TIMING
IN
TEMPORAL TRACKING

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PREFACE

A development which has already been in progress for a long time, in industrial as well as in military work, is that of decrease in the physical load of tasks to be performed. The recent acceleration in this trend is known as automation.

The decrease in physical load is accompanied by an increase in the importance of perceptual and fine-manipulatory features of the tasks. The way of measuring perceptual load has therefore become a subject of great interest.

Michon, who obtained his doctorate with the present study, became interested in the timing of behaviour when he considered one of the proposed methods of measuring perceptual load. In that method the deterioration of performance is evaluated when an additional load, due to a second task, is placed upon the worker. Michon introduced key-tapping as a second task, and found the irregularity in tapping to be indicative for the level of perceptual motor load. In order to understand this phenomenon basically, Michon started this study on time perception; it deals with very fundamental aspects of human behaviour. So in fact a practical question inspired this basic study, which will certainly help to evaluate the key-tapping method as a measure for perceptual load.

A second point that I wish to mention is about the way in which Michon treats the problem. He completely deviates from the classical way of studying time perception in that he introduces the method of systems analysis which is so frequently used for engineering problems and, also, in spatial tracking. Although this approach is, of course, the idea of the author, it may be recalled that in the Institute for Perception RVO-TNO people of different disciplines together work on perception problems, under one roof. This set-up has doubtless enabled an environment in which Michon's ideas could develop fruitfully.

This approach to the study of time perception will open new ways for experimental psychology.

I hope, and expect, that Michon will continue this kind of inventive work on practical problems and basic issues.

PIETER L. WALRAVEN

CONTENTS

CHAPTER I - INTRODUCTION

1. THE PROBLEM

This study deals with the temporal aspects of skilled behavior. We will investigate the response of human subjects to sensory inputs which vary in time. Specifically our concern will be the relation between the temporal structure of an input and that of the associated output. Other properties of the experimental situation will be considered only to the extent to which they affect this relation.

With Bartlett (1951), Lashley (1937, 1951), Miller, Galanter and Pribram (1960), and others, we are convinced that it is not in the last place the fine structure of the timing between successive elements in a string of actions which characterizes skilled performance (Michon 1966a).

We might, for instance, study the performance of a pianist playing a Beethoven sonata and measure to what extent his performance would be in agreement with the specified duration of each note in the score. Melody and intensity would enter the picture only insofar as they would affect the precision of the temporal relations. A pianist will be called a 'skilled performer' even by his least benevolent critic, so long as his timing is impeccable, although his 'interpretation' may be way below an acceptable minimum. In fact there is evidence that 'interpretation' is accomplished more by introducing well balanced variations in the timing of notes than by varying their loudness (Henderson 1936; Stetson and Tuthill 1923).

Rather than trying to cope with the intricacies of Beethoven's piano sonatas, however, we will restrict ourselves to a simpler skill.

In its simplest form the 'timing' of skilled actions can be studied in key tapping. Here the subject is asked to produce a sequence of taps by means of a stylus or a Morse key. The sequence may be long or short and it may have a constant or a variable rate. It may be the reproduction (continuation) of an example presented earlier or synchronization with a concurrently presented sequence. In the limiting case just a single interval is involved, a 'sequence' of two taps only, in which case we have the condition which is typical of the classical time perception experiment. Usually however, the series is longer and the skill involved is to tap repeatedly as accurately as possible, either synchronizing with a stimulus sequence or reproducing such an input.

We intend to single out some of the properties of the mechanisms which underly the ability to evaluate short time intervals (*time perception*) and which make subjects respond quite appropriately to the temporal information in sequential stimuli (*timing*).

In the early days of 'time psychology' no distinction was made between time perception and timing in serial behavior. Later, for unknown reasons, it came into existence and consequently the two topics have developed along quite different lines (Michon 1964b; Weitz and Fair 1951). The notable exception is Fraisse, who did considerable amounts of research on both rhythm and time perception (e.g. Fraisse 1956, 1957[1]). Nevertheless the literature provides no convincing arguments at all for the assumption that evaluation of a single interval is essentially different from that of a sequence of intervals. The explanations offered to account for the temporal aspects of behavior (see Sec. I.2) are essentially identical for time perception and for (anticipatory) timing in key tapping or rhythmic performance. Consequently we will accept key tapping as a valid tool to study the mechanisms by which human beings evaluate short intervals of time.

Though rhythmic performance or synchronization are likely to require more complex processing of information than a 'single interval' experiment, performance under sequential conditions will reveal much better the properties of the time evaluation mechanism. Single interval experiments in fact look at the responding system only when it is in a transient state. Hence they deal with a special case and provide only partial information about the dynamic characteristics of the timing system. On the other hand we should – at least in principle – be able to derive this special case from more general knowledge about the system, obtained by means of a more adequate, i.e. sequential, input.

It is well known that the subjective evaluation of time is highly dependent on factors other than the temporal information from the stimulus condition. The effects of the stimulus and response organi-

[1] Fraisse's monograph (1957) has been translated recently. From now on we will exclusively refer to the English version of 'Psychologie du Temps': (Fraisse 1964).

zation, the intensity of the stimuli as well as their various other properties, the amount of information processed and the cognitive processes involved, all markedly influence our estimates of duration, both at a gross level (systematic errors) and in short term fluctuations (variance). We will indicate this complex of factors with the term *information processing load.* It will be analyzed in somewhat greater detail in Sec. I.3, and at a later point we will study its effect on the timing mechanism (Chapter VI).

In summary then, our objective is to study the timing aspects of a simple form of skilled behavior, i.e. key tapping. Time will thus be treated both as dependent and independent variable, whereas other aspects of the experimental situation may serve as parameters.

2. MECHANISMS OF TIME EVALUATION

The use of key tapping as a response mode imposes a lower limit on the range of intervals that can be studied. Bartlett and Bartlett (1959), reviewing the available literature, concluded that subjects cannot tap much faster than 10 taps per second, although at the level of muscular innervation the shortest possible interval is considerably shorter. The upper limit is in principle determined by practical considerations only. We will, however, restrict the range to intervals of at most 5 sec. There is evidence that intervals of more than 3 to 5 sec, are evaluated by different processes than shorter durations (Fraisse 1964; Whitrow 1960).

The evaluation of short durations between approximately 50 msec and a few seconds is frequently called 'time perception', an expression indicating, more than anything else, that neither experimenter nor subject are able to formulate how and to what extent the latter uses cognitive or bodily cues. As long as it is not possible to specify the processes involved in the estimation of short intervals, we may define time perception operationally as the ability of a subject to behave differentially in response to intervals of various durations, while experimentally noticeable use of cognitive, physiological, or motor cues is absent. The mechanism of which it is a manifestation will be called, metaphorically, the 'time sense' throughout the text.

The sheer number of hypotheses offered to explain time perception has been characterized as chaotic by more than one author (see for instance Frankenhaeuser 1959; Nichols 1891; Wallace and Rabin 1960). We have pointed out elsewhere (Michon 1965) that the apparent multitude of explanations rests on a very simple formal model, which is presented in Fig. 1.

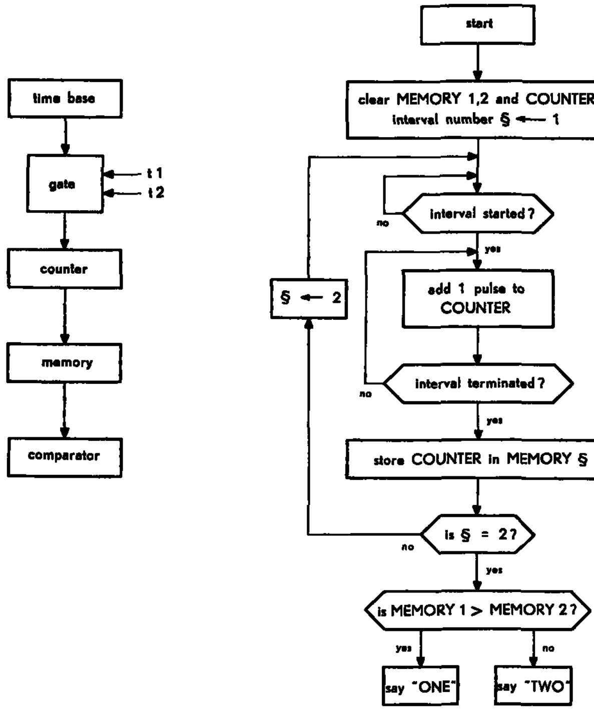


FIG. 1 – Formal model of the 'time sense' underlying most historical theories. The single presentation pair comparison experiment. At left a functional representation, at right a flow diagram showing the decision structure.

All theories postulate a 'time base', a periodic, quasi-periodic, stochastic or even progressive process, which delivers signals of some sort at successive points in time. The idea almost automatically includes the concept of a basic unit of subjective time, known in the literature under such names as 'perceptual moment' or 'time quantum'. A necessary implication of postulating a (quasi-)periodic time base is that it repeals itself as soon as one allows intervals to be evaluated not only in integral multiples of the basic (quasi-)period, but also in halves, quarters or even 47/349-ths of such an elementary duration in order to explain experimental results. The only alternative is to postulate a very short basic interval, e.g. in the order of 0.1 msec as suggested by Creelman (1962).

In the second place the signals generated by the time base have to be counted during the interval that is to be evaluated. This requires a gating mechanism, triggered by the 'begin' and 'end' signals of the stimulus intervals, and a counter mechanism or integrator which accumulates the time base pulses received during the interval.

Thirdly, it is impossible to present two intervals simultaneously in time evaluation experiments, and in addition an evaluation of the length of an interval can only be given *post hoc*. Comparison of intervals is therefore necessarily a retrospective comparison of intervals presented successively. This requires the presence of a memory in which the contents of the counter can be temporarily stored.

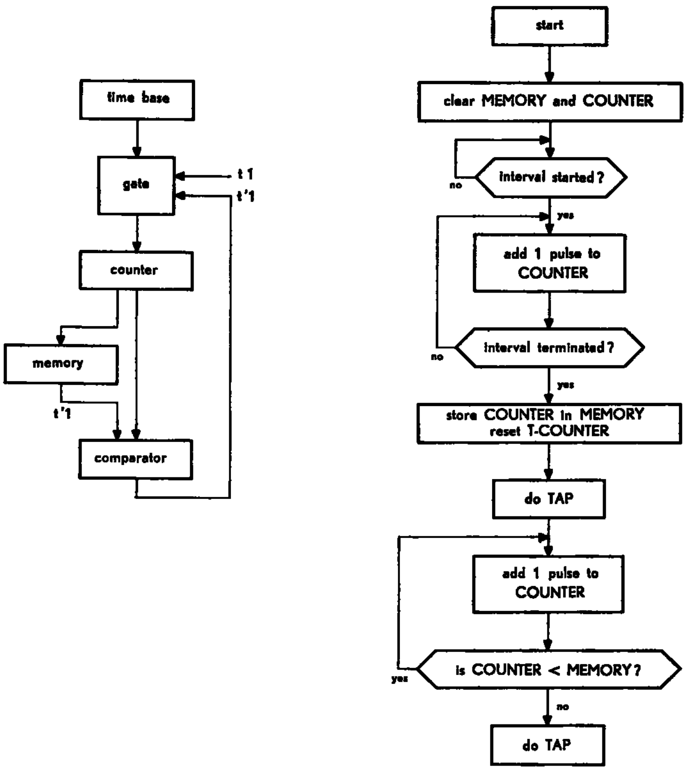


FIG. 2 – Formal model of the 'time sense'. Modification of Fig. 1, representing the single presentation reproduction experiment.

Finally a comparator or judging mechanism is needed, to compare the two intervals and to determine the final response.

The diagram on the left in Fig. 1 indicates the functional structure of this model in the form of a block diagram. The situation represented is that of the paired comparison method. The information flow diagram at the right shows the logical steps necessary to determine which of the two successive intervals is the longer.

This model can be modified and made to fit other response methods. In case of the method of reproduction – represented in Fig. 2 – the first interval is 'measured' and stored as before. The subject now provides his own starting signal for the second interval and continuously monitors the difference between the stored duration and the increasing 'count' of the second interval. When the difference is equal to zero, the 'end' signal is given.

Many processes have been proposed as time basis. Nichols, in 1891, already listed some 50 older hypotheses and Michon (1965) also mentioned a number of more recent suggestions. A slightly augmented list from the latter paper appears in Table 1.

It will be evident from the selection offered in this table, that the majority of the authors attributed the role of time base to very specific processes, sometimes observable, like pulse frequency (most recently investigated by Ochberg, Pollack and Meyer 1964) or respiration cycle (Münsterberg 1889), sometimes purely hypothetical, like James' 'brain traces' (James 1890), fluctuation of attention (Schumann 1893) or 'expectancy' (Baker 1962).

None of these theories seems to have great explanatory merit. They try to account primarily for the fact that some intervals are estimated with greater accuracy than slightly longer or shorter intervals. Most of the proposed processes – if periodic – have periods around 100 msec or around 700 msec.

The former refer to the possibility, already mentioned, that psychological time is divided into 'perceptual moments' of approximately 100 msec. Many perceptual phenomena, such as the perception of pressure waves in the subauditory range of sound frequency (Stroud 1955) or the apparent regularity of temporally irregular visual patterns (Lichtenstein 1961) can be neatly coped with, if one assumes that psychological time is discrete in character. The basic idea is that perceptual information is integrated over a duration of some 50 to

TABLE 1 – Sample of mechanisms and processes proposed as explanatory basis for the 'time sense'.

