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TIMING BEHAVIOR AND DEVELOPMENT: COMMENTS ON SOME ANIMAL AND HUMAN DATA

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ABSTRACT: This paper discusses timing behavior as measured by Fixed Interval (FI), Differential Reinforcement of Low rate (DRL) or Differential Reinforcement of Response Duration (DRRD) performances, in humans and animals at different developmental stages. Infants and rats display similar behavior patterns in FI and DRL. From childhood on, humans develop species-specific behavior patterns in FI, which differ from those of animal species. However, DRL patterns do follow similar developmental trends in animals and humans. These discrepancies and similarities may be explained by the availability of cognitive and linguistic tools in humans, and the degree of schedule constraint on behavior. Motivation and reinforcer variables as well as indices favorable to a cross-specific timing mechanism (such as scalar timing) are briefly commented upon. Available data tend to show that humans shift from contingency-shaped or "animal-like" behavior, in infancy, to rule-governed behavior. This transition is progressive and does not seem to erase forms of adaptation to temporal constraints that humans share with other species.

RÉSUMÉ: Ce texte discute, dans une perspective développementale, la régulation temporelle du comportement obtenue dans les programmes operants à Intervalle Fixe (FI), de Débit de Réponse Lent (DRL) et de Renforcement Différentiel de Durée de Réponse (DRRD) chez l'animal et l'humain. Les très jeunes enfants et les rats produisent des patrons de réponse similaires dans les programmes FI et DRL. Dès l'âge de 5 à 6 ans, les humains développent, dans le programme FI, des patrons de réponse qui diffèrent de ceux des autres espèces. Toutefois, les patrons de réponse enregistrés dans le programme DRL chez l'humain suivent, au cours du développement, des tendances similaires à celles des autres espèces. Ces différences et similitudes peuvent être partiellement expliquées par la disponibilité, chez l'humain, d'outils cognitifs et verbaux, et par le degré de contrainte spécifique à chaque programme de renforcement. Les variables motivationnelles, celles liées au processus de renforcement et les indices favorables à l'existence d'un mécanisme d' "horloge interne" commun à toutes les espèces sont brièvement commentés. Les données disponibles tendent à montrer que, de la très jeune enfance à lâge adulte, l'humain passe d'un comportement "similaire" à celui de l'animal et contrôlé par le seul processus de renforcement à un comportement gouverné par des règles. Cette transition est progressive et ne semble pas éradiquer les formes d'adaptation que les humains partagent avec les autres espèces animales.

Time estimation in animal species has been extensively investigated over the last decades, due to the technical facilities provided by

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operant procedures in the laboratory. Interest has been further stimulated by the discovery that behavior emitted by various species can be described in terms of empirical laws such as the power law and Weber's law (Catania, 1970; Platt, 1979) and by the development of the scalar timing model (Gibbon, 1977). This theory offers a plausible account of various sets of time regulated behaviors in terms of their underlying mechanisms. Historically, the human psychology of time was studied with procedures different from those used with other animals. These procedures, designed for the study of absolute and differential thresholds of duration in humans, collected data based on the subject's verbalizations. The method used for threshold duration could not be used with animals before the operant methodology was developed. Since then, animal psychophysics has been widely studied. The sensitivity of organisms to the duration of external stimuli is only one aspect of the psychology of time. Another is the measure of response timing, i.e., the patterning of overt behavior in relationship to various temporal constraints, made possible as a result of Skinner's (1938) pioneering work. The application of operant procedures across nonhumans and humans over the last 20 years or so has yielded systematic comparisons. Comparing nonhumans and humans is not only of interest because of methodology, but because it addresses the fundamental question of similarities versus differences, of continuity versus discontinuity between animal and human timing behavior, in relationship to the possible role of symbolic processes and language in accounting for discontinuity, if the discontinuity is found.

Data obtained with classical temporal regulation (Fixed Interval, FI) and temporal differentiation procedures (Differential-Reinforcement of Low rates, DRL, and Differential Reinforcement of Response Duration, DRRD) will be successively described and commented upon. For each of these procedure types, two questions will be addressed:

a) Do adult animals and humans exhibit similarities in response timing?
b) Do timing performances undergo developmental changes?

A third question will be discussed separately: Do animals and humans share common timing mechanisms?

TEMPORAL REGULATION: THE FI PROCEDURE

The Fixed Interval schedule reinforces the first response emitted after a specified interval of time has elapsed since the last reinforcement. Responses emitted during the interval are without consequences. They are just superfluous. Trained animals such as pigeons

and rats typically develop a particular response pattern: a pause (after each reinforcement) followed by a progressive acceleration of responding, up to the next reinforcement. In a variant of this pattern, animals may, instead of progressively accelerating response rates, maintain a constant rate until reinforcement. This response pattern is labeled "break and run." It has been described mostly with pigeons (Schneider, 1969) but can be observed in other species such as, rats or mice, as well. (For a discussion of response patterning in FI, see Dews, 1978). FI behavior is sensitive to schedule parameters. Pause duration increases and response rates decrease when the interval value increases. It must be noticed here that temporal regulation of behavior (i.e., the pause-response pattern) is not required by the FI schedule. It develops spontaneously as a consequence of training, at least in the "classical" laboratory species such as pigeons and rats. The quality of temporal regulation can be assessed from the cumulative record of responses, the distribution of responses in successive segments of the interval, the duration of the post reinforcement pause or the Curvature Index of Fry, Kelleher, and Cook (1960), that integrates most of the features of performance (Richelle & Lejeune, 1980).

a) Adult Animals and Humans

Whereas adult animals perform as just described, i.e., pause after each reinforcer, and resume responding towards the last part of the interval, adult humans do not. They exhibit either a high-rate (high constant response rates throughout the interval) or a low-rate pattern (one or very few responses at the very end of the interval as can be seen in Lowe, 1979, Fig. 5.1). The high rate pattern is insensitive to schedule parameters. It does not change when the duration of the interval is increased or decreased. In the low rate pattern, response rates depend upon FI value since only one or a few responses are emitted at the end of the interval. As reviewed by Lowe (1979), response patterns may, however, be sensitive to response cost if responding is made more effortful. When response force is increased to a few hundred grams, the high-rate pattern may drift to the low-rate type (Azrin, 1958).

