerous situations [13–15, 58].

While some studies into aircraft maneuvers found support for the τ or TTC hypothesis [8, 65, 66, 68, 69], others found that a combination of τ and altitude [24, 25] or τ and sinkrate [70] was used by pilots to time the flare maneuver. The results of Prowse et al. [71] confirm the imprecision of TTC estimation found in car driving research, thereby questioning its potential as a cue, although it should be noted that this particular study did not involve real pilots but unexperienced subjects. On the other hand, Palmisano et al. [8] found that TTC estimation could be very accurate with an explicit aimpoint in the scene, appropriate training (feedback) en when focussing on the horizon or runway end, rather than on the aimpoint itself.

Pleijsant et al. [72] studied the effect of the presence of texture on TTC estimation, while minimizing possible other cue influences. The presence of ground texture was found to provide significantly better TTC estimates, which was later confirmed by Palmisano et al. [8].

3.3. Visual Cues

A 'visual cue to motion' is a characteristic in the visual scene which reveals (self) motion. Put simply, it is a time derivative of any of the visual cues to depth discussed in §2. This could for instance be the slow expansion of an object as it comes nearer (Linear Perspective/Relative size cue), the change of shape (linear perspective), the fact that one object moves in front of another (occlusion, (motion) parallax), an object slowly appearing from the fog (aerial perspective), etcetera.

As the availability and nature of visual depends heavily on the visual scene, a general discussion here is not very meaningful. Visual cues and visual cue research specific to aircraft landing will be discussed in §4.1.

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[5] Actually τ is formulated from an ego-motion perception point of view (moving in forward direction), while the time-to-contact (TTC) is more general and can include objects moving toward the observer under an angle. Although the terms τ and TTC are often used interchangeably, there may be differences in the basic perception or thresholds.

4. Visual Perception during Landing

Although every airport is different, the standardized runway markings (fig.5) and common textural elements such as grass, trees, buildings, roads, cars, etc. provide basic visual cues for every landing. §4.1 provides an overview of these candidate cues, after which some perception thresholds will be discussed in §4.2. Illusions reported by pilots or accident investigations can also reveal which cues pilots use, therefore a short overview of illusions during landing approaches will be given in §4.3. Finally, an overview of supra-threshold cues which are thought to be used in the glide phase, flare phase, and for flare timing will be selected in §4.4, §4.5 and §4.6 respectively.

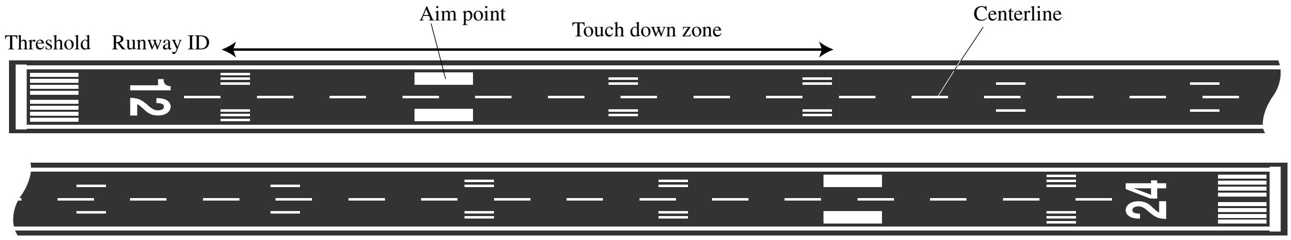
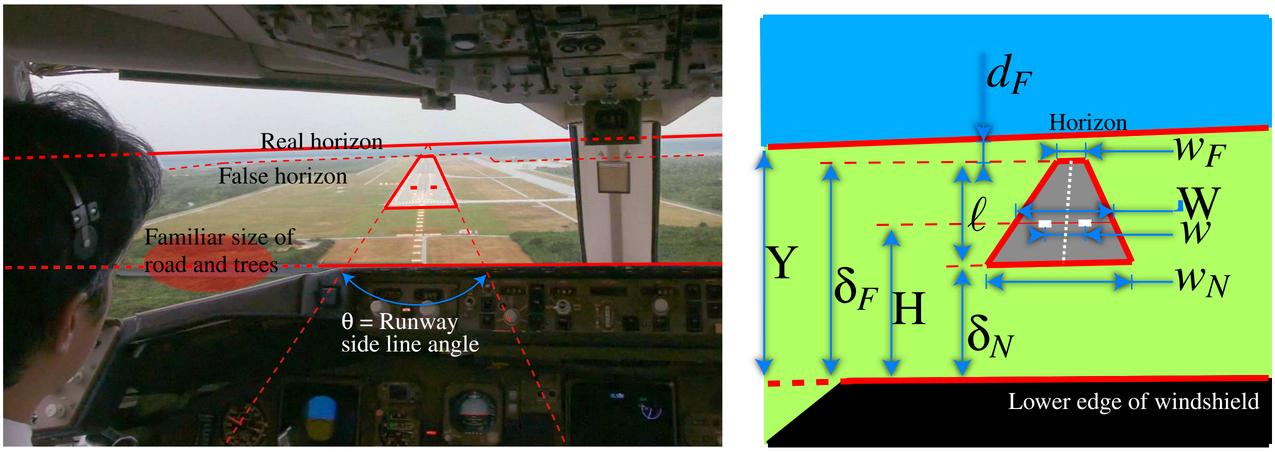


Figure 5: Typical runway markings. The aimpoint (one of the Touch down zone markings) and the side lines are considered important cues. The runway ID number (e.g. ‘12’) shows its heading (ca. 120° from the straight north direction).



(a) (b)

Figure 6: Definition of some visual cues for longitudinal landing control. (a) A picture from the cockpit. A false horizon is visible below the real horizon due to the edge between land and sea. Familiar size can be used as a distance (altitude) cue, and the runway side line angle can also be an altitude cue. (b) Minimalistic view of the landing scene with various distances that can be used as cue. Note that the depression angle $d_F = Y - \delta_F$; similarly cues $d_N = Y - \delta_N$ and $d_H = Y - H$ (the latter being the H-distance or ‘implicit horizon’) can be constructed. Additionally, ratios such as ℓ/W may be used as cue.

4.1. Suggested Cues

Many researchers have proposed visual cues and how a pilot could use them in the control of his aircraft during the final approach and landing. This paper will only consider cues for the control of longitudinal motion in depth and will not further consider cues for alignment with the runway (e.g., the apparent inclination of the runway center line), cues for stabilizing roll motion (e.g., the apparent inclination of the horizon) etcetera.

Table 1 shows the cues mentioned in various literature, where * means the cue was positively mentioned or included in the investigation, ○ means the cue is used by pilots (result of investigation) and × means the cue is not used by pilots. A ? indicates some uncertainty regarding the interpretation of the results.

Most visual cues defined in in table 1 are explained in fig. 6 and will not require further explanation; they are simply a (change of) distance between two points or lines. This distance is generally given as a subtended angle, i.e., the angle between the ‘light rays’ traveling from these points, meeting at the eye (see fig.7). The

Table 1: Overview of visual cue research in aircraft landing and the cues they discuss. The abbreviations in the row 'Research Method' mean: T=Theoretic, Q=Questionnaire, X=eXperience, E=Experiments. Footnotes in the table can be found in Appendix A.

Reference	[52]	[73]	[43]	[74]	[75]	[76]	[77]	[78]	[28]	[4]	[79]	[80]	[81]	[41]	[82]	[23]	[83]	[42]	[84]	[44]	[85]	[86]	[86]	[24]	[7]	[8]	[25]	[70]	[87]	[66]	[4, 88]
Research focus	General				Glide																		Flare Timing							Flare	
Research Method				E	T	T	T	E	Q/X	Q/X	T	Q	E	?	T	E	X	?	E	E	E	E/Q	E/Q	E	Q	E/Q	E	E	T/E	E	X
Optical Flow																															
Optical flow	*[2]								*	*				*			○	*		*	*			*			*				
Focus of expansion		*	*[3]						*	*		*[4]		*		*		*		*	*			*				*			
Field of View										*					○[5]																
motion parallax																	*														
runway intersection point1																															*
Widths																															
apparent runway end width (w_F)						*	*															○	○								
app. runway start width (w_N)						*	*								*							○	○								
Marker separation (w)		*	*	*													*								*						
runway visual angle (app. width, W)										*			?[6]							*	*					*[7]	○[8]				
Heights																															
H-distance ($d_H = Y - H$)				○[10]	○	○	○	○	*			*		*		*			*	*	*					?[9]					
Runway End-Horizon (d_F)									*	*															○						
horizon height (Y)			*[11]	*		*	*								○[12]			*		*	*					*					
apparent runway height (ℓ)					×	*	*			*	*[13]		?[14]							*	*	○									
Far runway end (δ_F)		*	*[15]												*																
Near runway end (δ_F)					×					*					○[16]	?[17]															
Size/Shape																															
Runway size (Expansion)					×			×	*	*		○					*														
Runway shape (perspective)						×	○	×	?[18]			○	*				○					○	○		○	*					
Runway form ratio (ℓ/W)						×	*						○																		
familiar size (texture)			*		*				*	*		○		*			*	*		*	*		*		○	*	?				
Other																															
runway sideline angle (θ)				*	*	*	○	?	?[18]	*	*[13]		?[19]	*					*	*	*	○	○				?				
$d\theta/dt$				○[20]	×																								O		
TTC (τ)				*										*										○[21]		○	○[22]		*		
Binocular	○[23]									×															×[24]				*		
Runway tilt (for lateral control)					○				*																						
STATES																															
Altitude	25	26	27	*	○					*													*	○	*			○			
sink rate	25			*						*													○		*			*			
Altitude tau (Altitude/Sink rate)				*																								○		○	
air speed			*[28]	*																			*					*			
pitch angle			*[28]	*						*																		*		*	
longitudinal position				*	○														*				○[29]					○			
Notes							30							31		32								33	34	34		35			

