The Role of Binocular Cues in Human Pilot Landing Control

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Abstract

The paper discusses the possible use of binocular cues by aircraft pilots in the final landing phase through a review of literature. The review includes medical and psychophysical literature, as well as works on pilot training, certification and flight experiments. It was found that stereopsis can be used as a depth cue up to several hundred meters. However, in situations where monocular cues are available, its practical limit should be expected to be 20–65m and stereopsis is very unlikely to be of significant importance beyond 100m. These limits imply that for small aircraft, helicopters and ground operations stereopsis will be beneficial. For simulation or human pilot modeling regarding the landing of mid-sized jet aircraft stereopsis can be ignored. Other interesting findings include the importance of the wide field of view which comes with binocular vision and the notion that effective use of monocular depth cues can be trained.

Keywords: Aviation Medicine, Human Factors, Aircraft Landing, Visual Cues, Ophthalmology, Stereopsis, Monocular Pilots

1 Introduction

Just like 30 years ago [1, 2], the pilot is still of great importance for landing aircraft safely as automatic landing systems are still not used most of the time [3, priv.comm.]. Reasons mentioned by airline pilots include the technical requirements on aircraft and airport, training level of the crew, limiting weather conditions, the pilot's feeling of being in control and simply the joy that pilots have in their work [3, priv.comm.]. Moreover, research has shown that manual landings generally result in a lower sink rate at touch down [4] which increases passenger comfort.

During the final approach and landing, pilots obtain most of the information needed for their landing control from the view through the windshield [5–9]. Still little is known about *which* parts of the visual scene are of main importance to the pilot. Such knowledge could be of great benefit for a variety of applications such as training or evaluation of pilots, optimization of cockpit display design, development of enhanced vision systems, improving the realism of important cues in flight simulators, etc., etc.[10–13].

In this context the University of Tokyo has a research project on the modeling of human pilot control, which focuses on the final approach and landing of mid-sized jet aircraft. Previous research in this project [14–16] has focused on the use of visual cues which were suggested by pilots of All Nippon Airways —a partner in the project—: horizon, touchdown zone markings and runway side lines. Literature has suggested many other cues [5, 9, 12, 17–23], which are progressively being investigated.

This paper discusses the possibility of using binocular cues for depth estimations. The discussion will not be limited to the application to mid-sized jet aircraft (such as the Boeing B767 and Airbus A320), but has a general aviation or even wider scope. As this topic comprises aeronautical as well as medical and psychophysical aspects, a glossary is provided in Appendix A and a short overview of principles commonly used in ophthalmology can be found in Appendix B.

Monocular cues and optical flow [24] are beyond the scope of this review and will be discussed in a later paper.

2 Binocular Vision

Binocular vision is the part of human vision which utilizes both eyes. It opposes monocular vision, where only information from a single eye is considered. Binocular vision is often associated with depth perception, but the use of two eyes also extends our field of view and can improve perception of monocular cues due to 'probability summation' [25–27]. Although commonly 'binocular vision' just means the use of both eyes and includes the aforementioned features, in a narrower sense the term often excludes the monocularly perceivable cues and limits the definition to the two cues specific to binocular vision: 'vergence' —the simultaneous movement of the pupils of the eyes toward or away from one another during focusing— and 'stereopsis' —depth perception based on the disparity of the two retinal images resulting from the slightly different viewpoint of each eye.

The question whether binocular vision is beneficial in aircraft piloting is interesting for several reasons. It is commonly accepted that depth and distance perception are of crucial importance in landing tasks [18, 24, 28–32], and that stereopsis provides a most compelling depth cue [33–35]. However, this does not necessarily mean that stereopsis always provides the best information, nor that the human brain treats it as such. If stereo vision provides important cues, making them available in training simulators could improve simulator fidelity and training effectiveness. Besides, a lack of stereoscopic ability could be an issue when recruiting or licensing pilots.

It has been shown that training can help to use monocular cues more effectively for depth estimation [12, 36–41]. Although stereopsis is an innate ability, some researches have also noted training effects for binocular cues [42–44]. However, in these cases other explanations for the training effects are possible, such as inter-subject acuity differences or usage of monocular cues which could not be completely suppressed.

