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Are we coming near a general Model of Psychological Time?

**Some questions from the comparative and developmental
approaches.**

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INTRODUCTION: HOW DISTINCT ARE HUMANS?

Chronobiological studies have abundantly shown that humans share with other animals fundamental properties of basic biological rhythms. If civilisation has artificially modified a number of natural factors, it has not really liberated humans from the constraints of long established cycles, especially the circadian periodicity: Modern societies, by pushing to an extreme degree the changes in time schedules, be it for work or leisure, have indirectly revealed how strongly has been maintained our species' dependence upon biological time constraints. Do we similarly share with other animals major properties of psychological time? This is the question this chapter addresses to. The answers which shall be proposed are far from complete and far from being in all cases decisive. Reasons for that situation are, among others, that our knowledge on psychological time from a comparative point of view is much less developed than it is the case for biological time, and, more importantly, that some drastic differences between lower animals and humans are likely to derive, as in many other aspects of behaviour, from the use of language in our species, with all its consequences on psychological, especially cognitive functions.

As pointed out in the introductory chapter, the study of psychological time has been stagnant for many years, attracting but a few experimenters, working essentially on human subjects, be it only because appropriate techniques for parallel studies in animals were lacking. Progresses in experimental procedures, mainly in the operant conditioning laboratory, provided the experimenters, since the fifties, with efficient tools to explore psychological time in animals. Abundant empirical data were collected and theoretical models designed to account for them (for a review of the work carried out until the late seventies, see Richelle and Lejeune, 1980). Interestingly enough, thanks to operant techniques, the quantity of data collected on animals quickly outstood those on humans traditionally obtained in the frame of psychophysical methods. One reason for this success was that human subjects cannot help resorting to mental chronometric tricks when submitted to time estimation, reproduction or production tasks involving durations beyond the range of a few hundreds milliseconds. Such contaminating variables escape the experimenter's control. A second reason is that some aspects of temporal regulations of behaviour appear only after prolonged exposure to experimental conditions, which is difficult to require from humans.

There is little doubt that the renewal of psychologists' interest for time, and the impressing progresses accomplished in the last 30 years or so are at least partly due to the contribution of animal studies. These studies, besides the enormous amount of data already mentioned, have generated theoretical models of behavioral and cognitive time which have been taken over or adapted by investigators working on psychological time in humans (for example, see Block, this volume). Times are ripe, not for a general theory of psychological time, but at

least for local synthesis from a comparative approach, which eventually will lead us to identify cross-species commonalities, which humans share with other animals, as well as specificities linked with species-specific features, humans possibly having in this respect a unique position because of their specific cognitive and/or linguistic endowment. As in other fields of psychology and sociology, the issue of human specificity is doomed to contamination by unscientific presuppositions, and, depending on one's own inclination, emphasis will be put on continuities or on discontinuities. Some have argued that the capacity to estimate durations, be it of external events or of one's own behavior, does not basically change from lower animals (or at least from lower vertebrates) to man, and have hypothesised that psychological duration is the foundation from which eventually derive all most complex elaborations such as time concepts, temporal reasoning, experience of time and the like, possibly specific to humans (for a defence of continuity see Richelle, 1968, Richelle, Lejeune, Fery and Perikel, 1985). On the opposite side, others argue that duration itself, whatever its phylogenic history, is, in humans, an elaborate product of cognition (see, for example, Michon, 1990). In the midway stand those which admit that the perception of duration is very much the same in humans and in animals, while other aspects of psychological time (conceptual or subjective) are typically human (for a brief discussion of the issue, see Richelle, 1992).

METHODOLOGICAL CAVEAT

Although the following is rather trivial from a methodological point of view, some words of warning are in point concerning the type of comparison(s) from which conclusions can be drawn. A sound comparative approach would require careful study of a number of species, both very distant and very close phylogenically, so that the status of differences and resemblances observed can be adequately interpreted. However, most discussions are still based on the study of a very limited number of species. As could be expected, most researches on psychological time have been carried out on traditional laboratory species, i.e. rats, pigeons, occasionally monkeys. The anthropocentric trend of the dominant cognitivist school of thought has not favoured the exploration of a wider range of species, the results of which might question the validity of theoretical models proposed. We shall come back later to this issue.

Similarly, models are more often than not built upon and validated by empirical evidence gathered in one or a few selected experimental situations, disregarding the diversity and the complexity of temporal regulations when observed in a variety of contexts and constraints. The rationale for giving privilege to one procedure is quite weak, and consequently the generality of any model so constructed is weak itself. We shall turn in a moment to the most popular model in the field, but one should keep in mind that it is essentially based on data collected in animals

using the so-called peak procedure, undoubtedly an interesting response timing technique, but far from condensing all what would appear relevant to an understanding of psychological time.