Patterns in humans can also be influenced by conditioning history. Weiner (1965) obtained a high rate FI pattern after a Fixed Ratio (FR) schedule in which reinforcement rate depends upon response velocity. Similarly, previous training with the Differential Reinforcement of Low rate schedule (DRL) which reinforces inter-response times exceeding a critical value, induces a low-rate pattern in FI. Finally, FI performance is highly sensitive to verbal instructions and self instructions. Lippman and Meyer (1967) obtained high rates, low rates or both patterns in different groups after ratio, low rate or mini-

mal instructions, respectively. Humans who receive minimal instructions describe the contingencies as requiring low or high rates when invited to report verbally after the session. They replace the absence of task-specific instructions with their own hypotheses about the contingencies at play and follow self-made rules. Thus, FI performance in human adults seems to obey "high rate" or "low rate" rules, that generate patterns different from those obtained with animals. To sum up, human performance seems to be "rule governed" rather than "contingency-shaped," as is the case in animal species.

Does this mean that animal-like patterns of timing behavior cannot be obtained in human subjects? Matthews, Shimhoff, Catania, and Sagvolden (1977) contend that discrepancies between animal and human FI behavior might be due to procedural differences. If animal-like patterns are to be expected from humans, these should be given minimal instructions, be exposed to response shaping and be rewarded with reinforcers that require a "consummatory" behavior truly interrupting the flow of free operant responding, as is the case with animals. These guidelines, however, led to mixed results, with a high intra- and inter-subject variability in performance. Following an animal-fair procedure with humans does not yield animal-like performances in every case. It is not a sufficient condition to obtain such a behavior.

Other attempts have been more fruitful. Animal-like FI performance can be obtained in adult humans if an observing contingency is added to the operant response. Lowe (1979) instructed humans to push on a response panel to get points that could be exchanged for money at the end of the session. Each response briefly lit the display of a digital clock giving in minutes and seconds the time elapsed since the last reinforcer delivery. A pause-scallop pattern could be obtained with this procedure. Furthermore, performance was sensitive to schedule parameters. Pauses increased and response rates decreased when the interval value increased, as in rats and pigeons. Post-reinforcement pauses plotted against interval duration could be described by power functions $Y = kX^n$ (where Y is the duration of the pause and X the duration of the interval, k and n empirical constants), be it in rats, pigeons or humans, with k ranging from 1.2 to 1.8 and n from 0.63 to 0.81. Thus, providing a response-dependent clock induces an interval-based formulation of the contingencies, obviates the need for covert timing behavior and yields an animal-like FI pattern, sensitive to schedule parameters. In other words, the response-dependent digital clock may have suppressed interference from self-produced conscious interpretations.

If such cues interfere with performances, it might be advisable to study FI behavior in experimental settings where the subject is "unaware" of the contingency at play or in infancy, i.e., at an age where

producing or using cues is highly improbable. Both attempts proved successful.

Bailey and Lowe (1988) instructed adult humans to manipulate a computer keyboard for points which were displayed on the computer screen. The real contingency was hidden. Points were not given for keyboard manipulation, but movements of the swivel chair on which the subjects sat were reinforced according to a FI schedule. Keyboard response patterns were disorderly whereas chair movements followed the typical pause-response pattern. Furthermore, the subjects could not describe the contingencies at play when questioned after the session. The confirmation of such data would show that "awareness" about the contingencies, which generates self-produced cues or rules, can mask or interfere with schedule control.

The issue of learning without "awareness" (which does not mean without "consciousness") has been extensively studied some 30 years ago. It has several aspects that cannot be discussed here (see among others, Nisbett & Wilson, 1977; Schacter, 1987; Wearden, 1988). Participants may be "unaware" of the response (small movements as in Hefferline, Keenan, & Harford, 1959; autonomic response such as in Brener, 1977), or of stimuli ("subception," as in Lazarus & McCleary, 1951, where a galvanic skin response can be elicited by unnoticed stimuli). They also may report efficient response strategies (i.e., strategies yielding reinforcers) which do not match with the contingencies and thus are incorrect from the experimenter's point of view, as is, for example, the case when humans on DRL report complex sequences of behavior ending in the operant response (Wearden, 1988, labels these reports "coincidental awareness"), or when they make erroneous reports about their own behavior or experimental events. These studies are plagued with methodological problems and often lack appropriate means to detect participant's "awareness" (Eriksen, 1960). However, procedures such as the one reported above, in which the response-reinforcer contingency is hidden behind false information and instructions might prove an efficient strategy to disentangle the variables at work.

Lowe, Beasty, and Bentall (1983) reported FI performances of two infants aged 9 and 10 months. The infants sat in a high chair or on their mother's lap, in front of a big horizontal cylinder that could be touched (response). They were reinforced with music or food items. After response shaping by successive approximations, infants were submitted to FI schedule values ranging from 10 to 50 s. Sessions usually ended after 12 to 30 reinforcers had been obtained. Performance in both infants closely resembled the scalloped pattern of animals. The second criterion, i.e., the sensitivity to schedule parameters, was also met. The post-reinforcement pause was a negatively accelerated increasing function of schedule value, as can be seen on
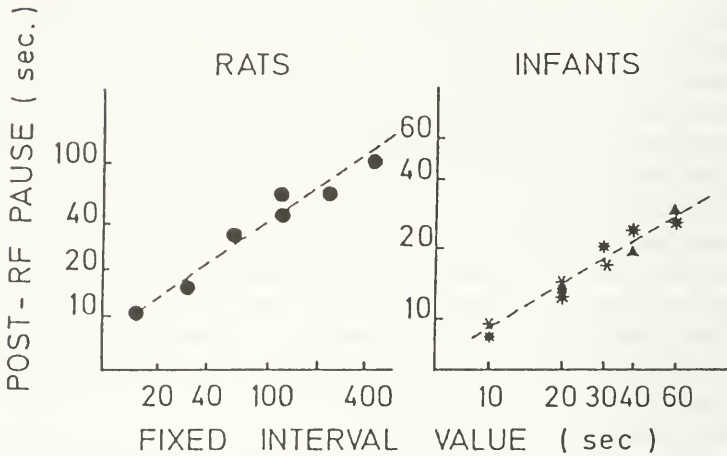
FIGURE 1. Duration of the post-reinforcement pause (ordinate) plotted as a function of FI value (abscissa), in rats (left) and human infants (right). Redrawn and modified after Figure 9 (p. 177) from Bentall et al. (1985). Abscissa and ordinate are in log scale.

the right part of Figure 1; furthermore, response rates were inversely related to the duration of the interval, as in the case with rats (Bentall, Lowe, & Beasty, 1985).

