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Interindividual variability of learning in stereoacuity

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Abstract *Background:* In the evaluation of therapies aiming at binocular vision, for instance by the use of prisms or orthoptic training in the case of heterophoria, stereoacuity is often the primary outcome measure. To assess therapeutic effects it is necessary to separate them from perceptual learning with repeated testing. Learning stereoacuity has been investigated only in a few studies with up to six subjects. *Methods:* To ascertain the interindividual variability of learning in stereoacuity we examined 24 subjects, 12 with and 12 without experience in psychophysical experiments. In a two-alternative forced-choice paradigm, subjects reported whether a vertical bar appeared in front of or behind a reference frame. Estimates of stereo threshold were obtained using an adaptive staircase procedure ("best PEST"). *Results:* We found a highly significant learning effect ($P<0.0001$) with a marked interindividual variability. In some subjects the stereoacuity improved by a factor of >30 and in others it did not improve at all. The median of the learning factor was 1.7. There was no significant difference between novices and experienced subjects. *Conclusion:* The great interindividual variability of learning in stereoacuity has important implications for therapeutic tests that use stereoacuity as an outcome measure: To distinguish therapeutic effects from improvements due to repeated testing, each subject's individual learning behaviour has to be taken into account, for example by starting out with an adequate training phase. The number of test repetitions required to reach a fairly constant level appears to be similar among individuals: in our paradigm most of the learning occurred within the first six blocks with 100 target presentations each.

Introduction

Stereopsis is regarded as the most refined feature of binocular vision. Accordingly, quantification of stereopsis by measuring stereoacuity is a suitable means of evaluation for therapeutic measures whose aim is to achieve binocular vision. For example, if one were to compare the efficacy of orthoptic training with that of prisms or surgery in patients suffering from heterophoria, it would be important to recognise perceptual learning during repeated testing. Therefore it is necessary to know the interindividual variability of the learning behaviour with respect to both its amount and the time course.

Stereoacuity is a form of hyperacuity, a term coined by Westheimer [27] to describe the ability of the visual system to detect spatial relations with the precision of a fraction of a photoreceptor's diameter. It is well known that the various forms of hyperacuity can improve with practice. This has been documented for vernier [5, 6, 7, 14, 17, 19, 25], curvature [5] and orientation acuity [5]. Concerning stereoacuity, only a few subjects have been examined, and improvement by learning has not been found in all of them. Kumar and Glaser [14] presented three subjects with a large number of different stereo stimuli. They observed learning effects, but in each subject stereoacuity improved with another kind of stimulus. Fahle and Henke-Fahle [6] studied six subjects. Only in four of them did stereoacuity become better. Fendick and Westheimer [8] studied the learning behaviour of two subjects with stereo targets imaged on the fovea and in peripheral regions. In the periphery the stereoacuity improved in both subjects, in the fovea only in one of them.

In view of the limited knowledge of training effects in stereoacuity we investigated 24 subjects, 12 with and 12 without experience in psychophysical experiments.

Methods

Subjects

Medical students and employees of our department were asked to join a screening procedure. They had to comply with the following three conditions: Corrected visual acuity at least 20/20 with each eye, difference of visual acuity between both eyes not more than a factor of 1.26, and absence of strabismus, ascertained with the unilateral cover test. Screening was continued until 24 subjects were recruited. They were between 19 and 57 years of age with the median at 27 years. A first group comprised 12 volunteers who had never participated in a psychophysical experiment (KH, KS, BH, KK, CW, AL, KB, PE, ML, TF, MG, HG). A second group comprised 12 employees of our department who had often taken part in psychophysical experiments, but had never performed the stereoacuity test employed here or participated in any other study of stereoacuity. Among these were three orthoptists (TK, UZ, HL), two physicians (FP, BS), five postgraduates of various sciences (AR, TH, SH, JK, PM) and two laboratory assistants (MS, CK). Subjects were informed that the goal of the experiment was to ascertain the reproducibility of a stereoacuity test. As an introduction to the task, they viewed several sample stimuli with a disparity of about 500 arcsec. All subjects gave informed consent to take part in the experiments.

