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# The Freiburg Stereoacuity Test: automatic measurement of stereo threshold

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**Abstract** *Background:* There is a need for a stereotest with the following properties: (1) Natural viewing conditions, i.e. stimulus contours visible for each eye alone, but no or hardly any cue for monocular detection, and (2) suitability for threshold determination over a wide range of disparities. To comply with these requirements, we developed the Freiburg Stereoacuity Test. *Method:* The stimulus configuration is shown on a visual display unit (VDU) using phase-difference haploscopy with ferromagnetic liquid crystal shutters. The stereo target consists of a vertical bar that can be presented "in front of" or "behind" a frame. The sizes of the bar and the frame are kept constant relative to the stereo disparity. Anti-aliasing allows for disparities finer than the pixel raster. To mask monocular cues the bar is displaced randomly to the right or left. The stereo threshold was determined in two observers with normal eyes, using first the method of constant stimuli and then the best PEST. Both procedures were repeated with observers wearing scatter transparencies that reduced their visual acuity to about 1/10. In addition, the two observers with insight into the test design and two strabismic patients performed the best PEST procedure with one eye only. *Results:* With constant stimuli both observers achieved a stereoacuity of 2.6 arcsec and 3.1 arcsec, respectively, taking a hit rate of 75% as the threshold. The best PEST revealed a stereoacuity of 2.5 arcsec and 3.0 arcsec, respectively. The scatter transparencies raised the threshold to 261 and 257, respectively. With one eye only, the two observers with insight into the test design exploited the subtle position cue and reached a coarse pseudostereopsis. The two strabismic patients did not utilise the position cue. *Conclusion:* The Freiburg Stereoacuity Test allows determination of stereoacuity over a wide range of disparities (1–1000 arcsec). Although the stimuli can be seen with each eye alone, monocular depth cues are sufficiently masked. The Freiburg Stereoacuity Test is available at http://www.ukl.uni-freiburg.de/aug/bach/fst/.

## Introduction

Stereopsis is the ability to detect, on the basis of binocular disparity, whether a single small feature, e.g., a line, is in front of or behind other features. Julesz [9] called this ability "local" stereopsis and distinguished it from "global" stereopsis that manifests itself in the ability to see a cluster of disparate random dots, not standing out as single elements, but marking a plane as being in front of or behind a reference plane. Random-dot tests have the advantage that they avoid monocular cues, but they differ considerably from natural viewing conditions. Moreover, in random-dot tests an ambiguity can occur as to which elements belong to each other on the retinae, so that relatively large disparities are required to provide depth sensation. To avoid these drawbacks we endeavoured to develop a test that allows measurement of "local" stereoacuity over a wide range of disparities. Monocular cues had to be obscured.

Conventional methods for measuring stereoacuity suffer from one or more of the following shortcomings: The number of presentations at each disparity step is small, the threshold is not systematically estimated, and monocular cues are present so that stereoacuity cannot be distinguished from position hyperacuity. Using computer graphics, we avoided these shortcomings and developed the "Freiburg Stereoacuity Test". Our test resembles the classical three-rod test, but bears three advantages: (1) statistical evaluation is performed online; (2) monocular position information is masked by random lateral offset of the stereo target [17]; (3) the distance between the stereo target and the reference contours is adjusted to mimic typical situations in real life: The reference contours are close to the stereo target when a high stereoacuity is required, e.g., when threading a needle, and the reference contours are distant when gross stereopsis is required, e.g., when pouring a cup of tea. Increasing the distance between the stereo target and the reference contours for large disparities carries the additional advantage that any overlap of the stereo target with the reference contours is avoided.


**Fig. 1** Display for the right eye in real size (to be viewed from 4.5 m) when the stereo disparity between the vertical bar and the frame is 100 arcsec. The pattern with random black-and-white squares that extends up to the borders of the VDU is trimmed in the figure. Due to anti-aliasing the edge of the bar is slightly fuzzy, allowing for disparities finer than the pixel raster (Fig. 2). To mask monocular cues the bar is shifted randomly to the right or left; depicted is a displacement to the left. For larger and smaller stereo disparities, the sizes are scaled proportionally, with the constraint that the distance between the bar and the frame is kept at a minimum of 300 arcsec

## Methods

The Freiburg Stereoacuity Test

*Technical design*

The stimulus is presented at a distance of 4.5 m on a visual display unit (VDU), 36 cm wide and 27 cm high, with a resolution of 800×600 pixels and a frame rate of 120 Hz. A high luminance (390 cd/m$^2$) is achieved by a special black-and-white VDU (GD403, Richardson Electronics). The screen is driven from the mainboard graphics card of a standard computer (Macintosh G4). The software for the generation of the stimulus and the interactive determination of the threshold is written in C++.

