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# Assessing spatial vision — automated measurement of the contrast-sensitivity function in the hooded rat

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**Abstract**

The contrast-sensitivity function (CSF) provides a concise and thorough description of an organism's spatial vision; it is widely used to describe vision in animals and humans, to track developmental changes in vision, and to compare vision among different species. Despite the predominance of rats in neuroscience research, their vision is not thoroughly studied due to the complexity of psychophysical measurement and a generally held notion that rat vision is poor. We therefore designed an economical and rapid method to assess the hooded rat's CSF, using a computer monitor to display stimuli and an infrared touch screen to record responses. A six-alternative forced-choice task presented trials in which a sine-wave grating (S+), varying in spatial frequency and contrast, was displayed at different locations along with five gray stimuli (S−). Nose pokes to the S+ but not the S− produced water reinforcers. Contrasts were tested at each spatial frequency with a simple adaptive procedure until stimulus detection fell below chance. Psychometric functions were obtained by maximum-likelihood fitting of a logistic function to the raw data, obtaining the threshold as the function's point of inflection. As in previous studies with rats, CSFs showed an inverse-U shape with peak sensitivity at 0.12 cyc/deg and acuity just under 1 cyc/deg. The results indicate the present computer-controlled behavioral testing device is a precise and efficient instrument to assess spatial visual function in rats. 

*Keywords:* Vision; Behavior; Psychophysics; Contrast sensitivity; Acuity; Touch screen; Computer

## 1. Introduction

Vision presents a singularly clear window into the study of brain-behavior relations. At the level of behavior, tests which relate stimulus magnitude to response probability yield psychophysical functions of unparalleled order (e.g. Uhlrich et al., 1981). The ability to precisely define the effective dimensions of stimuli has yielded exacting research on the neural pathways and brain processes involved in vision (e.g. Legg, 1986). The retina's laminar organization, its anatomical separation from other structures, and the topographic organization of projections via the optic nerve make vision an ideal system for correlating post-trauma cellular events with behavioral effects and post-lesion neuroplasticity (Lund et al., 1976; Yamadori, 1981; Dreher et al., 1985; Duvdevani et al., 1990; Sautter and Sabel, 1993; Sabel et al., 1995, 1997a,b; Sabel, 1999).

Most research on vision is accomplished with large mammals and birds rather than with the more accessible laboratory rat. Rat vision is probably understudied because of the popular belief they have poor vision and therefore uninteresting visual systems. Qualitatively, however, rat vision is much like that of other species (Birch and Jacobs, 1979; Uhlrich et al., 1981; Silveira et al., 1987) and of sufficient complexity to be a valuable model for research. Within and across species, the most common assessment of spatial vision involves training subjects to discriminate between patterned stimuli made up of light and dark bands (optical gratings) and gray patches of equal luminance. Test sessions arrange trials in which gratings and gray stimuli are simultaneously presented, reinforcing responses to the gratings and

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extinguishing responses to the gray stimuli. Grating acuity can be determined over a series of trials by making the grating bands narrower (increasing spatial frequency), to the point where a subject can no longer distinguish the grating from the gray stimuli. Spatial contrast sensitivity is similarly determined by making the luminance of bands more alike (decreasing contrast). Contrast sensitivity depends on spatial frequency and needs to be tested over a range of frequencies for comparing organisms. Many experiments now indicate that grating contrast sensitivity provides a sensitive psychophysical measure of spatial vision (Campbell and Robson, 1968; Ginsburg et al., 1980; Olzak and Thomas, 1986; Regan, 1988; Strasburger et al., 1996).