Scarce as they are, experimental results reported above show that animal-like FI behavior can be obtained in humans 1) if they are distracted from self-produced cues or rules by an external clock or if they are "unaware" of the contingency and 2) if they are conditioned at infancy, i.e., before mastery of language and crucial language-related cognitive tools.

b) Developmental Changes

The importance of verbal factors, as emphasized by Lowe (1979), has been confirmed by subsequent developmental research (Pouthas, 1985; Bentall & Lowe, 1987; Bentall et al., 1985). Whereas infants follow a pause-scallop pattern in FI, the behavior of children aged 2½ to 4 years is highly variable and irregular. It is accompanied by unsystematic and diverse verbalizations, which probably interfere with performance. Children cannot refrain from responding and are unable to follow low-rate instructions over the complete training period. Control by instructions is more readily achieved in children aged 5 to 9 years. The inability to comply with a low-rate instruction in the youngest subjects is congruent with Luria's (1961) analysis, according to which the use of verbal skills for regulation of motor behavior and
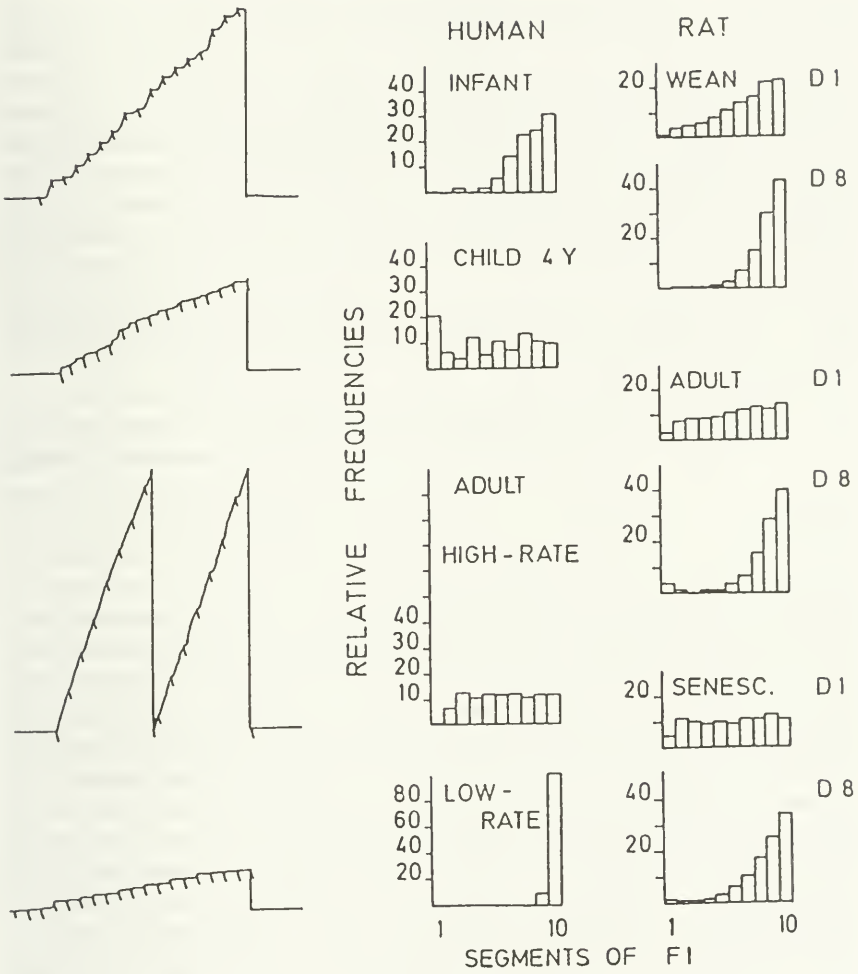
FIGURE 2. Performance of humans (left and middle columns) and rats (right column) on a FI 60 s schedule (unpublished data). Humans: the left column shows sample cumulative records of responses; the middle column presents the same behavior as relative frequency distributions of responses per successive segments of the interval. Rats: the right column presents relative frequency distributions of responses per segments of the interval. In each column, and from top to bottom: performance at different ages (weaning, adulthood and senescence for rats; infancy, childhood and adulthood for humans). For rats at each age: average performance at training Days 1 (D1) and 8 (D8).

self-control is not functional before the third or fourth year of life. From about 5 years on, the irregular FI response pattern evolves progressively towards the adult-like low- or high-rate patterns. Coherent descriptions of the contingencies and related response rules appear simultaneously. The evolution of FI performance, as illustrated in the left part of Figure 2, thus seems to mirror the development of language, i.e., the development of the ability to describe accurately the own behavior and to formulate response rules that will be translated accurately at the behavioral level. Cumulative records of performance match with verbal comments or rules only in humans above 5 to 6 years, i.e., at an age where response patterns resemble those of adults (two cumulative records at the bottom left of Figure 2).

In a related developmental study (Lejeune, Jasselette, Nagy, & Perée, 1986), weanling (20-day-old), adult (3-month-old) and senescent rats (24-month-old) were subjected for 8 days to a massed learning procedure. They performed five 30-min FI 60 s sessions a day. Data showed that the rate of FI acquisition is inversely related to the age of the subjects. Weanling rats obtained the highest performance scores in FI, followed by adult and senescent rats, as can be seen on the right part of Figure 2. At the first day of training, the temporal patterning of responses was inversely related to the age of the subjects: weanling rats displayed a clearcut increase in response rate over the successive segments of the interval (right part of Figure 2). Response rates also were inversely related to the age of the subjects. This developmental trend does not seem to reflect a fundamental difference in the underlying timing mechanisms. It is however worth noticing that the highest response rates were correlated with the longest post-reinforcement pauses and the highest Curvature Index values in the weanling rats, and that these features remained significantly different from those exhibited by adult and senescent subjects, over the first 20 to 30 sessions. The high response rates in weanling rats may be related to age-specific high levels of general activity (Moorcroft, 1971). However, operant activity is not spread out over the complete fixed interval. Responses are efficiently inhibited after the delivery of each reinforcer. Weanling rats displayed various types of collateral activities during the post-reinforcement pauses. Three major types emerged after 12 to 15 sessions: ano-genital grooming, tail-nibbling and "sleeping" in a curled-up position (head bent under the body and closed eyes). Various collateral activities were also noticed at the other ages, but to a lesser extent. We have so far described similarities as well as differences between developmental data of animals and humans in FI. Before further discussing these data, some results obtained with temporal differentiation procedures will be presented hereafter.