Leaving out Pavlovian and a few other procedures, operant conditioning offers a wide variety of schedules to explore temporal regulations. A complete description of them would take more space than available here (it can be found in Richelle and Lejeune, 1980; Lejeune, 1993; Lejeune and Macar, 1994). Suffice it, in the present context, to remind the main categories of these procedures, not for the sake of showing the imaginative production of experimenters, but to point to the crucial problems they raise to a theory of psychological time. If a model, such as Church's model that will be discussed below, draws its empirical evidence mostly from one temporal regulation procedure, such hyperselective choice must be duly justified by demonstrating that other procedures do not add but marginal or irrelevant information on psychological time. Failing to provide such demonstration, it must account for any empirical data as provided by any other procedure.

A major distinction must be drawn among operant procedures between those which bear upon a subject's capacity to estimate the duration of external events and those which permit an analysis of a subject's capacity to control adequately the occurrence of its own activities in time. In the first case, time is processed as any sensory information (in spite of the fact that no receptor is specifically devoted to time as a stimulus), while in the second case, time is integrated in the regulation of action. Time perception is complemented by timing. Some procedures are especially appropriate for the study of the first aspect, for example by using discrimination tasks in which the subject has to tell the difference between an external stimulus of a given duration and a standard stimulus. Other procedures, such as the *Fixed-Interval schedule* (FI) or the schedule of *Differential Reinforcement of Low response rates* (DRL), are designed to study the timing of motor responses. Do these two categories of temporal regulations proceed from common mechanism(s) and obey the same laws? Or do they reflect different processes? The question has generally not been addressed because cognitive psychology has put emphasis on information processing, to the expenses of the motor, efferent side of behavior.

Another no less important distinction among procedures is related to what could be called the adaptive value of temporal regulations. In short, we are confronted here with a paradox. In some procedures, such as the FI schedule, temporal regulation appears spontaneously, entrained, so to speak, by the periodicity of the reinforcement (or strictly speaking of the availability of the reinforcer). In that situations, subjects develop very typical regular patterns of responding, exhibiting long pauses after reinforcement, followed by anticipatory activity as the time of reinforcement approaches, while "waiting" is by no means a condition for reinforcement. In other procedures, like DRL, the response is to be postponed until a critical duration has elapsed, usually since the previous response, making the timing of behavior the

very condition for reward (such procedures are also known as temporal differentiation procedures, because they select or differentiate a temporal characteristic of behavior). The temporal regulation can be said to be spontaneous in the first case, required in the second. Paradoxically, the same subject is able to withhold responding for much longer periods of time in the first case, when it is not necessary, than in the second, when it is required.

Finally, exploring different procedures is also intended to focus more specifically on the timing processes proper, in other words, to capture psychological time in its purest manifestations, getting rid or controlling all sorts of presumably irrelevant variables, such as motivational state, attentional constraints, species-specific limitations, etc. For example, rather than using short operant responses as is usually the case in DRL schedules, leaving uncontrolled the subject's activities between responses, one can use a prolonged response, which the subject must maintain for a critical duration if it is to be rewarded (*Differential Reinforcement of Response Duration schedule*, DRRD). One variant of the FI schedule, aimed at isolating the timing mechanisms proper, has been popularised by Roberts (1981) and Church (1984) after an earlier experiment by Catania (1970) as the *peak procedure*. Besides psychophysical procedures (bisection and generalisation), it has provided an important amount of data used to support Church's model.

FORMAL MODELS

Currently discussed formal models of psychological time in humans are mainly derived from psychophysical studies (see Eisler, this volume). They are based on empirical data collected in experiments on the discrimination of duration (differential threshold) and on scaling (the bisection procedure being the most widely used). Without entering the intricacies of a highly sophisticated field, let us mention that, on the whole, psychophysical studies both on animal and humans confirm that Weber's Law applies to time as it does to other stimulus dimensions. In other respects, some motor performances are best described by using a linear function ($M = bt + a$), others by a power function ($M = kt^n$) [where M is the average performance and t the temporal parameter of the task; a , b and k are fitted constants].