Valid and reliable threshold values critically depend on the procedures used to present stimuli. Systematic biases in thresholds are minimized when (1) target gratings and gray stimuli are placed in randomly selected positions during trials and when (2) a forced-choice procedure is used to collect objective performance data. Sessions must also program sufficient trials at each detectable stimulus value to obtain reliable thresholds. In the classic method of constant stimuli, one stimulus is repeatedly presented during a session; alternatively, adaptive staircase procedures adjust a stimulus parameter up or down on a trial-by-trial basis depending on whether the subject is correct or incorrect on the last trial (reviewed by Treutwein, 1995). Subjects' performance data are used to generate psychometric functions relating accuracy to contrast at a given spatial frequency. Contrast threshold, the smallest contrast required to detect a particular grating, is operationally defined as the point of inflection in the psychometric function (see Fig. 3). Contrast thresholds combine to generate a contrast-sensitivity function (CSF), providing a complete picture of the relation between threshold contrast and spatial frequency. The CSF plots contrast sensitivity versus grating spatial frequency, with the $x$-axis cutoff point representing grating acuity (see Fig. 4). CSFs have been generated for humans (Campbell and Green, 1965) and various other vertebrates including monkeys (De Valois et al., 1974), cats (Campbell et al., 1973), pigeons (Nye, 1968) and falcons (Uhlrich et al., 1981), hooded and albino rats (Birch and Jacobs, 1979; Silveira et al., 1987), and goldfish (Northmore and Dvorak, 1979); they have been used to study developmental changes in vision (Movson and Kiorpes, 1988); and they reveal more disturbances in pattern vision resulting from pathologies than elementary measures like acuity (Bulens et al., 1988; Regan, 1988).

The present experiment sought to test a simple but sensitive method to obtain a CSF for hooded rats in an automated fashion. The hooded rat was chosen over the albino rat because its pigmented eye produces better acuity and contrast (Birch and Jacobs, 1979), making it the more sensitive model for the study of neural trauma and recovery (Sabel et al., 1997a). In addition, albino rats are mutants that possess an abnormal visual system. A major impediment in the study of animal psychophysics is the collection of reliable data with a reasonable investment of time and physical resources. In the present study, economy was achieved by employing a standard computer monitor to display stimuli and a commercially available infrared touch screen to detect nose-poke responses made to stimuli. Touch screens have been used for vision-related behavioral testing with a variety of species but only recently with the rat (Markham et al., 1996; Aggleton et al., 1997). Computer software controlled grating generation, stimulus display counterbalancing, response recording, and reinforcer delivery. A six-alternative forced-choice procedure was employed to minimize the probability of reinforcement for rats adopting random search behavior. During daily sessions, a simple adaptive procedure presented a spatial frequency at successively decreasing contrasts in blocks of trials, while spatial frequency varied between sessions. CSFs were generated with thresholds obtained by fitting the raw accuracies at each spatial frequency with statistics designed to model transition functions (Harvey, 1997a).

## 2. Methods

### 2.1. Subjects

Seven 3-month-old male, hooded Long–Evans rats were used for the study (BDE-Han strain, Zentralinstitut für Versuchstierzucht, Hannover, Germany). Rats were maintained on a 12:12 h dark-light cycle (lights on at 06:00 h) at an ambient temperature of 24–26°C (65% humidity) with food available ad libitum. Before training, rats were handled for 15 min per day and a water-deprivation schedule was placed into effect. Water was withdrawn for 24 h the first day and then administered 15 min daily until the rats reached 85–90% of their ad lib body weight (approximately 1–2 weeks). Thereafter, rats were given water after each daily session for 20 min.

### 2.2. Apparatus

Testing was conducted in a standard rat chamber (Coulbourn Instruments, USA), measuring 300 × 245 × 290 mm, equipped with a 0.06-cc-cup water dipper (Coulbourn Instruments, Fig. 1A). The chamber was modified for nose poking by adding a 2 × 3 array of 41 mm square openings centered in the aluminum wall opposite from the water dipper (Fig. 1B). The openings were positioned such that an adult rat could observe the lower row of stimuli without raising its

front legs or moving its head from the perpendicular. In order to nose poke the upper stimuli, a rat raised itself on its hind legs and assumed an approximate 45° attitude (a fully reared rat could raise its head above the top of the array).