term "depression angle", which means the subtended visual angle of a point with respect to the horizon, is also often found in literature. A few cues will be explained a little further here.

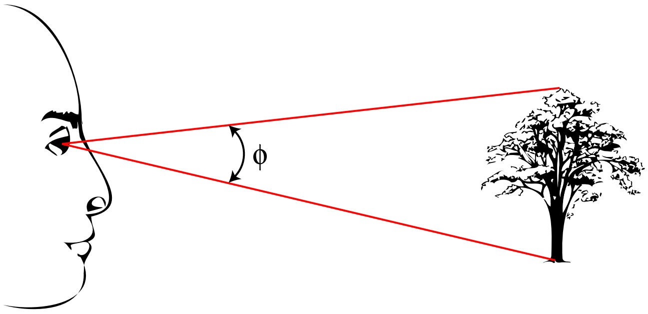


Figure 7: ϕ is the angle subtended by the tree also called the 'subtense of the tree' or the 'visual angle of the tree'. This angle (or distance in the visual plane) is given in degrees (°), minutes of arc (60arcmin=60'=1°) or seconds of arc (60arcsec=60"=1'). For example, an object moving to the left with 1cm/s at 1m (=100cm) in front of the observer, will have a (subtended) angular speed of $\tan^{-1}(1/100) = 0.57°/s$ *or* $\tan^{-1}(1/100) * 60 = 34 arcmin/s$.

Familiar size or **texture/textural detail** is a cue resulting from linear perspective (§2.1). As we know the size of many common objects (such as trees, cars, buildings, grass), and we know that things appear smaller when they are further away, we can use their apparent size to make estimates about distance or altitude.

Runway side line angle (here to be called θ) is not referring to a subtended visual angle, but to the apparent angle the runway side lines make in the visual plane due to linear perspective. This cue is strongly related to the **runway perspective** cue, although the latter may include for example the ratio between the apparent widths of the far and near runway ends. The runway side line angle is a cue to altitude and independent of horizontal distance. The change of this cue (rotational speed) was suggested as a cue for flare timing in previous research by the author [74, 87]. The apparent angle and subtended angle are easily confused, especially because other researchers did actually suggest the subtended angle as a cue[25].

H-distance, **Implicit horizon** and **Touchdown zone/Runway/Marker depression angle** all refer to the same distance between the aimpoint markers on the runway (which should be the heading point) and the horizon. During the glide phase, this distance should be kept constant to keep a constant glide path (this follows from simple geometric relations). Note however that 'Implicit horizon' has a second meaning: a horizon which is not explicitly visible, but derived from convergence of ground lines or texture gradients.

Optical Flow —as noted in §3.1— is especially providing for attitude, heading direction and descend rate information, and works best with a wide field of view. The author is not aware of any empirical research where specific optical flow cues are quantified and used for modeling human aircraft landing control. Such research to the use of (peripheral) optical flow as cue is however an interesting direction for additional research, especially when considering the FOV requirements for simulator and augmented or synthetic vision displays which are increasingly being used. Moreover, in research on augmentation using peripheral motion cues, pilots referred to the added cues as feeling "natural" [89].

4.2. Thresholds

In order to find out whether the proposed cues are actually useful in practical situations, it is important to review motion thresholds and the 'just noticeable difference' (JND) of the cues.

In determining thresholds a distinction should be made between central and peripheral vision. The highest visual acuity is obtained in the central region of the retina — called 'macula lutea'— which covers approximately 6-10 deg of visual angle in diameter. The 'fovea' is at its center and accounts for 1-2° of visual angle [90]. The periphery on the other hand, has advantageous properties in dim light conditions [90 §1.306] and plays an important role in detecting optical flow [48, 49].

4.2.1. Foveal Threshold for Point Movement

Several sources mention visual perception thresholds for the motion of a point of a few minutes of arc subtended per second [91–96, 97 p.673].

It should however be noted that various factors influence the threshold value [90 §5.203]. First of all longer exposure times will allow the perception of even slower movements [92]. Furthermore, increases of the threshold with up to a factor 10 have been mentioned when (fixed) references are absent [98], while other research showed about a factor 2 for a 16s exposure to the stimulus and no consistent change of the threshold for exposures of 0.25s [92]. The luminance level also influences the threshold for perception of motion [92, 90 §5.207].

Another thing to keep in mind is that too fast motion will result in motion blur. This will happen at subtended angular speeds of more than 12∼32°/s [95]. Only for angular speeds approaching 200°/s however, will the visual information be totally useless [96].

Wewerinke [85] (alt. [44]) specifically looked at motion perception thresholds relating to the runway visual scene. He found a threshold of 6∼18arcmin/s for a line moving with respect to a parallel reference line.

4.2.2. Foveal Threshold for Rotation

Although Gurney and Wright [39] say their research mainly focuses on 'peripheral vision' thresholds (only one figure shows results for central vision), this is only 6.5 degrees from the center of the display, and would certainly match with the situation of the apparent runway sideline rotation during landing. However, the experiments present the subjects with a rotating optical flow (like what the pilot would see in a roll motion[6]). The threshold found in these experiments was about 0.04°/s.

For rotation of a single line much higher thresholds have been found[85] (alt. [44]) and generally 2.5°/s is adopted as threshold[75, 99][7].

4.2.3. Peripheral Motion Thresholds

McColgin [100] performed experiments to find motion thresholds for peripheral vision using standard altimeter-like instruments. He found that for peripheral vision angles ranging from about 20∼80° horizontally, the threshold for rotation speed ranged from 2∼8rpm (=$12 \sim 48^\circ/s$), while the thresholds for linear motion ranged from 2∼14 strokes/min (=4∼27arcmin/s subtended). Contour plots were depressed by about a factor 2 for the vertical peripheral direction. Link and Vallerie [101] performed a similar study, but focused on the differential thresholds (i.e., the threshold for detecting changes in the rate of motion). Although the results of these studies may be very important for designing cockpit displays, it should be noted that this laboratory approach tests for rotational cues very different from the optical flow induced rotations experienced when observing the outside scene during landing.

In experiments with a flows of moving dots (which is closer related to the optical flow perception as happens in the periphery) Tynan and Sekuler [93] found thresholds of 8 arcmin/s at 15 degrees off-center, to 13 and 25 arcmin/s at 22.5 degrees and 30 degrees into the periphery respectively (0.13, 0.22 and 0.42°/s).

4.2.4. Just Noticeable Differences

The amout a cue has to be different from a reference value to be perceived as actually being different is called the 'just noticible difference' (JND). There are various cues we want to keep stationary during an approach and landing and there are some cues that may trigger an action once they reach a certain reference value. The JND is therefore interesting to know whether differences in a cue could be distinguished with enough accuracy to reach the displayed accuracy in control.

JND of heading from optical flow (e.g., for keeping heading-point at the aimpoint/touchdown markers). The accuracy with which the center of expansion of the optical flow —and thus the heading— can be determined is about 1° [34, 40, 46, 102–104], which is quite a lot considering the fact that the glide slope the pilot is to maintain is only 3°. The contribution of Warren et al. [103] includes a large overview of previous research on this issue and they found the lowest value (0.66° in the best case) while noting that *"richer environments, including nonplanar or shaded surfaces with expanding features, are likely to yield even better performance"*. They attribute the lower value to the fact that they used a discrimination task (as [34, 46, 102]), rather than a pointing task (as did Johnston et al. [45] who found accuracies of 5∼10°). It may well be that such a discrimination task is closer to the reality of vehicular control.