3 Benefits of Binocular Cues

Accurate depth and distance perception is required in a number of flight-related tasks. Stereopsis is considered an important depth cue especially for close range operations such as landing [29, 30], formation flying [29, 30, 45, 46], aerial refueling [30, 45], helicopter operations [10, 30, 45], and ground operations [45, 46].

Stereopsis is a physiological rather than a psychological cue and provides a relatively strong depth impression. Therefore stereopsis could become the dominant depth cue [34, 47, 48], and help prevent visual illusions arising from monocular cues [45, 49 p59].

The United States Navy requires good stereopsis for all its aviators in actual control of aircraft, stating: *"Stereopsis is not an absolute must in flying an aircraft, and in fact the FAA does not require this to be tested. [...] However, the visually demanding environment of carrier aviation requires every sense a pilot can have.[30] "*.

4 Critical Remarks on the Possible Use of Binocular Cues

The vast majority of research on visual guided flight does not mention binocular cues at all, or states they are irrelevant for one or more of the following reasons, which will be further investigated in the subsequent sections:

- Stereopsis —and vergence even more— is limited to distances too close to be relevant (e.g., there would be no time to integrate the cue and base action on it before touchdown).
- Real flight experiments have shown that monocular pilots can still land aircraft safely.
- With many monocular cues available, the contribution of stereopsis is negligible.

4.1 The Limit of Vergence

There is general agreement that vergence is of limited use as a cue to depth [26 §3.1.1, 28 p120, 34, 50–55, 56 §5.901]. Experimental results have been reported where several subjects were not able to use vergence at all, or simply ignored it as a distance cue [52]. As vergence is effective only within a few meters, it would be limited to use within the cockpit as far as aircraft landing is concerned.

Wrong vergence cues may cause confusion in flight simulation, which is one of the reasons why professional simulators have collimated displays (other reasons include more realistic head motion parallax and accommodation) [57–60]. In collimated displays lenses or (curved) mirrors are used to make the projected image seem distant enough for vergence cues to be ineffective.[1]

4.2 The Limit of Stereopsis

The limit of stereopsis can be expressed in two ways: the maximum distance at which an object can be detected as nearer than an object at infinity, or as the minimum retinal disparity which still results in a depth discrimination. The former is generally given in meters, the latter in seconds of arc. Limit distance and limit disparity are interconvertible (see Appendix B), but because of the current application to aircraft landing we will mostly use the limiting distance.

The reported maximum distances up to which stereopsis can be used vary widely: from 6m [29, 62] up to 6.5km [29]. These extreme values should of course be taken with a grain of salt: the limit of 6.5km was calculated from best acuities obtained under ideal laboratory conditions, and the reports of 6m are not backed by experiment data. Other works have reported a clear benefit of stereopsis at 6m [63, 64], although it may be of little practical value if very strong monocular cues are available [65]. Table 1 provides a more complete overview of the limits of stereopsis reported in literature and includes some notes on how they were obtained.

[1] On his website, Lee [61] describes an interesting do-it-yourself project on collimation of his PC monitor using a Fresnel lens.

It appears that the determined limits strongly depend on the way the experiment is conducted. Westheimer [66] for example shows that stereoscopic acuity varies widely for laboratory tests with different types of —or without— reference stimuli. Lots of other variables such as illumination level, fixation point, stimulus size, and stimulus orientation also influence acuity [56 §5.918, 67]. Moreover, there are big inter-personal differences in stereo acuity [68].

A point of concern is that there is no consensus about the influence of viewing distance on the stereo acuity, as this would affect the interconversion of limit distance and limit disparity. Ogle [69] and Brown et al. [70] mention no change between 0.4 and 10 meter, but more recent work finds a higher threshold at close range [71, 72]. In their overview Boff and Lincoln [56 §1.615] also mention an improvement of the acuity upto 5∼10m, but note a possible deterioration for higher distances.

Because of possible viewing distance effects and because of the big influence of small measurement errors, limit distances calculated from acuity values obtained through close range laboratory experiments are disputable.

Although extrapolation from laboratory experiments is far from ideal, it is practically impossible to eliminate monocular cues in outdoor experiments. Unfortunately, a comparative 'monocular viewing only' test to remove the effect of monocular cues post-hoc is not valid, because probability summation can improve the perceivability of monocular cues when using both eyes [25–27, 56 §1.814, 73 p699].