A 14 inch VGA monitor was centered behind the six-hole array (Siemens Nixdorf; 31.4 kHz line frequency; 60–70 Hz frame rate). Stimuli were presented on the 199 × 140 mm central portion of the monitor. An infrared touch screen (Carroll Touch, USA) designed for 14 inch monitors was fitted over the monitor face. A clear sheet of 2 mm thick polycarbonate plastic separated the recording area of the touch screen and the surface of the monitor (Fig. 1A). The distance from the inside surface of the aluminum wall to the plastic was 24 mm and the infrared beams, directly in front of the plastic, were 52 mm from the monitor surface. Additional 60 mm spacers were inserted between the touch screen and the monitor to increase the subject's viewing distance to stimuli (Fig. 1A). In order to produce circular gratings, an opaque poster-board mask with six 35 mm circular holes was attached to the monitor side of the plastic window (Fig. 1B). Holes in the mask aligned with openings in the aluminum chamber wall. At the moment of nose poking, this configuration resulted in stimuli subtending 70° of visual angle at a distance of 70 ± 2 mm to the stimuli. The slight hyperflexion of the stimulus presentation area on the monitor did not significantly alter spatial frequency and was disregarded.

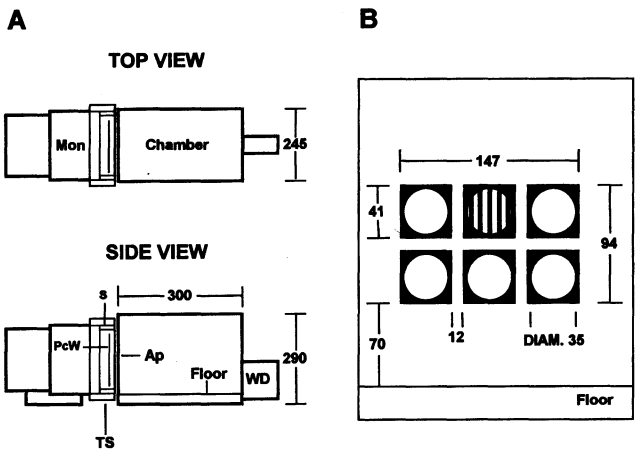


Fig. 1. Scale drawings of the testing apparatus with dimensions in mm. (A) Top and side views of the operant testing chamber, water dipper (WD), infrared touch screen (TS), and VGA monitor (Mon). Dashed lines within the touch-screen housing represent, from left to right, the monitor face, spacers (S), polycarbonate window (PcW), and apertures (Ap) in the aluminum chamber wall. The horizontal dashed line near the bottom of the chamber indicates the chamber floor. (B) Front view of the square nose-poke apertures in the chamber wall and circular stimulus masks on the touch screen. The dashed line at the bottom of the panel represents the chamber floor. The stimulus in the upper row's middle position is a square wave grating (i.e. with abrupt transitions from dark to light). A sine wave grating, i.e. an actual stimulus, is not shown because it will not reproduce faithfully in print. A special sine wave grating that serves as a demonstration of the contrast sensitivity function is the Campbell–Robson chart. It can be found under http://vsoc.berkeley.edu/izumi/CSF/A_JG_RobsonCSFchart.html. See the Vision Science home page, http://www.visionscience.com/, for a broad range of material in vision research.

The experiment was controlled with an MS-DOS based PC and software written in Turbo Pascal. Events were timed with millisecond accuracy. The $x$- and $y$-axis resolution of the touch screen was 3.15 mm; response events were sampled 40 times per s. The touch-screen response-recording area (41 × 20 mm) over each stimulus subtended the lower 20 mm of the openings in the aluminum wall. To reject, as valid responses, sweeping motions with the head (including observation of the stimulus) or intrusion of the body or tail, nose pokes were recorded only if the rat removed its rostrum within a 12.6 mm radius from the point of entry. The nose poke itself, i.e. the breaking of the infrared beams, had to occur within the lower 20 mm of the stimulus. A nose poke to a stimulus was recorded when the rat broke the infrared beams in this area and removed its rostrum within a 12.6 mm radius from the entry point. This feature preferentially selected nose pokes by averting incidental reinforcement of sweeping motions with the head (including observation of the stimulus) or intrusion of the body or tail. Consequences for nose pokes were thus arranged to follow the withdrawal of the nose. Visual observation and video recordings assured that all subjects responded by nose poking.