TEMPORAL DIFFERENTIATION: THE DRL AND DRRD PROCEDURES

In the Differential Reinforcement of Low rate (DRL) schedule, reinforcement is contingent upon response spacing. The DRRD schedule, a variant of DRL schedule, reinforces response durations instead of Inter-Response-Times (IRT). These schedules are labeled "temporal differentiation" schedules because they reinforce and select a temporal characteristic of the operant: its delay with regard to the preceding response or its duration. They are fundamentally different from FI. Reinforcement is contingent on the temporal regulation of behavior, whereas it is not in FI. To assess the quality of performance, IRTs or response durations can be sorted according to their duration and cast in time bins. Trained rats exhibit a clearcut modal IRT or response duration, close to the reinforcement criterion.

a) Adult Animals and Humans

As was the case with FI, recent data have addressed both the comparative and developmental aspects of response timing in animals and humans. Data obtained with adult animals in DRL or DRRD depend on multiple factors among which are the length of the critical IRT or response duration, the species and the nature of the operant response. One data sample will be described here. It is representative of the performance obtained in pigeons with a perching response.

Adult homing pigeons were trained to hop on a perch protruding from the rear wall of their conditioning cubicle and to step quickly off. After acquisition of the brief perching response, the experimenter reinforced inter-response-times between successive brief perching responses. Baseline data were collected for DRL values of 10, 20, 30, 40, 50, 60, and 70 s. IRTs were cast in bins and Gaussean functions could be fit to the relative frequency distributions of temporal estimates for each schedule value (Jasselette, Lejeune, & Wearden, 1990). Peaks were localized on the Gaussean curves and coefficients of variation were computed (i.e., the ratio between the standard deviation and the peak of the distribution of temporal estimates). Performances displayed two major features, as can be seen on the left part of Figure 3. First, peak time matched with, or was close to the critical IRT at each schedule value. Secondly, the coefficient of variation remained roughly constant, up to DRL 50 s. It tended to increase at DRL 60 and 70 s, which might indicate a slight loss in the accuracy of behavior. Overall, the values of the coefficient of variation remained between .20 and .30, a range obtained in other parametric experiments with DRL or reinforcement of response latency schedules (Catania, 1970;
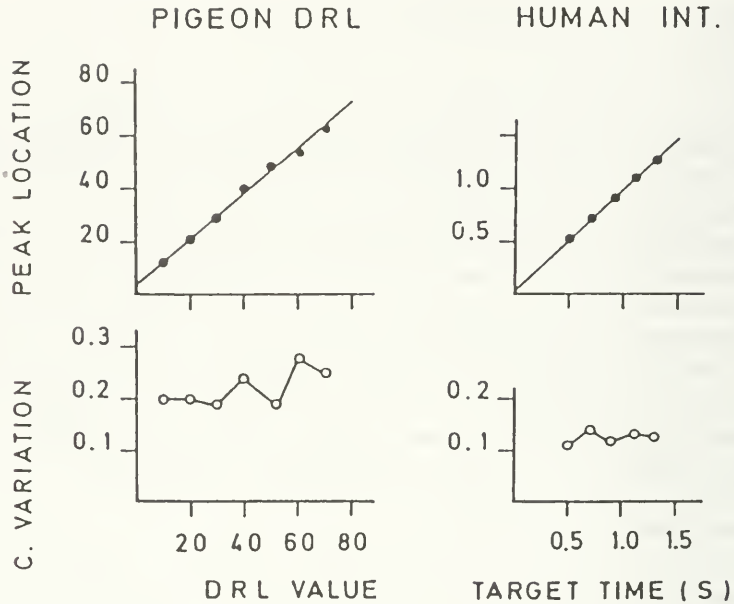
FIGURE 3. Top: location of peaks of Gaussean functions fitted to relative frequency distributions of temporal estimates. Left: IRT data from pigeons at DRL 10, 20, 30, 40, 50, 60, and 70 s with a perching response. Right: interval production data from humans (target times: .5, .7, .9, 1.1, and 1.3 s; data from Wearden & McShane, 1988). Regression of peak times against target times yield slope, intercept and r^2 (proportion of variance accounted for) values of .87, 3.71, and .99 for pigeons, .96, .05, and .99 for humans. Bottom: coefficients of variation (c. variation, i.e., the ratio between standard deviation and peak of the distribution of temporal estimates) for pigeons (left) and humans (right).

Platt, 1979). The mean temporal estimate and the coefficient of variation may be considered as reflecting the subject's representation of the schedule parameter and the subject's sensitivity to time (Roberts, 1981).

Bearing the language issue in mind, experiments with adult humans were designed to control the verbal factor. This was achieved either by choosing schedule parameters which render conscious time-spanning or counting strategies difficult (Wearden & McShane, 1988) or by requesting a deliberate chronometric counting (Wearden, 1991a).

In the first experiment, Wearden and McShane instructed people to produce empty time intervals of .5, .7, .9, 1.1, and 1.3 s. The participants held one button in each hand and had to press them in succession to start and stop a milliseconds counter. Accurate feedback to

two decimal places in seconds was given after each response. Durations to be produced were scheduled in a random order. Data analysis as described above for the pigeon DRL experiment yielded accurate mean interval productions as well as constant coefficients of variation within a .10-.15 range (right part of Figure 3), which is much lower than values obtained with the pigeons.

In the second experiment, intervals to be produced were 2, 4, 8, 16, and 32 s and the humans were requested to count (Wearden, 1991a). Means and coefficients of variation of the distribution of temporal estimates were obtained from 14 people. As in the preceding experiment, mean intervals matched target time. However, coefficients of variation declined sharply (from .09 to about .05) between target times of 2 and 8 s, without further change at 16 and 32 s. Striking features of these results, with regard to the preceding ones, are the progressive decline of the coefficient of variation and its very low absolute value.

In a research by Laties and Weiss (1963), human adults were requested to space leverpresses by at least 24 s. Each correct IRT lit a lamp and incremented a counter. Correct responses were rewarded with money at the end of the session. The modes of the IRT distributions of 11 out of 14 participants were between 24 and 28 s (they overmatched target time) and the spread of the IRT distributions was very narrow (as can be seen for example on the bottom left graph of their Figure 2).

In an experiment where the authors served as subjects, Zeiler, Scott, and Hoyert (1987) described interval productions of .5, 2, 8, and 32 s. In one of their conditions, those intervals had to be produced without an upper boundary. A "correct" feedback light flashed after intervals equal to or greater than the minimum target time. An "error" light followed responses that were too short. After completion of the experiment, the authors reported that they had been unaware of counting or performing other time-spanning collateral behavior. Mean times produced increased with the minimum target duration. They also overmatched the minimum target duration, as in Laties and Weiss (1963). The coefficients of variation, although following different trends in individuals (increase, decrease or stability) were in the .10-.15 range found by Wearden and McShane (1988) with their short-duration interval production task (.5 to 1.3 s).