Apparatus

We used the Freiburg Stereoacuity Test [3]. The essential features of this test are the following: The stimulus is presented at a distance of 4.5 m on a visual display unit (GD403, Richardson Electronics) 36 cm wide and 27 cm high, with a resolution of 800×600 pixels and a frame rate of 120 Hz. The monitor is driven from the mainboard graphics card of a standard computer (Macintosh G4). The separation for the right and left eye is achieved by a pair of ferroelectric liquid crystal shutter goggles (FE1, Cambridge Research Systems). The shutter goggles are synchronised to the monitor frequency so that every second image is presented to the right and left eye, respectively. Each eye receives its image at a frequency of 60 Hz, which is just above flicker fusion frequency.

The stereo target consists of a vertical bar that is surrounded by a frame (Fig. 1). A pattern with random black-and-white squares surrounds the frame (edge length 180 arcsec). 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 sufficient stimulus width and length at small disparities, the frame height is kept at a minimum of 3600 arcsec and the frame width at

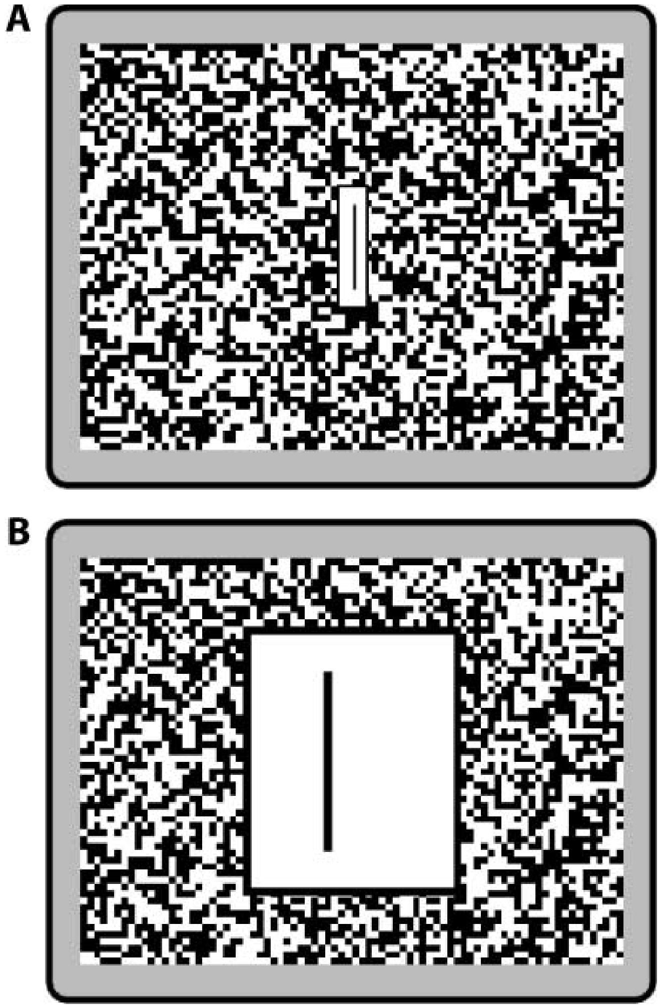

Fig. 1A, B Freiburg Stereoacuity Test. A vertical bar appears with variable disparity either in front of or behind a reference frame. The size of the bar and the frame are kept at a constant factor relative to the disparity of the bar. To obscure monocular cues the bar is randomly displaced to the left or right. **A** Example of fine stereo disparity. **B** Example of gross stereo disparity

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 actual disparity. The distance between the bar and the left or right inner frame edge is 3 times the disparity, but is clamped to a minimum of 300 arcsec for disparities below 100 arcsec to comply with the spatial requirement for fine stereoacuity [16].