### 2.3. Stimuli

The stimuli were vertically oriented achromatic sine-wave gratings, varying in spatial frequency and contrast. Monitor resolution was set to 640 × 480 pixels, each being 0.39 mm wide. The standard VGA graphics board offered 64 luminance levels (6-bit gray palette). Mean stimulus luminance was 51 cd/m$^2$ as measured with a standard light-meter (Gossen Panlux). Grating contrast $C$ was defined in Michelson units: $C = (L_{max} - L_{min})/(L_{max} + L_{min})$, where $L_{max}$ and $L_{min}$ are the grating's maximum and minimum luminance, respectively. The contrast values used in our study were: 4, 8, 13, 20, 31, 42, 56, 75, and 100%. Grating spatial frequencies were integer multiples of the pixel width (Bach et al., 1997); the grating with highest spatial frequency had a period of 2 × 0.39 mm. Nine spatial frequencies, calculated from a viewing distance of 70 mm, were evaluated: 0.041, 0.075, 0.10, 0.12, 0.17, 0.22, 0.31, 0.52, and 0.78 cyc/deg. An additional spatial frequency of 0.14 cyc/deg was used solely for training.

### 2.4. Viewing distance

Spatial frequencies are calculated for an effective viewing distance of 70 mm which is attained ± a few millimeters when the rat lightly touches the screen. Even though the rat is free to view the stimuli from a larger distance, we are confident that the decision for nose poking is made at the smallest distance for three reasons: (1) Due to the CSF's high-spatial-frequency roll-off (see Fig. 4), stimuli with spatial frequencies above about 0.15 cyc/deg that are visible at the closest distance are invisible at higher distances, so a reward will only be given for decisions made at the closest distance; (2) The rat cannot increase the viewing distance once it explores at close distance (see below); and (3) The rat explores the locations before each nose poke.

### 2.5. Procedure

Sessions were scheduled individually for each rat on a daily basis at the same hour (earliest start at 08:00 h) in a darkened room during the rat's light cycle. A grating of 0.14 cyc/deg at maximum contrast, known to be within the rat's range of sensitivity, was used to shape the nose poke toward gratings. A shaping session began with the presentation of the training grating at one of the six positions. No other stimuli were presented during these training sessions. Successive approximations to nose poking the stimulus were reinforced by manually operating the water dipper with a push button. The dipper consisted of a small metal cup attached to the end of an arm connected to a solenoid. The dipper, when activated, was raised vertically out from a water reservoir and the cup was presented through a circular opening in the floor of the dipper housing. The dipper was operated until the rat consumed the water; the rat became aware of the reward by the solenoid click and the simultaneous activation of a tiny light above that illuminated the cup. Once a rat successfully nose poked a stimulus, the screen was darkened, the water dipper presented water for 5 s, and after a 15 s inter-trial interval (ITI), the stimulus reappeared at a new position in the array. Nose pokes to locations in the array without stimuli had no consequences. This tracking procedure continued until nose poking was reliably learned and rats completed a 40-trial session within 1 h.

Training for establishing the operant-conditioned behavior continued with a discrimination learning in which a 4 s fixed interval (FI) timed from the beginning of each stimulus presentation was added. The FI permitted the rat a short period in which exploration of openings would have no consequences. After the FI, the first nose poke to the training grating darkened the screen, produced 5 s of water, and a 15 s ITI. A nose poke after the FI to any location without a grating darkened the screen for a 25 s time-out and scheduled a correction trial in which the grating was presented in the same location. Once performance stabilized at above 90% accuracy over three consecutive sessions, gratings were presented with solid gray stimuli, equal in luminance to the grating mean to shape the behavior for stimulus discrimination. During the ITIs or time-outs, the screen was uniformly illuminated at 25 cd/m$^2$ to maintain photopic adaptation.

