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Pattern Recognition of Rat Behavior

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KERNAN, W J , JR , P J MULLENIX AND D L HOPPER *Pattern recognition of rat behavior* PHARMACOL BIOCHEM BEHAV 27(3) 559–564, 1987 —Analysis of animal behavior has been an arduous task requiring a human observer to record and classify individual motor acts A computer pattern recognition system is introduced which simplifies this task by minimizing the need for human intervention This system uses two video cameras with horizontal and vertical views of the behavior of a control and an experimental rat as they explore a simple environment for 15 minutes Their behavior is sampled at a rate of one frame/second Data from the video cameras are then converted into a form acceptable to Micro Vax I and VAX 11/750 computers Each video picture is reduced to a 256 by 256 array, and ultimately each 15 minute observation session generates 28,800 blocks of information at 512 bytes each Using a mathematically complete set of moments to the fourth order and the associated scalar invariants, the computer is programmed to identify the five major body positions of the rat including standing, sitting, rearing, walking and lying down The computer also is programmed to identify the behaviors of grooming, head turning, whole body turning, looking, smelling, sniffing and washing face This computer pattern recognition system not only speeds up behavioral classification, it alleviates the much criticized subjectivity introduced by human observers

Automated behavior Locomotor behavior Pattern analysis Rat

THE value of observing spontaneous behavior in detection of central nervous system (CNS) deficits has been demonstrated in many studies of toxic substances [1, 5, 6, 9] Widespread use of these observational techniques, however, is not commonplace because they are labor intensive They require the investigator to observe, classify and record behavior at the rate of its occurrence Although the permanent records provided by film [7] and videotapes [1] have aided observation, behavioral classification and recording have remained the burden of a human observer Using time-lapse photography as an example, it takes an experienced observer no less than 2 5 hours to classify and record the events occuring in 900 frames of film At that rate, generation of multiple dose-response curves, the mainstay of toxicological interpretation, is practically impossible to accomplish

Beyond the inordinant amount of time it takes a human to "read" a film, there remains a question of observer bias Good observer reliability is achievable, but a time-consuming confirmation by a second observer is often used to help prevent bias For example, the reproducibility of behavioral classification by the same observer is high, correlations between behavior sequence data reread by the same observer have ranged from 0 83 to 0 94 [9] Correlations between the same sequence data read by different observers were lower, however, ranging from 0 70 to 0 84 [9] Thus, observer bias is not prohibitive to behavioral classification, but certainly there is room for improvement critical to overall detection capability

The purpose of this study is to develop a method that will improve the speed and reliability of behavioral classification A computer pattern recognition system is introduced, one that classifies the behavioral acts of rats The utility of computer pattern recognition for classifying behavior with minimal human intervention has been demonstrated in studies of nonhuman primates [3,4] In contrast to the primate study, the system introduced here incorporates the basic experimental design special to time-lapse photographic analysis of rat behavior [7] The time-lapse photographic technique

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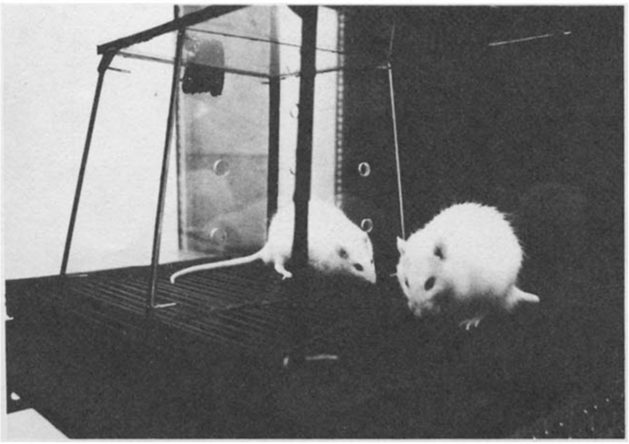

FIG 1 The test environment It accommodates the simultaneous observation of control and experimental rats and the chamber walls are slanted to be invisible to the video cameras