Nature of the mechanism	Specific process	Author(s)
I. Perceptual (immediate)		
1. 'Time sense'	receptors	Mach (?) (1865, 1911)[1]
	general sense (analogous to spatial sense)	Czermak (1857)
2. Attribute	protensity	Titchener (1905) Curtis (1916)
II. Cue-theories (mediate)		
A. External events	number, rate, differences between events, &c. (overlearning of mental content)	Guyau (1902) Janet (1928) Frankenhaeuser (1959) Loehlin (1959) Woodrow (1951)
B. Internal Events		
1. Non-nervous physiological	cell-metabolism	Bünning (1963)
	metabolism (time of day)	Thor (1962a, b)
	heart rate	Ochberg *et al.* (1964)
	respiration cycle	Münsterberg (1889)
2. Neurophysiological	alpha-rhythm	Wiener (1948) Latour (1966)
	cerebral processes	Dimond (1964)
	cerebellar processes	Braitenberg and Onesto (1960)
	'pace makers' of the brain (metabolism of brain cells)	Hoagland (1933, 1966)
3. Psychological	attention	Schumann (1893)
	expectation	Baker (1962)
	brain trace decay	Lipps (1883) James (1890)
	sensori-motor feedback cycle	Adams and Creamer (1962)
4. Hypothetical	neural scanning	Pitts and McCulloch (1947)
	information sampling (perceptual moment)	Von Baer (1864), Richet (1898), Stroud (1955)
	pulse-counting mechanism (signal detection theory)	Creelman (1962)

[1] It is highly dubious that Mach may be considered as the major representative of this view, as Fraisse (1964, p. 80f.) seems to believe.

200 msec, and processed as a single 'sample' (Stroud 1950, 1955; White 1963).

There is no direct physiological evidence in support of this hypothesis and it appears that most authors since Wiener (1948) have been somewhat reluctant to assume that the perceptual moment is directly related to the alpha-rhythm of the brain, which displays periodicities with comparable frequencies. In the second place it remains to be seen if the discrete character of psychological time can also be observed where the test of the hypothesis matters most: in experiments on subjective time evaluation.[1]

The proposed time bases which have their periods clustering around approximately 700 msec, refer to a point on the time scale where the discrimination threshold for duration is lowest (Fraisse 1964, p. 141f; Michon 1964b). In the second place this is a point where subjects show neither under- nor overestimation in their evaluation of intervals. This so called 'indifference point' was already found in the very first experimental investigation into the domain of subjective time (Höring 1864), and since then it has been a source of considerable disagreement. In the course of the past century the indifference point has moved from a reported 1.5 sec down to approximately 0.7 sec. It has been argued that this might simply be a consequence of the range of stimuli used, but even though there may be an effect of range or 'anchors', this cannot explain the whole phenomenon. Woodrow (1934) showed, by presenting large numbers of subjects with only one single stimulus interval, that the indifference point is basically range independent (see also Fraisse 1964, p. 119f.).

Even so it remains less than evident, how processes which have intrinsic periodicities close to the indifference point could serve as 'time base', unless we assume with Gooddy (1958) that they combine with all other periodic and quasi-periodic processes in the organism into a general 'clock form'. This view – also put forward by Carrel (1931) – may be philosophically valid, but it is hardly a suitable point of departure for a quantitative analysis of the time sense.

Finally, the results of different authors are frequently contradictory: Schaefer and Gilliland (1938) obtained negative results with respect to

[1] Recently a very able review of the 'psychological moment' theory was presented in an unpublished doctoral dissertation by Allport (1966), who stated (Sec. 2 : 2) that "the conclusion that the alpha period does indeed serve as a unit of time in the programming of events in the CNS, leading to a response seems reasonably well justified".

several of the physiological variables listed in Table 1, and there are, for instance, negative findings of Gardner (1935) contrasting with positive results of Stern (1959) with respect to the effects of metabolism (thyroid function).

The obvious conclusion is that it is premature to attribute the role of time base to any specific process. More recent investigators, like Creelman (1962), treat it as a purely hypothetical process. Creelman's outstanding merit is to have shown that time perception can be treated purely quantitatively, without reference to any of the physiological or psychological suggestions previously mentioned, by using the framework of signal detection theory. This model (Creelman 1962; reprinted in Swets 1964) has been described in detail by Michon (1965).

A further important feature of the functional model of Figs 1 and 2, apart from the time base, is the memory store in which the intervals are stored temporarily. It becomes manifest in an effect which is well known in psychophysics: the time-error or time-order error (Woodworth and Schlosberg 1954, p. 226f.). The first of two successive stimuli in a pair comparison experiment is subject to 'decay', which affects the accuracy of the later judgment. With respect to the time-order error in time perception experiments, Frankenhaeuser correctly pointed out (1959, p. 21) that "in respect of subjective time, succession is itself an inherent characteristic of the experience" and hence it is "not an error caused by methodological inadequacies which we want to eliminate, but rather a typical expression of the phenomenon we want to study".

The time-order error has been observed in two forms. Classically it is found that in the course of time the interval stored decreases in length (Frankenhaeuser 1959; Woodrow 1951). Creelman (1962) on the other hand found an increase of the variance as a function of time delay. The two findings appear to be compatible when interpreted as two aspects of one particular, imperfect, storage mechanism (See Sec. III.3.3).

3. NON-TEMPORAL INFLUENCES ON SUBJECTIVE TIME EVALUATION

Psychological time is notoriously inhomogeneous. Accelerations and decelerations in subjective time experience are frequently a source of surprise to everyone, and there is a considerable body of experimental data about the conditions under which such changes may occur. Fraisse (1964), Loehlin (1959), Orme (1962), and Wallace and Rabin (1960), among other authors, have reviewed many of the relevant studies.

A first group of factors which is affecting the apparent inhomogeneity of subjective time, without being itself temporal, is organic. Among these factors are body temperature (François 1927, 1928; Hoagland 1933, 1966), time of the day (Thor 1962a, b) and metabolic disturbances (Stern 1959). Noticeable shifts in time perception have also been reported in experiments with drugs (Frankenhaeuser 1959; Goldstone, Boardman and Lhamon 1958; Sterzinger 1938; etc.). Abell (1962), Goldstone and Goldfarb (1962), Webster *et al.* (1962), and Weinstein *et al.* (1958), for example, reported experiments on the perception of short intervals in psychiatric patients.

Although organic factors may exert a considerable influence on the results of time evaluation, they are likely to remain fairly constant within the context of a single experimental session. To the present study they will only contribute part of the error variance.

Related to these factors are the effects due to the structure of the sensory and motor systems. The sensory modality to which the temporal stimulus is applied is known to affect the accuracy of time estimation considerably. This is an old finding (see Fraisse 1964, p. 104f.), which has been amplified by recent studies, among others by Hirsh, Bilger and Deatherage (1956) and Goldstone and Goldfarb (1964). In all studies pertinent to this topic it was found that the ear is superior to any other sensory system as a receptacle for duration. Thus it is likely that the properties of the 'time sense' will be obscured if we use a temporally insensitive input device like the eye. Only if we use the ear as an input modality may we be able to establish the limiting conditions and functional relations of the timing system.

The same argumentation applies with respect to the response modality. In the present study we will deal exclusively with intervals produced in time, not with their symbolic representation in numbers of seconds as obtained in verbal estimation methods. Although the actual limit on tapping speed is of the order of 10 taps per second (Bartlett and Bartlett 1959), the variations due to the intrinsic 'noise' of the motor system would dominate at rates higher than 3 or 4 taps per second and drown all variability due to other components of the system.

The most important factors influencing the inhomogeneity of psychological time, are those related to the specific instructions and task conditions under which the time evaluation is carried out. The number of studies in this area is very large; there are reviews by Fraisse (1964), Frankenhaeuser (1959), Loehlin (1959), Orme (1962) and Wallace and Rabin (1960), among others. In retrospect this type of research seems to derive directly or indirectly from an influential essay by the French philosopher Guyau.

According to Guyau (1902, p. 85f.) "the estimation of duration is related: 1) to the intensity of internal images (..of stimuli..); 2) to the extent of the differences between the images; 3) to the number of images and their differences; 4) to the rate of succession of these images; 5) to the mutual relations between the images, their intensities, their common properties and their discrepancies, between their various durations and temporal interrelations; 6) to the time necessary to conceive these images and their interrelations; 7) to the intensity of our attention toward those images or to the positive and negative feelings associated with them; 9) to the needs, desires or affections which accompany the images; 10) to the connections between the images and our expectations and perspective of the future."[1]

Although the scientific vocabulary has changed (see Michon 1965, p. 409), it will be evident that Guyau has listed many of the characteristics of what we, nowadays, call 'human information processing', and we will call this complex of factors accordingly 'information processing load'.

Information processing load encompasses a wider range of concepts than was originally subsumed under the heading of 'information theory in psychology' (Attneave 1959; Garner 1962; Quastler 1955, Van de Geer 1957a, b), which theory after all failed to provide the psychologically rich framework it originally promised. Information psychology in this sense is gradually being replaced by formulations in terms of information processing systems, either discursively stated (Broadbent 1958; Sanders 1967a, b) or formally with explicit reference to information processing by computers (Newell and Simon 1963; Reitman 1965).

It is likely that formalization of task factors and instructions, using the information processing approach, will solve much of the confusion

[1] The eigth item in this list is omitted – probably erroneously – in the 1902 edition, which was available to the present author.

about the influence of various factors on time evaluation. Michon (1965) gave an example of contradictory findings which probably resulted from insufficient conceptual clarity, for instance with respect to such ill defined concepts as 'concentrated intellectual work' (Wundt) and 'concentrated attention' (Mach). Wundt (1911, p. 95f.) improperly equated the two and then drew the wrong conclusion about Mach's mental abilities.

Loehlin's (1959) factor-analytic study has been the most systematic enterprise thus far to determine what factors are responsible for the inhomogeneity of subjective time. He found four factors which were related to the specific tasks performed during time evaluation, and interpreted them as *interesting* vs. *boring*, *filled* vs. *empty* intervals, *activity* vs. *passivity* of the subject and degree of *repetitiveness*. Loehlin's general conclusion was that time appears to go 'faster' (i.e. the internal time base slows down), the more a task constitutes a 'unit' in the subject's experience. Comparison with Guyau's list reveals a high level of coincidence; Loehlin's four factors apparently are major aspects of the information processing required to perform a task.

Theoretical frameworks providing explanations for the way information processing influences subjective time evaluation are far less numerous than they are for the psychophysical aspects of time. Frankenhaeuser (1959) is a representative of the cognitive cue theory of time perception. Her hypothesis was that the average number of events experienced during an interval is the basis for our judgment of its duration. In fact it is assumed that there is a subjective unit of time, based on overlearning of an 'average mental content per unit of duration', analogous to the overlearning of the monetary value of coins (Woodrow 1951). If there are only few events during an interval, for instance, it will take relatively much time to reach the critical number of events and consequently clock time will seem to pass quickly; this will happen in tasks with high redundancy.

A second point of view is represented by Treisman (1963), who related the information processing load to a conceptually different internal process derived from the recent discussions about arousal and vigilance: a 'specific arousal process', which determines the pace of the time base.

The difference between the approaches seems to be primarily formal. In Treisman's approach inhomogeneity of subjective time is caused by changing a (pseudo-)physiological process, while Frankenhaeuser's hypothesis depends on a judgmental process apparently closely related to ideas about short term memory. At the level of specification given by the authors, however, it is difficult to point out any essential differences between the two hypotheses.

4. SERIAL EVALUATION OF TIME INTERVALS

Thus far our exposition has largely centered around data and theoretical considerations that derive from 'single interval' studies. A search for original contributions to the theory of time perception from the field of rhythm has been in vain. (See Weitz and Fair (1951) for a bibliography and Fraisse (1956) for a recent experimental study).

Rhythmic skill is attributed to essentially the same kind of processes as time perception. The absence of theoretical distinctiveness does not imply that the processes involved are in fact identical. Especially in the range below 0.5 sec a different mechanism may be involved in the evaluation of a single interval than in the evaluation of a sequence of intervals (Michon 1964b). Fraisse (1956), on empirical grounds, distinguishes between the perception of rhythm (sequences of intervals under 500 msec) and the perception of time (over 500 msec).

A second distinction between single and multiple interval experiments is found in the direction of the systematic error in time estimates. L. T. Stevens (1886) found that, whilst sequentially produced intervals longer than approximately 600 msec are systematically judged longer than the standard, intervals under 600 msec are judged systematically shorter. The reverse is true of the single presentation condition (see Fraisse (1964, p. 116f.) for a review).

Other empirical findings, such as the shape of the differential threshold curve and the point of maximum accuracy appear to be comparable under the two experimental strategies. Although no straightforward explanation for the sign-difference of the systematic error offers itself, it might be a consequence of the storage problems which will occur when information about successive intervals is stored sequentially.

No systematic suggestions could be found in the literature about the storage of sequential temporal information. However the presence of a 'running average' or an accumulating storage, like those found in quality control systems (Page 1954), is suggested by an experiment of Baker (1962). Baker presented his subjects with a series of irregular intervals with an average duration of 100 sec or 150 sec, and asked them to produce an interval, subjectively equal to the average of the series. Subjects were fairly well able to do so, but with less precision if the stimulus series was made less regular. Furthermore Baker found that more recent intervals had a greater influence on the estimates than intervals earlier in the sequence. The amount of data and the technique used to investigate the serial dependencies do not allow more quantitative conclusions, however.

This experiment indicates that the analysis of sequential relations is essential to our understanding of the functioning of the serial timing mechanism. Except for Baker's experiment such sequential analyses appear to be absent in the domain of timing and time perception.

When we try to formalize the serial presentation situation in terms of information flow, we see that Fig. 2 can easily be adapted to account for the recurrence of taps. In principle the arrangement shown in Fig. 3 is the same as that of Fig. 2.

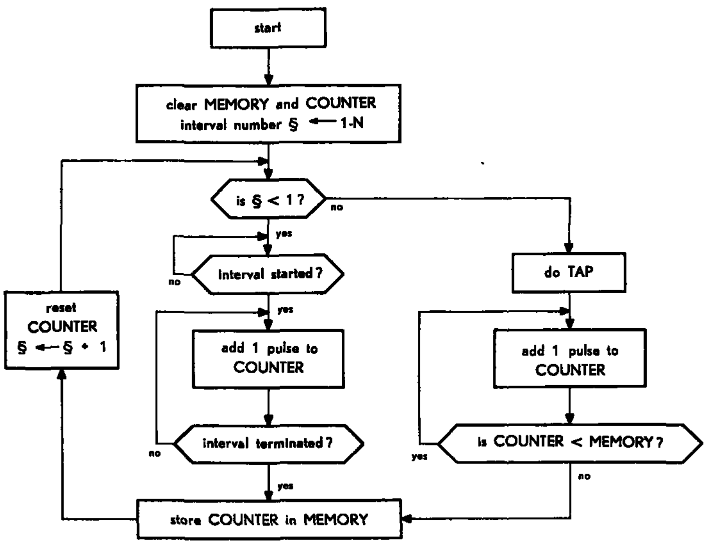


FIG. 3 – Flow diagram for the serial reproduction experiment. Modification of Fig. 2, to account for repetitive tapping.