Testing proper began after the operant-conditioned behavior was firmly established, i.e. when discrimination between the grating and gray stimuli reached the previous stability criterion. The testing task incorporated all of the features of the last training sessions. Each test session scheduled trials with a single spatial frequency and different contrasts. Frequencies were presented in random order to each subject until all spatial frequencies were tested. Grating contrast was systematically reduced during a session in blocks of trials, beginning with a block at 100% contrast. The first block at full contrast ended if the rat correctly completed three trials in a row or if 20 trials were completed, irrespective of the number correct. The remaining blocks, each with reduced contrast, were exited if the rat completed two trials in a row correctly or after eight trials with at least two non-consecutive trials completed correctly. The higher exiting criterion in the first block improves percent-correct resolution at high performance where an error by chance has an unduly large effect. A session ended after (1) a block in which a subject completed less than two correct trials or (2) after meeting criterion in the last block at the lowest (4% Michelson) contrast.

## 3. Results

Fig. 2 shows the training performances of individual rats over sessions. The left panel shows acquisition of the stimulus-tracking performance and the right shows acquisition of the discrimination between the grating and solid-gray stimuli. Acquisition of stimulus tracking was rapid, showing above-chance accuracy in the first session and better than 90% accuracy in five to seven days. The mean number of sessions to meet the tracking criterion is 9.7 (S.D. = 2.3). The training of the discrimination between the grating and solid gray stimuli reached criterion in an additional 2 weeks (13.0 days, S.D. = 3.7). These initial training sessions lasted approximately 20–30 min, with no evidence of within-session satiation effects such as pausing or changes in accuracy.

Contrast thresholds were estimated for individual subjects at each of the nine spatial frequencies by fitting a logistic function to the raw accuracy data with a

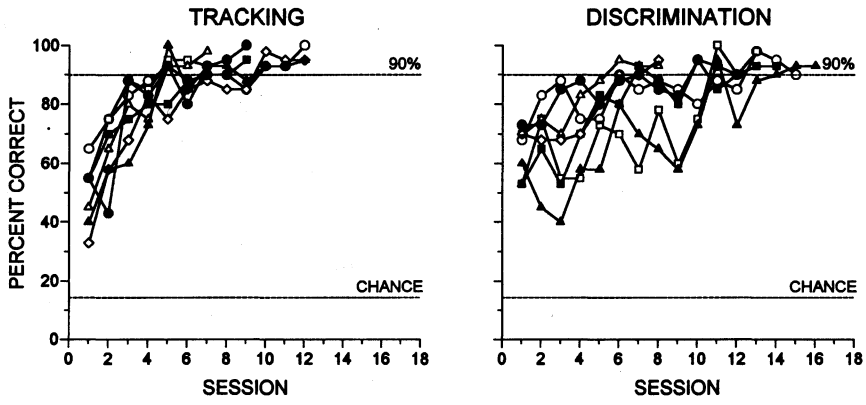


Fig. 2. The left plot shows acquisition of tracking of the single, randomly positioned maximum-contrast grating (0.14 cyc/deg) without gray stimuli. The right plot shows acquisition of the discrimination between the grating and gray stimuli. Different data point shapes identify individual rats. The dashed lines show the 90% performance criterion and the 16.7% chance performance level.

maximum-likelihood fitting program (MLPFIT program by Harvey, 1997a). Fig. 3 illustrates a logistic function fit to data from one subject at a spatial frequency of 0.17 cyc/deg. The dark solid line shows the best-fitting logistic function and the dotted lines, connected at the function's point of inflection, indicate that the contrast threshold for this spatial frequency lies at 14.8% (i.e. $10^{1.17}$).