As already alluded to, the by far most popular model is the so-called *scalar model*. It has been initially proposed by Gibbon (1977), but had been in some respects anticipated by Treisman (1963). However, it is better known as Church's model, having been especially elaborated, and subsequently modified according to empirical and theoretical progresses or shift of emphasis, by Church and his co-workers (Church, 1984, 1989; Church and Broadbent, 1990; Gibbon and Church, 1990, 1992; Church, Meck and Gibbon, 1994). It is essentially a description in terms of formal variables, to which psychological variables are matched. Both the

description in formal and in psychological terms have evolved with time, paralleling the evolution of ideas in cognitive psychology.

In its classical form, which could be labelled "temporal information processing model", the model involves, as shown in Figure 1, three levels, i.e. a timer proper, memories and a decision unit. At the lower level, an internal time base sends pulses, via a switch, to an accumulator. The latter - at the second level - feeds the working memory if there is a delay between the duration to be measured and the opportunity to respond (as is for example the case in *symbolic matching-to sample* or *duration discrimination procedure*). The content of the accumulator or of working memory is permanently being assessed with respect to the reference memory in which relevant informations as to the duration to be estimated are stored. At the third level, decision is made after a comparator matches the informations processed in working memory to those stored in the reference memory. Component boxes can be viewed as plausible inferences as to the processes underlying time estimations, although some of them could be questioned and revised - in fact have been questioned and revised (see Church and Broadbent, 1990) - along the connectionist line of thought. The scalar model has essentially two distinctive features, deriving from its very structure and especially the place of the reference memory which provides the standard for comparison before each decision to respond occurs: (1) the reference memory stores the estimations of the critical duration in the shape of a Gaussian distribution, with the variance being a function of the square of the mean; (2) mean and standard deviation of this distribution are proportional to the critical duration. In other words, the performance should exhibit two characteristics if the model is to be validated: (1) the central tendency of time estimations should coincide with the critical duration to be estimated and (2) the coefficient of variation (that is the ratio of the standard deviation to the mean, σ/μ), the major evidence of an organism's sensitivity to time, should remain constant whatever the absolute value of the critical duration. If the latter is modified, the subject will "re-scale" its timing units according to Weber's Law.

The scalar model, initially elaborated in the context of animal studies, has been applied to human data as well (Wearden, 1991a). Several studies have shown its adequacy to account for a number of empirical data, suggesting that it could be seen as a robust candidate as a general model, especially in unifying human and animal time. However, even if particular samples of behavior do fit the assumptions of the model, the question remains open as to its generality, *within* and *across-procedures*, *within* and *across-species*, and throughout development.

IN SEARCH OF PURE TIME

The first point has been dealt with in several now classical reports (Catania, 1970; Platt, 1979; Stubbs, 1979; Zeiler, 1986). According to Zeiler (1983, 1986), Weber's law does not

always fit temporal differentiation data because behavior is jointly governed by timing and non-timing processes which cannot be disentangled. "Pure timing" (Zeiler, 1985) is mixed with behavioral noise depending upon non-timing factors. Despite such a pessimistic view, the quest for unbiased timing within the frame of temporal differentiation or regulation data has followed five main roads which are described below with reference to the scalar model.

In the first, the model is corrected or modified so as to account for discrepancies between observed behavior and the requirements of the model. These discrepancies are seen as the result of the overlapping of two processes, a random response production process being superposed to the scalar timing process proper (Wearden, 1985).

Secondly, attempts have been made to design interference-free procedures suited to unveil pure clock time, such as the peak procedure where, at least theoretically, response rate and response timing are truly dissociated (Catania, 1970; Roberts, 1981; an earlier attempt was made by Mechner and Guevrekian, 1962).

Thirdly, some experimenters have been looking for rare bias-free cases among empirical data. For example, the differential reinforcement of inter-response-times (IRTs) between discrete perching responses in pigeons yielded data in agreement with both requirements of scalar timing theory. The central tendency of the IRT distributions matched the reinforcement criterion and the coefficient of variation remained approximately constant, over durations ranging from 10 to 70 seconds (Jasselette, Lejeune and Wearden, 1990).

Fourthly, obstacles to the capture of pure time might depend on interindividual variations. For instance, only those subjects were retained for peak procedure training (18 out of 36) which exhibited the highest response rates on the second of a 2-session Random Interval pretraining (Roberts and Holder, 1984, experiment 1).