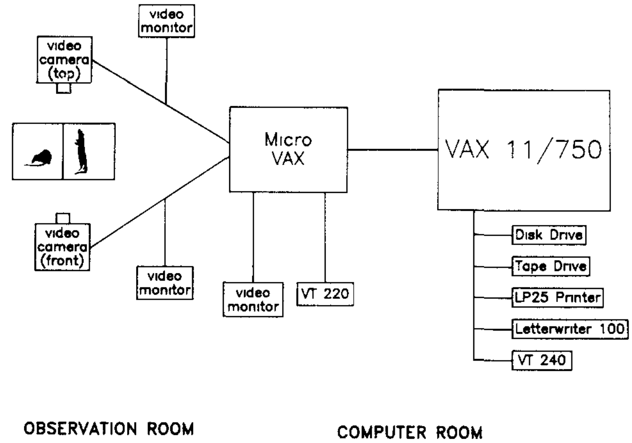

FIG 2 Configuration of the computer pattern recognition system

serves as a model framework because of its extensive development [7,8] for determining the most complete set of parameters of behavioral change (initiations, average durations, sequences and time distribution), for multiple motor acts (15 or more) over a long observation time (15 minutes or more) at a rapid rate of behavioral sampling (one per second)

OBSERVATIONAL ENVIRONMENT

In the redesign of the time-lapse photographic method to utilize pattern recognition techniques, an effort has been made to keep the test environment as close to that in prior experiments as possible Consequently, as before, the new environment consists of a clear Plexiglas box divided in half by a clear partition with small (1 2 cm) holes This design allows the simultaneous testing of a control and an experimental rat placed on opposite sides of the partition In that the animals can see and smell each other, their behavior is not that of isolated animals The feature of simultaneous testing of control and experimental animals is preserved here for a number of reasons First, any accidental change in environmental conditions, noise, temperature etc , is experienced by both animals at the same time Second, the limited social interaction triggers enough spontaneous behavior that frequency counts of a limited number of behaviors are high, which in turn allows good statistical comparisons Finally, testing animals two at a time reduces the overall length of time required to complete the experiment

Only a few notable changes in the test environment have been made for the purposes of this study In order to minimize reflections from the Plexiglas walls of the box, the walls are slanted in a fashion that makes them invisible to the video cameras The box, therefore, can be described more specifically as having a trapezoidal shape at its top and bottom, where the two trapezoids are separated by 23 5 cm The top trapezoid has parallel sides 42 cm and 32 cm in length that are separated by 24 cm The parallel sides of the bottom trapezoid are 52 5 and 40 cm long, separated by 31 cm The general shape of this box is shown in Fig 1 In addition, the single time-lapse camera placed approximately 5 feet in front of the box has been replaced with two video cameras at approximately one meter, one oriented horizontally and the other vertically In the observational environment designed for pattern recognition of primate behavior [3,4], three orthogonal video cameras were necessary because of the more complex movements performed by this species The simpler movements of rats make the third orthogonal view unnecessary and the feature of testing two animals at a time make it impractical The only other change in the test environment is that the Plexiglas box is not situated in a sound attenuated chamber Rather, it is positioned in a small room dedicated to these experiments This room is somewhat isolated from the rest of the laboratory area, it is quiet and all data are taken with the room door closed Lights are carefully placed so that close to uniform lighting throughout the test area allows good contrast between the animals and the black background built behind and below the Plexiglas box

PATTERN RECOGNITION SYSTEM

The complete system can logically be divided into the following phases data acquisition, pattern analysis and pattern classification Data acquisition is the process of converting the data from the physical source (video image) into a form acceptable to the computer for further processing Pattern analysis includes all computations needed to identify the invariant characteristics of the original data and any associated classes of patterns Finally, pattern classification assigns each observation of the rat to a particular behavioral act In the initial development, pattern analysis and pattern classification must be carried out in a mixed order requiring some degree of iteration and interaction For example, reliability measures of pattern classification may reveal a critical change needed in pattern analysis Many such iterations may be required before the pattern recognition problem is satisfactorily solved