The geometric means of the contrast thresholds at each spatial frequency were used to produce the CSF presented in Fig. 4: contrast sensitivity (reciprocal of contrast threshold) is plotted against spatial frequency (cyc/deg of visual angle) on logarithmic coordinates. The function for the rats clearly shows the anticipated inverse-U shape, with peak sensitivity at a frequency of about 0.10 cyc/deg. The solid curved line in Fig. 4 is a third-order polynomial regression fit to the log data ($\log[f(x)] = -0.128 - 1.955\ \log(x) - 0.717\ \log(x)^2 + 0.378\ \log(x)^3$; $r^2 = 0.989$). Extrapolation from the polynomial regression produces an estimate of acuity at 0.86 cyc/deg.

## 4. Discussion

Individual organisms and species differ in the absolute range of contrast and frequencies they perceive, but their CSFs always assume an inverted-U shape (Uhlrich et al., 1981). Peak contrast sensitivity is obtained at intermediate spatial frequency; sensitivity falls thereafter in a nearly linear relation with increasing spatial frequency until targets can no longer be detected (the high-cutoff point — zero sensitivity — at maximum contrast and spatial frequency). The linear drop-off, presumably, reflects optical limitations concerning the retinal receptor mosaic. At low spatial frequencies, sensitivity in the human critically depends on temporal characteristics of stimuli, with static stimuli producing intermediate sensitivity and rapidly changing stimuli producing sensitivity somewhat below the CSF maximum (Strasburger et al., 1993). The latter finding suggests that sensitivity at lower spatial frequencies is limited by neural mechanisms. The present methods generated a CSF with the same overall characteristics reported by previous studies of the hooded rat. Peak sensitivity is at 15% contrast and occurs at 0.12 cyc/deg, similar to what others have reported in their behavioral and electrophysiological investigations (Birch and Jacobs, 1979; Legg, 1986; Silveira et al., 1987). Our estimate of acuity is close to 1.00 cyc/deg, which is also similar to what others have found (Lashley, 1930; Birch and Jacobs, 1979; Dean, 1981; Silveira et al., 1987). The present results prove valid despite large differences in the stimulus display device and procedures. The reliability of measurements for each rat is apparent from the small standard errors.

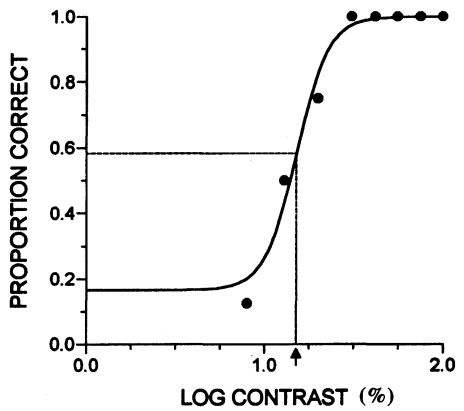


Fig. 3. Raw accuracy data for one rat at a spatial frequency of 0.17 cyc/deg, showing percent correct as a function of log Michelson contrast. The solid curve shows the best fitting logistic function and dashed lines indicate the point of inflection. The arrow on the $x$-axis of this example indicates that the threshold is 14.8% ($\log^{-1}$ 1.17) Michelson contrast.