JND of (retinal) distance (e.g., for keeping the proper H-distance). Subjects could set two parallel lines to a distance equal to one presented 10s before with an accuracy of 0.5° subtended visual angle [85]. Slightly lower values (6∼20arcmin) are mentioned for instantaneous changes [97 p.673].

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[6] rotating around the aircraft's longitudinal axis.

[7] Naish [75] mentions "Rotation due to vertical motion is only observable below a height of about 120ft [...]". 120ft [=37m] altitude, with a typical descend rate of 3.5 m/s at a 60m wide runway would result in a rotation of the side line (w.r.t. the image vertical) with 2.5°/s.

JND of (retinal) speed Differences in speed of about 10∼25% are perceivable, depending on the speed [96, 105]. It should be kept in mind that this experimental value holds for (more or less) instantaneous changes; matching a perceived speed with a mental reference may have higher inaccuracies.

JND of angles (e.g., for relating runway side line angle to a specific altitude). Experiments have shown that angles can be set equal to a reference presented 10s before with an accuracy of 5° [85].

4.2.5. Perception Induced Time Delay

Once a visual cue is above threshold, it takes some time to actually perceive the cue and base actions on it. Sensori-motor time delays of 0.15∼0.45s are generally mentioned for simple tasks[44, 85, 106–108,109 p.48] (150-200ms until first perception, then 150-250ms until action [106]) while decision making tasks will require the integration of cues and are thought to take at least some 3∼4s [110 p.212, 52 Vol.1 §15.2]. It should however be mentioned that time delays are variable and depend not only on the task, but also on the pilot's instantaneous attention, commitment, and muscle tension [111]. These time delays should of course be considered in modeling, but also in the selection of appropriate cues, as cues should be above threshold at the onset of perception, rather than at the onset of the corresponding action.

4.3. Illusions

Practically every visual cue is susceptible to illusions. For instance the "barber pole"[8] [112] is a good example of an illusion where the optical flow is not corresponding with the actual direction of motion. The "Ames room" [113 p183–189] plays perceptual tricks with linear perspective and the in the "hollow face illusion" the brain interprets a concave mask of a face as a convex one, thereby (partly) ignoring binocular depth cues [114, 115].

Recently, several general publications regarding visual illusions in aircraft landing have resulted from the Flight Safety Foundation's Approach-and-Landing Accident Reduction (ALAR) Task Force [116–119]. Although the level of detail and background information and the illustrations differ, all publications are more or less similar and shortly describe the main illusions pilots should be aware of and include some advice to decrease the crew's vulnerability. However, these documents are purely intended for pilots and do not offer a scientific approach to the perceptual problems.

4.3.1. Runway Width Illusion

Many have warned pilots for the "runway width illusion" which may appear when landing on a narrower (wider) runway than the pilot is used to [28, 81, 83, 117, 118, 120–122, 52 Vol.1§15.2.1]. In such a case, the pilot is likely to fly a lower (higher) approach as he developped a mental model where altitude is coupled to the apparent width of the 'normal' runway.

Several researchers have actually investigated this effect. Both Lintern and Walker [123] and Mertens and Lewis [81] found pilots highly susceptible to this illusion in dynamic simulations, even when pilots were informed of the actual runway width before the experiments [81]. Reynolds [120] on the other hand found that pilots did not suffer the illusion in dynamic experiments, although they did when they had to make altitude estimates based on a static scene. Non-pilot participants suffered the illusion in both the static and dynamic experiments. Galanis et al. [121] performed a theoretical study, showing that the apparent runway width is indeed an important cue for maintaining a proper glide path, meaning that the runway width illusion is likely to have dramatic consequences.

4.3.2. Sloping Runway/Terrain Illusion

Another well known illusion is the "sloping runway illusion" or "sloping terrain illusion" [28, 42, 83, 117, 118, 122, 124–126].

When the runway is up (down) sloping, the pilot should follow a shallower (steeper) approach path. However, if the pilot is not aware of the slope, he will interpret the different runway perspective cues as flying at too high (low) altitude and — if maintaining the same glide path — will land/crash short of the runway (overshoot the runway).

If the terrain in front of the runway is up (down) sloping, the pilot may have the impression that his approach altitude is too high (low). In this case not the perspective cues of the runway, but properly perceived altitude cues of the terrain directly below him (e.g., familiar size) confuse the pilot.

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[8] The barber pole is a vertical cylinder with a spiral painted on it. When the cylinder spins around its axis, it creates a vertical optical flow. This effect is related to the "aperture problem".

The NTSB Accident Database reveals only a few accidents where the sloping runway illusion may have played a role [127]. Kraft [124, 125] did some experiments verifying that pilots indeed fly lower approaches over an up sloping city (the simulated night approaches include some “black hole illusion” effects, see §4.3.4). One reason —besides the fact that the shape of the runway changes— for the different approaches over sloping terrain may be that it creates a false horizon [78] which would especially be important if insufficient other cues are present to derive the real horizon.

4.3.3. (Un)familiar Size Illusion

The “(un)familiar size illusion” occurs when a pilot estimates his altitude or distance based on the apparent size of ‘familiar objects’ which in reality have a different size than the ones the pilot is familiar with [83, 52 Vol.2 §3.6.2.1]. For example, a pilot who is used to landing on an airport surrounded tall trees, may greatly overestimate his altitude when approaching an airport surrounded by small bushes.

In some sense this illusion is similar to the runway width illusion (§4.3.1), however, where the runway width illusion may also originate in the different apparent angle of the runway side lines, the (un)familiar size illusion is purely based on the relative-size-of-things-cue.

4.3.4. Black Hole Illusion

The ”black hole illusion” is a term for spatial disorientation during night approaches, mostly due to limited optical flow and familiar size cues and the absence of horizon information [28, 42, 117, 118, 124, 126, 128–132, 52 Vol.1§17.3.2]. In effect the black hole illusion is similar to the atmospheric “whiteout” condition, where the horizon and ground texture are obscured by snow or fog, or (less severe) where snow covers the landscape and conceals any ground texture.

Gibb [131] offers an extensive review of the problem, including references to accidents where this illusion is thought to have played a role. The paper also mentions 9 possible reasons for misperception of altitude and distance resulting from this illusion, most of which would be resolved if sufficient ground texture would be available to calibrate the apparent runway dimensions with the “familiar size” cues and to have a clear ground plane (or horizon) as reference.

Experiments have confirmed that pilots have trouble with orientation in black hole conditions and that they generally fly (dangerously) low approaches [124, 128–130].

4.3.5. False Horizon Illusion

False horizons often appear, for example when distant mountains obscure the true horizon, or when a shoreline is more or less parallel to the true horizon (in case of approach toward the sea, the sea and sky may blend through haze). Generally this is no problem, as the pilot can derive an horizon from apparently converging parallel ground lines and texture gradients. In nigh situations however, the edge formed by the most distance city lights may form a false horizon, and due to the lack of other cues, this may remain unnoticed [83, 117, 52 Vol.1§17.3.2].

4.3.6. Atmospheric Illusions

Unusual atmospheric conditions can cause several illusions [28, 83, 117, 118, 132]. An example is that brighter runway lights or clearer (unpolluted) air than usual give the illusion that the airport is very near. Water Refraction (rain on windshields) can also cause runway lights to look dimmer (day time) or sharper (night time), and thus influence the perceived distance to the runway. Water refraction can additionally give the perception of being too high.

Entering a fog layer can create the illusion of pitching up. When the pilot does not recognize this illusion, he will suddenly steepen the approach. The ’whiteout condition’ has already been discussed with the black hole illusion (§4.3.4) because of the strong similarities.

4.4. Cues Appropriate for Glide Phase

It is suggested that pilots perform control actions on two hierarchical levels [43, 44, 84, 133–135]. The high frequency inner loop control is to maintain a certain pitch attitude [43] using the horizon height cue [44, 84, 136]. The outer loop (supervisory) control is to adjust the nominal pitch when a deviation from the glide path is recognised. Especially the visual cues that form the input for this outer loop control are interesting and are focused on in this paper.