At the viewing distance of 4.5 m each pixel subtends 20 arcsec. Disparities smaller than the width of a pixel are attained by “anti-aliasing” [1,22]: The margins of the vertical bar are smoothed with a gradual transition of the luminance following a Gaussian profile. The Gaussian profile has a standard deviation of 2 pixels. The profile can be shifted to the right or left by fractions of a pixel. Anti-aliasing requires accurate control of luminance, taking into account the inherent non-linearity of cathode ray tubes. For that reason the monitor is “gamma corrected” [2] to achieve a linear grey scale centred on a mean luminance of 220 cd/m^2. The goggles transmit approximately 14% of the light, resulting in a mean luminance of 31 cd/m^2 as seen by the subject.

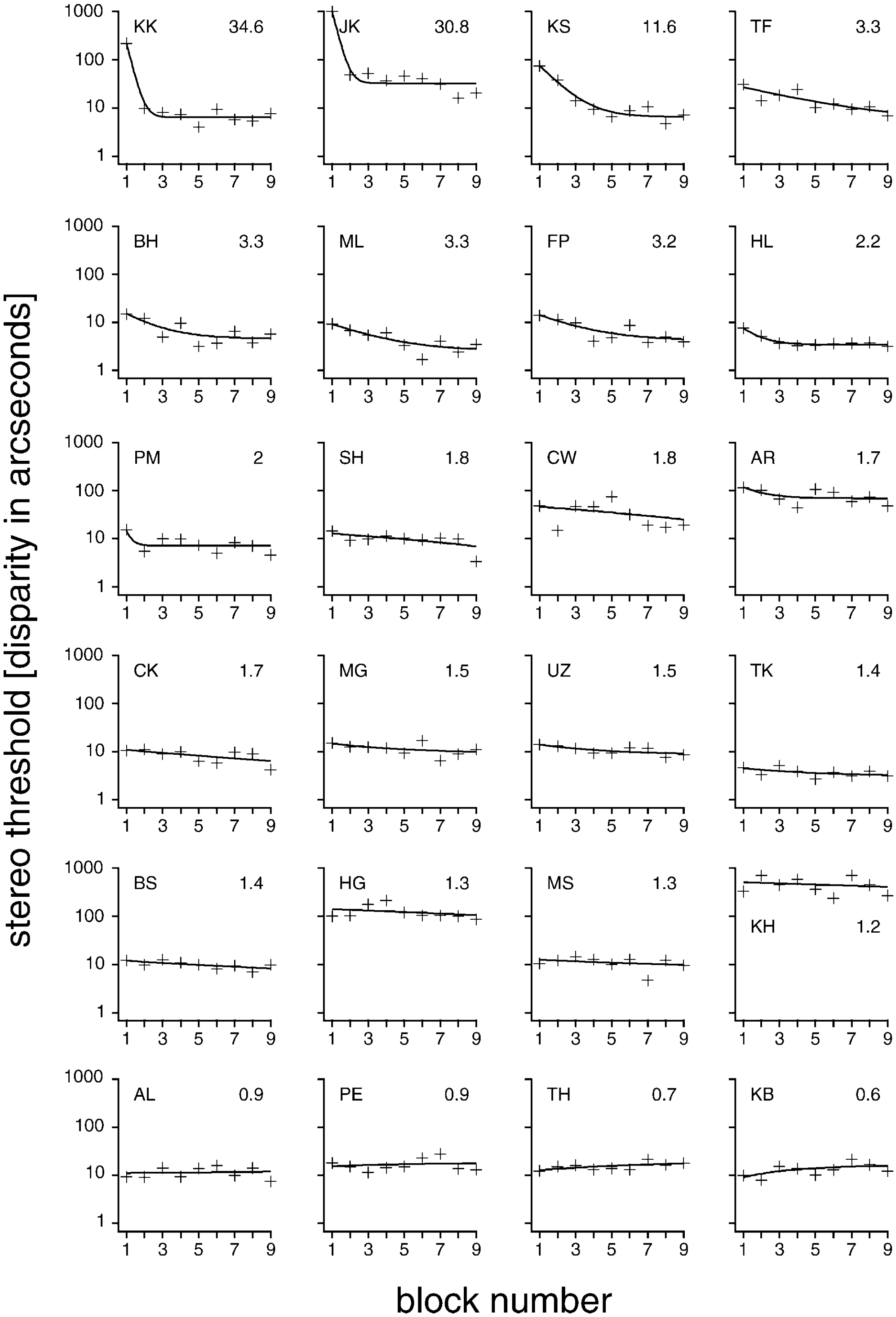

Fig. 2 Stereo threshold over the course of the nine training blocks. Each graph represents one of the 24 subjects, identifiable by their initials. The *crosses* indicate the threshold as calculated by the best PEST after 100 trials. The *solid lines* are the exponential fit functions. The *numbers* in the top right corners represent the learning factors (ratio of initial over final threshold). Subjects are sorted by their learning factor in decreasing order. A wide variability in amount and course of learning is seen

Procedure and data analysis

We used a two-alternative forced-choice paradigm in which the subject had to report whether the bar appeared in front of or behind the frame. The stimulus disappeared when the subject had made his or her choice by pressing the appropriate button on a response box. At the beginning, most subjects took about 10 s to make their decision, at the end of the test sequence about 2 s. The next stimulus was presented after an interval of 0.5 s during which the random square pattern covered the whole field. Data were analysed online using the “best PEST” (best parameter estimation by sequential testing; [10, 15]). The best PEST assumes that the psychometric function has a sigmoid form (in our design a logistic function) and takes the point where the slope is steepest for the threshold. After each response the best PEST calculates the most likely threshold on the basis of all previous responses and sets the next stimulus accordingly. After the initial 12 trials and then after every 5th trial we presented a "bonus" trial with a disparity 5 times the current threshold estimation to keep up the subject's motivation. Bonus trials were included in the best PEST analysis. The value reached after 100 trials (one block) was taken as the stereo threshold. A test session consisted of three blocks. The interval between blocks was at least 10 min. Each subject attended three sessions on three consecutive days, nine blocks altogether.

As will be seen, subjects differed widely in their learning behaviour. After several attempts of quantification with various algorithms, including multiple time constants, we chose as a parsimonious description an exponential fit per subject as follows:

$$f_i(b) = c_{i1} + c_{2i} * \exp\left(-\frac{b-1}{\tau_1}\right)$$

where i identifies the subject, b the block number (1–9), c_1 the asymptotic threshold, c_1+c_2 the threshold after the initial block and τ the time constant (in blocks).

As there was no obvious grouping of the data by session (which comprised three blocks), we chose to define the learning curve in blocks. To quantify the strength of learning by a single number, we calculated a "learning factor" for subject i as $f_i(1)/f_i(9)$. Thus a learning factor greater than 1 indicates a decrease in stereo threshold or an increase in stereoacuity.

Results

A repeated-measures ANOVA revealed a highly significant learning effect (P<0.0001) and no significant difference between novices and experienced subjects. The initial stereoacuity ranged from 4.5 to 1000 arcsec with a median at 14.7 arcsec (Fig. 2); the final stereoacuity ranged from 2.8 to 406 arcsec, median 8.7 arcsec. The learning behaviour varied considerably among the 24 subjects. The learning factor ranged from 34.6 to 0.6 with a median at 1.7. Three subjects had a learning factor of ≥10, ten subjects of 3.3 to 1.7, and seven subjects of 1.5 to 1.2. In four subjects the learning factor was below 1.0. The time course of learning also differed widely among subjects. Omitting the four subjects with learning factors below 1.0 the time constant of the fitted exponential function ranged from 0.3 to 41.5 blocks with a median at 3.5 blocks.

Discussion

In nearly all subjects the stereoacuity increased over the course of the nine blocks with 100 stimulus presentations each. A general assessment of all subjects is, however, precluded by the marked interindividual variability. In 17 of the 24 subjects the stereoacuity increased from the first to the ninth block by factors between 1.4 and 34.6. In the other seven subjects factors between 0.6 and 1.3 were found, which means that, for practical purposes, these subjects did not learn at all. The greatest improvements, with factors >30, occurred in subjects who had started with a high threshold (=220 arcsec). The time course of learning also differed widely. In three subjects (KK, JK, PM) stereoacuity improved mainly during the first two blocks, whereas in others it improved monotonically during the nine blocks. Although most of the learning occurred within the first six blocks, informal testing showed that learning can continue far beyond the ninth block. For instance, one of the authors of the present study (CS) reached 9 arcsec at the 10th block and levelled off at about 2 arcsec from the 30th block onwards. We also observed long-term retention: retesting four of our subjects after several months showed that they had maintained the stereoacuity reached after the nine blocks of the formal experiment.