Let us consider the situation in which the subject repeatedly reproduces a standard or sequence of standard intervals given at the outset. The first N intervals are evaluated as standard intervals and stored in memory in some weighed combination. The first subject-produced tap will coincide with the last signal of the standard. From that first tap on, the subject will compare the memory contents with the interval in progress. When the difference between stored and actual interval equals zero, the memory is updated, a tap is given and a new cycle starts. Crucial to this arrangement are again the properties of the time base providing pulses to the counter, the way the memory does or does not combine old and new information, and the rate at which the memory contents decay. Experimental data will have to provide these parameters.

In the case of a synchronization experiment, in which the subject aims at coincidence of his taps with an external train of signals, the flow diagram becomes more complicated since the task requires monitoring of the external input. Several alternative models suggest themselves, but to present these at this point would be premature. We return to them at a later point when we shall summarize our empirical findings (Chapter VII). In how far the 'internal standard' of the reproduction experiment is functionally equivalent to the 'external standard' in the synchronization condition also remains to be seen.

We expect the concomitant aspects of the experimental situation – the information processing load – to exert an influence on the time evaluation processes involved in key tapping as much as they do in conventional time perception experiments. This idea has been worked out in some detail by the present author in studies on the measurement of information processing load or perceptual (-motor) load (Michon 1964a, 1966a, b). In these investigations the regularity of key tapping during the execution of a second task was used as an indicator of the load imposed on the subject by that task. The index of regularity was found to vary predictably with some of the quantifiable aspects of the second task.

Not much is known as yet about the way in which sequential timing is affected by non-temporal information. A thorough investigation would lead us too far beyond our present endeavor of providing a formal framework for the description of timing behavior, but we will deal with the interaction between temporal and non-temporal information in a few exploratory experiments in Chapter VI.

5. KEY TAPPING AS TEMPORAL TRACKING

Key tapping is in several respects comparable to manual tracking of a visual input; we may call it temporal tracking. It consists either of synchronizing with a time-varying input, which is analogous to pursuit tracking, or of keeping a sequence of taps as regular as possible, which may be looked at as a form of compensatory tracking, i.e. the subject tries to maintain his tapping rate at a previously set (internal) standard. Spatial tracking has been studied very extensively: Adams (1964), Ellson (1959), Licklider (1960) and Bekey (1962), in that order, offer reviews of increasing technical complexity.

An approach frequently adopted in the analysis of spatial tracking behavior is derived from electrical engineering, and is known as 'systems analysis'.[1] It is quite distinct from the classical approach to sensori-motor performance in that it takes into account the sequential relations that exist between an output and current, as well as previous, states of an input, and does so in a mathematically rigorous way.

In essence the technique, as it is employed in tracking studies, is to subject a 'black box' – a system of unknown composition – to a specified input and to describe the output of the system as a function of the input, taking into account all phase, frequency and amplitude relations. The analysis can be carried out either in the frequency domain in terms of sine wave responses, or in the time domain in terms of, for instance, step or pulse responses. In the first case the response of a system to a sinusoidal input is studied. The analysis is based on the possibility of describing any function of time by a weighed linear combination of simple sine waves (Fourier synthesis). Hence the response to an input function can be calculated if the responses to the simple functions $y = \sin \omega t$, for $0 \leqq \omega \leqq \infty$, are known.

If the analysis is carried out in the time domain, the system is, for instance, subjected to a step function

$$f(T) = \begin{cases} 0, T < 0 \\ 1, T \geqq 0 \end{cases} \tag{1.1}$$

and the way in which the system adapts itself to this sudden disturbance is studied.

[1] Much of what follows is based on: Licklider (1960), Ragazzini and Franklin (1958), Schwarz and Friedland (1965) and Truxal (1955).

The necessary assumption, made in both approaches, is that the system is linear. A linear system is characterized by the 'superposition principle' which states that the response to an arbitrary combination of inputs is equal to the combination of the responses to each input separately, or

$$Hf_1\,(T) + Hf_2\,(T) + \ldots + Hf_n\,(T) = \\ = H\,\{f_1\,(T) + f_2\,(T) + \ldots + f_n\,(T)\} \qquad (1.2)$$

in which $Hf_i(T)$ stands for the response to the input function $f_i(T)$. (See Schwarz and Friedland 1965, p. 12.) The function relating the output of the system at any moment to the input to which it is, and has been, subjected is called the 'transfer function', though it is not a function in the mathematical sense, but a complicated operator on the input function.

The transfer function is essentially a functional mathematical description of the system hidden in the black box. As such we are able to predict from it, what the response of the system will be to any given input function. Its main advantage is the fact that it takes into account the time-varying aspects of the input, i.e. its history. The major drawbacks of the transfer function as a model are, in the first place, that it is a very general model – the same transfer function can be derived for an infinity of actually realizable systems, whence it is void of psychological content – and in the second place that it hinges on the linearity assumption. The 'superposition' principle is very important because of its mathematical convenience, but is is only approximatively valid when we are dealing with living systems. Considering Eq. (1.2) in the light of absolute thresholds, for example, will make it obvious that such thresholds must reflect certain non-linear properties of the system, since they imply that some changes in the input signal will have no corresponding effect in the output. Usually biological systems contain other non-linear components as well, and usually these are difficult to cope with.

There are at least two ways of reducing these problems. First, one can stretch the linearity assumptions somewhat and deal with the system as quasi-linear, in which case all non-linearities are pooled and treated as 'noise' together with genuine noise generators in the system (Licklider 1960, p. 177f.). A second alternative is suggested by the work on human information processing models (Newell and Simon

1963; Reitman 1965). Many of the non-linear effects in human behavior, such as thresholds, can be treated as all-or-none or binary decision processes. Such either-or relations are difficult to incorporate into an ordinary transfer function, but can easily be accounted for in information processing models. Apart from this advantage the information processing approach allows us to circumvent the mathematical complexities of non-linear systems analysis, without any sacrifice in rigor. Finally it enables us to impart psychological content on a model more easily than can the vocabulary of systems engineers.

In this study we will approach key tapping as the temporal analogue of spatial tracking and treat it accordingly. The reason why we have adopted the systems approach rather than the customary regression analysis to account for serial effects is that we feel that the deterministic character of the transfer function with its stable parameters, is conceptually closer to the information processing approach than are stochastic models.

In conclusion of this section, key tapping studies which bear at least some relevance to the foregoing will be reviewed.

Accuracy of tapping has been determined by several authors. The first to employ sequential tapping was L. T. Stevens (1886), who studied tapping in the range between 0.27 and 2.9 sec. His subjects were required to synchronize with the clicks of a metronome and to continue tapping at the same rate after the metronome was halted. Stevens concluded that long intervals are progressively made longer and short intervals progressively shorter, with an 'indifference point' between 0.53 and 0.87 sec, depending on the subject. The longer the standard interval, the greater the overestimation, which may be as high as 10%. In reverse the same applies to short intervals.

The second finding of Stevens was that subjects tend to alternate longer and shorter intervals. This was taken as evidence for the existence of a correlation between successive intervals, due to a compensating mechanism. However, the argument is invalid since the alternation was observed relative to the previous interval and not relative to the average interval length.

Later investigators have essentially confirmed Stevens' results, and also specified the accuracy of performance (relative error) at different rates, which Stevens had left out of consideration. Because of trends, sometimes present in sequential tapping, some authors have not only used the variance as a measure of dispersion, but also the summed first differences between successive intervals (Fraisse 1956; Michon 1964a, 1966a, b). Irrespective of the measure used, it is found that accuracy passes through a maximum between 500 and 800 msec, decreasing to both sides (Bartlett and Bartlett 1959; Davis 1962; Fraisse 1956). This implies that Weber's law does not hold for time, but there is no common quantitative opinion as to what extent it does not hold (but see Treisman 1963). In terms of system properties it suggests that there may be an intrinsic periodicity in the organism which becomes tuned to the input interval when the two are approximately equal in length.

The same is suggested by the phenomenon of 'personal rate'. If subjects are allowed to tap at a rate which they prefer subjectively, all settle down at a rate which is not too far from the point of least variability mentioned above. Miles (1937), in a sample of almost 200 subjects, found that 80% spontaneously chose intervals between 200 and 700 msec and only 11% preferred intervals of more than 1 sec. Later authors have confirmed this. The personal rate has been used to demonstrate the influence of other factors on sequential time evaluation. Denner *et al.* (1963, 1964) showed that the personal rate changed after the subject had been exposed to temporal information presented at rates different from the preferred tempo. In our own, previously cited studies of the variability of the personal rate as a function of information processing load, irregularity was found to increase with load. No consistent changes in the personal rate itself were found though, which may indicate that only the variability is affected by the information processing load of a task and not the period length of the mechanism of which personal rate is the manifestation.

Data about the way sequentially produced intervals are distributed are very incomplete. Bartlett and Bartlett (1959) reported that the distributions of intervals longer than 1 second are normal, but those of very short intervals approach rectangularity, because the noise of the motor system starts playing a predominant role. Lichtenstein and White (1964) reported approximately normal distributions for intervals of 500 msec, and Ehrlich (1958) found the same for intervals of 600 msec. These findings might be indicative of a true gaussian noise being responsible for the variability in the results, but this conclusion is not warranted without additional evidence.

The adequate input to a dynamic system is a time-varying input as was pointed out earlier. Key tapping in response to such an input has been studied in the first place in experiments on rhythm. Here variations in interval length are usually very frequent. The number of intervals in a sequence is characteristically of the order of three to six, runs of equally long intervals usually being not longer than two or three. Hence we are likely to measure performance while the system is in a transient state. Secondly the rhythm is mostly reproduced after the stimulus has been presented – which requires a memory for several intervals at once. Synchronization, although very important in musical ensemble performance, has not been studied at all. Notwithstanding these restrictions we may make a few qualitative observations from such studies as Seashore's (1926) or Fraisse's (1956).

When short intervals are followed by one or two longer intervals, we observe an overshoot in the reproduced group, in at least the first long interval after the shift. An overshoot in the other direction may be observed if the transition is from long to short (Fraisse 1956, ch. 4,5). These findings suggest that there is an effect of preceding intervals on later performance, in other words: a dynamic relation. The size of the overshoot decreases in some cases when the shift becomes smaller, just as we would expect if the overshoot were relative to the size of the shift.

Three more studies should be mentioned. Gottsdanker (1954), comparing manual and temporal tracking, had subjects extrapolate (continue) quadratically accelerated and decelerated series. From his results it can be inferred that in both conditions subjects lagged behind the expected value extrapolated from the previously produced intervals. Since his was a continuation experiment, the results may not be directly comparable in terms of lags and leads in synchronization performance, but they are suggestive of a comparable dynamic response to internal as well as external standards.

Ehrlich (1957, 1958) compared continuation and synchronization in key tapping. Although he also did not apply any sequential statistics, his experiments are close to our endeavor and deserve a more extensive reference.

In one study Ehrlich (1957) compared tapping at the personal rate (average interval length of 6 subjects: 605 msec) and synchronization with a 600 msec standard sequence. The results showed that four subjects had less variable results when performing at their own rate than when they were synchronizing. This was taken as evidence for the thesis that spontaneous tapping is at least as regular as synchronizing and that the responsible 'neuro-motor' mechanism is not regulated or 'driven' by the external input.

In a more comprehensive study Ehrlich (1958) dealt in some detail with this problem. Subjects were asked to synchronize with an isochronic (600 msec) sequence, or with linearly accelerating or decelerating series with rates of change of $\pm$ 10, 20, 50, 80 or 100 msec per interval and ranging between 300 and 2000 msec. In addition 'cyclic' sequences were given with alternatingly positive and negative acceleration, and a random sequence of intervals, also ranging between 300 and 2000 msec. Ten subjects were used altogether. The results of this study may be summarized in the following points.

There were only very minor systematic errors, i.e. lags or leads with respect to the input sequence. Deviations from the accurate interval length were said to be normally distributed, but no quantitative analysis was provided.

The higher the rate of change, the larger the standard deviations of the results. This was taken as evidence by Ehrlich that the timing mechanism can only cope with stationary stimuli, and breaks down when the input is variable. Compensatory behavior (phase regulation) was said to be absent or at least very inadequate: the stimuli seemed to play no decisive role in maintaining the regularity of key tapping, but no analysis to illustrate this conclusion was provided.

Ehrlich's final conclusions deserve to be quoted in full (1958, p. 21): "Thus the decreased regularity of the accelerated and decelerated sequences should be nothing but the observable expression of a gradually failing mechanism, which normally is restricted to regulating uniform, repetitive actions". And he added (p. 22): "It seems to be difficult to go any further with our description. At this point the psychologist has to give the floor to the neuro-physiologist."

The present study will prove that the psychologist can in fact go a great deal further, without committing himself once again prematurely to any of the neuro-mythological mechanisms that have blossomed so abundantly in time psychology.

There remain a few remarks to be made on a recent study of Fraisse (1966), who investigated the adaptation of tapping immediately after the onset of the input sequence. He found that the correct rate is established after about three intervals, which implies an 'overshoot' like we have noticed before, and that little systematic error remains in a subject's performance. He showed in addition that the same is true, when the rate of the input sequence is suddenly doubled or halved, an experimental condition which is related to the 'step function input' used in the present study.

The interpretation given by Fraisse is, like that of other authors in the field, completely qualitative and offers no conceptual framework for a quantitative framework to describe data.