Nearly complete separation for the right and left eye is achieved by a pair of ferroelectric liquid crystal shutter goggles (FE1, Cambridge Research Systems). The voltage applied to the liquid crystals controls their transparency. The shutter goggles are synchronised to the monitor frequency so that images are presented alternately to the right and the left eye. Each eye receives its image at a frequency of 60 Hz, which is just above flicker fusion frequency. Compared to standard liquid crystal shutters [12], the ferroelectric LCDs switch more rapidly (≈50 µs) and have a higher on:off ratio (1:500). In a previous version of the Freiburg Stereoacuity Test [4, 5] the stimuli for the right and left eyes were separated by mirrors instead of shutters.

The stereo target (Fig. 1) consists of a vertical bar that is surrounded by a frame. Outside of the frame a pattern with random black and white squares (edge length 180 arcsec) is displayed. The frame and the squares serve as the reference plane. The vertical bar is presented with a stereo disparity up to 1000 arcsec.

In a display with sharp black-and-white edges the stimulus position would be limited to steps according to the size of the pixels (20 arcsec at a distance of 4.5 m). To overcome this limitation, "anti-aliasing" [2, 16] is applied: The margins of the vertical bar are smoothed with a gradual transition of the luminance following a gaussian profile (Fig. 2). The gaussian profile has a standard deviation of 2 pixels. The profile can be shifted to the right or left in steps of less than 1 arcsec at a distance of 4.5 m. The gradual transition from black to white is acceptable since it merges with the blur of the retinal image brought about by the optics of the eye. The optical point-spread function of the eye resembles a gaussian profile of at least 120 arcsec width at half magnitude [6]. Thus, any shift of a point stimulus changes the relative illumination of a group of neighbouring photoreceptors. The visual system evaluates these changes, making possible a spatial resolution far beyond the grain of the photoreceptors, as exemplified in the various forms of hyperacuity, including stereoacuity [6].

The anti-aliasing technique requires accurate control of the luminance, taking into account the inherent non-linearity of cathode ray tubes. Linearisation of luminance requires a correction with an inverse gamma value [3], which is determined by a simple psychophysical adjustment task: Two fields are presented adjacent to each other. One is the reference field, consisting of a grid with black and white stripes. Viewed out of focus it appears as a homogeneous grey field with a luminance of 50%. The other field consists of a homogeneous grey. Its luminance has to be equalled by the operator to that of the reference field. Any residual non-linearity at both ends of the luminance scale is avoided by using only the 5%–95% range. This can easily be tolerated since a reduction of stereoacuity would be expected only below 50% contrast [10].

The size of the bar and the frame are kept constant relative to the disparity of the bar. The inner frame width is 8 times the disparity and the inner frame height 10 times the disparity. The length of the vertical bar is 70% of the inner frame height so that a gap remains between the top and the bottom of the bar and the inner frame edge. To obtain a sufficient stimulus width and length at small disparities, the frame height is kept at least at 3600 arcsec and the frame width at 800 arcsec. To mask monocular cues the bar is not centred with respect to the frame but placed randomly, trial by trial, to the right or left of the centre by the amount of the