It follows from these experiments that 1) interval production in adult humans might be similar to animal performances (i.e., accurate mean and constant coefficient of variation) if chronometric counting is rendered inoperant; 2) human performances might differ depending on whether chronometric counting is or is not involved (Wearden, 1991a); 3) differential response feedback seems to play a secondary role and, 4) humans are more sensitive to the temporal criterion than

pigeons and rats. Their temporal estimates are within a narrow range around mean values. Such a species-related difference has already been described in psychophysics of time where Weber fractions of humans undermatch those found in animal species.

b) Developmental Changes

Given that human adults emit temporal estimates with an accurate mean value and a constant coefficient of variation when they are prevented from counting or do not use conscious time mediating strategies, temporal regulation was, as in FI, explored at an age where such tools are probably not at hand. Developmental data are available for two infants and young children (see left part of Figure 4). Responses are usually a button or leverpress. Reinforcers are a small piece of food, a slide or puppet display. Infants and young children are able to reduce response rate over successive sessions (Pouthas, 1985; Weisberg & Tragackis, 1967). Pouthas and Jacquet (1983) further showed that 18- to 24-month-old children trained on DRL 5 s can fill interresponse times with collateral activities such as systematic locomotion or furniture manipulation. Between 1 and 3 years, they can inhibit motor behavior for a while but are unable to precisely time their operant responses. As infants do, they emit very high proportions of too short IRTs as well as numerous long ones, far exceeding the minimum critical delay. As a consequence, their IRT distributions are in some cases "U" rather than bell shaped. More precise temporal differentiation seems to develop around the age of 7 years, as the capacity to inhibit motor activities matures (Stein & Landis, 1978; Macar, 1988). Five-year-old children move a lot during experimental sessions. Seven-year-olds remain quiet and count (Pouthas & Jacquet, 1987). As was the case in FI, 4½-year-old children can benefit from instructions to wait between successive responses and from descriptions of the temporal characteristics of the task. They also are able to self-instruct ("I must wait"). However, most of the youngest cannot explain the "rule of the game," even if their behavior is adjusted to the contingencies.

Concerning the relationship between operant behavior and language, two opposite theoretical positions can be distinguished (see Wearden, 1988; Pouthas, Droit, Jacquet, & Wearden, 1990). The first, labeled "verbal control" or "cognitive," considers that cognitive or verbal changes should precede changes in nonverbal behavior. According to the second, labeled "epiphenomenalist," nonverbal behavior is directly controlled by the reinforcement contingencies, verbalizations being a posteriori by-products derived from the observation of relationships between nonverbal behavior and its consequences. Verbal behavior would thus not be the prior and necessary condi-
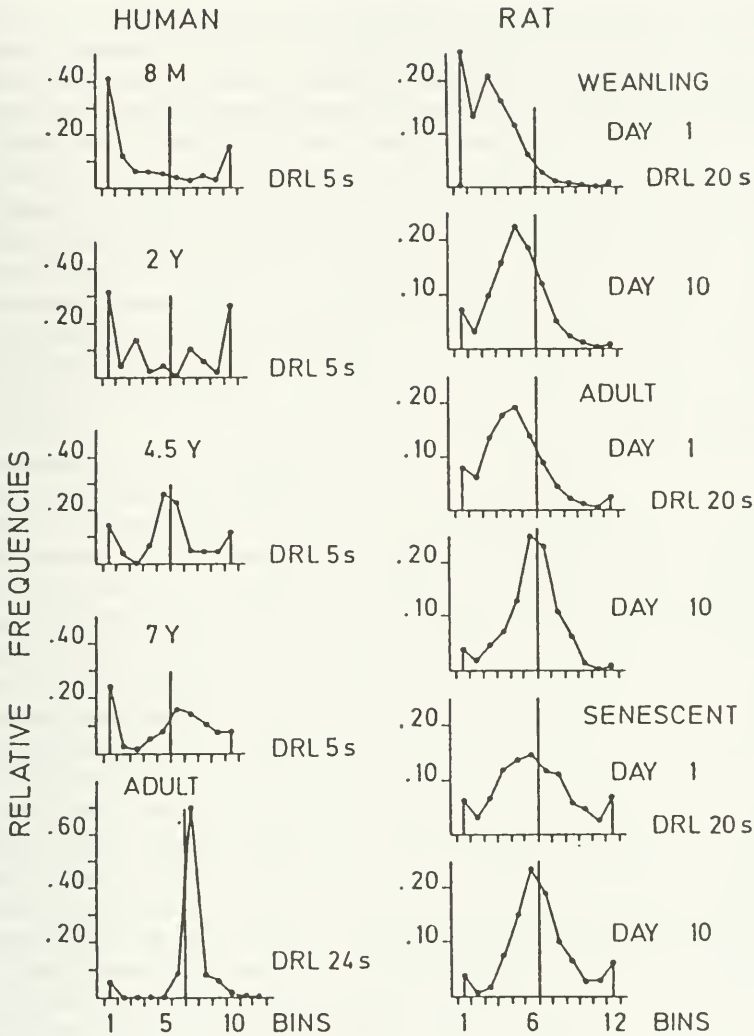
FIGURE 4. Sample relative frequency polygons showing the distribution of temporal estimates (IRTs) in 10 or 12 bins for humans (left column) and rats (right column). From top to bottom: IRT distributions at different ages in humans (M = month, Y = year) and rats (at each age, average performance at training Days 1 and 10). The IRTs at the right of the vertical lines are reinforced. Notice the different ordinate scales for humans and rats. Bottom left graph: redrawn and modified after Laties and Weiss, 1963, Figure 1 (p. 87); other human data: redrawn and modified after Pouthas, 1985, Figures 3 (p. 106) and 4 (p. 107).

tion for changes in nonverbal behavior to occur. Opposing a cognitive and epiphenomenalist theory is probably a crude oversimplification. A third view, possibly closer to empirical and developmental descriptions could be phrased as follows: nonverbal contingencies would suffice to account for a number of aspects of timing behavior (especially those referred to as "animal-like"), especially in infants and human adults under certain conditions; cognitive and verbal skills would enter the picture at a certain stage of development, initially as a simple, more or less accurate description of behavior and contingencies; and these higher order skills would eventually take over control of nonverbal behavior, after the current concept of top-down causation, or after the classical view of Luria (1961) as to the regulatory role of language on motor action, or the "rule-governed" behavior concept as proposed by Skinner (1974).