I Data Acquisition Hardware

The overall system (Fig 2) is composed of a Digital Equipment Corporation MICRO VAX I connected via an ethernet link to a DEC VAX 11/750 computer The VAX 11/750 has a floating point accelerator, a tape drive, a 456 MB disk for data storage, a line printer, a console, and a VT 240 graphics display monitor

The signals from each video camera (Cohu Model 5200) go into video processing boards (Imaging Technology, Inc , AP-512 and FB-512) in the MICRO VAX I computer This subsystem takes a frame from each of the video cameras once per second and applies a software discrimination level to reduce the video picture to a 256 by 256 array of binary data The data consists of either 0 or 1 depending upon whether or not the signal level has exceeded the discriminator level The entire process, from the one frame/second, the discriminator level, to the 256 by 256 array, is under software control and can be changed as desired The control system in the MICRO VAX I packs together four frames from each of the two video cameras and writes these data to temporary storage on its hard disk A second program, run concurrent with data acquisition, begins after twenty such records of four frames have been written This program transfers the data over the ethernet connection to the VAX 11/750 where they are written to a record file on its disk system Each 15 minute observational session corresponds to a file of 28,800 blocks of 512 bytes of data This is a compressed data format in which every bit is utilized in representing the original observational data

The tape drive on the VAX 11/750 is used for archival storage The large disk volume on this machine is required for the extensive data generated in any single experiment The VT 240 graphics display terminal facilitated development of the pattern recognition system in that it allowed the investigators to see the data and classify the behaviors from thousands of observations These human classified data are then the starting point for development of pattern recognition programs that classify data without further human intervention

II Pattern Analysis Mathematical Techniques

The present computer pattern recognition system for the rat is based upon earlier work with the primate [3,4] Historically, Hu [2] developed the scalar invariants for second order moments which he used to identify letters Teague [11] provided a convenient method for calculating higher order moments and a reference list of the associated scalar invariants for any given order This use of scalars, which are invariant to rotation, reflection and changes in magnification, is in general quite convenient for computer classification of behavior The system to be described here uses moments to the fourth order To transform a camera-based coordinate system to a centralized coordinate system where the origin is at the center of the animal, a mathematically complete set of moments of the desired order is necessary

Using the software discriminator system, the density function f(x,y) is a binary representation of the pixel intensity With this function the moments in a view can be represented as

$$M_{\alpha\beta} = \sum_i \sum_j x_i^\alpha \, y_j^\beta \, f(x,y) \tag{1}$$

Moments in this form are not properly normalized for the calculation of the scalar invariants, but the normalization is straightforward The moments used for the scalar invariants must be "central moments," that is, the coordinate system must have its origin at the center of mass of the rat The notation used here for the different moments is as follows

1 $M_{\alpha\beta}$ = unnormalized moment $\alpha\beta$ in the video coordinate system with origin in the upper left-hand corner
2 $\gamma_{\alpha\beta}$ = unnormalized moment $\alpha\beta$ in the centralized coordinate system, i e , the origin is at $\bar{X},\bar{Y}$
3 $\mu_{\alpha\beta}$ = normalized moment $\alpha\beta$ in the centralized coordinate system

In this notation $\bar{X}$ and $\bar{Y}$ are defined as

$$\bar{X} = M_{10}/M_{00} \tag{2}$$

$$\bar{Y} = M_{01}/M_{00} \tag{3}$$

For the calculation of the scalar invariants, the relationships among the important moments are

$$\gamma_{20} = M_{20} - 2\bar{X}\,M_{10} + \bar{X}^2\,M_{00} \tag{4}$$

$$\gamma_{02} = M_{02} - 2\bar{Y}\,M_{01} + \bar{Y}^2\,M_{00} \tag{5}$$

$$\gamma_{30} = M_{30} - 3\bar{X}\,M_{20} + 3\bar{X}^2\,M_{10} - \bar{X}^3\,M_{00} \tag{6}$$