6. PROGRAM OF THIS STUDY

We are now in a position to formulate the program of this study. We have found that many of the findings on key tapping have been derived from preciously few data. Moreover, even investigations that were based on more extensive data do not report any comprehensive statistical analysis. In two respects all studies on key tapping that we referred to in the preceding sections are deficient. First, they contain no data on the distribution of intervals; most only give means and standard deviations, few indicate qualitatively the shape of the distributions. Secondly, no sequential statistics have been computed, although we found that it is likely that each tapped interval depends to some extent on preceding intervals.

It is exactly these two aspects of the data, that will have to provide us with the information we need about the type of dynamic mechanism that is responsible for timing in key tapping. The main objective of Chapters III and IV is to provide such data, for the case of stationary and modulated inputs respectively. We will derive from these data some formal properties of a 'time sense' conceived of as a dynamic system.

In Chapter V some of the collected data will be reconsidered in the light of the hypothesis that psychological time is discrete in character.

In Chapter VI we shall deal with the influence of information processing load on the formal properties of the timing mechanism. This chapter specifically reports three exploratory experiments on the impact of a well defined component of information processing load, event uncertainty, on timing behavior.

Chapter VII finally, offers a recapitulation and a synthesis of the experimental results of the earlier chapters. In particular we will place the results in the formal framework of the information processing models treated in the sections 2 and 4 of the present chapter.

First however, a technical prologue to the experimental chapters that follow will be given in Chapter II.

CHAPTER II - EXPERIMENTAL PROCEDURES

1. SOME DEFINITIONS

In some experimental conditions subjects have been presented with auditory stimulation consisting of sequences of clicks, and were required to tap in synchrony with these clicks. This condition will be called *synchronization* in contrast to *continuation*, where no concurrent click sequence is presented and the subject tries to extrapolate a series of auditory intervals presented earlier.

In the second place we distinguish between *stationary*, or *isochronic*, and *modulated* sequences. In the first case the intervals of the stimulus sequence and – ideally at least – the intervals of the response sequence are all of exactly the same duration. This type of input is comparable to the 'direct current (D.C.) level' in an electrical system: a constant voltage applied to the input of the system.

Modulation of the input and studying the response to it, is the main technique for testing dynamic systems (Sec. 1.5). In the present context modulated sequences consist of intervals which are not all of the same length. A sequence may be called random, for example, if the durations of successive intervals are independent of one another. The intervals may be constant up to a point and then suddenly change to a different but equally constant value; this type of modulation can be called a step function. Several types of modulation will be used in this study; examples are shown in Fig. 4.

A special way of representing intervals which will be used systematically throughout this monograph is shown at the top of Fig. 4. Instead of indicating intervals as marks on a time line, the length of the interval is plotted as a value on the ordinate of a Duration/Order diagram. Along the abscissa successive intervals are equidistant and labeled by their rank order number in the sequence. Using this representation we avoid some of the problems which we would encounter if we undertook to draw Duration/Duration diagrams of our experimental results.

In order to distinguish between the various aspects of time considered in this study, a number of special symbols will be used as fixed conventions. They are defined in the 'List of Special Symbols' at the end

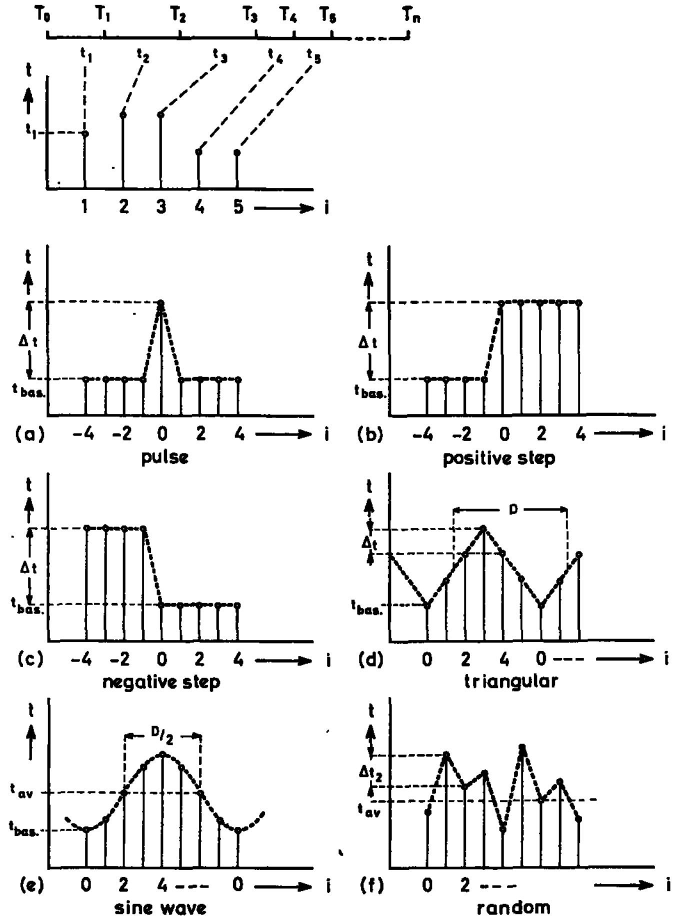


FIG. 4 – Graphical representation of stimulus and response sequences. Top: linear and two-dimensional (Duration/Order) representation of intervals; *a-f*: some input functions.

of this monograph (page 119). Other symbols used in the text conform to statistical and mathematical conventions or will be defined where necessary.

2. APPARATUS AND BASIC PROCEDURES

The basic equipment used in the experiments is depicted in the diagram of Fig. 5. Most of the components of this setup were developed in the Institute for Perception RVO-TNO. It consists in essence of a very precise stimulus timing set and an equally precise response timing and recording set. Since in some experiments the two parts interacted they are shown together in one figure.

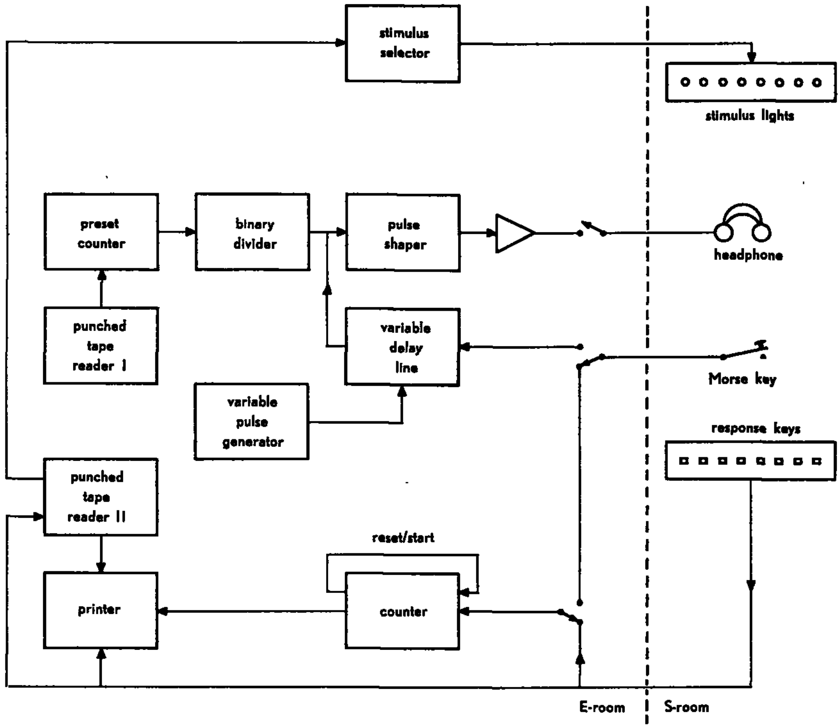


FIG. 5 – Block diagram of experimental apparatus.

During an experiment the subject was seated in an isolated room, with all the necessary stimulus presentation and response production equipment, but no timing and recording apparatus, in order to rule out temporal cues from the sounds of relays, punched tape readers, etc. The illumination level in this room was kept at a comfortable level. Outside noise could not always be avoided entirely but was to some extent attenuated by the earphones the subjects were wearing.

The subjects produced intervals in one of two ways. In experiments where no controlled variation of information processing load was involved they tapped a delicately adjusted *Morse key*, with a spring load of approximately 50 grams. If on the other hand they were required to respond differentially to a set of stimuli (from 2 to 8 alternatives), they pressed the appropriate *response keys* of a set of eight. The spring load of these keys was not identical for all fingers, but all fell within a range between 25 and 35 grams. An essential part of the instruction was to make the subject respond abruptly, and teach him to avoid pendular movements of fingers or arm.

In each of the two methods the response intervals were measured in milliseconds by means of a digital *counter* (Hewlett and Packard 521D) which after each response was automatically reset and started. The intervals measured were printed on paper tape by means of a Hewlett and Packard 561B *printer*. The values printed were exactly 200 msec less than the actually produced intervals, because of the print-reset-start latency. This arrangement restricted the possible range of intervals at a lower limit of 200 msec, which was not serious since the lower bound imposed by the intrinsic noise of the human motor system is of the order of 300 msec. Intervals below that value have not been studied.

When differential responding was required, both the stimuli presented (selected by means of *punched tape reader II*) and the responses given by the subject were printed along with the response time, thus allowing an error analysis.

The apparatus used in the synchronization experiments was triggered by another *punched tape reader* (*I*) which read the sequence of encoded interval durations. These were fed into a digital *preset counter*, operating in milliseconds, which could be given any preset value between zero – in which case it produced exactly the encoded sequence – and 10 sec, which then was added to the encoded values. A *binary divider* could furthermore change the internal clock speed of the preset counter by factors of 2,4, 8 or 16. By means of this provision the average interval length could for instance be doubled without changing the ratios between the intervals in the sequence, while using only one piece of single punched tape. The output of the preset counter was finally *shaped* into square pulses, *amplified* and fed into a *headphone* in the subject's room. The clicks presented to the subjects were kept throughout at a level of 45 db above threshold.

In some of the earlier experiments the intervals were not generated by means of the digital counter just described, but by means of a Hewlett and Packard 202A low frequency oscillator. This undoubtedly introduced slight variations in the length of the input intervals. However, fluctuations were found to stay well within the tolerance limits specified by the manufacturer, and hence will not have deviated more than 0.5% from the average. Moreover such fluctuations were always very slow in comparison to the average interval length. Consequently they will have manifested themselves as trends in the data, rather than as noise-like short term fluctuations.

In one experiment (Exp. 5) subjects had to synchronize with their own delayed output sequence of taps. The output, i.e. the last tap produced, was fed through a *discrete step delay line,* and subsequently back to the earphones. The delay was variable in 60 steps of equal length, since the line essentially consisted of 60 flip-flop circuits which were triggered one after another at regular intervals. In addition the length of the steps could be varied by means of an external clock, a *variable pulse generator.*

3. SUBJECTS

Six subjects (B, M, N, S, vdV and vD) took part in the experiments on a regular basis. They were full time employees of the Institute for Perception RVO-TNO. Experiments in which other subjects were used, are specified as such. All six regular subjects, five male and one female and aged from 20 to 30 years, were highly trained during earlier experiments not reported in this study, pilot experiments and special training sessions. All had normal hearing, except for N, who showed a slight impairment of one ear between 5 and 10 db with respect to the threshold for clicks. No special correction needed to be made for this.

Because all subjects were in some way involved in the project, they may be considered to have had adequate motivation to sit through the sometimes quite strenuous experimental sessions.

4. DATA COLLECTION AND REDUCTION

The amount of data collected in a single experimental session – no session was longer than 30 min – varied considerably as a function of the average interval length. On the average about 500 intervals were collected per session, usually in runs of 100 or 200. No data have been left out of consideration except when contaminated by technical failures. The first 10 or 15 intervals of a run, though, were systematically discarded, because we wanted to exclude initial effects from our analysis.

Uninterrupted runs never lasted more than 10 minutes.

If a subject complained of fatigue or loss of concentration, or if he showed marked deviations from his ordinary level of performance, the session was adjourned.

The large amount of data obtained (approximately 500,000 intervals) made it necessary to use computer facilities. Yet, much of the data have been reduced by sheer manpower. Specifically most of the more complicated, time consuming, calculations such as serial correlation, spectral analysis, trend elimination and tests of goodness of fit, have been executed with a digital computer.

CHAPTER III
THE RESPONSE TO STATIONARY INPUT SEQUENCES

1. INTRODUCTION

An isochronic sequence of intervals may be looked at as if it were a 'direct current (D.C.) level'. If we apply a constant voltage c to a linear electrical circuit, the output will also be a constant voltage, though not necessarily equal to the input. The response to a time-varying input, when superimposed on a D.C.-level, will not alter its characteristics since

$$H\ \{f(T) + c\} = Hf(T) + c', \tag{3.1}$$

in accordance with the superposition principle (Sec. I.5). A variable response to a constant input on the other hand, is indicative of spontaneous activity of the system. Such activity may consist purely of 'true' noise, but may also result from non-linear properties of the system. An analysis of the response to stationary inputs is therefore a necessary prelude to the study of modulated inputs.

We may, in principle, expect several types of spontaneous activity in the 'time sense'. In the first place there can be the non-stationarity or drift of the system parameters, which occurs in most living systems. Under its influence the tapping response will be affected even when the instruction is that the subject keep his tapping rate as constant as possible. Fortunately such trends are usually slow in comparison to the tapping intervals and thus can be accounted for quite easily.

In the second place we may expect to find considerable interval-to-interval variation: time evaluation experiments are notorious for their large variances. Before we attribute such short term fluctuations to random processes in the organism, we shall have to determine if there are any sequential relations, periodic or a-periodic, hidden in the apparent 'noise' produced by the subject. Such relations can be extracted from the noise by means of autocorrelation techniques. If no serial relations are indicated by the (linear) autocorrelation function, we will assume that there is a stochastic process without memory underlying the variations in performance. From the characteristics of the interval distributions we may then proceed to infer what type of stochastic mechanism is involved (McGill 1963; Restle 1961).

Related to the foregoing is a third non-linear effect which may show in the data: quantization of psychological time will reveal itself in the response distributions as multimodality since, if there is such a thing as a 'time quantum' τ, a response interval will ideally consist of an integral multiple of τ.