- **H-distance** is probably the main cue for keeping the glide slope. It is directly related to the glide slope and would allow the pilot to control it with 0.5° accuracy. Also the predictable effects (illusions) of sloping terrain and sloping runways have been shown to arise from this cue [78]. Some suggest that the distance (i.e., subtended angle) between the near runway end and 'visible horizon' is used, because in general the true horizon is blurred much and a visual horizon exists slightly lower [75].
- **Focus of expansion** is likely to be used in combination with the H-distance. Although it is reportedly of slightly less accuracy, some imply that seeing this cue should be trained [28], leading to the belief that trained pilots may achieve better heading estimations than general subjects in the laboratory experiments presented. Illusions due to the loss of optical flow, such as the black hole illusion, and the positive effects of ground textures in simulation tasks confirm this.
- **Horizon height** and to a lesser degree the **field of view** are important for the inner loop (pitch) control as peripheral vision and a horizon reference would be important for attitude information. Additionally, optical flow in the periphery could provide information about groundspeed and altitude (the flow speed increases at lower altitudes).
- **Familiar size** is often mentioned by pilots, and could provide a rough cue to altitude and distance during the glide. The use of the cue is supported by the vulnerability of pilots to illusions resulting from unfamiliarly sized objects, sloping terrain or the absence of ground texture. It is however a cue of lower relative importance than the H-distance and the focus of expansion. The same holds for related cues as **runway size** and **runway visual angle (apparent width)**.
- **Runway shape (perspective)** cues such as **Runway sideline angle (θ)**, **Apparent runway height** and **runway form (height-width)** change only little over most of the glide phase. However, they may also be used for noticing large errors in the approach path, especially in the final part of the glide, as these cues will grow more sensitive to glide path changes.

4.5. Cues Appropriate for Flare Phase

Not much research has been done to identify flare control. One reason my be that it is proactive, rather than nulling or tracking feedback control which are easier to capture in models. Another reason may be that it is so short that it has long been difficult to get sufficient data due to the low sampling rates of sensors[137].

Another striking thing is that there are two very different instructions on where a pilot should focus during the flare. One advises the far runway end [43, 73, 122] while the other advocates looking down 10$\sim$15° and observe the movement of the point where the line of sight intercepts the runway [4, 88]. The latter method relies on the fact that this point will move forward when gaining altitude (meaning a too strong pitch up, and a ballooning flare), and slowly toward the pilot in the case of a proper flare.

Looking at the far runway end would help to adjust the aim point (focus of expansion) and thus level off the plane. At the same time it gives a wider overview of the complete visual scene, where cues as the (movement of the) runway sideline angle and optical flow in the visual periphery may contribute.

- **Runway side line angle** (θ) is likely to be used for altitude and the **change of the runway side line angle ($\mathbf{d}\theta/\mathbf{d}t$)** for sink rate as well.
- **Focus of expansion** is likely to be used when the pilot is watching the far runway end. He can smoothly pull the control stick and increase pitch attitude to adjust the focus of expansion toward the far runway end.
- **Field of view** is important for sufficient optical flow cues to attitude, sink rate, and heading.
- **Horizon height** could be a cue if the pilot is using fixed pitch-rate control or has a specific pitch angle as objective.
- **Time to contact** τ might be used as a cue, but it remains the question through which optical variable it is perceived. The appearance of τ as a guide for flare control [66] might as well be a result of 'natural', smooth control based on some other cue or objective[67].
- **Familiar size** is not likely to be used, because any reference objects for altitude are so close by that they are blurred due to motion. At the same time, horizontal distance is of little meaning during the flare as the main objective is to touch down soon, but softly.
- **H-distance** can not be used because generally the aimpoint markers are out of sight. Additionally, a internal reference of how this distance should change would be needed, rather than a fixed reference distance.

- **Apparent runway height**, **runway visual angle (apparent width)**, **near runway end**, **runway start width**, etcetera cannot be used, because the cues are not visible to the pilot anymore.

4.6. Visual Perception for Flare Timing

It is generally agreed on that the main variables in deciding on the flare initiation are altitude and sink rate. Sometimes the longitudinal position plays a minor role, especially when there is a significant risk of landing short or overshooting the landing point.

One combination of these is the altitude tau (see eq.1), although it is sometimes stated differently. For instance *"Ten percent of the vertical velocity in feet [per minute] is a good estimate for the level-off lead point."* [52 Vol.1, §2.4.5] and "$h_{\text{flare}} = -6\dot{h}$"[9] [138] represent exactly the same 'flare initiation at constant τ' rule. The only vision based tau cue reported in literature was based on the (change of) apparent runway width.

- **runway angle** could be an important cue to altitude. This matches with the reported runway width illusion.
- **Time to contact** (τ) has been reported by several researchers, but generally in combination with sink rate. As the sink rate is included in the TTC as well, it is more likely that not perceived τ but another combination of perceived altitude and perceived sink rate is used.
- **Runway angle change** (maybe also from peripheral motion) has been put forward by the author recently [74, 87] and is still being investigated as a possible cue in ongoing research. It can be shown that even for large jet aircraft the apparent rotation of the side lines is above threshold several seconds before the flare should be initiated.

5. Conclusion

Manual landing control of human pilots is mainly guided by visual inputs. Modeling therefore starts with the selection of visual inputs that could realistically be used by the pilot to control the aircraft. This paper focused on the two main phases of the visual approach to landing —the glide and the flare— and the timing of the flare initiation. Several visual cues and pilot models put forward in literature have been reviewed and related to the specifics of the landing task by analyzing their thresholds and their connection with well known visual illusions.

Although many factors play a role, it can be concluded from this investigation that the H-distance together with the focus of expansion is the main cue during the glide. Flare initiation timing is clearly based on altitude and sink rate cues, but how these are visually perceived has not irrefutably been determined yet. Little research regarding the control during the flare phase was found, and disagreements even exist about the area the pilot should give his visual attention to.

Although optical flow and the importance of a wide field of view to perceive the flow with peripheral vision have been mentioned often, no clear research quantifying flow or classifying flow cues (patterns) was found for aircraft landing. This could be an interesting direction for future research.

Models of aircraft landing control by human pilots could give insight in perception and thinking processes of pilots and could therefore help in transferring knowledge form veterans to student pilots. It could also shed a new light op perceptual illusions, or how we can recognise them early and find alternative visual cues. Also in simulator design and in the design of augmented reality displays, knowledge of visual scene processing can help to increase effectiveness, while limiting computational or resolution requirements.

References

[1] K. Wien. "Plane Answers: When Do Pilots Use the Autopilot?". Online, May 2008. URL `http://www.gadling.com/2008/05/02/plane-answers-when-do-pilots-use-the-autopilot/`.

[2] J.W. Rustenburg, D.O. Tipps, and D. Skinn. "A Comparison of Landing Parameters from Manual and Automatic Landings of Airbus A-320 Aircraft". Technical Report UDR-TM-2001-00003, FAA, Nov. 2001.

[3] P. Kasarskis, J. Stehwien, J. Hickox, A. Aretz, and C. Wickens. "Comparison of Expert and Novice Scan Behaviors During VFR Flight". In *Proceedings of the 11th International Symposium on Aviation Psychology*, Columbus, OH, 2001. The Ohio State University.

[4] A.H. Hasbrook. "Anatomy of a Landing: Cue by Cue". *Business and Commercial Aviation*, vol. 29, pp. 54–60, Aug. 1971.

[5] A.A. Spady, Jr and R.L. Harris, Sr. "How a Pilot Looks at Altitude". In J.W. Stickle (Eds.), *The 1980 Aircraft Safety and Operating Problems Conference, part 1*, pp. 237–248. NASA Langley Research Center, Mar. 1981. #L-14254; NASA-CP-2170-PT-1.

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[9] with h and $\dot{h}$ altitude and rate of climb in similar units, e.g., m resp. m/s or ft resp. ft/s

[6] N. Moray. “Monitoring Behavior and Supervisory Control”. In K.R. Boff, L. Kaufman, and J.P. Thomas (Ed.), *Handbook of perception and human performance*, vol. II - Cognitive processes and performance, ch. 40. Wiley, 1986. ISBN 0-471-82956-0.

[7] D. Benbassat and C.I. Abramson. “Landing Flare Accident Reports and Pilot Perception Analysis”. *The International Journal of Aviation Psychology*, vol. 12, no. 2, pp. 137–152, 2002.

[8] S. Palmisano, S. Favelle, G. Prowse, R. Wadwell, and B. Sachtler. “Investigation of Visual Flight Cues for Timing the Initiation of the Landing Flare”. Technical Report #B2005/02121, Australian Transport Safety Bureau, Jun. 2006.

[9] P.A. Craig, J.E. Bertrand, W. Dornan, S. Gossett, and K.K. Thorsby. “Ab Initio Training in the Glass Cockpit Era: New Technology Meets New Pilolts. a Preliminary Descriptive Analysis”. In *13th International Symposium on Aviation Psychology*, 2005.

[10] D.A. Gordon. “Perceptual Basis of Vehicular Guidance”. *Public Roads*, vol. 34, no. 3, pp. 53–68, 1966.