$$\gamma_{03} = M_{03} - 3\bar{Y}\,M_{02} + 3\bar{Y}^2\,M_{01} - \bar{Y}^3\,M_{00} \tag{7}$$

$$\gamma_{11} = M_{11} - \bar{X}\,M_{01} - \bar{Y}\,M_{10} + \bar{X}\bar{Y}\,M_{00} \tag{8}$$

$$\gamma_{21} = M_{21} - 2\bar{X}\,M_{11} + \bar{X}^2\,M_{01} - \bar{Y}\,M_{20} + 2\bar{X}\bar{Y}\,M_{10} - \bar{X}^2\bar{Y}\,M_{00} \tag{9}$$

$$\gamma_{12} = M_{12} - 2\bar{Y}\,M_{11} + \bar{Y}^2\,M_{10} - \bar{X}\,M_{02} + 2\bar{X}\bar{Y}\,M_{01} - \bar{Y}^2\bar{X}\,M_{00} \tag{10}$$

$$\gamma_{31} = M_{31} - 3\bar{X}\,M_{21} + 3\bar{X}\bar{Y}\,M_{20} + 3\bar{X}^2\,M_{11} - 3\bar{X}^2\bar{Y}\,M_{10} - \bar{X}^3\,M_{01} - \bar{Y}\,M_{30} + \bar{X}^3\bar{Y}\,M_{00} \tag{11}$$

$$\gamma_{13} = M_{13} - 3\bar{Y}\,M_{12} + 3\bar{X}\bar{Y}\,M_{02} + 3\bar{Y}^2\,M_{11} - 3\bar{X}\bar{Y}^2\,M_{01} - \bar{Y}^3\,M_{01} - \bar{X}\,M_{03} + \bar{X}\bar{Y}^3\,M_{00} \tag{12}$$

$$\gamma_{22} = M_{22} - 2\bar{Y}\,M_{21} + \bar{Y}^2\,M_{20} - 2\bar{X}\,M_{12} + 4\bar{X}\bar{Y}\,M_{11} - 2\bar{X}\bar{Y}^2\,M_{10} + \bar{X}^2\,M_{02} - 2\bar{X}^2\bar{Y}\,M_{01} + \bar{X}^2\bar{Y}\,M_{00} \tag{13}$$

$$\gamma_{40} = M_{40} - 4\bar{X}\,M_{30} + 6\bar{X}^2\,M_{20} - 4\bar{X}^3\,M_{10} + \bar{X}^4\,M_{00} \tag{14}$$

$$\gamma_{04} = M_{04} - 4\bar{Y}\,M_{03} + 6\bar{Y}^2\,M_{02} - 4\bar{Y}^3\,M_{01} + \bar{Y}^4\,M_{00} \tag{15}$$

The $M_{\alpha\beta}$ in these equations are expressed in a form for which each pixel has unit area, instead of using limits such that both X and Y lie between −1 and +1 This formulation of the unit area has some advantages in the initial processing of data The relationship between the μ's and the γ's as defined above is

$$\mu_{\alpha\beta} = \frac{\gamma_{\alpha\beta}}{\gamma_{00}^{(\alpha+\beta+2)/2}} \tag{16}$$

The somewhat unusual normalization factor in this equation is taken from Teague [11] and is related to invariance of the moments as the magnification or scale changes In the measurement of animal behavior, the movement of the subject toward or away from the camera, as well as size differences between animals, make this factor important With the μ's as defined above, Teague's scalar invariants which correspond to the description of fourth-order moments are the following

$$S1 = \frac{3}{\pi}\,[2(\mu_{20} + \mu_{02}) - 1] \tag{17}$$

$$S2 = \frac{9}{\pi^2}\,[(\mu_{20} - \mu_{02})^2 + 4\mu_{11}^2] \tag{18}$$

$$S3 = \frac{16}{\pi^2}\,[(\mu_{03} - 3\mu_{21})^2 + (\mu_{30} - 3\mu_{12})^2] \tag{19}$$