A further point must be given attention to in this chapter, namely the difference between synchronization and continuation, the latter being treated as tapping 'in synchrony' with an internal standard. The feedback of temporal information is likely to be more complicated in the former situation, since the subject may extract additional information from the time difference between a click and the corresponding tap, but it is not yet clear how far this possibility is an advantage to the subject in the case of isochronic input sequences. Ehrlich (1957) found for instance that synchronization does not show less variability than continuation at the personal rate, as we saw in Sec. I.5. Analytically the presence of any compensatory mechanism which makes use of this extra information must reveal itself in the autocorrelation function of an output sequence as being dependent on at least some of the preceding intervals.

Finally we shall have an opportunity to look into the problem of the applicability of Weber's law to time perception, which has been questioned for more than a century (Fraisse 1964; Mach 1865; Michon 1964b; Nichols 1891; Treisman 1963).

2. THE ISOCHRONIC INPUT – EXPERIMENT 1

Procedure

Four subjects from the regular pool of six – S, vD, M and N – produced two series of 200 intervals at each of 6 standard durations: 333, 500, 667, 1000, 1667 and 3333 msec, both in the synchronization and the continuation mode; 96 series in all.

The apparatus was described in Sec. II.2.

In a pilot experiment, of which some results will be mentioned, three subjects each produced two series of 200 intervals at each of 10 standard durations: 333, 400, 590, 667, 833, 1250, 1667, 2500 and 3333

TABLE 2 – Averages and standard deviations (without (s) and with (s^*) trend-elimination) of responses to stationary input sequences. All data are given in msec ($n = 200$, except a : $n = 190$ and b : $n = 197$).

A. *Continuation*

Subject	t	First Series			Second Series		
		$\hat{t}_{av}$	s	s^*	$\hat{t}_{av}$	s	s^*
S	333	272	15.4	15.4	351	20.9	20.3
	500	441	23.1	23.2	523	32.1	32.2
	667	669	38.2	37.5	703	42.8	41.7
	1000	877	64.1	49.7	1145	97.9	76.2
	1667	1833	180.9	170.2	2290	395.9	232.9
	3333	3974	495.8	406.9	4115	722.2	691.2
vD	333	328	16.1	15.9	337	17.2	17.3
	500	506	19.9	19.6	534	27.5	27.2
	667	682	21.8	21.7	706	28.6	28.6
	1000	1037	41.7	40.7	1140	50.9	49.9
	1667	1997	128.9	113.4	1897	160.1	97.4[a]
	3333	3984	372.0	256.6	5280	727.3	500.7
M	333	320	18.4	16.8	315	17.8	16.3
	500	505	21.7	20.7	491	18.9	18.9
	667	654	32.4	29.0	667	29.7	29.6
	1000	1101	70.6	53.0	1060	45.1	45.3
	1667	2370	244.5	152.6[b]	1851	178.2	95.4
	3333	3949	494.9	399.3	3597	405.0	321.7
N	333	313	11.1	10.9	312	16.2	10.6
	500	492	15.4	14.9	473	14.3	14.1
	667	661	22.9	20.1	643	22.1	22.3
	1000	1089	68.4	61.6	984	46.6	42.3
	1667	1691	110.4	89.9	1927	133.1	92.8
	3333	4156	684.6	666.5	3559	538.9	539.0

B. *Synchronization* (values of s)

t	Subjects							
	S		vD		M		N	
	1	2	1	2	1	2	1	2
333	18.1	20.6	20.6	17.1	14.7	17.9	16.6	13.2
500	30.1	26.8	23.3	21.1	18.8	19.6	16.2	18.7
667	42.9	44.9	30.2	28.2	30.1	31.4	23.4	23.7
1000	75.8	55.9	50.3	40.5	50.2	51.1	47.6	46.0
1667	137.4	128.0	87.1	107.4	103.5	103.0	82.6	87.7
3333	330.2	366.5	267.9	245.4	229.2	253.5	257.6	273.5

msec. The stimuli in this pilot study were generated with the low-frequency oscillator (see page 26). Not all cells of this design were filled however, and data were collected in a less detailed form than in the main experiment.

Results

Non-stationarity. Slow spontaneous variations in tapping rate were determined by fitting to each of the 96 series a polynomial

$$t_i = a_0 + a_1 i + a_2 i^2 + \ldots + a_k i^k \tag{3.2}$$

in which t_i is the duration of the i-th interval (see the List of Special Symbols, p. 119). The method of least squares (Lewis 1963) was used to find the best fitting polynomial and the maximum degree resulting in a significant reduction in the amount of residual variance.

For the synchronization series no consequential improvement resulted from the trend elimination, quite unlike the continuation sequences for which polynomials of degrees up to 7 were found to reduce the variance of the results considerably. This can be inferred by comparing the columns s (raw standard deviation) and s^* (standard deviation after trend elimination) in Table 2A.

Fig. 6 shows the trends of the continuation sequences graphically on a logarithmic scale. Two points deserve to be mentioned with respect to this diagram. First, the range of the trends becomes larger with t, both in an absolute and a relative sense. This points to a relatively small efficiency of storing the internal standard – or a considerable decay factor – when the intervals are long. In the second place the trends do not follow a consistent pattern although we find a systematic error in the average ($\hat{t}_{av} - t \neq 0$), away from the indifference point at approximately 700 msec (see Table 2A: $\hat{t}_{av}$). This is in agreement with L. T. Stevens' historical data, both qualitatively and quantitatively (Stevens 1886).

The conclusion – also to be drawn from Fig. 6 – is that the major shift in $\hat{t}_{av}$ takes place during the very first 10 or 15 intervals after the discontinuation of the standard sequence, which were not taken into account in the present analysis though.

All subsequent analyses of the data have been carried out on trend eliminated data (residuals).

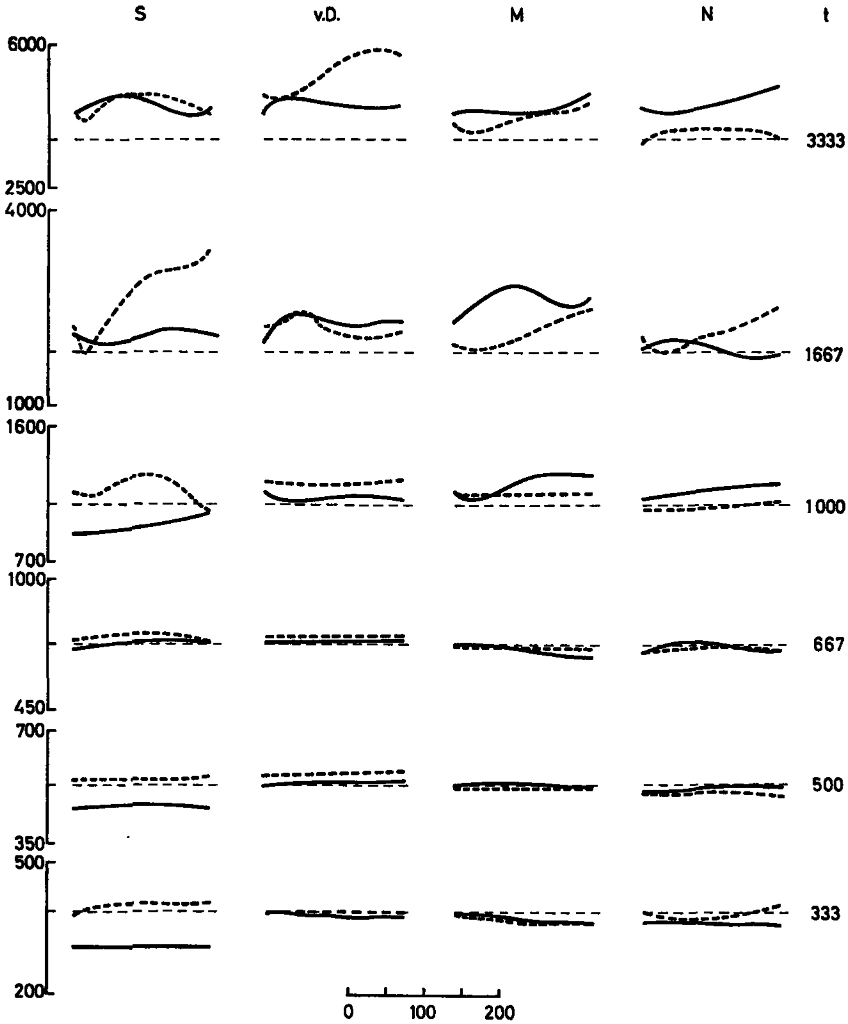


FIG. 6 – Trends, eliminated from the raw data of the continuation sequences of Exp. 1. The vertical time scale (msec) is logarithmic.

Short term variations. The correlation between an interval $\hat{t}_i$ and its predecessors $\hat{t}_{i-1}$, $\hat{t}_{i-2}$, . . . is expressed in the autocorrelation function

$$R(k) = \frac{\sum_{i=1}^{m} (\hat{t}_i - \hat{t}_{av1})\,(\hat{t}_{i+k} - \hat{t}_{av2})}{m\, s_0\, s_k}, \tag{3.3}$$

in which $m = n - k$,

$$s_0 = \left\{ \left(\sum_{i=1}^{m} \hat{t}_i^2 - (\hat{t}_{av1})^2 \right) / (m-1) \right\}^{0.5}, \tag{3.4}$$

while s_k is identical to s_0 except that the summation is not over $1 \leqq i \leqq m$ but over $k + 1 \leqq i \leqq n$. $\hat{t}_{av1}$ and $\hat{t}_{av2}$ are the averages of the first m intervals and the last m intervals respectively. This function is essentially Pearson's product-moment correlation coefficient, calculated over m pairs of values of $\{\hat{t}_i\}$, for different lags $k \geqq 0$.[1]

We have calculated $R(k)$ for lags $0 \leqq k \leqq 15$ for 8 continuation and 8 synchronization series, randomly chosen from the set of 96. This number was judged to be sufficient since the function $R(k)$ was fairly invariant over subjects and values of t, although it was evident that trend elimination had not always been complete in the 1667 and 3333 msec series. The average $R(k)$ functions of the continuation and the synchronization series are shown in Fig. 7.

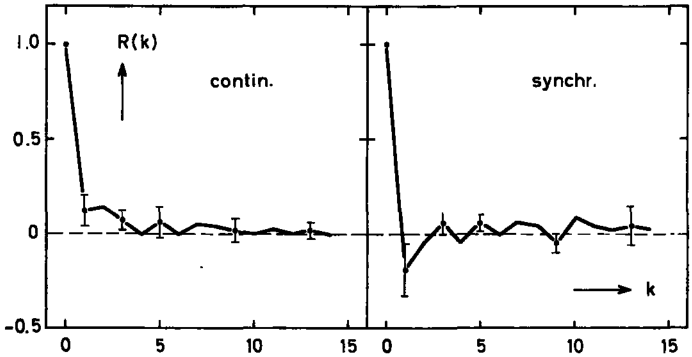


FIG. 7 – Autocorrelation functions (average of eight) of continuation and synchronization sequences. Vertical bars indicate standard deviations.

Since $R(k)$ has to exceed $\pm$ 0.181 to be significant at the 1% level, under the assumption that it is allowed to consider separate values of $R(k)$ for different k as independent for a first approximation,[2] it may

[1] An extensive treatment of continuous and discrete autocorrelation functions can be found in Blackman and Tukey (1959).

[2] In fact $R(k)$ should be evaluated integrally and not for individual values of k. A good test should take into account the overall variations in $R(k)$. No simple tests are available however, and moreover they would in all likelihood not have altered our conclusions.

be concluded from Fig. 7 that there is in both experimental conditions hardly any serial dependency, even with respect to the immediately preceding intervals (i.e. for $k = 1, 2$). Yet it seems possible to distinguish between the two presentation modes. It can be seen in Fig. 7 that in the synchronization condition $\hat{t}_i$ tends to be negatively correlated with $\hat{t}_{i-1}$, and perhaps slightly with $\hat{t}_{i-2}$, whereas there is a trace of positive correlation in the continuation series. A Student t-test for the difference between the averages of $R(1)$, $R(2)$ and $R(3)$ under the two response modes gave $t = 9.63$, 4.17 and 0.37 respectively, the first two values of t being significant at the 1% level, with 7 degrees of freedom.

Our conclusion is that there is a distinction between the two modes. The trend towards positive serial correlation in the continuation mode may be the result of an incomplete trend elimination, since the function $R(k)$ seems to approach 0 only very gradually. It may however, just as well be the manifestation of a more fundamental distinction between the two conditions. This may be clarified by later parts of our analysis.

The synchronization condition shows a, perhaps minor, but demonstrable effect of negative feedback (compensation), which proves that at least some of the extra information provided in this situation is used to maintain the synchrony between input clicks and output taps.

Grosso modo, however, we can agree with Ehrlich's (1957) contention that a synchronization error in tapping is not systematically compensated for. In fact it is, but only very little, and for a first approximation we may perhaps leave the effect out of consideration.

Analysis of extreme deviations. Before we adopt this strategy, we have to consider the possibility that the effect of compensation is present but buried in the variations due to other noise factors in the system. It was suspected on the basis of some early unpublished observations that there is a compensatory mechanism to deal with extreme deviations (of random origin) from a regular tapping rate. Since such extreme deviations are rare, the mechanism would operate only infrequently, whence the effect on the autocorrelation function $R(k)$ is suppressed when it is determined for the response sequence as a whole.

The data on which this observation was based are of course suspect, since our analysis consisted of looking at the records and sampling some convincing instances. Nevertheless, the effect may be real: it might indicate that there is a threshold below which errors in regularity are not – or not noticeably – compensated for.