[11] A. Kemeny and F. Panerai. “Evaluating Perception in Driving Simulation Experiments”. *Trends in Cognitive Sciences*, vol. 7, no. 1, pp. 31–37, Jan. 2003.

[12] N.L. Biggs. “Directionaal Guidance of Motor Vehicles – A Preliminary Survey and Analysis”. *Ergonomics*, vol. 9, no. 3, pp. 193–202, 1966. ISSN 0721-832X.

[13] D.N. Lee. “A Theory of Visual Control of Braking Based on Information About Time-To-Collision”. *Perception*, vol. 5, pp. 437–459, 1976.

[14] D. Crundall, D. Clarke, P. Ward, and C. Bartle. “Car Drivers’ Skills and Attitudes to Motorcycle Safety: A Review”. Technical Report Road Safety Research Report No. 85, Department for Transport, London, UK, May 2008.

[15] E.R. Hoffmann and R.G. Mortimer. “Drivers’ Estimates of Time to Collision”. *Accident Analysis and Prevention*, vol. 26, no. 4, pp. 511–520, 1994.

[16] E.R. Hoffmann. “Human Control of Road Vehicles”. *Vehicle System Dynamics*, vol. 5, pp. 105–126, 1975/76.

[17] P.H. Wewerinke. “Modeling Human Learning Involved in Car Driving”. In *IEEE International Conference on Systems, Man, and Cybernetics – Humans, Information and Technology*, vol. 2, pp. 1968–1973. IEEE, Oct. 1994. ISBN 0-7803-2129-4. URL `http://doc.utwente.nl/58970/`.

[18] S.E. Palmer. *Vision Science – Photons to Phenomenology*. MIT Press, Cambridge, MA, 1999. ISBN 0-262-16183-4. [Ch. 5].

[19] J.E. Cutting and P.M. Vishton. “Perceiving Layout and Knowing Distances: The Integration, Relative Potency, and Contextual Use of Different Information About Depth”. In W. Epstein and S.J. Rogers (Ed.), *Perception of Space and Motion*, Handbook of Perception and Cognition, ch. 3, pp. 69–117. Academic Press, 2nd edition, 1995. ISBN 0-12-240530-7.

[20] J.E. Cutting. “How the Eye Measures Reality and Virtual Reality”. *Behavior Research Methods, Instruments, & Computers*, vol. 29, no. 1, pp. 27–36, 1997.

[21] K.N. Ogle. “Perception of Distance and of Size”. In H. Davson (Eds.), *Visual optics and the Optical Space Sense*, vol. 4 of *The Eye*, ch. 14, pp. 247–269. Academic Press, 1962.

[22] J.O. Entzinger. “The Role of Binocular Cues in Human Pilot Landing Control”. In *Proceedings of AIAC13*. The Thirteenth Australian International Aerospace Congress, Mar. 2009. URL `http://jorg.entzinger.nl/`. Paper #480.

[23] G.D. Edwards and J.L. Harris, Sr. “Analysis of Visual Stimulus in Aircraft Approach to Landing Operations”. Final Report SIO Ref.74-8, Scripps Institution of Oceanography, Visibility Laboratory, San Diego, Apr. 1974.

[24] S.K. Advani, J.C. van der Vaart, R.Th. Rysdyk, and J. Grosz. “What Optical Cues Do Pilots Use to Initiate the Landing Flare? Results of a Piloted Simulator Experiment”. In *AIAA Guidance, Navigation, and Control Conference and Exhibit*, 1993. #AIAA-93-3561-CP.

[25] M. Mulder, J.M. Pleijsant, J.C. van der Vaart, and P.C.W. van Wieringen. “The Effects of Pictorial Detail on the Timing of the Landing Flare: Results of a Visual Simulation Experiment”. *The International Journal of Aviation Psychology*, vol. 10, no. 3, pp. 291–315, 2000.

[26] J.P. Bittner. “The Use of Texture in Improving the Simulation of Low-Level Flight”. Master’s thesis, Graduate Department of Applied Science and Engineering, University of Toronto, Canada, 1997.

[27] J.J. Koenderink and A.J. van Doorn. “Invariant Properties of the Motion Parallax Field due to the Movement of Rigid Bodies Relative to an Observer”. *Optica Acta [Journal of Modern Optics]*, vol. 22, no. 9, pp. 773–791, 1975.

[28] A.H. Hasbrook. “The Approach and Landing: Cues and Clues to a Safe Touchdown”. *Business and Commercial Aviation*, vol. 37, no. 5, pp. 39–43, Nov. 1975.

[29] W. Langewiesche. *Stick and Rudder: An Explanation of the Art of Flying*. McGraw-Hill, 1990. ISBN 0070362408. URL `http://books.google.com/books?id=zlaqYZYJZwQC`. [Ch. 16 on landing].

[30] J.J. Gibson. *The perception of the visual world*. Houghton Mifflin, Boston, 1950.

[31] J.J. Gibson. “The Optical Expansion-Pattern in Aerial Locomotion”. *The American Journal of Psychology*, vol. 68, no. 3, pp. 480–484, Sep. 1955.

[32] J.J. Gibson, P. Olum, and F. Rosenblatt. “Parallax and Perspective During Aircraft Landings”. *The American Journal of Psychology*, vol. 68, no. 3, pp. 372–385, Sep. 1955.

[33] J.J. Gibson. *The ecological approach to visual perception*. Houghton Mifflin, Boston, 1979.

[34] K.L. Macuga, J.M. Loomis, A.C. Beall, and J.W. Kelly. “Perception of Heading Without Retinal Optic Flow”. *Perception & Psychophysics*, vol. 68, no. 5, pp. 872–878, 2006.

[35] W.F. Clocksin. “Perception of Surface Slant and Edge Labels from Optical Flow: A Computational Approach”. *Perception*, vol. 9, no. 3, pp. 253–269, 1980.

[36] W.H. Warren, Jr. “Self-Motion: Visual Perception and Visual Control”. In W. Epstein and S.J. Rogers (Ed.), *Perception of Space and Motion*, Handbook of Perception and Cognition, ch. 8, pp. 263–325. Academic Press, 2nd edition, 1995. ISBN 0-12-240530-7.

[37] B.K.P. Horn and B.G. Schunck. “Determining Optical Flow”. In M. Brady and H.G. Barrow (Ed.), *Computer Vision*, pp. 185–203. Kluwer, 1981. ISBN 0444875115, 9780444875112. [Reprinted from the journal Artificial intelligence, vol. 17, August 1981].

[38] S. Grossberg, E. Mingolla, and C. Pack. “A Neural Model of Motion Processing and Visual Navigation by Cortical Area MST”. *Cerebral Cortex*, vol. 9, no. 8, pp. 878–895, Dec. 1999.

[39] K. Gurney and M.J. Wright. “Rotation and Radial Motion Thresholds Support a Two-Stage Model of Differential-Motion Analysis”. *Perception*, vol. 25, no. 1, pp. 5–26, 1996.

[40] N.G. Hatsopoulos and W.H. Warren, Jr. “Visual Navigation with a Neural Network”. *Neural Networks*, vol. 4, no. 3, pp. 303–317, 1991.

[41] J.M. Flach and R. Warren. “Low-Altitude Flight”. In P.A. Hancock, J.M. Flach, J. Caird, and K.J. Vicente (Ed.), *Local applications of the ecological approach to human-machine systems*, vol. 2 of *Resources for Ecological Psychology*, ch. 3, pp. 65–103. Lawrence Erlbaum Associates, Hillsdale, NJ, 1995. ISBN 0805813802.

[42] E.S. Calvert. “Visual Judgments in Motion”. *Journal of the Institute of Navigation*, vol. 7, pp. 233–251, 1954.

[43] *B767 Training Manual*. All Nippon Airways (ANA), 10th edition, Jul. 2006. [English version].

[44] P.H. Wewerinke. “A Theoretical and Experimental Analysis of the Outside World Perception Process”. In *14th Annual Conference on Manual Control*, pp. 535–555. NASA, 1978. #N79-15625.

[45] I.R. Johnston, G.R. White, and R.W. Cumming. “The Role of Optical Expansion Patterns in Locomotor Control”. *The American Journal of Psychology*, vol. 86, no. 2, pp. 311–324, 1973.

[46] S. Palmisano and B. Gillam. “Visual Perception of Touchdown Point During Simulated Landing”. *Journal of Experimental Psychology: Applied*, vol. 11, no. 1, pp. 19–32, 2005.

[47] D.C. Burr, M.C. Morrone, and L.M. Vaina. “Large Receptive Fields for Optic Flow Detection in Humans”. *Vision Research*, vol. 38, no. 12, pp. 1731–1743, Dec. 1998.