It can be concluded that the limits of human stereopsis are very dependable on the task, and can often only be obtained by extrapolation or by trying to minimize secondary cues as best as possible. For this reason many different values are mentioned in literature and no agreement has been found yet. Nevertheless, many papers just cite or even re-cite values without even taking their determination method into account, thus creating the false impression that a certain value is commonly accepted.

4.3 Monocular Pilots Can Land

In his plea not to withhold people with bad stereo vision a piloting license, Diepgen [62] lists a number of stories of successful monocular pilots and experiments that compare binocular with monocular landings. The answer to his self raised question *"Do Pilots Require Stereopsis?"* is *"No"*. Although the nuance between 'require' and 'benefit from' may seem small, it is essential for the question we are asking here. This question is not whether monocular pilots should be allowed to fly aircraft, but what cues pilots are using in general. Therefore, the fact that monocular pilots can land aircraft successfully does not rule out the possibility that stereopsis is normally used as a depth cue in aircraft landing.

The FAA allows pilots who lose binocular vision to fly, but only after a 6 month adaptation period[2], and imposes restrictions on the use of contact lenses for reasons of loss of stereopsis without proper adaptation [49 App. D]. Actually, research quoted by Diepgen [62] to prove that pilots don't *require* stereopsis, at the same time indicates that binocular pilots do use and thus probably *benefit from* stereopsis.

2 Similarly, the German Society of Ophthalmology suggests a 3 month no-driving period in case of acute monocularity for car drivers [87 §3.5].

Table 1: Reported limits of stereoscopic depth perception

Ref.	Reported limit	Limit in original unit	Method	Note
[29]	800∼6500m	0.5∼4 miles	From acuity	From Verhoeff Stereopter (η_t=16.38arcsec), resp. from η_t=2arcsec Vernier acuity from [54, 73]. 4mi would be a theoretical maximum, however, presented as *"stereopsis is probably of value to at least a distance of 4 miles"*.
[74]	1200m	1200 m	From assumed acuity & Extrapolation of outdoor exp.	Assumes η_t=10arcsec. Also makes a log/log line fit for ratio binocular/monocular thresholds from experimental data, extrapolates to point where ratio is 1, which does not take probability summation into account (i.e. a 'residual' factor of 1.4 [73 p 699] because 2 eyes are better than 1); Up sloping terrain may have provided monocular cue [75 p205].
[53]	667∼1110m	667∼1110 m	From assumed acuities	Assumes η_t=20∼12arcsec. Also cites 580m [76] and 3000ft=914m [77] (wrong and indirect reference; should be 1300∼1900ft from [75]).
[76]	580m	580 m	Outdoor exp.	Experiments with pseudoscope; Also cites >240m [78].
[75]	396∼579m	1300∼1900 ft	Outdoor exp.	Monocular cues may have played a role; probability summation is not taken into account.
[29]	550m	600 yard	Cites [73]	[73] refers to [75, 76] mentioning 580m.
[54]	>453m	>495 yard	From assumed acuity	Calculated from an assumed acuity of η_t=30arcsec, called *"a large figure"*
[56]	∼450m	∼450 m	[unknown]	§5.901; *"a meaningful cue to distances up to ∼450m"* (instead of *"distances"* probably *"relative depth"* should be read); Also: *"the most effective cue in central vision up to ∼65m"* (probably from [79])
[38]	274m	300 yard	[unknown]	
[80]	>240m	>800 ft	Flight exp.	During flights between 500∼800ft altitude, *"objects on the field appeared to S[ubject] to be smaller and farther away"*. Effects on landing performance were also found.
[78]	>240m	>240 m	From acuity	Acuity (*"at least"*) η_t=60.5arcsec from experiment with needles at 34cm, 68mm interpupillary distance.
[81]	>200m	>200 m	[unknown]	*"[Stereopsis'] effectiveness, however, in contributing to the perception of metric distance is limited probably to no more than 100 m although it must contribute to the perception of depth order well past 200m."*
[30, 49, 82]	200m	200 m	[unknown]	200m is reported as a limit obtained mathematically [30]. Hall et al. [49 p48] cite 'USAF research personnel' (names given) on a limit of 600ft, but that beyond 20∼25ft monocular cues become important.
[83]	160m	160 m	Cites [84]	160m is the maximum experiment distance discussed in [84], not the limit of stereopsis. Also: *"at 50 m, the perceivable depth difference is about 3m"* (cites [53], value probably calculated from 12arcsec acuity mentioned there)
[35]	>91m	>300 ft	From acuity	based on η_t=2.3arcmin acuity from experiment with video screen; Better acuity might be found if using a higher resolution screen.
[79]	64m	210 ft	From assumed acuity	States stereopsis is the dominant cue up to 210ft=64m, unless there is strong motion parallax. Real 'limit' of stereopsis is thus supposedly significantly higher.
[59]	∼30m	∼30 m	[unknown]	
[10]	∼30m	∼30 m	Cites [26]	Unclear where they got the 30m from. Maybe from diplopia threshold (as it is ca 7arcmin, [26 Fig. 23.42]), which is actually the point where the 2 retinal images are so different that the mind cannot integrate them to 1 stereo view anymore (so it is almost the 'opposite', i.e. threshold on the wrong side)
[62]	6m	6 m	cites [85]	Gregory [85] mentions 20ft, but changed this to *"perhaps 100 metres"* in the 4^{th} edition. (No experiment or other source mentioned.)
[29]	5.5m	6 yard	Cites [86]	Why [86] is associated with 6yd is unclear (cf. >453m above), maybe there is a mixup with the vergence limit (<6m [86 p526], on the Howard-Dolman apparatus).