To check this possibility the following procedure was adopted. By means of a digital computer all 96 series of trend-eliminated data were scanned for deviations from the average interval length which exceeded $\pm 2\, s^*$. Taking into account the sign of the deviation, the values $\hat{t}_{i-10}$, $\hat{t}_{i-9}, \ldots, \hat{t}_i, \ldots, \hat{t}_{i+10}$ were tabulated for each extreme value of $\{\hat{t}_i\}$. These results were averaged over single sequences and subjects. The essential parts of the averaged responses $\{\hat{t}_i\}$ for $-2 \leqq i \leqq 4$, are shown for each value of $\hat{t}_{av}$ and separately for both response modes in Fig. 8. It is clear that performance in the case of the intervals of 1000 msec and less is identical for both conditions. Only for longer intervals is there a discrepancy between the two. The synchronization responses are essentially identical for all values of $\hat{t}_{av}$.

We conclude that it is possible to differentiate between the two response modes on the basis of the compensatory behavior. The difference probably reflects the generic difference between an external and an internal standard. The latter is likely to be influenced by the most recent history of the system, which the external standard is not. If the internal standard follows the actual output with a certain lag, – due to averaging over preceding terms, – overcompensation with respect to the momentary value of the weighed internal standard may mean undercompensation with respect to the 'grand mean' of the output sequence.

Yet, since in a sequence of 200 intervals there are to be expected

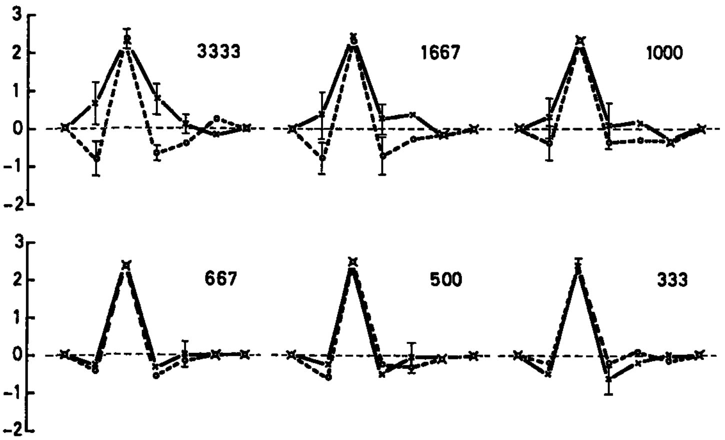


FIG. 8 – Compensation of extreme deviations for each input interval length. Solid lines represent the continuation condition, dashed lines stand for synchronization series.

only about 10 extreme deviations which exceed $\pm 2s^*$, and since the effect of compensation does not extend beyond the first two intervals following the extreme, there is no immediate reason to doubt that most fluctuations from one interval to another can be treated as serially independent. We shall have to determine more precisely however, what the threshold of the compensatory mechanism implies, and how it operates (see Sec. III.3 and Chapter IV).

The relation between variability and interval length. The relation between the variability and the average length of the response interval has been plotted in Fig. 9, for each of the four subjects. Except at the lower end of the range of $\hat{t}_{av}$, where s^* (or, by definition the differential threshold $\delta\hat{t} \equiv s^*$) seems to approach an asymptote, the results can be expressed by an exponential relation:

$$\delta\hat{t} = k\hat{t}_{av}^{1.5} + a, \tag{3.5}$$

where k is a constant of the order of 0.040 and a may be visualized as the intrinsic noise level of the motor system. The slopes of the least squares linear regression lines fitted to the data plotted in Fig. 9 do not deviate significantly from the lines with slopes 1.5 actually drawn.

Once more the results of the two presentation modes appear to be identical, which is further confirmed by some results of the pilot experiments, of subjects M and N, which have also been plotted in Fig. 9. The exponent being larger than 1, the relation between $\delta\hat{t}$ and $\hat{t}_{av}$ cannot be explained in terms of a simple stochastic process; a suggestion for a more complex mechanism will be made in the discussion (Sec. III.3.3).

Distributions of interval durations. The type of stochastic process responsible for the variations in interval length reflects itself in the distributions of intervals. Some of these distributions are shown in Fig. 10. Each class interval of the distributions shown was 5 msec, and a smoothing procedure has been applied to suppress some irregularity, such that

$$x'_i = \frac{0.5\,x_{i-2} + x_{i-1} + x_i + x_{i+1} + 0.5\,x_{i+2}}{4}. \tag{3.6}$$

All distributions of $t = 1667$ and 3333 msec, and some of 1000 msec show quite pronounced multiple peaks, suggesting very strongly that

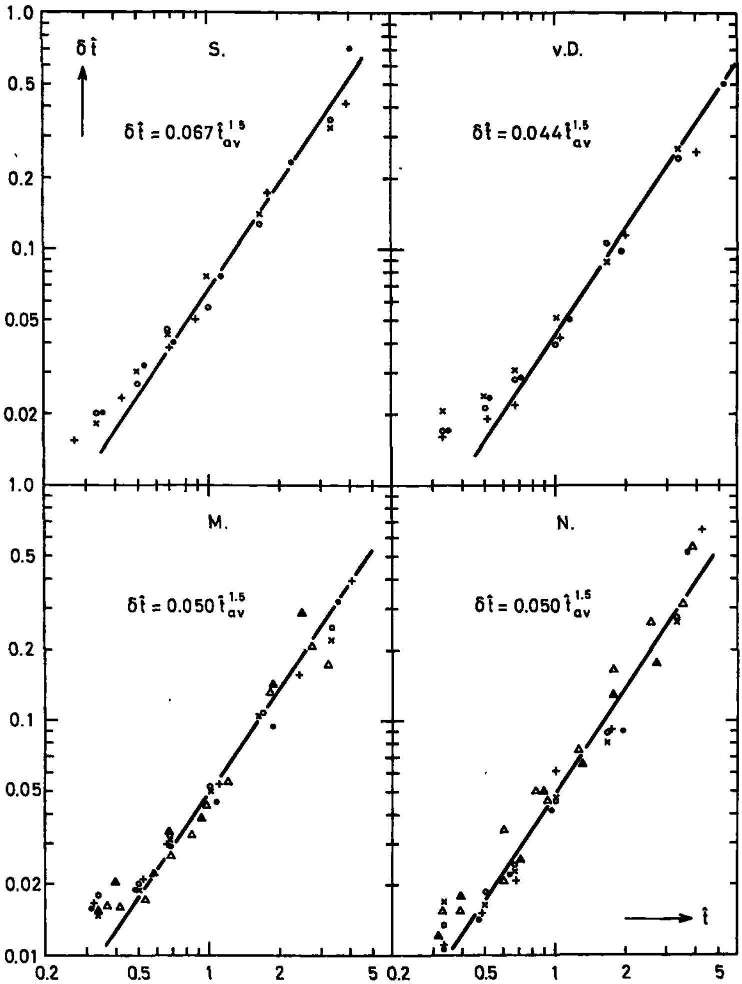


FIG. 9 – Variability of the response to isochronic input sequences as a function of the average length of the output intervals. Time in sec.

Continuation	1st series:	+	2nd series:	•
Synchronization	1st series:	×	2nd series:	•
Pilot Study	1st series:	▵	2nd series:	▴

response intervals are quantized, an important fact, which will be treated in detail in Chapter V. The absence of multimodality in the distributions of shorter intervals can be caused by the intervals falling within the range of a single 'peak' or time 'quantum'.

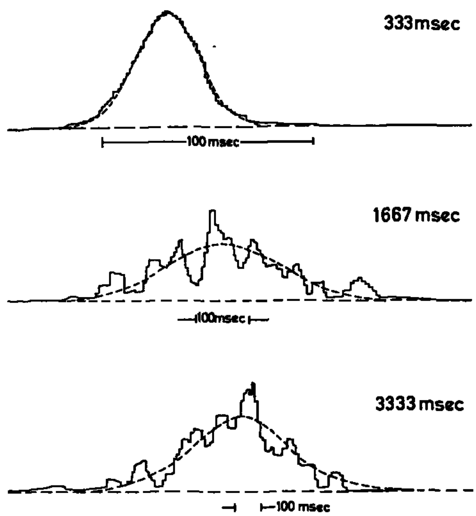


FIG. 10 – Examples of response interval distributions. The dashed curves are normal distributions fitted to the actual distribution. N.B. The very thin tails of the distributions are recording artefacts.

In order to suppress the multimodality shown in Fig. 10 and to bring out the gross shape of the distributions, further smoothing was achieved by increasing the width of the class intervals to a point where unimodality was obtained, the average number of classes being about 25. The distributions then were compared with a normal distribution by means of a χ^2-test (Lewis 1963, p. 227f.). The probability levels associated with the χ^2-values range from very high to very low and have been plotted in Fig. 11. The two distributions of p-levels deviate significantly from the expected distribution as is shown by the χ^2-values in Fig. 11.

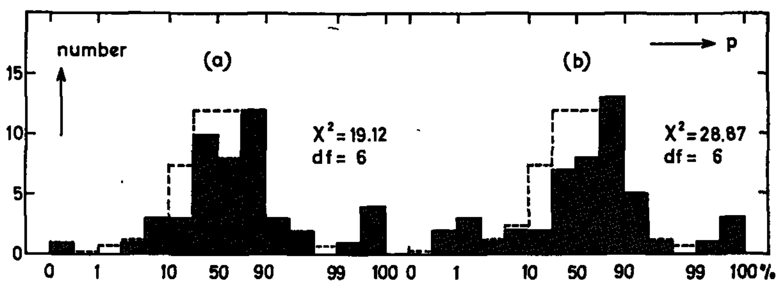


FIG. 11 – Distribution of p-values associated with the χ^2-test for normality of interval distributions. (a) continuation; (b) synchronization. Dashed lines represent the expected distributions of p-values.

A closer inspection of the exceptions did not reveal any common feature. Hence we will consider them as irregularities in the general pattern and treat the distributions for our present purposes as resulting from a normal – or binomial – random process.

3. DISCUSSION

3.1. Synchronization vs. Continuation

In retrospect we may conclude that there are observable differences between the two presentation modes in at least two respects. In the first place there are trends in the continuation sequences which may easily extend over a range of 20% of the average interval length. We have found no particular pattern in the course of these trends, but it is evident that most of the displacement with respect to the standard interval length occurs very early in a series and may be considered as a transient effect. The second difference found between continuation and synchronization performance was in the compensation of extreme deviations (exceeding $\pm 2s^*$) at long intervals. When the intervals were shorter than some value between 1667 and 1000 msec, no distinction could be made again.

It seems plausible that both effects are the result of special features of the 'internal standard' which the subject maintains in the continuation condition. Unlike the external standard, the internal standard will follow the fluctuations in the output sequence to some extent – albeit with a certain delay and in a smoothed fashion. This can account for the observed discrepancy, as we have argued before (p. 36). On the basis of the present data we are not in a position to analyze the properties of the internal standard in a quantitative way. The data – such as were shown in Fig. 10, for instance – make it plausible however, that the 'running average' which is the internal standard, is based on a few preceding intervals only, e.g. a number between 3 and 7.

There is some evidence (Ehrlich 1958) that subjects from time to time lose external control in the synchronization condition and apparently 'track' an internal standard for a few intervals until the synchronization error becomes too large, or perhaps until some other decision intervenes. In a later chapter (Chapter V) we shall be in a better position to evaluate such loss of external control, when we shall generate synchronization errors externally.

3.2. Correction of large deviations (Compensation)

Compensation of discrepancies between the standard – both external and internal – and the actual response seemingly occurs only if a particular 'tolerance level' is exceeded. This situation is in the first place reminiscent of dynamic quality control systems in industry (Page 1954). Changes in machine operations, to maintain a certain standard of quality are usually very costly, and have to be kept to a minimum. Products are therefore allowed to vary freely within certain limits and corrective action is taken only when these limits are exceeded. The decision rules may be based on a variety of statistics such as fixed or weighed averages, and numerous strategies are employed to bring quality back to standard. A psychological theory of the perceptual moment based on these techniques was developed by Shallice (1964).

A plausible alternative for the 'quality control' paradigm is the assumption that the compensatory mechanism depends only on the absolute size of the error $\varepsilon_i = \hat{t}_i - t_i$, which itself is of course a function of t_{av}. If the error is smaller than a threshold value below which it cannot be detected or below which it is not possible to perceive the direction of the error (Hirsh and Sherrick 1961), no action will be taken, but for the rest the compensation will be entirely a function of ε only and not of $\hat{t}_{av}$. Since $\delta\hat{t}$ is directly associated with $\hat{t}_{av}$ the consequence is that the compensation of small errors which are easily detectable, will have no noticeable effect on the output sequence $\{\hat{t}_i\}$ or its various statistical properties.

Assume, for example, that $t_{av} = 1$ sec and that $\delta\hat{t}$ at 1 sec is equal to 50 msec. Then an error ε_i at instant i, which is of the order of magnitude of 0.5 $\delta\hat{t}$ and which is compensated for 80% at instant $i + 1$, would change the value of $\delta\hat{t}$ from 0.050 to 0.054 when averaged over a number of observations. This would be a difference which is not easy to detect in experimental data. An error $\varepsilon_i = 1.5\ \delta\hat{t}$, on the other hand would have the effect of changing $\delta\hat{t}$ from 0.050 to 0.078.

This alternative seems to be more attractive than the quality control mechanism, since it explicitly recognizes the phenomenological distinction between the duration of the intervals of a sequence and the experience of a time difference between tap and click, the synchronization error.

We are, of course, interested in compensation effects that are observable, and in the way in which such compensation is effectuated. Both points can be studied more appropriately if the deviations are introduced by the experimenter rather than by chance. Only then can we determine the dynamic properties of the compensatory mechanism quantitatively. This will be undertaken in Chapter IV.

We may conclude this part of the discussion by stating that, as long as the discrepancy between input click and output tap is relatively small, the compensation effect is drowned in fluctuations which can be treated by a fair approximation as originating from a stochastically independent gaussian source.