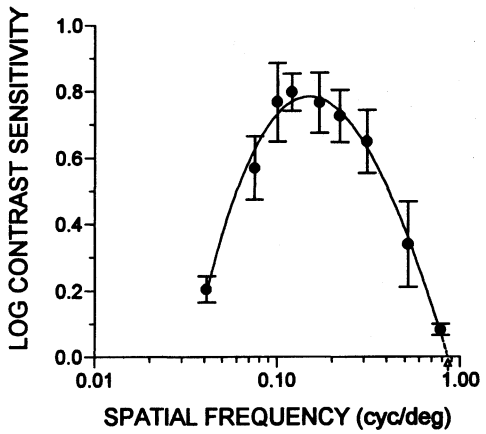


Fig. 4. Contrast-sensitivity function for the seven hooded rats in the present study. Spatial frequency is plotted on the $x$-axis and log contrast sensitivity (log [1/contrast-threshold]) is plotted on the $y$-axis. The $x$-axis is scaled logarithmically. The solid curved line is a third-order polynomial regression fit to the log transformed data. Each data point is the arithmetic mean for the seven rats; vertical bars represent the standard error of the mean. The dashed section of the regression line extrapolates to the high-cutoff point of the CSF (i.e. acuity) as indicated by the arrow on the $x$-axis.

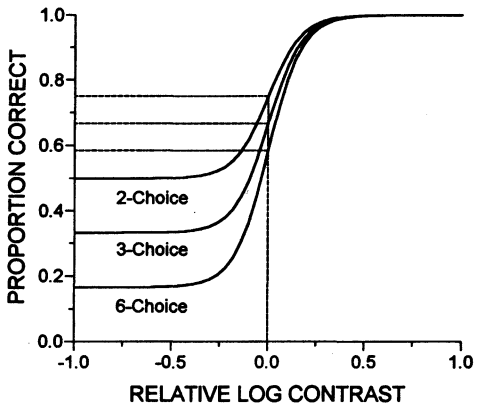


Fig. 5. Comparison of logistic functions for two-, three-, and six-alternative forced-choice tasks. The functions illustrate that more alternatives produce a steeper slope and a more sharply defined threshold. Functions are normalized with a threshold of 0.0 log-contrast (1% Michelson contrast on the $x$-axis). The function's equation is $f(x) = \gamma + (1-\gamma)/(1 + 10\,e^{-\beta * x})$, where $\gamma$ is the probability of a correct response by chance; the function's slope parameter, $\beta$, is set to 5.0. The inflection point in each function is marked with a horizontal and vertical dashed line.

A methodological advantage over previous studies may be the use of a spatial six-alternative forced-choice task combined with the touch screen as the response-recording device. One benefit is the rapidity with which rats were trained to discriminate between gratings and gray stimuli. Training with two alternatives as is often used can be slow since random response patterns are reinforced with a high probability (50% instead of 17% with six alternatives). The second benefit is that more alternatives make the slope of the psychometric function steeper and therefore the function's transition region that contains the threshold (inflection point) is narrower, as illustrated in Fig. 5. Consequently, procedures with more than two alternatives seem to require fewer trials to estimate a threshold with a given accuracy (Treutwein and Strasburger, 1999).

Certain technological and procedural considerations that arise in psychophysical vision testing with humans and other species (Bach et al., 1997; Strasburger, 1997a,b) are less critical with rats. A standard VGA computer monitor is just sufficient for testing rats and SVGA offers some headroom both on the contrast-sensitivity and acuity scales: the maximum spatial frequency employed in the present study (limited by pixel density and minimum viewing distance), with the touch screen a few centimeters from the monitor, is close to the rat's capabilities but does not allow a direct measure of acuity (see dashed line in Fig. 4). Variations in luminance across the screen, inherent to computer monitors, are perceivable by humans but lie outside of the rat's range of sensitivity. The standard 6-bit VGA palette, permitting a minimum contrast of 2.5%, does not directly restrict contrast threshold estimation because the rat's contrast sensitivity is low (5% Michelson contrast best threshold), although it does restrict the precision at maximum contrast sensitivity due to the limited contrast resolution. Although these hardware issues did not appreciably affect the present results with the hooded rat, both spatial and contrast resolution can easily be enhanced with a higher-resolution 8-bit graphics card. Higher resolution would allow a direct, adaptive measurement of acuity and improved precision at maximum contrast sensitivity. Concerning the choice of adaptive procedures, the simple method employed in the present study proved adequate to generate threshold measures with a small number of trials. More complex methods (reviewed in Treutwein, 1995) planned for future studies can further reduce session duration without compromising the reliability of thresholds.