For example, Roscoe [88] showed that the accuracy with which a pilot can land at a specified point deteriorates with the loss of stereopsis and limitation of the field of view. Lewis and Krier [89] found that monocularly controlled jet aircraft landings by experienced pilots were not significantly less accurate in touchdown location, but approaches were steeper and sink rates at touchdown were higher. Additionally, the pilots were observed to make more head movements (probably to get more depth cues from motion parallax), and pilots said to feel more uncertain. Later works confirmed these findings for low-time pilots [1, 31], although Lewis et al. [31] did not find the approaches significantly different.

The way pilots were made effectively monocular in these experiments limited their field of view severely and thus did not only take stereopsis away. Pilots have noted that peripheral vision is important for the estimation of sink rate [priv.comm.]. Other sources mention the influence of the field of view on the determination of the aircraft's attitude [82 vol.2,§3.4.5.1.5], which is closely related to the sink rate.

An example where stereopsis as a cue was removed without limiting the field of view is Pfaffmann's study [80]. In his experiments, in the non-stereopsis cases, flares were initiated too high, objects were reported to seem smaller from altitudes of about 500–800ft (152–244m), and pilot workload was said to be increased. However, two notes must be taken: firstly, the landing spot did not contain a clear runway outline, so less monocular (linear perspective) cues were available, and secondly, very small aircraft were used which flare much closer to the ground and react more direct to pilot inputs than jet airliners.

Both Pfaffmann [80] and Grosslight et al. [1] reported that the first monocular landings in their experiment series were clearly inferior, but that pilots quickly adapted. A similar effect was reported in a car-driving experiment which tested for the effects of acute loss of stereopsis [90]. This quick adaptation biases conclusions based on averaged performance. It also indicates that pilots normally *do* use binocular cues.

Another point which biases findings that binocular cues are useless, was raised by Mayer and Lane [91]. By a statistical analysis, they found that monocular pilots have more flight hours and show a stronger motivation to renew or extend their license. The also note that monocular prospective pilots are likely to give up due to delays or difficulties in obtaining a student license. Furthermore, experienced and self-assured pilots who really 'live for flying' are more likely to go on after losing stereopsis. Therefore, success stories of monocular pilots are biased. However, it must be stated that monocular cues are generally abundant and using them properly is a matter of training [12, 36–41]. Since monocular pilots have already learned to use monocular cues more effectively in daily life, this may provide them an advantage.

4.4 Monocular Cues Dominate

As noted before, various authors have proposed widely ranging limiting distances for stereopsis. This is a result of both the experimental environment and the fact that the *practical* range of stereoscopy as a depth cue is much smaller than the *theoretical* range. Not only does the resolution of depth perception deteriorate at far distances, but also will monocular cues provide more and easier perceivable depth information. Cutting and Vishton [92 p80] provide a nice overview of cues and their relative importance at different distances.

Some sources suggest that binocular cues could help avoiding visual illusions [34, 45, 47, 48, 49 p59]. Although stereoscopic depth information generally has some influence in overall judgments [93 p2270, 94, 95], most researchers find that monocular cues are dominant even for depth judgments within a few meters [67 §11.2, 93 p2270, 94, 96 p155, 97]. The general conclusion seems that stereopsis is ignored when strong monocular cues are present, and that its impact strongly depends on the presence of other cues.