[48] P. Pretto, M. Ogier, H.H. Bülthoff, and J.P. Bresciani. “Influence of the Size of the Field of View on Motion Perception”. *Computers & Graphics*, vol. 33, no. 2, pp. 139–146, Apr. 2009.

[49] B. Amblard and A. Carblanc. “Role of Foveal and Peripheral Visual Information in Maintenance of Postural Equilibrium in Man”. *Perceptual and Motor Skills*, vol. 51, no. 3, pp. 903–912, 1980.

[50] S.N. Roscoe. “The Effects of Eliminating Binocular and Peripheral Monocular Visual Cues upon Airplane Pilot Performance in Landing”. *The Journal of Applied Psychology*, vol. 32, no. 6, pp. 649–662, Dec. 1948.

[51] V. Cavallo and M. Laurent. “Visual Information and Skill Level in Time-To-Collision Estimation”. *Perception*, vol. 17, no. 5, pp. 623–632, 1988.

[52] *Air Force Manual 11-217 (Flying Operations – Instrument Flight Procedures)*. USA Department of the Air Force, Jan. 2005. URL `http://www.e-publishing.af.mil/`. [Formerly AFM 51-37 and AFM 11-212].

[53] D. Regan, K. Beverley, and M. Cynader. “The Visual Perception of Motion in Depth”. *Scientific American*, vol. 241, no. 1, pp. 136–151, 1979.

[54] B. Rokers, L.K. Cormack, and A.C. Huk. “Strong Percepts of Motion Through Depth Without Strong Percepts of Position in Depth”. *Journal of Vision*, vol. 8, no. 4, pp. 6, 1–10, 2008. URL `http://journalofvision.org/8/4/6/`.

[55] M.J. Morgan and E. Castet. “Stereoscopic Depth Perception at High Velocities”. *Nature*, vol. 378, no. 6555, pp. 380–383, 1995. ISSN 0028-0836.

[56] D.N. Lee. “Visual Information During Locomotion”. In R.B. MacLeod and H.L. Pick, Jr (Ed.), *Perception: Essays in Honor of James J. Gibson*, ch. 14, pp. 250–267. Cornell University Press, Ithaca and London, 1974. ISBN 0801408350.

[57] D.N. Lee. “How Movement Is Guided”. [online], 2006. URL `http://www.perception-in-action.ed.ac.uk/publications.htm`.

[58] E.R. Hoffmann. “Estimation of Time to Vehicle Arrival-Effects of Age on Use of Available Visual Information”. *Perception*, vol. 23, no. 8, pp. 947–955, 1994.

[59] J.R. Tresilian. “Visually Timed Action: Time-out for ’tau’?”. *Trends in Cognitive Sciences*, vol. 3, no. 8, pp. 301–310, Aug. 1999.

[60] J.B.J. Smeets, E. Brenner, S. Trébuchet, and D.R. Mestre. “Is Judging Time-to-Contact Based on ’tau’?”. *Perception*, vol. 25, no. 5, pp. 583–590, 1996.

[61] D. Regan, S.J. Hamstra, S. Kaushal, A. Vincent, R. Gray, and K.I. Beverley. “Visual Processing of the Motion of an Object in Three Dimensions for a Stationary or a Moving Observer”. *Perception*, vol. 24, no. 1, pp. 87–103, 1995.

[62] R. Gray and D. Regan. “Accuracy of Estimating Time to Collision Using Binocular and Monocular Information”. *Vision Research*, vol. 38, no. 4, pp. 499–512, 1998.

[63] D.N. Lee, F.R. van der Weel, T. Hitchcock, E. Matejowsky, and J.D. Pettigrew. “Common Principle of Guidance by Echolocation and Vision”. *Journal of Comparative Physiology. A, Sensory, Neural, and Behavioral Physiology*, vol. 171, no. 5, pp. 563–571, Sep. 1992.

[64] G.J.P. Savelsberg, H.T.A. Whiting, and R.J. Bootsma. “Grasping Tau”. *Journal of Experimental Psychology: Human Perception and Performance*, vol. 17, no. 2, pp. 315–322, 1991.

[65] M. Jump and G.D. Padfield. “Progress in the Development of Guidance Strategies for the Landing Flare Manoeuvre Using Tau Based Parameters”. *Aircraft Engineering and Aerospace Technology*, vol. 78, no. 1, pp. 4–12, 2006.

[66] M. Jump and G.D. Padfield. “Tau Flare or Not Tau Flare: That Is the Question: Developing Guidelines for an Approach and Landing Sky Guide”. In *AIAA Guidance, Control and Navigation Conference*, San Fransisco, 2005. #AIAA-2005-6404.

[67] A.M. Brouwer, E. Brenner, and J.B.J. Smeets. “When Is Behavioral Data Evidence for a Control Theory? Tau-Coupling Revisited”. *Motor Control*, vol. 7, no. 2, pp. 103–110, Mar. 2003.

[68] G.D. Padfield, G. Clark, and A. Taghizard. “How Long Do Pilots Look Forward? Prospective Visual Guidance in Terrain Hugging Flight, Florence, Italy”. In *31st European Rotorcraft Forum*, Sep. 2005.

[69] G.D. Padfield, D.N. Lee, and R. Bradley. “How Do Helicopter Pilots Know When to Stop, Turn or Pull Up? (Developing Guidelines for Vision Aids)”. *Journal of the American Helicopter Society*, vol. 48, no. 2, pp. 108–119, 2003.

[70] J. Grosz, R.Th. Rysdyk, R.J. Bootsma, J.A. Mulder, J.C. van der Vaart, and P.C.W. van Wieringen. “Perceptual Support for Timing of the Flare in the Landing of an Aircraft”. In P.A. Hancock, J.M. Flach, J. Caird, and K.J. Vicente (Ed.), *Local*

applications of the ecological approach to human-machine systems, vol. 2 of *Resources for Ecological Psychology*, ch. 4, pp. 104–121. Lawrence Erlbaum Associates, Hillsdale, NJ, 1995. ISBN 0-8058-1380-2.

[71] G. Prowse, S. Palmisano, and S. Favelle. "Time-to-Contact Perception During Simulated Night Landing". *The International Journal of Aviation Psychology*, vol. 18, no. 2, pp. 207–223, 2008.

[72] J.M. Pleijsant, M. Mulder, J.C. van der Vaart, and P.C.W. van Wieringen. "How Do Pilots Perceive Time-to-Contact from the Ground Surface? Results of a Visual Simulation Experiment". In *Conference on human decision making and manual control, Soesterberg, June 10-12, 1996*. Delft University of Technology, 1996. ISBN 90-370-0152-1. URL `http://www.library.tudelft.nl/ws/search/publications/search/metadata/index.htm?docname=382359`.

[73] *B767 Training Manual (Basic information)*. All Nippon Airways (ANA), Sep. 1999. 12-5-(1) – 12-5-(5) [slides in Japanese].

[74] J.O. Entzinger. "Modeling of the Visual Approach to Landing Using Neural Networks and Fuzzy Supervisory Control". In I. Grant (Eds.), *CD Proceedings of the 26th International Congress of the Aeronautical Sciences (ICAS2008), Anchorage, Alaska, USA*, Edinburgh, UK, Sep. 2008. Optimage Ltd. URL `http://jorg.entzinger.nl/`. Paper #440.

[75] J.M. Naish. "Control Information in Visual Flight". In *Seventh Annual Conference on Manual Control*, pp. 167–176, 1972. NASA SP-281.

[76] G. Galanis, A. Jennings, and P. Beckett. "Towards a General Model of Perception for Simulation". In *SimTecT 97 Canberra*, pp. 21–26, Mar. 1997.

[77] G. Galanis, A. Jennings, and P. Beckett. "Glide-Path Control Information from Runway Shape". In *SimTecT 96 Melbourne*, pp. 377–382, Feb. 1996.

[78] G. Lintern and Y.T. Liu. "Explicit and Implicit Horizons for Simulated Landing Approaches". *Human Factors*, vol. 33, no. 4, pp. 401–417, 1991.

[79] J.A. Perrone. "Slant Underestimation: A Model Based on the Size of the Viewing Aperture". *Perception*, vol. 9, no. 3, pp. 285–302, 1980.

[80] R.H. Riordan. "Monocular Visual Cues and Space Perception During the Approach to Landing". *Aerospace Medicine*, vol. 45, no. 7, pp. 766–771, Jul. 1974.

[81] H.W. Mertens and M.F. Lewis. "Effect of Different Runway Size on Pilot Performance During Simulated Night Landing Approaches". Technical Report FAA-AM-81-6 / AD-A103190, FAA Civil Aeromedical Institute, Feb. 1981. URL `http://handle.dtic.mil/100.2/ADA103190`.