Finally, obstacles to the capture of pure time have been attributed to intraindividual variations. Consequently, parts of the data obtained on individual subjects have been discarded, because they did not fit the assumptions of the model. This now widely used strategy has progressively drifted from a "reasonable" grooming of the data (discarding only extreme "deviant" response patterns) towards dropping rather high proportions of the performances of individual subjects. Recent cases are for example described in papers discussing multiple timing or the sources of variance in scalar timing, on the basis of single trial analysis. For instance, are retained individual break-run-break patterns characterized by "good starts" and "good stops", the criterion "good" being defined with regard to the critical temporal parameter, and thus to expected response timing (Cheng, Westwood and Crystal, 1993; Church, Meck and Gibbon, 1994; Leak and Gibbon, 1995). What one would expect, of course, from such a strategy, is validation of the model! Ironically, as the search goes on, and as increasingly sophisticated procedures are put to work in collecting or analysing data, pure timing seems to remain ever more elusive.

In the first solution, appeal has been made to various "extra-temporal" variables, such as motivation and attention. Attention has been especially in favour in the recent years. However, the idea is not new. Attentional effects were discussed in the frame of the initial version of the temporal information model, in which the different stages of time processing were phrased in psychological terms. Attention was considered as a peripheral factor acting either at the level of the switch or when a sample duration is retrieved from reference memory. Indeed, experiments using the prior entry or the unbalanced probability methods in bisection or peak procedure showed that attentional factors can modulate performance (Meck, 1984). Attention holds the forestage in attentional models of timing (for example, Zakay, 1989), in which the limited attentional resources are supposed to be distributed between a timer (analogous to the clock stage in Church's model) and a processor devoted to the treatment of non-temporal aspects of stimuli. If, in double task procedures, attention is directed towards the stimulus processor, errors in time estimation will increase, and vice-versa (Macar, Grondin and Casini, 1994). So far, the attentional model has only been thoroughly tested with human subjects. If a parametrical relationship between attention and timing could be drawn from analogous experiments run with animal species, the part of behavior neglected in solution 5 might be rehabilitated, eventually resulting in a more comprehensive account of performance. In this respect, it is worth noticing that most recent theoretical attempts integrate the information processing and attentional models (Block and Zakay, in this volume).

Attention is, however, only one of a number of variables plausibly affecting performance. Inhibition might be another one. The hypothesis of a balance between the ability to inhibit motor output (and thus operant responses) and the quality of response timing was proposed by Richelle (1972), not to mention, much earlier, pavlovian conditioning theory. This hypothesis has so far remained dormant and is still awaiting for experimental tests, admittedly more difficult to design than in the case of attention, because inhibition is an internal variable quite difficult to control as a independent variable (the only indirect attempts are the classical pavlovian disinhibition tests, and a few operant analogues; see Richelle and Lejeune, 1980).

The last two solutions raise basic problems to which psychologists have been confronted on many occasions: how should we deal with between and within subjects variations? Can we legitimate a selection of subjects among a sample, or of data among the whole range of observation in individual subjects? Neutralising between-subjects variability by analysing only group results has been another, more conformist way to elude the difficulty. Referring again to the peak procedure, response rate functions have usually been derived from averaging group performance over several sessions. To which extent are such functions really representative of time estimation capacities in the species is by no means clear. Close examination of individual performances would suggest that it is not the case. For instance, average data collected on senescent rats using the peak procedure (Lejeune and Soffié, in preparation) seems to confirm

response rate functions described by Meck, Church and Wenck (1986), that is, the peak time is shifted to the right. However, inspection of individual response rate functions revealed that three out of 10 old subjects still matched young adults, whereas the rightward shift was observed in the others.

The fifth solution, i.e. rejecting some of the individual trials as "bad", might, at first sight, be legitimated by assuming a two-processes model, as considered in solution one above. But assuming that pure time is contaminated by some other factors does not dispense from identifying the factors at work, and does not legitimate a priori rejection of some data, since rejection could only be acceptable if based on explicit criterion, which in turn implies that contaminating factors have been identified. Experimenters in the 60ties and 70ties were confronted to the problem, but did not beg it by a priori rejection. Early data collected with the DRL procedure provided evidence for two distinct types of IRTs, some of which very short, limited by responses emitted in "bursts", others much longer, matching the critical delay for reinforcement. These bursts were systematically studied and eventually fairly well explained, and legitimately distinguished from timing responses proper (for a review of these classical studies, see Richelle and Lejeune, 1980).

THE COMPARATIVE DATA.

Cross-species comparisons are obviously a prerequisite to any general theory of psychological time, as well as to any specific theory of human psychological time. That research strategy has been shown to be productive in the field of chronobiology, unveiling both universal and species-specific characters of biological rhythms. Curiously enough, it has hardly been applied to the study of time in behavior.