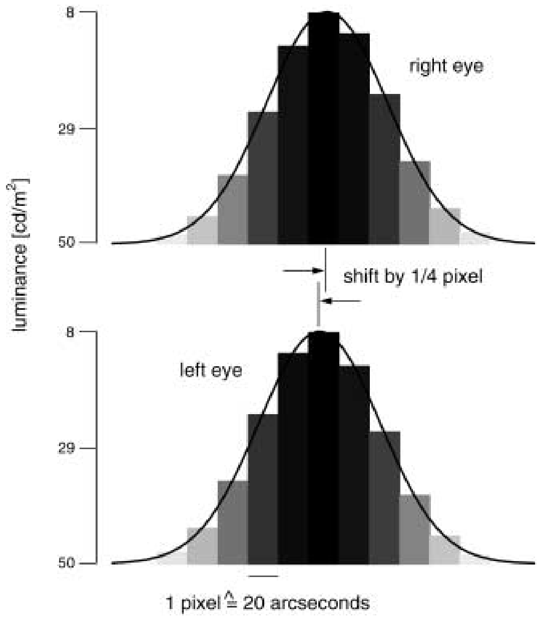


**Fig. 2** Luminance across the vertical bar, following a gaussian profile. In the example depicted here the horizontal position of the profiles for the two eyes differs by one fourth of a pixel, corresponding to 5 arcsec. For disparities above 125 arcsec a plateau is interspersed between the two slopes of the gaussian profile. The luminances indicated in the figure refer to our experimental setup. The VDU was surrounded by cardboard of about 0.5 m width with a luminance of 11 cd/m². All values were measured through the shutter goggle

actual disparity. The distance between the bar and the left or right inner frame edge is 3 times the disparity, but is clamped to 300 arcsec for disparities below 100 arcsec to comply with the spatial requirements for fine stereoacuity [13].

*Procedure*

The stereo disparities are chosen on a logarithmic scale, as used for instance by Norcia et al. [15]. The stimulus duration ends when the observer makes his or her choice by pressing either the “in front” or the “behind” button on a response box, a standard numerical USB keypad, connected to the computer by an extension cord. (It turned out that observers responded above threshold after about 1 s, below threshold after about 1–5 s). The next stimulus is presented after an interval of 0.5 s in which the random-dot pattern covers the whole field.

Various strategies for threshold determination can be implemented in the Freiburg Stereoacuity Test, for instance the method of constant stimuli and adaptive staircase procedures such as the best PEST (parameter estimation by sequential testing [11]).

## Validation

*Subjects*

We examined the suitability of the Freiburg Stereoacuity Test in two observers with normal eyes (authors CS and GK) and in two cooperative patients who had been strabismic from birth and had never experienced stereopsis. The two observers had performed the test during its development in many preliminary sessions and knew all technical details. Observer 1 was 32 years of age. Her refraction was –0.5 cyl 170° in the right and –0.25 sph in the left eye, but she never wore her correction. Her uncorrected visual acuity was 1.1 in the right eye and 1.4 in the left eye. Observer 2 was 65 years of age. His refraction was +1.25 cyl 90° in both eyes, and he always wore his correction. His corrected visual acuity was 2.0 in the right and 1.9 in the left eye.

Strabismic patient 1 was 48 years old. He had been strabismic since early childhood and had esotropia of about 5°. The leading left eye was emmetropic with a visual acuity of 1.6. The squinting right eye was slightly hyperopic and had a visual acuity of 0.1. Strabismic patient 2 was 16 years old. At the age of 6 months his parents noted a left esotropia, which was treated with spectacles and occlusion. Beginning at the age of 14 years the esotropia gradually turned to an exotropia of 16°. The leading right eye was emmetropic with a visual acuity of 1.5. The visual acuity of the squinting eye was 0.8 with a correcting lens of –0.5 D.

All visual acuities were measured with the automatic Freiburg Acuity Test [1].

*Stereo threshold with constant stimuli*

We used a two-alternative forced-choice paradigm without instantaneous feedback about the correctness of the responses. In a first run, we varied the disparity between 1 and 1000 arcsec on a scale with steps of 0.3 log units (factor 2.0). In five further runs we varied the disparity in steps of 0.1 log units (factor 1.26) between 1 arcsec and a level at which 100% correct answers had been reached in the first run. In each run, each disparity was presented 10 times in random order. The runs were separated by at least 10 min of rest. Analysis was based on a maximum likelihood fit to a psychometric function (Fig. 4), as described by Meigen et al. [14].

*Stereo threshold with an adaptive staircase procedure*

Since the determination of a threshold with constant stimuli is very time consuming, we examined whether a more rapid procedure could be applied. For this purpose we implemented the best PEST [8, 11]). The best PEST assumes that the psychometric function has a sigmoid form and takes the point where the slope is steepest as the threshold. Following Liebermann and Pentland [11] we chose a logistic function. It describes the hit rate P depending on the stereo disparity as follows:

$$P_{d0}(d) = p_{guess} + \frac{1-p_{guess}}{1+(d_0/d)^s}$$

where $p_{guess}$ is 1/2, d0 is stereo threshold, s is slope, and d is disparity.