[82] D.K. Schmidt and A.B. Silk. "Modeling Human Perception and Estimation of Kinematic Responses During Aircraft Landing". In *AIAA Guidance, Navigation and Control Conference, Minneapolis, MN, Aug 15-17, 1988, Technical Papers. Part 2 (A88-50160 21-08)*, pp. 1117–1126, Washington, DC. American Institute of Aeronautics and Astronautics. #AIAA 1988-4186-CP.

[83] D. Watson. "Illusions During the Approach and Landing". online. URL `http://www.pilotfriend.com/aeromed/medical/app_landing.htm`.

[84] P.H. Wewerinke. "The Effect of Visual Information on the Manual Approach and Landing". TR 80055U, National Aerospace Laboratory NLR, Amsterdam, The Netherlands, May 1980.

[85] P.H. Wewerinke. "Visual Scene Perception Process Involved in the Manual Approach". TR 78130U, National Aerospace Laboratory NLR, Amsterdam, The Netherlands, 1978.

[86] K. Mizumoto, O. Fujiwara, and N. Utsuki. "Quality of Pilot Landing Performance and Visual Information About Altitude and Distance". *The reports of the JASDF Aeromedical Laboratory: Tokyo, Japan*, vol. 18, no. 2, pp. 71–82, 1977.

[87] J.O. Entzinger and S. Suzuki. "Visual Cues in Manual Landing of Airplanes". In *Proceedings of KSAS–JSASS Joint International Symposium on Aerospace Engineering*, pp. 388–395. The Korean Society for Aeronautical & Space Sciences, Nov. 2008. URL `http://jorg.entzinger.nl/`. Paper #C3-3.

[88] *Airplane Flying Handbook*. U.S. Department of Transportation, Federal Aviation Administration – Flight Standards Service, 2004. #FAA-H-8083-3A [Ch. 8 on landing].

[89] L.L. Vallerie. "Peripheral Vision Displays - Phase II Report". Technical report, NASA, Dec. 1968. URL `http://ntrs.nasa.gov/`. #BSD-68-643, #NASA-CR-1239.

[90] K.R. Boff and J.E. Lincoln (Ed.). *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson Air Force Base, Ohio, USA, 1988. URL `http://www.dtic.mil/dticasd/edc/TOC/EDCTOC.html`.

[91] H. Aubert. "Die Bewegungsempfindung". *Archiv für die Gesammte Physiologie des Menschen und der Thiere (Pflügers Archiv)*, vol. 39, pp. 347–370, Dec. 1886. [In German].

[92] H. Leibowitz. "Effect of Reference Lines on the Discrimination of Movement". *Journal of the Optical Society of America*, vol. 45, no. 10, pp. 829–830, Oct. 1955.

[93] P. Tynan and R. Sekuler. "Motion Processing in Peripheral Vision: Reaction Time and Perceived Velocity". *Vision Research*, vol. 22, no. 1, pp. 61–68, 1982.

[94] S. Anstis. "Motion Perception in the Frontal Plane: Sensory Aspects". In K.R. Boff, L. Kaufman, and J.P. Thomas (Ed.), *Handbook of perception and human performance*, vol. I – Sensory processes and perception, ch. 16. Wiley, 1986. ISBN 0-471-82956-0.

[95] K.N. Ogle. "Spatial Localization According to Direction". In H. Davson (Eds.), *Visual optics and the Optical Space Sense*, vol. 4 of *The Eye*, ch. 13, pp. 219–245. Academic Press, 1962.

[96] C.H. Graham. "Perception of Movement". In C.H. Graham (Eds.), *Vision and Visual perception*, ch. 20. Wiley, 1965.

[97] S. Duke-Elder (Eds.). *The Physiology of the Eye and of Vision*, vol. IV of *System of Ophthalmology*. Kimpton, London, 1968. ISBN 0853136262.

[98] H. Aubert. "Die Bewegungsempfindung – Zweite Mittheilung". *Archiv für die Gesammte Physiologie des Menschen und der Thiere (Pflügers Archiv)*, vol. 40, pp. 459–480, Dec. 1887. [In German].

[99] A.C. Beall. *Visual control of the base-to-final turn in fixed-wing aircraft*. PhD thesis, University of California, Santa Barbara, Mar. 1998.

[100] F.H. McColgin. "Movement Thresholds in Peripheral Vision". *Journal of the Optical Society of America*, vol. 50, no. 8, pp.

774–779, Aug. 1960.

[101] J.M. Link and L.L. Vallerie. “Differential Thresholds for Motion in the Periphery”. Technical report, NASA, Sep. 1969. URL `http://ntrs.nasa.gov/`. #BSD-69-701, #NASA-CR-1439.

[103] W.H. Warren, M.W. Morris, and M. Kalish. “Perception of Translational Heading from Optical Flow”. *Journal of Experimental Psychology: Human Perception and Performance*, vol. 14, no. 4, pp. 646–660, Nov. 1988.

[102] A.V. van den Berg. “Robustness of Perception of Heading from Optic Flow”. *Vision Research*, vol. 32, no. 7, pp. 1285–1296, Jul. 1992.

[104] W.H. Warren, Jr, B.A. Kay, W.D. Zosh, A.P. Duchon, and S. Sahuc. “Optic Flow Is Used to Control Human Walking”. *Nature Neuroscience*, vol. 4, no. 2, pp. 213–216, Feb. 2001.

[105] O.N.F. Mouton, M. Mulder, and M.M. van Paassen. “Thresholds for Visual Perception of Aircraft Velocity Changes”. In *Proceedings of the AIAA Modeling and Simulation Technologies Conference and Exhibit 18 – 21 August 2008, Honolulu, Hawaii*, 2008. #AIAA 2008-6844.

[106] K. Amano, N. Goda, S. Nishida, Y. Ejima, T. Takeda, and Y. Ohtani. “Estimation of the Timing of Human Visual Perception from Magnetoencephalography”. *Journal of Neuroscience*, vol. 26, no. 15, pp. 3981–3991, Apr. 2006.

[107] D.T. McRuer, L.G. Hofmann, H.R. Jex, G.P. Moore, A.V. Phatak, D.H. Weir, and J. Wolkovitch. “New Approaches to Human-Pilot/vehicle Dynamics Analysis”. Technical Report AFFDL-TR-67-150, Systems technology Inc. / Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, Feb. 1968.

[108] W.W. Johnson and A.V. Phatak. “Modeling the Pilot in Visually Controlled Flight”. *IEEE Control Systems Magazine*, vol. 10, no. 5, pp. 24–26, Aug. 1990.

[109] J.I. Elkind and D.C. Miller. “Adaptive Characteristics of the Human Controller of Time-Varying Systems”. Technical Report AFFDL TR 66-60 / AD-0665455, Wright-Patterson AFB Air Force Flight Dynamics Laboratory, 1967. URL `http://contrails.iit.edu/DigitalCollection/1966/AFFDLTR66-060.pdf`.

[110] J.W. Wulfeck, A. Weisz, and M.W. Raben. “Vision in Military Aviation”. Technical Report WADC TR 58-399, The Institute for Applied Experimental Psychology, TUFTS University, Wright-Patterson Air Force Base, Ohio, USA, Aug. 1997. URL `http://handle.dtic.mil/100.2/AD207780`. ASTIA DOC.NO. AD 207780.

[111] D.T. McRuer and H.R. Jex. “A Review of Quasi-Linear Pilot Models”. *IEEE Transactions on Human Factors in Electronics*, vol. HFE-8, no. 3, pp. 231–249, Sep. 1967.

[112] S. Wuerger, R. Shapley, and N. Rubin. ““on the Visually Perceived Direction of Motion” by Hans Wallach: 60 Years Later”. *Perception*, vol. 25, no. 11, pp. 1317–1367, 1996.

[113] W.H. Ittelson. *The Ames demonstrations in perception*. Hafner, New York, 1968. [together with “An interpretative manual” by Adelbert Ames].

[114] “Three Dragons (Dragon Illusion)”. Grand Illusions [Online]. URL `http://www.grand-illusions.com/opticalillusions/three_dragons/`. [Retrieved 2008/2009].

[115] B. Hartung, P.R. Schrater, H.H. Bulthoff, D. Kersten, and V.H. Franz. “Is Prior Knowledge of Object Geometry Used in Visually Guided Reaching?”. *Journal of Vision*, vol. 5, no. 6, pp. 504–514, 2005. URL `http://journalofvision.org/5/6/2/`.

[116] D. Newman. “Eyebal Error – Visual Illusions on Approach Can Have Deadly Consequences”. *Flight Safety Australia*, vol. 27, pp. 1043–1055, Sept./Oct. 2005. URL `www.casa.gov.au/fsa/2005/oct/27-32.pdf`.