Most animal data have been collected on traditional laboratory species, i.e. pigeons and rats, occasionally monkeys. Very few studies have been carried out with other species. Richelle and Lejeune (1980, 1984) mentioned about thirty studies, some of which anecdotal, and therefore of no use in the validation of models such as Church's model. Since that time, a few more species have been systematically studied, in a comparative perspective. Still, the very limited interest in that approach is striking. As it seems, whenever animal studies are invoked in the field of psychological time, it is more with the concern for generalising processes supposedly at work in humans than with the goal of understanding throughout phyletic history the organisms' capacities to cope with time, eventually up to the complex processing of time emerging in humans - if it can be demonstrated that it is the case (see Wasserman, 1993; Wearden and Lejeune, 1993).

Besides the numerous studies on rats, pigeons and, to a lesser extent, monkeys, empirical data are available on domestic cats (*Felis catus*), various strains of mice (C27/black, NMRI,

Balb/C among others), field-mouse (*Apodemus sylvaticus*), gerbils (*Meriones unguiculatus*), quails (*Coturnix coturnix japonica*), cichlid fishes (*Tilapia nilotica* L.), fresh-water turtles (*Pseudemys scripta elegans* W.) (Lejeune, 1971, 1993; Lejeune and Nagy, 1986; Lejeune and Wearden, 1991). The sample is far too small to permit conclusions as to universals of time which all species would share. In fact, a crude analysis of performances across species shows that some of them are more skilled than others in their temporal regulations. Mammals and birds, for example, perform better than fishes or turtles. At first sight, this would suggest that the mechanisms of the hypothetical internal clock, or, for that matter, of the scalar model, cannot be reduced to any simplified picture.

Closer analysis of available data, however, brings some support to the generalisability of the model. The coefficient of variation of temporal estimators as produced by the subjects indicate that, at least in some cases, sensitivity to time remains constant along different values of the critical delay. As will be reminded, this is one of the requirements of the scalar model. The second requirements, that is the matching of the central tendency of temporal estimators to the duration to be estimated, is also, at least in some species, fairly well met. Thus, in spite of cross-species differences in their sensitivity to time, reflected in the absolute value of the coefficient of variation, the constancy of the coefficient in a given species points to one important common feature. Figure 2 shows this phenomenon, and suggests that the scalar model could be compatible with different levels of sensitivity to time in different species, possibly derived from selective pressure in the peculiar environment in which they have evolved. In other terms, the mechanism of the internal clock could be the same, the differences observed between species being due to differences in the temporal resolution of the clock (just as chronometers can have different level of accuracy, to one tenth, one hundredth, or one thousandth of a second).

While coefficients of variation obtained under certain conditions remain constant, exceptions occur, in which the coefficient increases, or to the contrary decreases, as the time criterion increases. Data collected on fresh water turtles and cats illustrate the first case; turtle doves provide an example of the second case (Figure 3). No explanation has been proposed for the decrease of the coefficient of variation. The increase could result from the combination of a scalar process, the sensitivity of which remains constant, with a random response generating process, as hypothesised by Wearden (1985); balancing adequately the two components in a computer simulation has provided data matching those observed in real performances (Lejeune and Wearden, 1991).

The results discussed above would, at first sight, seem compatible with an evolutionary hypothesis, in which capacities for temporal regulations would correlate, for example, with an index of complexity of the central nervous system throughout the phyletic tree. However, the picture gets more complicated as one looks at the performances in zoologically close species:

important differences are observed, for example, between turtle doves and homing pigeons, or between laboratory mice of various strains and their wild cousin, the field-mouse (Lejeune, 1993).

The student of time enters further puzzlement when confronted with differences in timing capacities within the same species - within the same individuals of a given species - depending upon the sensory modality or the type of response involved in the experimental situation. Rats have been shown to be better "time estimators" when an auditory stimulus is used rather than a visual one, while the converse relation holds in pigeons (see Figure 4) (Meck and Church, 1982; Roberts, Cheng and Cohen, 1989). Similar conclusions are drawn from studies on cross-modal transfer of time estimations, from studies in which the probability of signals addressing different modalities has been manipulated and from studies exploring parameters such as intensity or "empty" vs "filled" stimulus duration (Meck and Church, 1982; Meck, 1984; Wilkie, 1987; Mantanus, 1981). These effects, however, seem also dependent upon the length of training, and would fade out after long exposure to time contingencies (Meck, 1984; Roberts et al. 1989), a possible condition to have access to "pure time", if it is accessible at all. Indeed, rats trained on an "around the clock" FI 60 schedule where 30 minutes conditioning sessions alternated with 90 minutes "rest" periods displayed after 25 days (i.e. 290 training sessions) low response rates and post-reinforcement pauses much longer than those usually obtained with the classical one-session-a-day practice and a smaller number of training sessions. In such a case, distributions of postreinforcement pauses look like a response rate function in peak procedure, with the average post-reinforcement pause close to 60 seconds (Richelle et al. 1985; Lejeune and Richelle, 1990).