$$S4 = \frac{144}{\pi^2}\left[(\mu_{03} - \mu_{21})^2 + (\mu_{30} + \mu_{12})^2\right] \quad (20)$$

$$S5 = \frac{13824}{\pi^4}\left[(\mu_{03} - 3\mu_{21})(\mu_{03} + \mu_{21})\left\{(\mu_{03} + \mu_{21})^2 - 3(\mu_{30} + \mu_{12})^2\right\} - (\mu_{30} - 3\mu_{12})(\mu_{30} + \mu_{12})^2 \left\{(\mu_{30} + \mu_{12})^2 - 3(\mu_{03} + \mu_{21})^2\right\}\right] \quad (21)$$

$$S6 = \frac{864}{\pi^3}\left[(\mu_{02} - \mu_{20})\left\{(\mu_{03} + \mu_{21})^2 - (\mu_{30} + \mu_{12})^2\right\} + 4\mu_{11}(\mu_{03} + \mu_{21})(\mu_{30} + \mu_{12})\right] \quad (22)$$

$$S7 = \frac{25}{\pi^2}\left[(\mu_{40} - 6\mu_{22} + \mu_{04})^2 - 16(\mu_{31} - \mu_{13})^2\right] \quad (23)$$

$$S8 = \frac{25}{\pi^2}\left[\left\{4(\mu_{04} - \mu_{40}) + 3(\mu_{20} - \mu_{02})\right\}^2 + 4\left\{4(\mu_{31} + \mu_{13}) - 3\mu_{11}\right\}^2\right] \quad (24)$$

$$S9 = \frac{5}{\pi}\left[6(\mu_{40} + 2\mu_{22} + \mu_{04}) - 6(\mu_{20} + \mu_{02}) + 1\right] \quad (25)$$

$$S10 = \frac{250}{\pi^3}\left[(\mu_{40} - 6\mu_{22} + \mu_{04})\left(\left\{4(\mu_{04} - \mu_{40}) + 3(\mu_{20} - \mu_{02})\right\}^2 - 4\left\{4(\mu_{31} + \mu_{13}) - 3\mu_{11}\right\}^2\right) - 16\left\{4(\mu_{04} - \mu_{40}) + 3(\mu_{20} - \mu_{02})\right\}\left\{4(\mu_{31} + \mu_{13}) - 3\mu_{11}\right\}\left\{\mu_{31} - \mu_{13}\right\}\right] \quad (26)$$

$$S11 = \frac{30}{\pi^2}\left[\left\{4(\mu_{04} - \mu_{40}) + 3(\mu_{20} - \mu_{02})\right\}\left\{\mu_{02} - \mu_{20}\right\} + 4\mu_{11}\left\{4(\mu_{31} + \mu_{13}) - 3\mu_{11}\right\}\right] \quad (27)$$

(Some calculations in Teague's Appendix A contained typographical errors that were noted and corrected for the purposes of this application to behavior)

Any application of higher order moments to the interpretation of a picture has at least potential problems with noise The major problem is noise well separated from the main pattern, such as that created when fecal material is deposited by the animal within the observational environment Noise well separated from the main pattern can contribute an exaggerated effect in higher order moments much as a long lever arm magnifies lifting force The pattern analysis program contains a segment specially designed to suppress such extraneous noise

III Pattern Classification Behavioral Taxonomy

The sixteen behavioral acts recorded in a previous time-lapse photographic study [5] served as the starting point for the present pattern classification programs These 16 acts can be divided into two mutually exclusive groups of activities, 5 major body positions and 11 modifiers These acts can be combined to form a total of 36 different behavioral activities The major body positions consist of stand, sit, rear, walk and lying down The modifiers consist of blank (no concurrent activity), groom, head turn, turn, look, smell, sniff, wash face, bob, scratch and paw Norton [7] has defined most of these rat behaviors in terms meaningful to human observers, and the pattern classification programs provided here define all but three modifiers in terms meaningful to a computer The three modifiers that the computer system has not been programmed to recognize are bobbing, pawing and scratching In the case of the time-lapse photographic system, a long shutter time enabled a human observer to quickly recognize these three acts A rapid movement of one portion of the body would blur the image of that portion on film Thus, "bobbing" corresponded to a blurring of the head, whereas "scratching" and "pawing" corresponded to a blurring of the paw in a particular position in space With the introduction of the video cameras, this blurring cue has been lost