The role of language in temporal differentiation performance has been recently investigated in children aged 4½, 7, and 11 years, submitted to the differentiation of a button press duration, i.e., a DRRD schedule (Pouthas et al., 1990). Each response was followed by a question about the schedule requirement (verbal probe). Other groups of children were interviewed after the experimental session. Results showed that overall performance scores were higher and increased with age in the probe groups only. A clearcut relationship between verbalizations related to time and accuracy of response durations emerged only in the 11-year-old probe group. For these children, time-related verbalizations were translated into behavior: relationships between temporal verbalization and accurate performance seemed to be causal rather than correlational. Most of the younger children displayed no correlation between verbalizations and performance accuracy. However, accurate response timing was possible without verbalizations related to the temporal aspects of the task. Children aged four-and-a-half to six years often expressed simple response rules ("I must press the button") followed by an accurately timed response. Further, they rarely formulated time-related rules when questioned. However, as noticed by Pouthas (1989), absence of correlations between behavior and content of overt verbalizations does not disprove rule-governance. Congruent verbal behavior is not a prior or necessary condition for accurate changes in nonverbal behavior to occur. In other respects, the question as to whether young children have a time concept based on a perceptual experience of duration rather than one derived inferentially from non-temporal cues, such as speed, distance, succession (Piaget, 1969) is still open to inquiry (Richie & Bickhard, 1988).

Taken together, these developmental data again tend to show that humans shift from contingency-shaped (in infancy and early childhood) toward rule-governed behavior (from late childhood on) or

from, as Kendler and Kendler (1962) put it within another context (discrimination learning), non-mediational or animal-like learning to learning mediated by language. Early childhood is characterized by a dissociation between saying and doing, between rules and performance. As was the case in FI, performance seems again to mirror the development of language.

Developmental data on temporal differentiation in animal species is available for albino rats (Lejeune & Jasselette, 1987; Lejeune, 1989). Weanling (20-day-old), adult (3- and 7-month-old) and senescent rats (24-month-old) were submitted to a DRL 20 s procedure. They performed 4 sessions a day, for a 10-day period. Each session lasted for half an hour, 250 responses or 40 reinforcers, whichever came first. The accuracy of performance was directly related to the age of the rats, as can be seen on the right part of Figure 4. Senescent rats emitted the highest median IRTs. They also earned the highest number of reinforcers, followed by adult and finally weanlings. Response rates were, as in FI, directly related to the age of the rats. Inter-response-time distributions showed that weanling rats emit high proportions of too-short IRTs, a feature that is almost totally absent in senescent rats. The old rats were most efficient but the spread of the IRT distribution around the modal IRT value was larger than in adults. Age-related differences faded out at the end of the 40 sessions run. An ANOVA computed over the last 12 sessions did not reveal significant differences.

DRL acquisition is age-related in the albino rat, as was FI acquisition. It is noteworthy that, whereas high response rates typical of weaning age could be inhibited in FI (post-reinforcement pauses often exceed 40 or even 50 s), they were not in DRL. This is congruent with the often described FI-DRL paradox. Animals fail at inhibiting responses when this inhibition is requested for reinforcement to be delivered. On the other hand, when this inhibition is not requested, as in FI, it spontaneously develops. Collateral behaviors identical to those observed in FI were found in DRL.

CONCLUSIONS FROM FI AND DRL SCHEDULES

Comparative and developmental data obtained in animals and humans, as reviewed above, suggest that:

1) Acquisition of FI and DRL behavior is age and schedule dependent in animals as well as in humans.

2) Infants or children display patterns of behavior which are somewhat similar to those described for weanling rats.

3) Transition from contingency-shaped to rule-governed behavior in humans is progressive and parallel to the development of cognition

and language. However, although adult humans display rule-governed behavior in DRL and FI, rules match with contingency requirements only in DRL whereas they do not in FI. Rule-governed DRL behavior in humans is much more "animal-like" than is rule-governed FI behavior. The reasons for this discrepancy have long been identified (Lowe, 1979). Fixed Interval per se sets no constraint on response output. The rate of reinforcement does not depend upon the rate or patterning of responses within the interval. As a consequence, several response patterns may be reinforced. In DRL, on the other hand, response rate is directly tied to rate of reinforcement. This constraint is powerful enough to select and mould cognitive strategies that fit with the contingency. Humans become aware of the critical delay (or response duration in the case of DRRD) and most often resort to overt or covert counting-like routines. The only difference between a child aged 6-7 years and an adult will thus be the degree of mastery of chronometric units as well as the capacity to focus attention and inhibit motor output. FI and DRL behavior in adult humans are both rule-governed but the nature of the rule depends on a "degree of behavioral freedom" that is large in FI, narrow in DRL. This does not explain why FI patterns in adults resort to clearcut high- or low-rate types. It only explains why multiple patterns might occur. A similar distinction was made by Wearden (1988), in terms of informationally rich (DRL) or poor schedules (such as FI), and by Galizio (1979) in terms of contact or no-contact schedules where "incorrect" behavior induced by false instructions can be reinforced and thus never matches with the "schedule typical" behavior of animals.

4) Transition from contingency-shaped to rule-governed behavior in humans does not eradicate forms of adaptation that humans share with animal species. Animal-like FI behavior was obtained in adult humans with a hidden FI contingency (Bailey & Lowe, 1988) and with an observing contingency added to the operant response (Lowe, 1979). However, the ability to make use of information provided by clocks is not restricted to the human species. Several experiments have shown that the performance of animals, be it in FI or DRL, can be controlled by external stimuli varying as a function of time (for a discussion about temporal regulation and external cues, see Richelle & Lejeune, 1980).

5) Animals and humans display collateral behavior between operant responses in DRL or during the post-reinforcement pause in FI, i.e., overt time-spanning activities such as fur grooming or tail nibbling in rats, nail plucking or drinking in children. These observations extend the generality of collateral behavior from animal to human species. The origin and functions of these collateral behaviors have been discussed elsewhere (Staddon, 1977; Richelle & Lejeune, 1980). There is no doubt that both animals and humans can benefit

from these time-bridging strategies. As shown by Pouthas (1985), very young children in DRL can refrain from responding by relying upon some collateral motor rhythm.

6) Human infants and rats at weaning age are highly sensitive to the FI schedule. This strengthens the analogy between the periodic delivery of the reinforcer in FI and the "Zeitgebers" in chronobiology. Both are events from the surrounding which synchronize behavior. FI performance would be sort of a behavioral link between acquired temporal regulations and biological rhythms. The synchronizing power of the periodic delivery of the reinforcer is further stressed by the fact that young rats and young children emit numerous very short IRTs in DRL and seem unable to efficiently inhibit motor output in this operant contingency.