Species-specific constraints appear even more obvious when performances are compared in the same species using different responses. A striking example has been described in pigeons, which showed to perform much better on a DRL schedule when a perching response was required than when the traditional key-peck was used (Lejeune and Richelle, 1982) (Figure 5). Moreover, as already mentioned, the coefficient of variation was fairly constant for increasing values of the critical delay, meeting the requirement of the scalar model (Jasselette, Lejeune and Wearden, 1990). That and other studies on response topography (for a review, see Lejeune, 1993) indicate that all motor responses are not equivalent in reflecting timing capacities of a given species, one major factor being the response amenability to central inhibitory control, as suggested by refined analysis of key pecks in pigeons exposed to DRL contingencies. "Bursts" of responses emitted with very short inter-response times (IRTs) do not have the status of real operant, and could be interpreted as some sort of displacement activity compensating for the inhibitory tension hypothetically induced by any time contingencies (Richelle, 1972). The fact that they influence very little the optimisation of performance, as shown by Wearden (1991b) supports that interpretation.

Empirical data collected on human adults using operant procedures, usually covering a very limited range of durations, have been compared with animal data, especially in attempts to validate the scalar model (Wearden, 1991a). They converge with data obtained with other methods traditionally used in psychophysics, which have led to models quite close to the scalar model (Allan, 1992). This, however, leaves out some interesting observations made on humans in some operant procedures such as the Fixed-Interval schedule. It has been shown that, as a rule, human adults do not exhibit the pattern of behavior usually observed in animals (which gave the old cumulative curve its typical scalloped shape, as shown in Figure 7). Human subjects either pause for a very long time (approximating the critical interval) after each reinforcement, ending up with one or very few responses sufficient to bring the reinforcer, or they produce a sustained train of responses throughout the interval. The first have obviously detected the temporal nature of the contingency and probably resort to some mental chronometric device which occasionally helps time estimation; the second misinterpret the situation as if it would require sustained responding. Such contrasting patterns appear to be cognitive interpretations, plausibly based on linguistic capacities. In the second group of subjects, the cognitive elaboration would result in a less adaptive performance than the one observed in animals. Comparison with animal subjects is not enough to decide whether language or some other human species-specific character is the crucial variable here. A developmental approach recommends itself to verify if the acquisition of language is responsible for the behavior observed in human adults.

DEVELOPMENTAL EVIDENCE

Developmental studies of psychological time have been mainly devoted, after the pioneering work of Piaget (1946), to the construction of the concept of time (Fraisse, 1948, 1982; Montangero, 1977) and to the progressive mastery of the linguistic tools expressing time relations (Bronckart, 1976; Ferreiro, 1971). By their very nature, such studies can only be carried out on subjects having already acquired language. The same applies to studies on time estimation proper, for reasons of experimental accessibility: the procedures used involve verbal instructions to the subjects. Operant procedures applied to infants or very young children have provided information which allow to compare their temporal regulations both to those of animals and to those of human adults, and consequently to better assess the role of language in the patterns characteristically observed in human adults.

In its turn, the comparative approach to infants and young children's performances requires reference to developmental data in animals. These have been, until recently, very scarce, not to say completely absent, reflecting a lack of interest for the heuristic and explanatory value of developmental research among experimenters in the operant tradition (for a

discussion of that particular point in a wider context see Richelle, 1992, 1993). The few studies reported below are recent and therefore still exploratory. They will be shortly discussed before returning to infant studies and to the role of language.

Development studies in animals

With very few exceptions (such as Marley and Morse, 1966), animal developmental studies of temporal regulations do not go back more than 15 years. Some of them were based on a life-span developmental approach and as such they provide data on aging subjects as well. Methodological difficulties involved in longitudinal studies in very young and very old animals have usually been discussed in depth and appropriately solved. For example, to avoid food deprivation in young animals, and reduce the interaction between learning processes and maturational factors in fastly growing organisms, subjects were submitted to four or five daily sessions, instead of one, over a period of 8 to 10 days. Precociously weaned rats (16 days) were conditioned, under those conditions, as early as 18 to 21 days of age (Lejeune, 1992). Also, nestleaving birds, more amenable to early conditioning, such as quails or ducklings were used (Lejeune and Nagy, 1986; De Paulo and Hoffman, 1981).