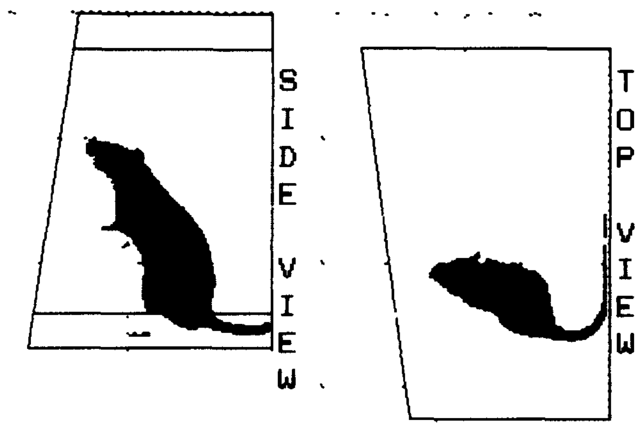

FIG 3 Rearing behavior as "observed" by the computer from a horizontal (side) and vertical (top) view

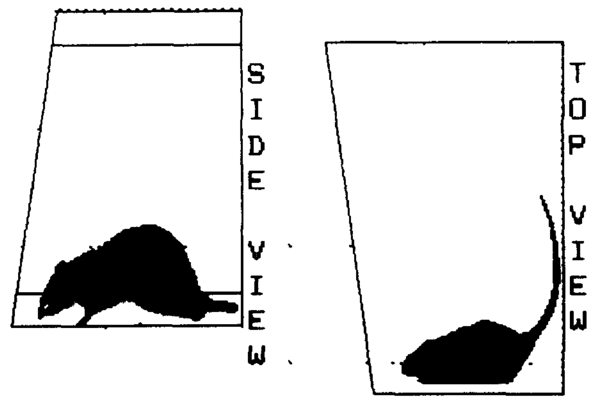

FIG 4 Standing behavior as 'observed" by the computer from a horizontal (side) and vertical (top) view

The technique used in the pattern classification process is a combination of two methods, one referred to as a "decision-theoretic method" and one as "discriminate techniques" ([10], p 61) The first relies upon similarity measurements If a feature vector $V = (V_1, V_2 \quad V_n)$ is used as a mathematical model to represent an original image, then each observation corresponds to a point in the N-dimensional space In any space, independent of the number of dimensions, a vector goes from the origin of the space to a particular point Therefore, there exists a logical relationship between the vector and a unique point in the space Two vectors can be compared by mathematical tests upon the vectors themselves, such as their product or the spatial separation of their corresponding two points It is expected that points corresponding to different behavioral acts, each belonging to the same spatial class, will cluster in the N-dimensional space such that their separation will, on the average, be small The separation of each of these points

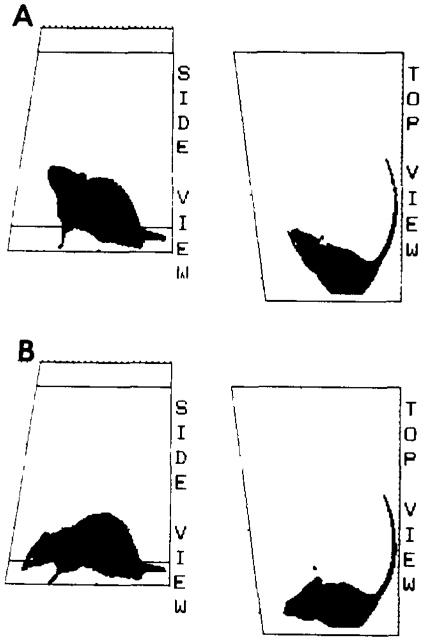

FIG 5 A Standing and looking behaviors as "observed" by the computer from a horizontal (side) and vertical (top) view during second X B Standing and turning behaviors "observed" during second X+1