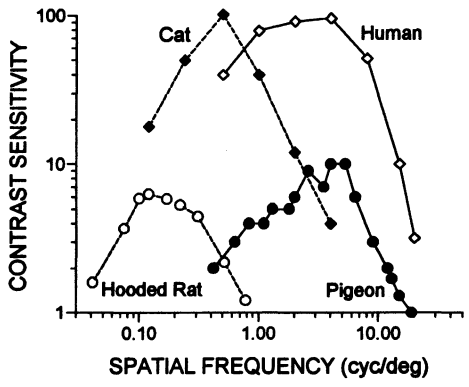


Fig. 6. Comparison of the contrast-sensitivity function for the hooded rat, pigeon, cat, and a human. Data for the pigeon, cat, and monkey reprinted from Ulrich et al. Cross-species correspondence of spatial contrast sensitivity functions, Behav Brain Res 1981;2:291–299, with permission of Elsevier Science. Data for the human are reproduced with permission of Harvey (1997b).

Fig. 6 shows CSFs from a human, cats, and pigeons, compared to that of rats in this study. It is clear that these CSFs differ mainly in maximum contrast sensitivity attained and in a shift along the spatial frequency axis. High contrast sensitivity serves in the discrimination of vague patterns or objects that differ little from the background. Note that, across species, a gain in acuity (highest spatial frequency processed) is partly accompanied by a loss of sensitivity at low spatial frequencies. This is unlike variations of the CSF within a species, where the causes for loss of acuity and of low-spatial-frequency processing are often independent. The comparative position on the spatial frequency axis across species might thus better be interpreted as an adaptation to a preferred viewing distance for survival. The fact that the rat's overall range of spatial frequenies processed (about 1–1/2 log units) is similar to that of the human or the pigeon (which possesses excellent pattern recognition capabilities) speaks for the hooded rat's vision being keenly adapted for seeing objects close up. At low spatial frequencies, the roll-off of contrast sensitivity is slightly steeper than in the human, and it is tempting to interpret this as the absence of a specific lowest-temporal-frequency channel. The hooded rat's contrast sensitivity range, about one log unit, is smaller than the cat's or the human's but is certainly substantial and far from deficient. Our measurements were under photopic conditions (similar to a clouded day) and it is an interesting open question whether the rat's sensitivity will be similar or different under scotopic conditions (similar to dusk or early dawn).

These considerations and our results speak to the promise of precise measurement of the rat's vision to correlate the effects of neurological phenomena with behavior. For example, injury to the rat optic nerve has been proposed as a model for the study of degenerative and regenerative processes post-trauma (Legg, 1986; Sautter and Sabel, 1993; Frank and Wolburg, 1996; Moore and Thanos, 1996; Sabel et al., 1997a,b). With the behavioral testing device described here, these studies can be extended by quantification of psychophysical parameters, thus improving the power of the model. Studies in humans, for example, have shown that the measurement of peak contrast sensitivity and acuity together markedly improves the ecological reliability of the visual test over that of each measure alone (Ginsburg et al., 1982; Cornelissen et al., 1995).

The methods presented in this study represent a substantial simplification in psychophysical measurement of the rat's vision with excellent precision. Rats quickly learned to nose poke gratings with a high degree of accuracy, produced sufficient data to estimate contrast thresholds in less than 30 trials, and generated complete CSFs in a matter of days. Computer automation, a computer monitor for stimulus display, touch-screen response recording, use of a six-alternative forced-choice task, and an adaptive stimulus presentation strategy were combined to produce an economical and precise method for obtaining psychophysical measurements of rat spatial vision.

## Acknowledgements

Hans Strasburger and Daniel Cerutti contributed equally and the author series does not reflect a ranking. We thank Matt Ward for his ambassadorial role in preparation of the touch system, Andreas Bohne for his technical advice, and Lewis O. Harvey for providing us with a human CSF. The Deutsche Forschungsgemeinschaft supported this research.

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