Looking more specifically at the landing of aircraft, another reason for the dominance of monocular cues emerges: Cibis [38] reports that linear perspective and apparent object size are the main cues for pilots, while motion parallax —often advocated as a strong monocular depth cue— is found not to be useful. Although only results from basic laboratory experiments were provided, the general conclusion makes sense. At airfields there are generally few 'obstacles' close to the runway that can provide strong motion parallax cues. Runways *do* on the other hand provide strong linear perspective cues and 'the size of familiar objects' such as runway width and markings can provide extra information about altitude [5, 7, 18, 98–102]. Therefore, *"poor stereopsis does not always result in poor distance judgment in landing aircraft, at least on prepared runways [28 p60]"*.

5 Conclusion

From literature, three main reasons were found why stereopsis would not be a useful cue when landing aircraft, and they have been analyzed:

- *Stereopsis —and vergence even more— would be limited to distances too close to be relevant.* It seems commonly agreed on that vergence is only a useful distance/depth cue up to a few meters. The limit of stereopsis is more controversial. The practical limit depends heavily on the observer's acuity and the visual environment (i.e., the availability of other cues). Stereopsis would be of practical use up to 20∼65m, and is very unlikely to be a cue of significant importance beyond 100m.
- *Real flight experiments would have shown that monocular pilots can still land aircraft safely.* Although this is a fact, the experiment results also indicate that pilots do actually use binocular cues when available (at least for the small aircraft considered in these studies). When made effectively monocular, originally binocular pilots fly steeper approaches, show increased head movement and report higher workload. However, quick adaptation to the new (monocular) situation increased the overall success rate in monocular landing experiments.
- *With many monocular cues available, the contribution of stereopsis would be negligible.* It has been shown that binocular cues, if available, are often fused with monocular cues, but are rarely dominant in distance or depth judgment. As runways provide strong linear perspective and size cues, these are likely to be decisive, considering the practical limits of stereopsis.

Before concluding, two general points should be made regarding the use of binocular cues for the landing of mid-sized jet aircraft. Firstly, in contrast with the discussed 'limits of stereopsis' experiments, pilots will not concentrate all their attention on judging whether two distant stimuli are at equal depth, they need to keep a broad situational awareness including many aircraft states [2, 5], among them the absolute distance to the touchdown point. Because of this lower attention and the absence of a reference stimulus, the role stereopsis plays may even be smaller than one would assume based on the discussed experimental results.

The second point is that a pilot is not looking straight down but shifts his gaze to the far end of the runway in the final phase of landing [103, 104 p5F.90, 105 p6.9]. Furthermore, large aircraft are still high above the ground and far away when landing-related decisions must be made [62]. *“Over the nose of the aircraft the distance from pilot to ground is too great for effective stereoscopic vision until the beginning of flareout, and by this time other cues may be more efficient. [28 p60]”*. Actually, for a Boeing 767, the blind area in front of cockpit reaches up to 37m (120ft) at touchdown [104], and at the start of the flare this will even be about 60m (200ft). These values are close to the practical limit of stereopsis, meaning that only some very last second adjustments —which may nevertheless be critical— can benefit from binocular depth information. Before the flare, a pilot of a mid-sized jet aircraft has to rely on monocular cues though.

Concluding, it is very likely that monocular cues do indeed dominate in practical situations. Stereopsis may only be of serious importance in very short-range tasks, possibly including formation flight, aerial refueling, taxiing, parking, helicopter flight and docking of spacecraft. Stereopsis as a cue for landing can generally be ignored, 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.