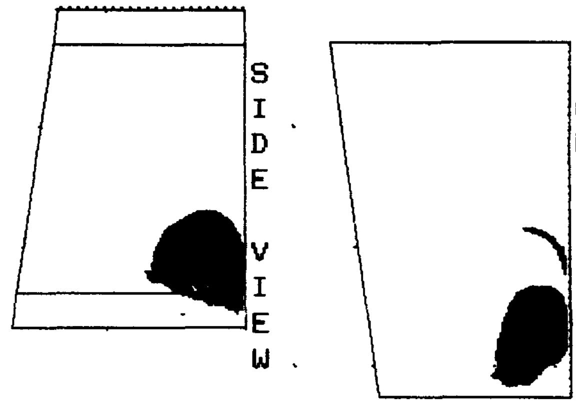

FIG 6 Sitting and grooming behaviors as "observed" by the computer from a horizontal (side) and vertical (top) view

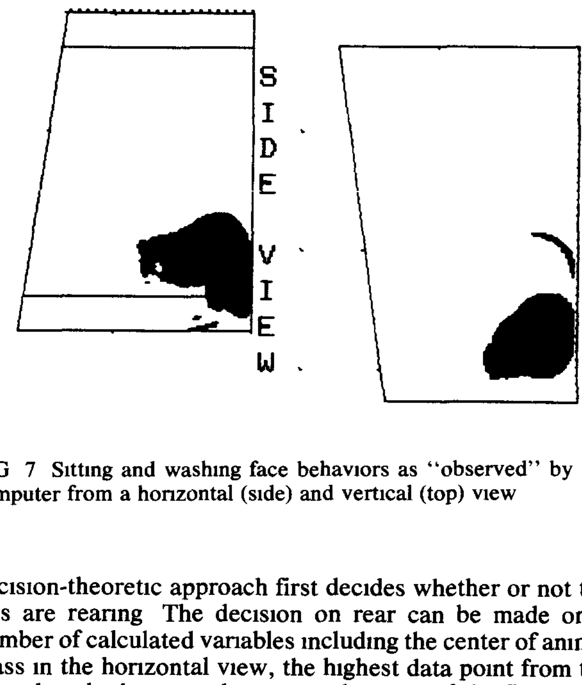

FIG 7 Sitting and washing face behaviors as "observed" by the computer from a horizontal (side) and vertical (top) view

from the region occupied by a second class is expected to be larger if this technique is to be useful in distinguishing the class to which an act belongs As the number of possible classes becomes large, the dimensions of the required feature space also increase

In contrast to the "decision-theoretic method," "discriminate techniques" exploit the dissimilarities between different classes These methods, in that they discriminate between one class and all remaining classes, are advantageous in the present application The decision process can be accomplished by a series of binary class separation rules, since the separation is always between one class and all remaining classes For example, the position of the vertically highest point of animal data in the vertically oriented view can be used easily to discriminate the act rear from all other major body positions Different feature vectors can be formed and used at each step of the decision process

To the extent possible, all decisions are made in terms of normalized, centralized moments or scalar invariants This method results in the major decisions not being affected by the size of the animal In turn, the classification program need not be modified to any major extent when the size of the animal varies with age, sex or general health Some decisions during the classification program cannot be made without reference to particular positions in space As an example, the operational definition of "sniff" requires that the nose of the animal be in close proximity with one of the holes connecting the two sides of the observational box Such a decision cannot be made using variables which are invariant to rotation, reflection or cage position, it must be made using a particular spatial point on the animal's body Similar decisions are involved in the classification of look, smell and, to some extent, turn and head turn