We set the slope of the psychometric function to 3 and assumed it to be constant across stereo acuities on a logarithmic scale. After each response the best PEST calculates the most likely threshold on the basis of all previous responses and sets the next stimulus accordingly (Fig. 3). The best PEST provides a feedback in that the stimulus decreases when the foregoing answer was correct. This feedback is so subtle, however, that it can be utilised only by sophisticated observers.

We limited the best PEST to 100 stimulus exposures. After the initial 12 and then after every fifth real stimulus we presented a “bonus” with a disparity five times the current estimation of the threshold to maintain the observer's motivation.

Observers 1 and 2 underwent the best PEST procedure 6 times after having passed the tests with constant stimuli.

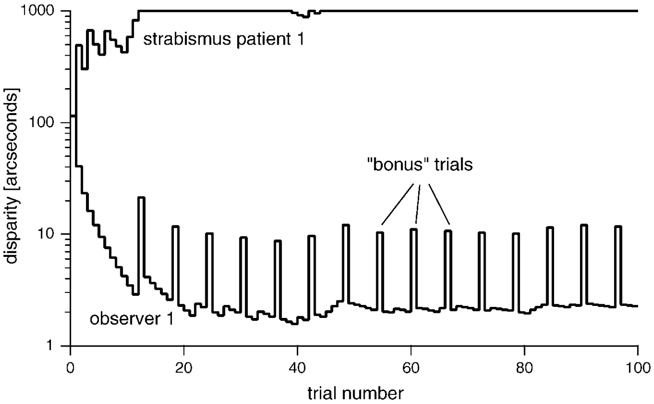


**Fig. 3** Best PEST: sequence of 100 stereo disparities presented to observer 1 and strabismic patient 1. If a response is correct, the next stimulus is harder to detect, and vice versa. Thus, the threshold is gradually approached. In the depicted example, observer 1 reached a stereoacuity of 2.3 arcsec. Strabismic patient 1 responded by mere chance so that the best PEST reacted with the largest possible disparity

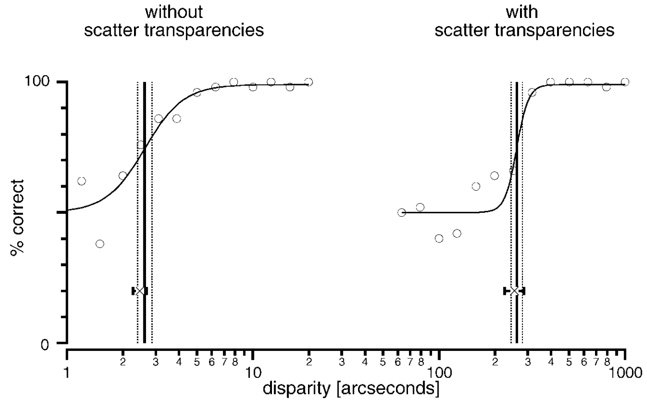


**Fig. 4** Psychometric functions obtained with constant stimuli (observer 1). The *solid line* indicates the 75% hit rate reached at 2.6 arcsec without scatter transparencies and at 261 arcsec with scatter transparencies. The *dashed lines* represent the 95% confidence intervals. The best PEST results are depicted as *crosses* (average of the 6 runs) and *horizontal bars* (95% confidence intervals)

*Stereoacuity with scatter transparencies*

Both the constant stimuli procedure and the best PEST were repeated with scatter transparencies in front of the eyes which reduced the visual acuity in observer 1 from 1.1 to 0.16 in the right eye and from 1.4 to 0.11 in the left eye, and in observer 2 from 2.0 to 0.18 in the right eye and from 1.9 to 0.14 in the left eye.

*Monocular controls*

Observers 1 and 2, who had performed the whole sequence of experiments described above and knew all the details of the test design, performed the best PEST with their left eye occluded. The two strabismic patients performed the best PEST 4 times with their squinting eye occluded.