3.3. The relation between variability and average interval length

If we disregard deviations exceeding the 'tolerance limit' and – at least for the time being – the apparent quantization effect observed in the interval distributions, the probability density function $\varphi(\hat{t})$ of the response intervals may be described simply by the normal density function,

$$\varphi(\hat{t}) = \frac{1}{s\sqrt{2\pi}} \exp\left\{\frac{-(\hat{t}-\hat{t}_{av})^2}{2\,s^2}\right\} \tag{3.7}$$

$\varphi(\hat{t})$ being the probability of an interval having exactly length $\hat{t}$. Since $s \simeq s^* = \delta\hat{t} = k\hat{t}_{av}^{1.5}$, in the range $\delta\hat{t} \geqq 0.5$ sec, we have

$$\varphi(\hat{t}) = \frac{1}{k\hat{t}_{av}^{1.5}\sqrt{2\pi}} \exp\left\{\frac{-(\hat{t}-\hat{t}_{av})^2}{2k^2\,\hat{t}_{av}^3}\right\} \tag{3.8}$$

Expression (3.8) is nothing but a convenient summary of a large part of the results of Exp. 1.

As was said earlier, there is no simple stochastic process in which the variance increases at a rate greater than that of the mean, and we have to think of a more complex mechanism to account for the 1.5 power relation between $\delta\hat{t}$ and $\hat{t}_{av}$. The exponential relation in fact suggests, according to Zwislocki (1965), a kind of self-regulating mechanism, of which the sensitivity decreases as a function of the size or intensity of the stimulus. Such mechanisms are difficult to visualize psychologically. The following essay to account for the results should therefore be considered as very tentative.

The relation expressed in Eq. (3.5) derives from the inevitability of the time order error in experiments on time evaluation (Sec. I.2). We have argued that one interval must be stored in memory whilst and as long as the next interval is in progress. We shall assume that this interval estimate is subject to decay while it is stored, i.e. during the period of storage the interval may increase or decrease in length randomly. It has a constant probability p_+ of increasing one basic unit of time, a probability p_- of decreasing one unit and a probability $p_0 = (1 - p_+ - p_-)$ of remaining unchanged. The length of the stored interval (t_S) will on the average, stay constant over time if $p_+ = p_-$ and in general Ave $(t_S) = t_S + n(p_+ - p_-)$, while Var $(t_S) = n \{(p_+ + p_-) - (p_+ - p_-)^2\}$, in which n is the number of points in time, since t_S was stored, at which an event (either +, — or 0) occurred.

Because in general, in the tapping situation, $n \propto t_S$, it will be evident that the variability $\delta\hat{t}$ of the tapping sequence $\{\hat{t}_i\}$ will be proportional to the square root of Var(t_S) and consequently $\delta\hat{t} \propto \sqrt{n} \propto \sqrt{\hat{t}_{av}}$.

If this mechanism is also 'self-regulating' in the sense described above, we have to make the additional assumption that the size of the unit steps up and down is a function of the sensitivity of the system, rather than a constant. Specifically, if the step size is directly proportional to $\hat{t}_{av}$, we will have the multiplicative relation $\delta\hat{t} = k_1\hat{t}^{0.5}.\ k_2\hat{t} = k\hat{t}^{1.5}$, where $k = k_1.k_2$.

In psychological terms this means that, after all, Weber's law would hold for time (Treisman 1963; Fraisse 1964, p. 141f.; Michon 1964b), were it not for the decay in time of the stored interval. One question which remains unanswered is, how Treisman (1963) and some other authors managed to avoid the decay of the memory component. In general we do find however, that results of threshold experiments reported in the literature are in fair agreement with the 1.5 exponential relation found in the present experiment (see Michon 1964b, Fig. 1; Woodrow 1932).

Three final remarks should be made. First, the assumptions made about the behavior of the stored interval requires the variance to be proportional to time-since-storage. This has been substantiated not only for time intervals, but for other stimulus dimensions as well (see Creelman 1962).

In the second place the proposed mechanism – however provisional – renders the position of a (quasi-)deterministic 'time quantum' less absolute: if an interval were estimated by counting successive quanta, the decay of the stored count would not be in units of constant size but at its best in integral multiples of such units, proportional to $\hat{t}_{av}$.

Thirdly, only if $p_+ = p_-$, will the average length of stored durations remain constant. If $p_+ < p_-$, for instance, the average will become smaller, or behaviorally, tapping becomes faster while the variance will change accordingly. The parameters p_+ and p_- may conceivably play a role in situations where information processing load is imposed on the subject. The information processing channel can be looked at as a 'single channel transmitter' which can deal with only one source of information at a time and alternates between different sources (Broadbent 1958; Egeth 1967; Welford 1967). It seems plausible that the probabilities of losing or gaining units of the stored interval t_S will be affected by the amount of non-temporal information imposed on the subject.

Although we will return to the problem of information processing load in Chapter V, we will not work out the foregoing speculative suggestions, since we will deal primarily with synchronization sequences. In that case the relation $p_+ = p_-$ is automatically guaranteed by external means, i.e. the input sequence.

CHAPTER IV
THE RESPONSE TO MODULATED INPUT SEQUENCES

1. INTRODUCTION

The present chapter is devoted to the problem of what determines the length of the 'next' interval produced by the subject in the course of synchronizing with a modulated input function. What earlier information is stored in 'temporal memory' and how are errors in synchronization, that are well above threshold, compensated for? Such very large errors do not occur spontaneously in normal tapping performance and have to be introduced externally by changing the rate of the input clicks, i.e. by modulating the input sequence. Continuation experiments are not feasible in this setting: the subject who has to change the rate of his internal standard in a prescribed manner, will act as a final rather than a causal system, which leads to problems beyond the scope of this study.

In the answer to the question posed in the last paragraph the dynamic properties of the timing system – or metaphorically: the 'time sense' – will become manifest. A dynamic analysis requires some mathematical manipulations of a kind that is not yet widely used in psychology. The following introduction to the technique of systems analysis by means of generating functions may contribute to make this powerful technique better known. The arguments and symbolism used in the next section are focussed on our present enterprise, but are based largely on the following texts, which offer more general and more refined expositions: Ragazzini and Franklin (1958), Schwarz and Friedland (1965) and Truxal (1955). Feller (1957) offers an illuminating chapter on generating functions.

2. GENERATING FUNCTIONS AND DISCRETE TIME SYSTEMS

We deal – *in abstracto* – with two series of numbers which represent sequences of input intervals and output intervals respectively. We are interested in the relation between these two series, and want to include the possibility that not simply $\hat{t}_i = f(t_i)$, but that

$\hat{t}_i = f(t_i,\ t_{i-1}, \ldots, t_{i-k})$. Moreover we want to generalize this expression and find a relation between input and output sequence, $\{\hat{t}_i\} = H\ \{t_i\}$, which is independent of the particular value of i. In the latter representation H is an operator – called the 'system transfer function' – which generates the output sequence $\{\hat{t}_i\}$ if $\{t_i\}$ is input to it. Generating functions and specifically the z-transformation (related to the Laplace transformation) may be used to achieve these goals.

A generating function is an expression for the sum of an infinite power series, and it will generate that series upon expansion in a unique way. It is an engineering convention to use an expansion in negative powers of a dummy variable z. Thus the sum $F(z)$ defined by

$$F(z) = \sum_{i=0}^{\infty} f(i) z^{-i} \tag{4.1}$$

is called the z-transform of the function $f(i)$.[1] For example, if $F(z) = z/(z-1)$, expansion by long division generates the series $1 + z^{-1} + z^{-2} + \ldots + z^{-k} + \ldots$, whence by Eq. (4.1) the original function is found to be $f(i) = 1$, for all $i \geqq 0$. Here and later it is always assumed that $t_i = 0$ for $i < 0$.

Conversely we may determine the z-transform of the function $f(i) = (\frac{1}{2})^i$:

$$F(z) = \sum_{i=0}^{\infty} f(i) z^{-i} = 1 + \frac{1}{2z} + \left(\frac{1}{2z}\right)^2 + \left(\frac{1}{2z}\right)^3 + \ldots = \frac{2z}{2z-1}. \tag{4.2}$$

Again by introducing the dummy variable z, we are able to regenerate the terms of the original series $\{1, 1/2, 1/4, 1/8, \ldots\}$ as coefficients of the power series of which $F(z)$ is the sum.

The z-transform makes the derivation of the transfer function of a dynamic system in principle very easy. In Fig. 12 the response to a simple pulse input t_0 at $i = 0$ is represented in the upper section of the figure. The response is shown as extending over the next few instants $i = 1, \ldots, 4$ and returns to zero for $i > 4$. The response function can be expressed as $\{t_0 h_0,\ t_0 h_1, \ldots\ t_0 h_k\}$. In the type of linear systems we are studying, the height of the input pulse (t_0), appears only as a multiplication constant in the response function. Hence we can say in general that the sequence $\{h_0,\ h_1, \ldots\ h_k\} = \{h_i\}$ (where it is assum-

[1] i is exclusively used to indicate the rank order (instant) of intervals, not to designate $\sqrt{-1}$.

ed that $h_i = 0$, for $i \geqq k$) is the transfer function we want to know. It fully determines the response of a linear system to any given input function. For, if the system is given a second pulse input t_1 at $i = 1$, the response to t_1 will interfere with that to the pulse given at $i = 0$, and later input terms will add their contributions and combine into a compound response function. The essence of the 'composition' or 'convolution' of successive terms is depicted in Fig. 12.

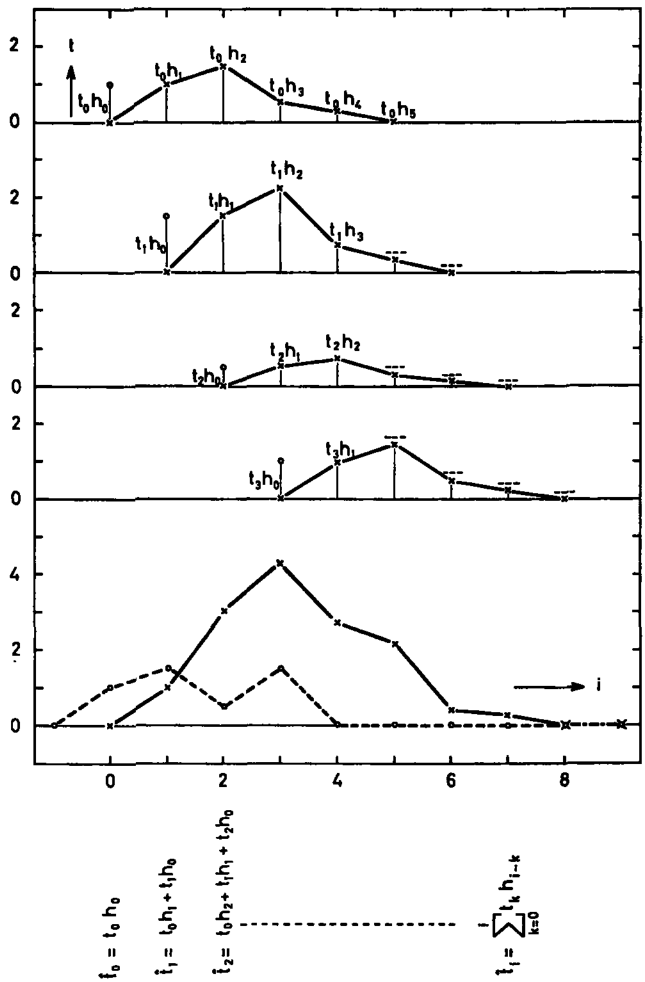


FIG. 12 – The principle of calculating a convolution sum.

Under the linearity assumptions all contributions simply add, and the general response term can therefore be expressed as

$$\hat{t}_i = \sum_{k=0}^{i} t_k h_{i-k}. \tag{4.3}$$

Now the use of the z-transformation in the present context will become clear: it relieves us from the need to carry out, step by step, the summation of Eq. (4.3) for each value of i separately. Instead we multiply the z-transforms of the input $\{t_i\}$ and transfer functions $\{h_i\}$, to obtain the z-transform of the response function $\{\hat{t}_i\}$, i.e.

$$\hat{T}(z) = T(z).H(z), \tag{4.4}$$

or, if input and output sequences are known and the transfer function is to be determined, we obtain by algebraic division:

$$\frac{\hat{T}(z)}{T(z)} = H(z). \tag{4.4a}$$

The relations expressed in Eqs (4.4) and (4.4a) follow directly from the multiplication or division. Since

$$T(z) = t_0 + t_1 z^{-1} + t_2 z^{-2} + \dots$$

and

$$H(z) = h_0 + h_1 z^{-1} + h_2 z^{-2} + \dots,$$

we have

$$T(z).H(z) = \hat{T}(z) =$$
$$= t_0 h_0 + (t_0 h_1 + t_1 h_0) z^{-1} + \dots + \left(\sum_{k=0}^{i} t_k h_{i-k} \right) z^{-i} + \dots$$

as required by Eq. (4.3) with respect to the response terms.

Once $\{h_i\}$ or $H(z)$ are known $\{\hat{t}_i\}$ can be directly predicted for any given input sequence $\{t_i\}$ at any point in time.

Although we have dealt with the sequences of intervals completely abstractly, we may consider them, more concretely, as input and output of a psychological system, the 'time sense'. A representation of the 'time sense' which to us is a black box of unknown composition, is given in Fig. 13a.

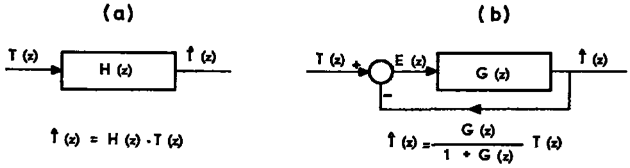


FIG. 13 – 'Black box' representation of dynamic system, without and with explicit feedback loop.

Since subjects are predicting the length of intervals on the basis of previous information, the black box must contain a feedback loop. Hence we may replace it by the diagram Fig. 13b, which is the basic layout of a system with negative, i.e. error correcting, feedback. The resulting error function transform $E(z)$ which is the z-transform of the difference between the transforms of input and output, passes through a 'reduced' black box, with transform $G(z)$, which describes the response function when the feedback loop is interrupted (open loop transfer function).

In Fig. 13b the various relations between the z-transforms are indicated. Since $E(z) = T(z) - \hat{T}(z)$ and $\hat{T}(z) = E(z).G(z)$, we can derive the relation between the transforms of the general transfer function, $H(z)$, and the open loop transfer function G(z):

$$H(z) = \frac{G(z)}{1 + G(z)}. \tag{4.5}$$

3. THE BASIC MODEL

The model proposed is extremely simple but can be refined and augmented easily with the technique introduced in the previous section. It rests on three basic assumptions.