Young (20 days), adults (3 months) and senescent (24 months) rats were compared in FI 60 seconds and DRL 20 seconds schedules (Lejeune, 1989, 1992; Lejeune, Jasselette, Nagy and Perée, 1986). Results are summarised in Figure 6. In the FI schedule, temporal regulation is best in young rats, in spite of a higher rate of responses, reflecting higher level of activity. In the DRL schedule, the response rate is similarly related to age, but in this case it has deteriorating effects on timing in young animals. Similar results were obtained with a schedule of differential reinforcement of response duration (DRR). In these cases, activity level interferes with timing. This could be nothing more than the aspecific effect of a trivial variable, - "general activity" as a characteristic of age - comparable to motivation, emotional arousal, etc. However, this does not explain why and how it is that spontaneous temporal regulations observed in FI do not suffer from general activity, a paradox that has been pointed to many years ago, that developmental studies show even more strikingly, and that until now no formal model of psychological time has explained in any satisfying way.

Whatever the contingencies used, differences between age groups fade out as training is extended in time, eventually to disappear after 40 to 50 sessions. This suggests that differences observed are not due to different processes of the internal clock - whatever it is -. It also warns the experimenter working on human subjects not to indulge in hasty conclusions from results collected on children, human adults or old people in a few short experimental tests, as it is generally the case.

Developmental studies in humans.

Exploratory and incomplete as they are, these findings will frame the data collected in infants and children in both comparative and developmental perspective.

The performance of infants in FI does not look like adults' performance. Infants show the typical pattern observed in animals, that is a pause after reinforcement, the duration of which is proportional to the interval (Lowe, Beasty and Bentall, 1983). Between 2 1/2 years and 5 years, the distribution of responses throughout the interval is erratic (Droit, Pouthas and Jacquet, 1990). Typical patterns of human adults, described above, appear around 5 years. This change could be due to the mastery of language, especially as a tool for self-description and self-instruction concerning the temporal contingencies and the way to meet them (Bentall and Lowe, 1987; Bentall, Lowe and Beasty, 1985). Erratic patterns observed between 2 and 5 would essentially reflect the linguistic immaturity. These findings suggest a progressive shift from contingencies controlled to rule governed behavior, the transition phase being marked by the competition of the two modes.

These interesting data, which fit nicely the course of cognitive and linguistic development, raise some problems of replication. Darcheville, Rivière and Wearden (1993) have reported, in infants 3 to 5 months of age, in a FI schedules (using increasing intervals from 10 to 80 seconds) a very low response rate comparable to what is observed in those adults who seem to have detected the time contingencies. Babies aged 9 to 13 months (comparable in age to the subjects of Lowe et al. 1983) have performances falling in one of the two categories described in adults. Individual patterns seem to correlate with the behavior observed in a self-control task, in which the subject has the choice between an immediate but short reinforcer or a differed but long one. Those babies which make the first choice exhibit high responding in the FI, while those which make the second choice show low rates. A number of methodological variables, such as the response used, the type of reinforcer, general aspects of the experimental situation, have to be checked before the debate can be closed. Notwithstanding, the findings throw some doubt on the purely cognitive interpretation of infants' performances in terms of language acquisition, and maybe suggest to explore more fully temperamental predisposition, a concept recently rehabilitated after a long period of disrepute (Kagan and Snidman, 1991). That line of reflexion also brings us back to the hypothesis giving inhibitory processes a major place in temporal regulations.

Adaptation to DRL and DRRD schedules does not leave much freedom: only one pattern of behavior provides the reinforcer. This constraint is essential in understanding the development of performances in young children and young animals. Contrary to what is observed in FI schedules, no major difference appears in DRL or DRRD performances as a function of age. In both schedules, young children and rats as well characteristically produce a

number of inadapted responses, which will progressively decrease as motor inhibitory functions develop (Lejeune and Jasselette, 1987a and b; Lejeune and Richelle, 1990). As it seems, the child becomes increasingly aware with age that it has to wait for a given duration (Pouthas, 1985, 1990, 1993). From its second year of age, it often fills the waiting time by producing collateral behavior (also observed in animals) of all sorts, sometimes requiring much motor energy, such as running around the room, turning its chair upside down, and the like. These collateral behaviors become less frequent with age (Pouthas, 1985; Pouthas and Jacquet, 1987). Some children at 4 years of age produce very accurate timing in DRL 5 sec.. Others take a bit longer, but eventually at the age of 7 the performance is usually excellent.