7) The operant behavior of young children aged 4½ or 7 seems to be mostly contingency-governed. Language seems to gain a causal role only later on, as the data from 11-year-old children submitted to response duration differentiation tended to show. The probing procedure, i.e., questioning children after each trial about the "rule of the game," does not inform about the role of language in the regulation of ongoing behavior. It sheds light on the relationship between response timing and the search or discovery of rules which might influence subsequent nonverbal behavior. However, resorting to a macrovariable such as "language" is void of explanatory value. Refined experiments are needed to isolate the critical factors at play.

DO ANIMALS AND HUMANS SHARE A COMMON TIMING MECHANISM?

The main theoretical account of timing performance in animal species is scalar timing (Gibbon, 1977, 1991; Gibbon, Church, & Meck, 1984). According to this theory, the hypothetical timing system has two major components: an internal clock which reflects the passage of time and a memory of the critical times associated with reinforcement in the past. Under a procedure such as DRL, the animal might start the clock with each response and end an interresponse time as the clock reading becomes close to the remembered reinforced IRT. Behavior based on a scalar process should have two properties. The first is the accuracy of the mean, i.e., average time estimates should match with reinforced time (in a DRL 20 s schedule, the mean IRT should match with the 20 s critical delay). The second is the constancy of the coefficient of variation, over a range of schedule parameters: the standard deviation of the temporal estimates should be a constant fraction of the mean. This property is congruent with the classical form of the Weber law which requires that the Weber fraction remains constant when durations to be estimated vary.

To evidence scalar timing in animal or human performances is not an easy task. Timing is often entangled with nontiming processes, which may distort the behavioral expression of the underlying timing mechanism. For example, DRL behavior is extremely sensitive to fluctuations in the level of motivation of the subjects. Even if, under favorable circumstances, the mean IRT matches with the DRL requirement, it will no longer be the case if the animal is hungry. The central tendency of the IRT distribution will shift to the left and undermatch target time, because increased hunger triggers high response rates which lower the mean IRT. Procedures have been designed, which allow for the isolation of "pure timing," uncontaminated by fluctuations in response rate. The most studied is the "peak procedure" which derives from a discrete trial FI procedure where intervals are signalled by an exteroceptive stimulus. In the peak procedure, some intervals are longer than the basic FI duration and are not reinforced (test intervals). After extensive training, response rate functions in the test intervals have a Gaussean-like shape, on which two crucial features can be isolated: peak rate, i.e., the highest response rate emitted at a given moment in the interval, and peak time, i.e., the precise moment at which peak rate occurs. Peak time is considered as the unbiased estimate of the moment at which reinforcement should occur, because it is not altered by a change in response rate which might be induced by manipulating the probability of the reinforcer (Roberts, 1981). This procedure has so far been tested with pigeons and rats, and over a limited range of critical values (10 to 50 s or so). Peak procedure data support scalar timing theory. Curves fitted to the response rate versus time functions did show that peak time matched with FI value and that the coefficient of variation of the fitted curves remained constant.

An evaluation of the scalar model with more classical procedures such as FI, DRL or duration reproduction has been undertaken, with mixed results. In some instances, and over a limited range of schedule parameters, scalar timing seems to hold. It was the case with the above described DRL perching behavior of pigeons. It seems also to be the case with some sets of FI data (Gibbon, 1977; Wearden, 1985) and with a duration reproduction procedure designed for pigeons (Zeiler & Hoyert, 1989). It also is the case with short interval production in humans (Wearden & McShane, 1988), and with long interval production without conscious chronometric counting (Zeiler et al., 1987, although these authors claim that their data do not fit with scalar timing theory). Some favorable evidence was also found with bisection and temporal generalization procedures which are closer to the psychophysical time estimation procedures used with animals (Allan & Gibbon, 1991; Wearden, 1991a, 1991b).

The claim that scalar timing mechanisms are common to human

and animal species would be premature. Considering data limited to animal species, several problems arise if one tries to reconcile different levels of performance accuracy with a scalar timing mechanism. This has been illustrated with FI data from various animal species: cats, rodents, birds, fish, and a freshwater turtle (Lejeune & Wearden, 1991). These various species were submitted to three to six FI requirements ranging from 30 to 900 s. Fixed interval response rate functions were fitted with Gaussean curves whose peak was forced at FI value. Within a species, coefficients of variation that were derived from the fitted curves were constant over some but not all FI values. They tended to increase with the duration of the interval. Furthermore, species differed markedly in the value of their respective coefficients of variation (the lowest being found in cats, the highest in the freshwater turtle). Even if these data could somehow be reconciled with scalar timing within a two-process model deriving performance from the interaction of a scalar timer and a nontiming process, the possibility of species-specific differences in timing capacity could not be ruled out. The weakness of such a two process model derives from the fact that variations in timing behavior cannot unambiguously be related to changes in one, the other or both interacting processes. The coefficient of variation cannot be taken as reflecting the "pure" functioning of the scalar timing mechanism. In other words, scalar timing theory is difficult to test. The quest for (a) timing mechanism(s) is at present torn between opposite positions. The first favors interspecies generality of a single mechanism (such as scalar timing). The second supports the view according to which several different timing processes might be involved, each tailored to a particular set of temporal contingencies (Macar, 1985). Both positions are at risk, the former of abusive generalization, the latter of generating only ad hoc models.

Much remains to be done to avoid far-fetched speculations. Differences or similarities that still have to be discovered might further be analyzed within an anagenetic perspective in comparative psychology (Rensch, 1947). This approach focusses on levels or grades in behavioral plasticity or versatility. It is essentially concerned with the range of behavior that animals can reveal when they are faced with challenges which differ meaningfully from those encountered in their natural habitat (Gottlieb, 1984). Suggestions made by Bitterman (1960, 1965) or Gottlieb (1984) among others, clearly indicate methodological guidelines which might be followed: compare closely and remotely related species, submit species to experimental alteration of the species-specific ecology and challenge them with species-atypical tasks. Bitterman (1960) further suggests to control sensorimotor and motivational factors by their systematic variation. A comparative psychology of time within the anagenetic perspective would also request that the species be submitted to an array of tasks or learning

situations which differ in complexity, in order to avoid conclusions based on artifactual differences (Bitterman, 1965). These recommendations, some of them made long before quantitative models of timing were designed, should not be overlooked if a valuable comparative psychology of time is to be developed.