Major body position The classification program using the decision-theoretic approach first decides whether or not the rats are rearing The decision on rear can be made on a number of calculated variables including the center of animal mass in the horizontal view, the highest data point from the animal in the horizontal view, or the ratio of the first order moments along the horizontal and vertical axes in the horizontal view (Fig 3) If the act is not a rear, the classification program next examines movement of the animal in the vertical view from one frame to the next If this movement exceeds a certain limit, the act is classified as walking The remaining three body positions, standing, sitting or lying down, are determined using a variety of checks involving scalar invariants and centralized, normalized moments In addition, for an "observed" act to be lying down, it must continue for at least three frames due to the long average duration known for this act [9] Except for the most difficult cases, the distinction between standing (Fig 4) and sitting (Figs 6 and 7) is based upon the comparison of the length of the long and short axes of the animal's body When this ratio represents a long stretched out body position, the act is automatically classified as standing

Modifiers In the classification of modifiers, the most important single piece of information is the location of the nose of the animal in at least the vertical view When the center of animal mass changes very little while the nose position changes significantly between adjacent frames in the vertical view, the modifier is designated as a head turn The actual program considers not only the position of the nose in this view but also the angle between the center of animal mass and the nose from one frame to the next Change in the angle of the major axis of the body between adjacent frames is classified as a turn (Fig 5 B) The nose position of the animal, if it is well above the center of animal mass in the horizontal view, is used to determine the modifier look (Fig 5 A) If the nose in this view is close to the cage floor or one of the walls outside the proximity of the center panel holes, the modifier is set to smell If the nose position is close to any of the center panel holes, then the modifier is designated a sniff The modifiers groom (Fig 6) and wash face (Fig 7) are distinguished using scalar invariants and the centralized moments of the distribution of the animal The modifier blank is at this level of the program a default condition when no other modifier has been specified

It should be obvious that two modifiers have the potential to co-occur, the animal could turn and look almost at the same time In the present version of the classification program, only a major body position and one modifier are allowed Thus, there exists a priority ranking among the modifiers This priority ranking is set such that movement takes precedence over nonmovement modifiers This means that if the conditions for turn or head turn are satisfied, they are recorded to the exclusion of all others All remaining modifiers, groom, wash face, blank, sniff, smell and look, are mutually exclusive

RECORD STRUCTURE AND DATA ANALYSIS

Using time-lapse photography at 1 frame/second, one 15 minute film of a pair of rats generated 900 frames from which 3600 entries [900 × (1 body position + 1 modifier) × 2 rats] of behavioral data were classified by a human observer Using computer pattern recognition, the same 15 minute observation session generates 28,800 blocks of information, 512 bytes each After processing through the pattern analysis program, the output consists of a separate record for each of the two animals that is 1604 blocks of 512 bytes Beyond classification of the actual behavioral activity, the computer output per rat, like time-lapse analysis, provides a measure of multiple parameters such as the number of initiations, the average duration and the distribution in time of each act or pair of acts In addition, the output per rat provides the following information for each camera view the center of mass x and y, the angle of the body orientation, the movement and change in the angle compared to the prior frame This entire record for one observation session of 900 frames corresponds to 300 blocks of 512 bytes each

CONCLUSION

Time-lapse photographic analysis of spontaneous rat behavior has been adjusted to accommodate computer pattern recognition techniques Although three behaviors (bobbing, scratching and pawing) were lost in this conversion, their infrequent occurrence rendered the loss of no serious consequence when comparing control and experimental animals In all, the computer pattern recognition system provides a noninvasive, sensitive measure of animal behavior which no longer requires a prohibitive amount of investigator time Compared to the 2 5 hours it took one observer just to classify a 15 minute film of one pair of rats, it is now possible to completely analyze the activity of at least 120 control and experimental rats in one week The results incorporate only minimal subjective judgements by the investigator, and all observation data are retrievable to answer unexpected questions This new system finally provides the technological advancement necessary for making dose-response curves in behavioral toxicity testing a relatively simple procedure

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