6 Considerations and Practical Implications

- It was found that many publications are based on laboratory rather than outdoor experiments, so their results should be used cautiously when applied to practical situations.
- Considering only monocular cues should be sufficient for a basic pilot landing model for mid-sized jet aircraft (such as the Boeing B767 and Airbus A320).
- Incorporation of binocular depth cues should be reconsidered when modeling small aircraft landings or helicopter control.
- When looking into binocular cues for the control of motion, static disparities as well as stereo-motion cues (‘dynamic stereopsis’) should be investigated. That is, the difference in velocity fields between the retinae should also be considered (see for example Regan et al. [106], Rokers et al. [107] and Morgan and Castet [108] as a starting point).
- From careful reading of literature regarding monocular flight experiments it emerged that a wide field of view (FOV) seems important. This was later confirmed by pilots of All Nippon Airways [priv.comm.]. It should be studied which cues could be obtained from the outer parts of the FOV and how these could help judging sink rate and/or attitude.
- A wide field of view and display collimation (to prevent wrong convergence, accommodation, and head motion parallax cues) should be regarded in relation to flight simulator experiments.
- The proper and effective use of monocular cues can be learned. This is why experience is important in pilot training. Recognition and usage of specific monocular cues may be trained with abstract exercises in a laboratory setting, which could be an alternative for expensive simulator training.

Appendix A Glossary

A.1 Ophthalmological terms

Accommodation – Automatic adjustment of the focus of the eye by the lens
Acuity (Visual∼) – Clarity of vision; Ability to distinguish details (see Appendix B)
  Stereo∼ – Minimum difference in distance which can be detected from stereoscopic cues
  Vernier∼/Hyper∼ – Minimum detectable horizontal (mis)alignment of two parts of a broken vertical line (as in reading a vernier scale)
Binocular – Utilizing both eyes
Disparity (Retinal∼) – Slight difference in the two retinal images due to the angle from which each eye views an object
Monocular – Utilizing only one eye
Ophthalmology – Branch of medicine that is concerned with the study of the eye
Parallax
  Binocular∼ – (see Disparity)
  Motion∼ – Monocular depth cue. As we move, objects that are closer to us move farther across our field of view than do objects that are in the distance
Probability summation – Theory stating that when the two eyes try to detect a stimulus, they will do as well as a single eye that has two independent opportunities (see [25–27])
Stereopsis – Depth perception based on the disparity of the two retinal images resulting from the slightly different viewpoint of each eye
  Dynamic∼ – Neuronal sensitivity for motion-in-depth, based on a change of disparity
Subtense (Angular∼) – Angle between the light rays from two separate points (see Appendix B)
Vergence – Simultaneous movement of the pupils of the eyes towards or away from one another during focusing
Verhoeff Stereopter – Apparatus used for stereo acuity tests. It displays 3 bars of which one is either in front of or behind the other two.

A.2 Aeronautical terms

Attitude – Angle between the aircraft's longitudinal axis and the horizontal plane. Also called 'pitch'. In a wider sense includes 'roll' (or 'bank', angle between the lateral axis and the horizon) and 'yaw' (or 'heading', angle between the longitudinal axis and the North)
Collimation – The process of making light rays parallel through lenses or mirrors (makes a simulated scene appear to be at far distance)
FAA – Federal Aviation Administration (of the U.S. Department of Transportation)
Flare – Maneuver a few seconds before touchdown, where the pilot slightly lifts the nose of the aircraft (pitch up, pull up) to decrease sink rate and land on the main landing gear first.
Level-off – (see Flare)
Round-out – (see Flare)

Appendix B Ophthalmological Principles

In ophthalmological literature, the size of an object or the distance between two points is often expressed in terms of (angular) subtense. Figure 1 illustrates this. The angle ϕ in the figure is the angle subtended by the tree or the 'subtense of the tree'.

A person's sharpness of sight or 'visual acuity' is the subtense of the smallest detail he or she can reliably distinguish. Acuity can be measured in many ways, for instance by means of the Snellen or Landolt C chart —often used by general practitioners— or by a vernier test (see Fig. 2). In this last test, the direction of the misalignment of two vertical lines is to be judged. Figure 3(a) shows a top-view of this test, where ϕ is the subtense of the misalignment. The Vernier acuity is the smallest subtense for which judgments can reliably be made. Vernier acuity is also called 'hyperacuity', because generally details of up to 2arcsec can be distinguished, against 1arcmin for the Snellen letters [56 §1.602].

The binocular subtense is defined in a different way, as depicted in Fig. 3(b). It depends strongly on the interpupillary distance (ipd=2a), which varies per person (ca. 50∼75mm [109]). More interesting than the binocular subtense is the difference in binocular subtense between the point of focus (F) and a stimulus point (P) at another distance. This difference, called 'disparity', causes point P to be depicted differently with respect to point F on each retina. If P is closer than F, we talk about a 'near', 'crossed' or 'positive' disparity. It F is closer, the disparity is called 'far', 'uncrossed', or 'negative'. The brain is able to recover relative depth information from disparities.