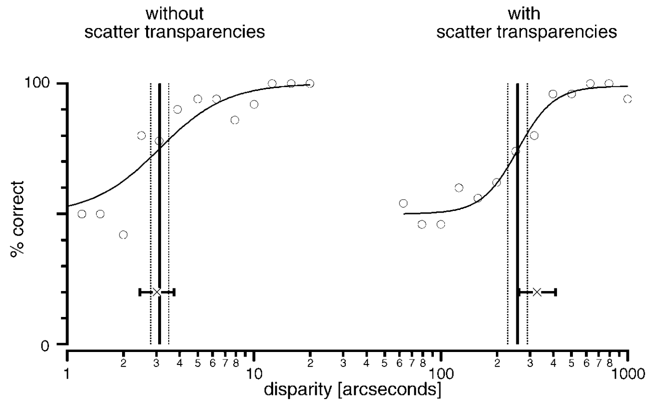


**Fig. 5** Psychometric functions obtained with constant stimuli and the results of the best PEST (observer 2). The 75% hit rate was reached at 3.1 arcsec without scatter transparencies and at 257 arcsec with scatter transparencies

## Results

The procedure with constant stimuli yielded sigmoid psychometric functions between hit rates of 50%, the chance level in the two-alternative test, and 100% (Figs. 4, 5). Applying the conventional 75% hit rate for the threshold, observer 1 reached a stereoacuity of 2.6 arcsec without and 261 arcsec with the scatter transparencies. The values for observer 2 were 3.1 arcsec and 257 arcsec, respectively. With best PEST the two observers reached very similar values (Figs. 4, 5). Observer 1 reached an average of 2.5 arcsec (95% confidence interval 2.3–2.7 arcsec) without scatter transparencies and an average of 254 arcsec (95% confidence interval 225–286 arcsec) with scatter transparencies. Observer 2 reached an average of 3.0 arcsec (95% confidence interval 2.4–3.7 arcsec) without scatter transparencies and an average of 327 arcsec (95% confidence interval 261–411 arcsec) with scatter transparencies.

With one eye only, the two observers, utilising the position cue, achieved a coarse pseudostereopsis: observer 1 at 56 arcsec, observer 2 at 26 arcsec. The two strabismic patients responded by chance.

## Discussion

The Freiburg Stereoacuity Test allows presentation of stimuli over a wide range of disparities. Using the antialiasing technique, a disparity as small as 1 arcsec can be realised on a standard monitor with resolution of 800×600 pixels at a distance of 4.5 m. By adjusting the distance between the stereo target and the reference frame to values as small as 300 arcsec very high stereoacuity can be reached, as exemplified by observer 1, whose stereoacuity of 2.6 arcsec is in the region typically reached by trained observers in differentiation tasks between “in front” and “behind” [7]. On the other hand, gross stereoacuities of around 1000 arcsec can also be measured with the Freiburg Stereoacuity Test, allowing, for instance, quantification of the detrimental effect of optical blur. This was demonstrated in observers 1 and 2, whose stereoacuity was reduced by scatter transparencies to about 250 arcsec.

The logarithmic scale used in our design has proved to be adequate since the shape of the psychometric function was quite similar when the stereoacuity was determined without scatter transparencies at about 2.5 arcsec and with scatter transparencies at about 250 arcsec. The alternative, a linear scale, would have resulted in very different shapes of the psychometric function at high and low stereoacuities; the curve would have been quite flat at 250 arcsec.

Implementing the best PEST demonstrated that the Freiburg Stereoacuity Test allows measurement of stereoacuity with a time-saving adaptive staircase procedure. The average of the best PEST results was in good agreement with the 75% correct answers used as the threshold in the two-alternative forced choice paradigm with constant stimuli. Moreover, the reproducibility of the best PEST, apparent in a small 95% confidence interval, is very good in trained observers.

As opposed to random-dot stereograms, the Freiburg Stereoacuity Test uses a stimulus that can also be seen monocularly. This bears the advantage that the viewing condition is natural and that very small stereodisparities can be detected, but also entails the disadvantage that the lateral position of the stereo target provides a monocular cue for depth. In the Freiburg Stereoacuity Test this monocular cue is masked by randomly placing the target to the right or left. The two observers who knew all the details of the test were able to utilise the position cue, achieving a coarse pseudostereoacuity of about 40 arcsec, about 10 times worse than their true stereoacuity. Nonetheless, the masking can be considered sufficient since two cooperative strabismic patients who had never experienced stereopsis and thus were used to relying solely on monocular cues for depth distinction were unable to solve the test.

In conclusion, the Freiburg Stereoacuity Test fulfils requirements that reach far beyond those conventionally requested for clinical stereo tests. Hence, the Freiburg Stereoacuity Test appears suitable for answering questions such as whether or not a given therapeutic intervention improves stereoacuity. The Freiburg Stereoacuity Test is available at http://www.ukl.uni-freiburg.de/aug/bach/fst/.

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