[117] *Instrument Flying Handbook*. U.S. Department of Transportation, Federal Aviation Administration, 2007. URL `http://www.faa.gov/library/manuals/aviation/instrument_flying_handbook/`. #FAA-H-8083-15A [Ch. 1 on visual & optical illusions].

[118] “Airbus Flight Operations Briefing Notes: Human Performance: Visual Illusions Awareness”. Airbus Safety Library [online], Sep. 2005. URL `http://www.airbus.com/en/corporate/ethics/safety_lib/`. #FLT_OPSHUM_PERSEQ11REV02.

[119] F.S.F. approach-and-landing accident reduction (ALAR) task force. “Fsf Alar Briefing Note 5.3 – Visual Illusions”. *Flight Safety Digest*, pp. 103–109, Aug.–Nov. 2000. URL `http://www.flightsafety.org/alar_resources.html`.

[120] N.B. Reynolds. “An Investigation into Landing Approach Visual Illusions”. Master’s thesis, University of Waikato, New Zealand, 2007. URL `http://adt.waikato.ac.nz/public/adt-uow20070223.112316`.

[121] G. Galanis, A. Jennings, and P. Beckett. “Runway Width Effects in the Visual Approach to Landing”. *The International Journal of Aviation Psychology*, vol. 11, no. 3, pp. 281–301, 2001.

[122] D.M. Jacobson. “Where to Flare”. In *The 1987 Australian Aviation Symposium: 'Innovate or Enervate'; Preprints of Papers, National conference publication no. 87/16*, pp. 125–128. Institution of Engineers, Australia, 1987. ISBN 0858253577. URL `http://www.jacobsonflare.com/download.htm`. [rev. 1999, online].

[123] G. Lintern and M.B. Walker. “Scene Content and Runway Breadth Effects on Simulated Landing Approaches”. *The International Journal of Aviation Psychology*, vol. 1, no. 2, pp. 117–132, Apr. 1991.

[124] C.L. Kraft. “Measurement of Height and Distance Information Provided Pilots by the Extra-Cockpit Visual Scene”. In *Visual Factors in Transportation Systems: Proceedings of Spring Meeting, 1969*, pp. 84–101, Washington, D.C., 1969. Committee on Vision, National Academy of Sciences–National Research Council.

[125] C.L. Kraft. “A Psychophysical Contribution to Air Safety: Simulator Studies of Visual Illusions in Night Visual Approaches”. In H.L. Pick, Jr, H.W. Leibowitz, J.E. Singer, A. Steinschneider, and H.W. Stevensons (Ed.), *Psychology: From research to practice*, pp. 363–385. Plenum, New York, 1978. ISBN 0306311321.

[126] R. Khatwa and R.L. Helmreich. “Analysis of Critical Factors During Approach and Landing in Accidents and Normal Flight”. *Flight Safety Digest*, vol. 17–18, no. 11–2, pp. 1–256, 1998–1999.

[127] N.T.S. Board. “Aviation Accident Database & Synopses”. Online. URL `http://www.ntsb.gov/NTSB/Query.asp`. [Accident Numbers NYC00LA202,NYC03LA144, ATL00FA075, LAX86LA318, ATL88FA230 on sloping runway illusion].

[128] H.W. Mertens. “Comparison of the Visual Perception of a Runway Model in Pilots and Nonpilots During Simulated Night Landing Approaches”. Technical Report #FAA-AM-78-15 / #AD-A054450, FAA Civil Aeromedical Institute, Mar. 1978. URL `http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA054450`.

[129] H.W. Mertens. “Comparison of the Visual Perception of a Runway Model in Pilots and Nonpilots During Simulated Night Landing Approaches”. *Aviation, Space, and Environmental Medicine*, vol. 49, no. 9, pp. 1043–1055, Sep. 1978.

[130] H.W. Mertens. “Perceived Orientation of a Runway Model in Nonpilots During Simulated Night Approaches to Landing”. Technical Report #FAA-AM-77-12, FAA Civil Aeromedical Institute, Jul. 1977. URL `http://tsgsystems.faa.gov/library/reports/medical/oamtechreports/1970s/media/AM77-12.pdf`.

[131] R.W. Gibb. “Visual Spatial Disorientation: Revisiting the Black Hole Illusion”. *Aviation, Space, and Environmental Medicine*, vol. 78, no. 8, pp. 801–808, 2007. ISSN 0095-6562.

[132] J.E. Hall, R.T. Francis II, J.A. Hammerschmidt, J.J. Goglia, and G.W. Black, Jr. “Aircraft Accident Report – Descent Below Visual Glidepath and Collision with Terrain Delta Air Lines Flight 554 McDonnell Douglas MD-88, N914DL LaGuardia Airport, New York October 19, 1996”. Technical Report NTSB/AAR-97/03, National Transportation Safety Board, Washington, D.C., Aug. 1997. URL `http://www.ntsb.gov/publictn/1997/aar9703.pdf`.

[133] R. Mori and S. Suzuki. “Modeling of Human Pilot Landing Approach Control Using Stochastic Switched Arx”. In *Proceedings of the AIAA Modeling and Simulation Technologies Conference, Chicago, Illinois*, aug 2009. #AIAA-2009-6031 [in press].

[134] R.J.A.W. Hosman, J. Schuring, and P. van der Geest. “Pilot Model Development for the Manual Balked Landing Maneuvre”. In *AIAA Modeling and Simulation Technologies Conference and Exhibit*, May 2005. URL `http://www.nlr-atsi.com/downloads/AIAA-2005-5884.pdf`. #AIAA-2005-5884.

[135] M.R. Anderson. “Inner and Outer Loop Manual Control of Carrier Aircraft Landing”. In *AIAA Guidance, Navigation and Control Conference, San Diego, CA*, 1996. #AIAA-1996-3877.

[136] R. Mori, S. Suzuki, K. Masui, and H. Tomita. “Neural Network Analysis of Pilot Landing Control in Real Flight”. *Journal of Mechanical Systems for Transportation and Logistics*, vol. 1, no. 1, pp. 14–21, 2008. ISSN 1882-1782.

[137] R.K. Heffley, G.D. Hanson, W.F. Jewell, and W.F. Clement. “Analysis of Pilot Control Strategy”. NASA Contractor Report TR-1188-2 / NASA CR-170399, Systems Technology Inc., Apr. 1983. URL `http://www.robertheffley.com/pages/bib.htm`.

[138] R.K. Heffley and T.M. Schulman. “Derivation of Human Pilot Control Laws Based on Literal Interpretation of Pilot Training Literature”. In *AIAA Guidance and Control Conference Albuquerque, NM*, pp. 513–519., New York, 1981. American Institute of Aeronautics & Astronautics. #AIAA-1981-1822.

Appendix A. Notes with table 1

1. When looking 10–15deg (angle with the horizontal) down at the runway, the point of intersection with the runway in the center of vision shifts toward you if you go down, away from you if you move up (ballooning flare)
2. for attitude estimation
3. until visual aiming point becomes visible, ILS glide slope indicator should be used
4. calls it motion parallax
5. important for altitude/sink rate
6. does not explain different approaches on length change
7. as supporting cue
8. if no texture
9. explicit horizon and aimpoint markings suggested
10. for the glide phase
11. during flare (to prevent early nose down, and for proper center line keeping)
12. second most important, gives information about rate of descend (This is because of its direct relation with pitch!)
13. it is mathematically possible to derive the glide slope from the apparent runway height and the apparent side line angle
14. does not explain different approaches on width changes
15. after power cut, to prevent early nose touch down
16. main cue, if visible (Note that the near runway end is used as aimpoint here, so markers/aim point may be the actual cue!)
17. mentioned, but in this experiment near runway end is aimpoint, so result is confusing
18. probably not (mentions numerous successful landings on square and circular runways)
19. does not explain different approaches on length change
20. for the timing of the flare initiation
21. uses τ of runway width (subtended angle of runway width at aimpoint markers)
22. If texture is available. τ of runway width (subtended angle of runway width at aimpoint markers)
23. upto about 200m
24. not from questionnaire
25. flare altitude =10% of the sink rate (per second)
26. at about 20$\sim$30ft (=7$\sim$10m)
27. constant flare altitude used for training
28. a combination of airspeed and pitch attitude is used in the glide
29. “the relation of the nose of aircraft to the runway”
30. see also [76]
31. assumes distance to cues in known
32. true horizon often not visible, but false horizon sufficient
33. notes that many pilots don’t know what cue they use
34. It is unclear what is meant by the “angle with runway” cue mentioned in the papers
35. results suggest a combination of Altitude, AltitudeTau and longitudinal position is used