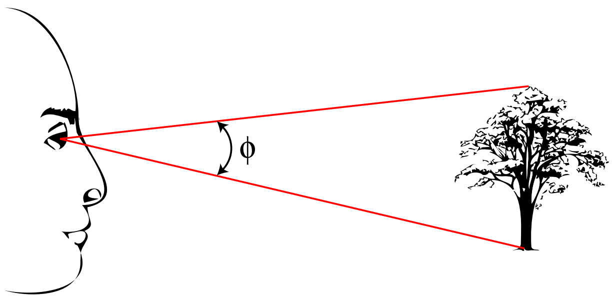

Fig. 1: ϕ is the angle subtended by the tree also called the 'subtense of the tree'.

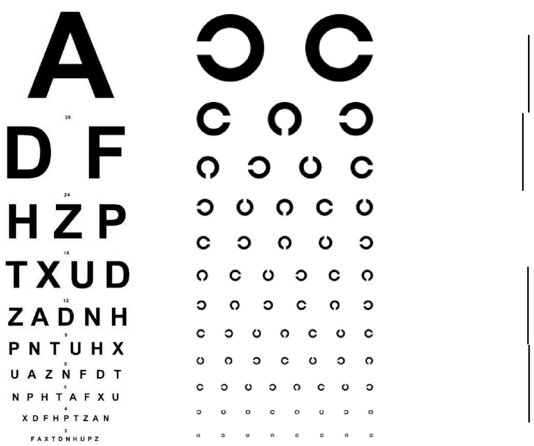

Fig. 2: From left to right: the Snellen chart, where letters must be named; the Landolt C chart, where the location of the gap must be named; and 2 samples of a vernier acuity test, where the relative position of the lower bar (left or right) must be named.

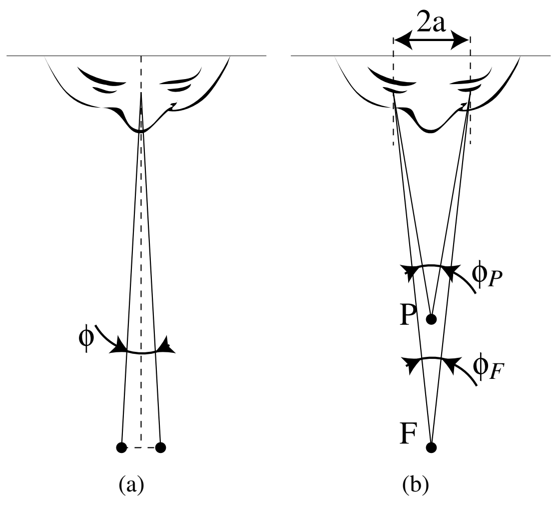

Fig. 3: Definition of subtense and disparity:
(a) ϕ is the general angular subtense of 2 points (cyclopian case).
(b) ϕ_F is the binocular subtense of the point of focus F and ϕ_P is the binocular subtense of point P. The disparity is defined as $\eta = \phi_P - \phi_F$.

The stereoscopic acuity (or threshold disparity η_t) is the smallest binocular disparity that results in a reliable depth judgment. Since the disparity becomes smaller as the stimulus point P gets closer to the point of focus F, stereoscopic acuity can be measured at any range.

The limiting range of stereoscopic vision is the greatest distance at which an object can just be detected as nearer than an object at infinity [54]. This range follows directly from the stereoscopic acuity and the interpupillary distance, because point F is located at infinity and thus has a binocular subtense of zero.

Note on interpretation of data from literature

When interpreting data from ophthalmologic experiments, care should be taken about exactly *what* is measured and under what conditions. It is important to keep in mind the difference between general visual acuity, Vernier hyperacuity and stereoscopic acuity, as these are easily confused. Boff and Lincoln [56] give good overviews of acuity tests and the influence of environmental factors (§1.602 resp. §1.603 for general acuity tests and §5.917 resp. §5.918 for stereo acuity tests). Westheimer [66] also discusses the influence of reference stimuli on stereo acuity.

Furthermore, many experiments lack a sufficiently large and ‘representative’ group of subjects. Often only a few of the researcher’s laboratory members are used as subjects, introducing the risk that better than average performance is obtained due to their training [110, 111].

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