Methodological variables are of prime importance, not only to test the generality of a model of timing, but also in comparative and developmental psychology. Perone, Galizio, and Baron (1988), among others, stress that variables such as the manipulandum or the reinforcer cannot be considered equivalent at different ages. They furthermore contend that crucial causal factors are difficult to isolate, entangled as they are with several other variables of lesser importance.

The methodology issue was pervasive in the analysis presented above. Two independent variables, which are particularly controversial within the human/animal comparison, will be briefly commented upon: the level of motivation and the reinforcer.

Humans do not usually display "considerable enthusiasm" for conditioning tasks, as Church, Getty, and Lerner (1976, p. 309) wrote about rats performing on a duration discrimination paradigm. They, nevertheless, do work for reinforcers with a very low nominal value and even do not consume the food reinforcers dispensed to them, as reported in Wearden (1988). For a rat, accurate responding can be an affair of life or death, but not for humans. Neither are schedule constraints equivalent, nor are the respective motivational states. Wearden (1988) suggests that humans primarily work to get information relevant to the task. Reinforcers also should be considered in terms of their informative rather than hedonic value, as influencing response strategies rather than directly shaping behavior. As Wearden notes, arguing that differences between animal and human performances are due to reinforcement magnitude effects is irrefutable because the operation of equating reinforcement is impossible to specify.

Sensitivity to information or apparent insensitivity to the hedonic value of the reinforcer are, however, not exclusive attributes of the human species. First, information can change animal behavior. Feedback stimuli following responses and dispensing information about their accuracy improve performance, as do stimuli redundant with the reinforcer. Animals also work to get information about the remoteness or probability of reinforcers (Hendry & Dillow, 1966). Secondly, animals such as pigeons can string together thousands of unreinforced responses, as is often the case in DRL schedules with critical delays exceeding 30 s or so. This apparently gratuitous and perseverative pattern of behavior (which results from reinforcement history and also depends upon the nature of the operant) has never been considered as disproving the potency of the hedonic value of the rein-
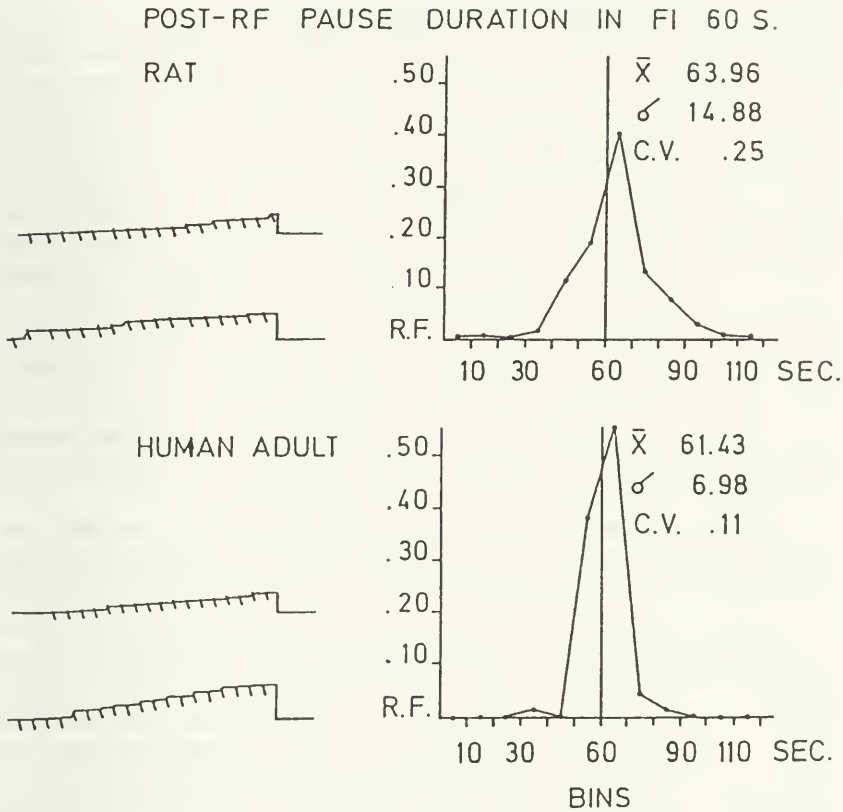
FIGURE 5. Sample cumulative records (left) and distributions of post-reinforcement pause durations in FI (right) for one rat at Day 16 on an around-the-clock schedule (top) and one adult human (bottom). Ordinate of the polygons: relative frequencies (R.F.); abscissa: time bins, with vertical lines at FI value (60 s). The Figure is drawn from unpublished data.

forcer. Human and animal species might differ by the relative balance between hedonic and informational aspects of the reinforcer, hedonic aspects being predominant in animals, informational ones in humans. Whether such subtle differences might lead to a revision of reinforcement theory is a question under debate (Wearden, 1988).

Differences between animal and human performances in temporal regulation or differentiation schedules are not always clearcut. Some differences may just be the consequence of our ignorance about several features of schedule control. For example, FI behavior somehow similar to the low-rate pattern typical of human adults (i.e., one or just a few responses per interval, on the basis of chronometric

counting) can be obtained from adult rats on an around-the-clock Multiple FI/Extinction schedule, where 30-min FI 60 s sessions alternate with 90-min rest periods, the animals thus performing 12 half-an-hour sessions a day (Figure 5). Within the same line, Wanchinsen and Tatham (1989) contended that the ratio- or interval-like behavior patterns typical of adult humans in FI are a mere consequence of their complex experimental history and might not be considered as reflecting features exclusive to the human species. Indeed, Wanchinsen and Tatham obtained human-like FI patterns in rats pre-trained on a Variable Ratio schedule. As Lowe (1979) reported, a high-rate FI pattern may be changed to a low-rate one if the response force is increased from a few to several hundred grams. A similar result might be achieved if humans were trained on high-duration intervals lasting for several minutes. Effortful response requirements would probably suppress superfluous behavior, animals and humans tending towards an optimal cost-benefit trade off.

The data presented above were sampled from a large set of experimental results. However, they do not bear upon all aspects of timing. For example, psychophysics of time has not been discussed (Macar, 1985). The elements gathered so far from comparative and developmental experiments tend to indicate that the most sophisticated timing skills of humans as exhibited when they resort to verbal interpretations and rules, are probably rooted in preverbal or animal-like patterns of behavior. It remains that, endowed as they are with refined verbal and cognitive capacities, humans will conserve primacy on animal species, in terms of rapidity of acquisition, ability to promptly shift behavior and fine-tuning of performance, as sensitivity indices such as the Weber fraction and the coefficient of variation tend to show.

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