It is obvious that human beings are confronted from birth with duration, through the frustrating experience of having to wait until their needs or demands will be satisfied. Waiting, which Janet (1928) rightly described as "active regulation of action", is the core of experimental procedures of time differentiation. They probably favor in *all* subjects the awareness of the role of time, while *some* subjects do eventually get aware of it in less constraining procedures, as FI schedules. The issue of awareness (or consciousness), in favor again in psychological and neuroscientists' circles, deserves systematic attention in the field of psychological time.

Conclusion

As stated in the first section of this paper, attempts to develop general models of psychological time are the product of increasingly rich informations collected during the last twenty years or so in various subfields of research devoted to various facets of time processing. They are based on the legitimate assumption that time processing can be described by a single model, however complex, and admittedly requiring qualifications to account for some of the peculiarities as might be observed at some levels of functioning. The scalar model has been taken as an example of such attempts, because it has been shown to encompass a number of data collected both in animals and humans, and to be open enough to new adjustments, at least to some extent, as formal models evolve from information processing to connectionist networks and as empirical findings multiply.

Comparative and developmental studies briefly exposed and discussed in the present paper offer a large bunch of such empirical data. Some of them seem to fit the model fairly well, confirming its validity, and corroborating its heuristic value. Others, however, are less easy to incorporate: either they simply do not fit the requirements of the model, or they just lay out of its scope. In both cases, they raise a problem as to the generality of the model. In the first case, the solution can be looked for either in the adjustment of the model itself - which might eventually become increasingly complex and qualified - or in the rejection of empirical evidence as irrelevant to a theory of "pure" psychological time, that is to say, data not fitting the model would be explained away as effects of non-temporal variables. In the second case, empirical

findings just raise different questions, which the model does not address, but which, nevertheless, might be sound questions in the frame of a theory of time; they will have to be accounted for one day or another. Maybe some new, enlarged, model will be needed. Maybe new models will do better, accounting for the real diversity of processes involved in psychological time, which seem to challenge the search for a single unified theory that seems so attractive to current students of time.

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FIGURE LEGENDS

Figure 1.- The internal clock model for processing of temporal information, after Church (1984). The six components of the model are organized in three levels (counter, memory, decision). When confronted to a duration to be estimated, the time base produces pulses which are sent through a switch to the accumulator where they are counted (these pulses are transferred to a working memory if there is a gap between the end of the duration to be estimated and the opportunity to respond, as is the case with duration discrimination procedures, for example). The comparator compares the duration in the current trial with a representation of the duration drawn from the reference memory, where durations reinforced during previous trials are stored. The decision to respond (*yes*) or not (*no*) is taken according to a norm of similarity between these two values.

Figure 2.- Average duration produced (above) and coefficient of variation of the time estimators (bottom) in time production tasks. (Abscissa: value of the critical delay to reinforcement, expressed as the fraction of the maximum delay used in gerbils (empty squares), pigeon (circles) and human adults (filled squares). [After Lejeune and Richelle, 1990, and Wearden, 1991a]

Figure 3.- Evolution of the coefficient of variation in temporal regulation under Fixed Interval (FI) schedules of reinforcement (ordinate), as a function of the interval duration (abscissa, expressed as a proportion of the interval used) in fresh-water turtles (filled triangles), turtle doves (circles) and cats (empty triangles). The range of durations explored in each species is mentioned at the right of the corresponding curve. Stars joined by broken line show values obtained from computer simulation, applying a complex model which combines a timing process and a non-temporal process in response production (the coefficient of variation of the timing process proper being 0.20, and the probability for a response not controlled by time being 0.05). For simulated data, FI intervals (abscissa) correspond to arbitrary units (after Lejeune and Wearden, 1991).

Figure 4.- Acquisition curves of pigeons in a time discrimination task involving either visual (white circles) or auditory (black circles) stimuli lasting 2 vs 8 seconds. [After Roberts et al., 1989]

Figure 5.- Interresponse times (IRT) curves obtained in a pigeon in a DRL schedule of reinforcement with a key-peck response (left) and with a perching response (right). Ordinate: relative frequencies; abscissa: IRT bins. [After Lejeune, 1989a]

Figure 6.- Top: curvature index (left) and response rate (right) in juvenile, adult and senescent rats during acquisition of behavior under a FI 60 seconds schedule over 10 days of training [the curvature index is an estimate of the quality of spontaneous temporal regulation in FI schedules]. Bottom: median IRT (left) and response rate (right) during acquisition of behavior under a DRL 20 seconds schedule over 10 days of training. [After Lejeune, 1990]