The proportion of "learners" and "non-learners" in our study is compatible with the results of other authors obtained in smaller groups. Of the two subjects studied by Fendick and Westheimer [8], only one improved with practice. Fahle and Henke-Fahle [6] found an improvement of stereoacuity with practice in four of six subjects. In the study conducted by Ramachandran and Braddick [20], stereopsis improved in all 11 subjects with training, but the task given by these authors was different from ours: they measured the time required for perception of a stereogram with a fixed disparity of 7.2 arcmin rather than the disparity threshold. Kumar and Glaser [14] found learning effects in all of their three subjects, but each of them improved with another type of stereo target.

The reasons for the great interindividual variation in perceptual learning found in our study are unclear. Prior experience in psychophysical experiments was probably not relevant, since the performance of the 12 subjects who had frequently participated in psychophysical experiments did not differ significantly from the performance reached by the 12 novices. The various time courses of learning may reflect different learning mechanisms: Drastic improvements from the first to the second block, e.g. in subjects KK and JK, may have been caused by cognitive factors such as better understanding of or concentration on the task. The more gradual improvements, e.g. in subjects KS, TF, BH, ML and FP, may have been due to specific mechanisms in the primary visual cortex. This idea is supported by several studies in animals that showed cortical plasticity at adult age after sensory deafferentiation in the somatosensory [18], auditory [21], motor [23] or visual domains [9, 12]. There is also evidence for cortical plasticity associated with perceptual learning in adult humans. During exposure with supra-threshold vernier stimuli [25, 26] and sub-threshold stereo stimuli [24], the activity recorded from scalp electrodes was found to change in parallel when the psychophysical threshold improved. The site of the electrodes from which the maximal changes were recorded suggested an origin in the primary visual cortex.

Previous researchers of visual functions also concluded that perceptual learning occurs in different phases. For instance, Fahle [4] found a fast learning phase during the first 30 min and a slow learning phase that extended up to 10 h or even beyond. In both phases the learning was very specific to the task. For example, an improvement in detecting a horizontal vernier offset was not transferred to a vertical offset. On the basis of this specificity, Fahle suggested that the structural basis for learning was localised in early levels of cortical processing. Karni and Sagi [13] studied learning in texture segregation (a mechanism of figure–ground segregation). The threshold levelled off within a few minutes. Further improvement only occurred after a rest of about 8 h, preferably overnight. Karni and Sagi suggested that the fast learning within the first few minutes may reflect a task-specific routine, while slow learning occurring after a rest may indicate a long-term modification of perceptual modules. In our study we did not encounter a latent phase: the stereoacuity improved irrespective of the duration of the interval between blocks.

The great interindividual variability of learning in stereoacuity revealed in our investigation has important implications for therapeutic studies that use stereoacuity as an outcome measure: To distinguish therapeutic effects from improvements due to repeated testing, each subject's learning behaviour has to be taken into account, for example by starting with an adequate training phase. Although the amount of learning is quite variable, the number of trials required to reach a fairly constant level appears to be similar among individuals: in our paradigm most of the learning occurred within the first six blocks (600 stimulus presentations).

Are the improvements of stereoacuity reached under laboratory conditions beneficial for everyday life? This appears unlikely, since learning effects in the various hyperacuity domains are limited to the type of target used for the training [5, 7, 20, 25]. Moreover, one should consider that improvements in a specific hyperacuity task might be achieved by allocation of limited neural resources and thus go along with a loss in similar tasks [11]. On the basis of these arguments we see no point in therapeutic training with an apparatus designed for measuring stereoacuity such as the Freiburg Stereoacuity Test.

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