(a) If the input sequence is isochronic, the subject will synchronize perfectly – disregarding the noise component in his performance – after the first two intervals, i.e. if $\{t_i\} = C$ for $i \geqq 0$, then $\hat{t}_i = t_i$ for all $i \geqq 2$.

This applies to the ideal case only. In our data we have tried to approximate this ideal by averaging out random variations in the responses.

(b) Memory for previous input intervals is restricted to a perfect

memory for the immediately preceding interval t_{i-1}. In the absence of further information, therefore, $\hat{t} = t_{i-1}$.
(c) If at any instant i we change the rate of an isochronic input to a different but also constant rate, an error will occur (see Fig. 14). We assume that the error $\varepsilon_{i-1} = \hat{t}_{i-1} - t_{i-1}$ is compensated for immediately and completely at the next interval, such that $\hat{t}_i = t_{i-1} + \varepsilon_{i-1}$. Consequently $\hat{t}_i = t_{i-1} + (t_{i-1} - \hat{t}_{i-1})$. Since *sub* (b) we assumed that $\hat{t}_i = t_{i-1}$ if the sequence is isochronic, we have

$$\hat{t}_i = t_{i-1} + (t_{i-1} - t_{i-2}) = 2t_{i-1} - t_{i-2} \tag{4.6}$$

as a general expression for the i-th response interval as predicted by the model. The relation expressed in Eq. (4.6) also describes the performance of the model when more complicated changes in input occur: irrespective of $\{t_i\}$ the predicted value $\hat{t}_i$ is a linear extrapolation from the last two input intervals t_{i-1} and t_{i-2}.

Since Eq. (4.6) only describes the local behavior of the system at instant i, where $i \geqq 0$, we have to derive the general expression for the relation between input and output sequences. Starting from Eq. (4.6) we find that the input function $\{t_i\} = \{1, 1, 1, \frac{1}{2}, -\frac{1}{2}, \ldots\}$ has as response $\{\hat{t}\} = \{0, 2, 1, 1, 0, -1\frac{1}{2}, \ldots\}$, as is shown by way of an example in Fig. 14. By our earlier arguments we arrive at

$$H(z) = \frac{\hat{T}(z)}{T(z)} = \frac{0 + 2z^{-1} + z^{-2} + z^{-3} + \ldots}{1 + z^{-1} + z^{-2} + \frac{1}{2}z^{-3} + \ldots} = \frac{2z - 1}{z^2} \tag{4.7}$$

for the transform of the model's closed loop transfer function, while the open loop transfer function is described by the transform

$$G(z) = \frac{H(z)}{1 - H(z)} = \frac{2z - 1}{(z - 1)^2}, \tag{4.8}$$

which follows directly from rearranging Eq. (4.5) and substitution of Eq. (4.7).[1]

$H(z)$ and $G(z)$ characterize the properties (a), (b), and (c). The experiments described in the remaining part of this chapter were designed to test this model, which may be called an 'ideal linear predictor'.

[1] A mathematically more elegant way of deriving the transfer function is to carry out directly the z-transformation of the difference equation describing the system (Eq. 4.6). This results in the expression Eq. (4.7).

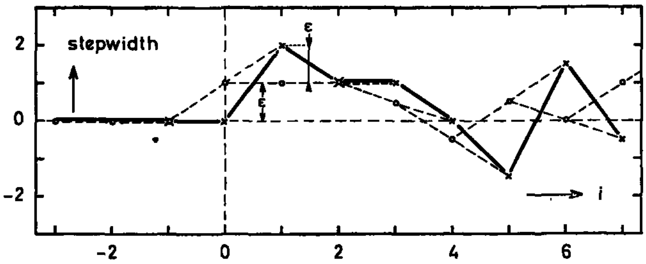


FIG. 14 – Graphical representation of the response (solid curve) of an ideal linear predictor to an input function (circles). Extrapolation of the difference between successive circles yields predicted values (crosses) of next output interval.

4. THE SIMPLE SINUSOIDAL INPUT – EXPERIMENT 2

The input sequence tested in this experiment is defined by

$$t_i = t_{bas} + \Delta t \sin \frac{2\pi i}{16}, \ (i \geqq 0). \tag{4.9}$$

The input varies between t_{bas} and $t_{bas} + \Delta t$, while one period, D, consists of 16 intervals.

Design.

Three subjects, vdV, B and vD each produced 10 complete periods with $t_{bas} = 600$ msec and with $t_{bas} = 1200$ msec, while $\Delta t = 0.32\, t_{bas}$.

Results and discussion.

The average response of subject vdV to both input sequences is shown in Fig. 15, in which the vertical scale for $t_{bas} = 1200$ msec is half as large as that of the other condition to make the two parts of the figure directly comparable. The input function is shown as a dashed curve, the values predicted by the basic model as a solid polygon. Qualitatively we see a number of predicted characteristics of the response function realized in the actual data exemplified in Fig. 15.

All subjects show overshoots at the extremes of the input function. They lag behind the input immediately after this overshoot, and lead from a point approximately one or two intervals past the 'zero' crossings of the input. It seems that the major departures from the model occur at specific points, rather than being caused by a serious defect in overall fit.

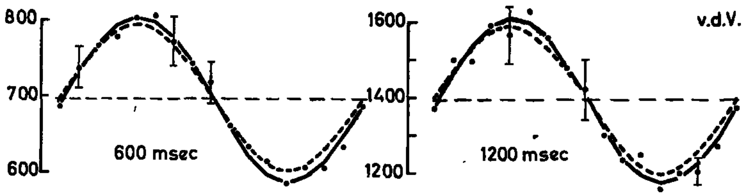


FIG. 15 – Responses (dots) of subject vdV to simple sinusoidal inputs (dashed curves). The solid polygon is the response as predicted by the basic model. Vertical bars indicate largest, median and smallest standard deviations. Time in msec.

At some points stepwise (quantal) adaptation to the changing input sequence is suggested. We expect such steps to be sporadic in the present experiment, since the average rate of change of the input function is quite considerable. Moreover the interval length changes continuously, so that no rest points are available to the subject and desynchronization of the steps with respect to the extremes of the output sequence may occur, which in turn would wipe out the effect in the average responses we are dealing with. In Chapter V a closer look will be taken at this problem (Sec. V.3).

It is evident that quantitatively the fit of the model is not perfect. An analysis of variance on the six sets of data showed however that we may pool them since neither the differences between subjects, nor the interval length, nor the interaction between the two factors were significant (all F-ratios were less than 1).

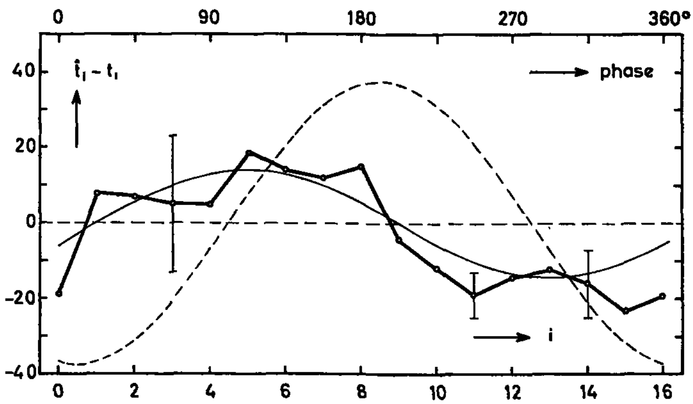


FIG. 16 – Average response (three subjects, two conditions) to simple sinusoidal input. The thin solid curve is the response as predicted by the basic model. Time in msec.

In Fig. 16 the pooled data are given in a different representation than that of Fig. 15. It shows the differences (in msec and 2 msec units for the two conditions respectively) between the input function (zero-line) and the basic model prediction (solid curve), the input function shifted one instant (dashed curve) and the actual data (points and solid polygon). Comparison of the least squares variance of the pooled data about the means of the actual data, and the variance about the values generated by the model, showed that 84% of the explicable variance[1] is accounted for by the model. The ratio between the variance contributed by taking the model predictions instead of the actual means and the irreducible variance about these means, was less than 1 which indicates that the model prediction is not significantly different from the observed data, when we take the variability of the data into account.

The conclusion is that the basic model as developed in the previous section, is a very good first approximation of the average response to a simple sinusoidal input function. Yet it seems likely that its fit can be improved upon, but possibly the sine wave modulation is not the most appropriate input to test this. It has in fact a predictable element in it, since it consists of regular periods of the sine function and is repeated a number of times in succession in the experiments. If the subject were able to use this possible source of advance knowledge, some sort of finality would creep into the performance of the system, and the response would be affected accordingly. The predictability can be diminished, of course, by making the input sequence more complicated.

5. THE COMPOSITE SINUSOIDAL INPUT – EXPERIMENT 3

If we are dealing with a linear system, the response to a combination of input functions can be predicted from the combination of the responses to each of the constituent input functions. Therefore, if the basic model is applicable to simple sinusoids, it will also hold for inputs composed of any number of such simple inputs. The following experiment tests this assumption for the combination of two and three simple sine wave inputs. The results will show whether the predictability of the future course of the input in Exp. 2 did affect the

[1] The term 'explicable' or 'explainable' variance is defined in the discussion of Exp. 4 (Sec. IV. 3).

performance of the subject in that experiment. If it did not, we probably need not be concerned about the effect of advance knowledge in other, even less predictable, conditions.

Design

The same three subjects, vdV, B and vD took part in this experiment. Each produced 10 complete cycles of 5 different input sequences. Three of these were simple sinusoidally modulated click sequences, just as in the previous experiment:

$$t_i = 600 + 192 \sin \frac{2\pi i}{D} \text{ (msec)}, \ (i \geqq 0), \tag{4.10}$$

where $D = 8, 12$ or 16. The fourth and fifth were linear combinations of two and three of these simple sequences:

$$t_i = 600 + \frac{192}{2} \left(\sin \frac{2\pi i}{8} + \sin \frac{2\pi i}{12}\right), \ (i \geqq 0), \tag{4.11}$$

and

$$t_i = 600 + \frac{192}{3} \left(\sin \frac{2\pi i}{8} + \sin \frac{2\pi i}{12} + \sin \frac{2\pi i}{16}\right), \ (i \geqq 0), \tag{4.12}$$

both in msec.

Results and discussion

As before, an analysis of variance showed no essential differences between subjects, nor in any of the other factors. Consequently the results of the three subjects have been pooled again.

Figs 17 and 18 show the equivalents of Figs 15 and 16 respectively, for each of the 5 input functions; in Fig. 18 performance is again plotted against the predicted values generated by the basic model. The diagrams show once more a close agreement between data and model. There seem to be two major 'defects' in the fit of the model to the data. The first is that there is a tendency – though not a consistent one – to overshoot more at the extremes than is predicted by the model. The second more prominent discrepancy is the lag which subjects show with respect to the predicted output. This lag is particularly clear when the rate of change of the input is quite high (see Fig. 18, $D = 8$ and the composite periods). This effect is an indication that a synchro-

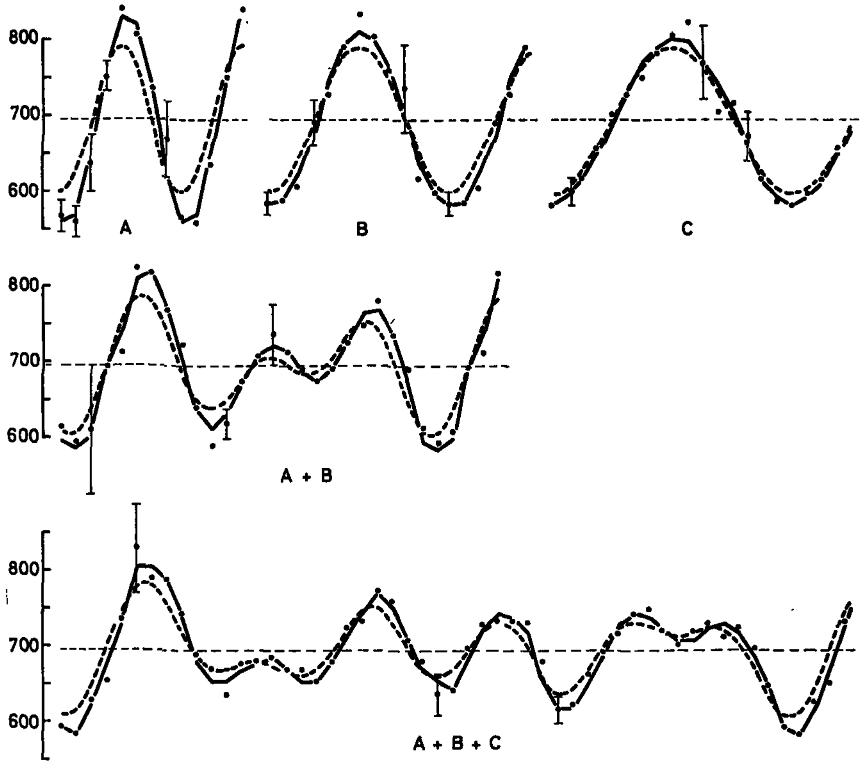


FIG. 17 – Responses (dots) of subject vdV to composite sinusoidal inputs and their constituents. The solid polygons are the responses as predicted by the basic model. Time in msec.

nization error is not completely corrected in the next interval, which we assumed in point (c) of Sec. IV.3, but is compensated in a number of steps greater than one.

Comparison of the variance about the means with that about the predicted values of $\hat{I}_i$ essentially confirms this. While altogether between 60 and 95% of the explainable variance is accounted for, it was found that for $D = 8$, and the two combined conditions $(8 + 12)$ and $(8 + 12 + 16)$ so much of the variance remains unexplained that a significant improvement might be obtained from a better prediction.

In conclusion we may say that the simple basic model predicts the average responses of our subjects to sinusoidal inputs – simple as well as compound – reasonably well. The hypothesis that the timing system is essentially dynamic, i.e. dependent on previous input and/or output

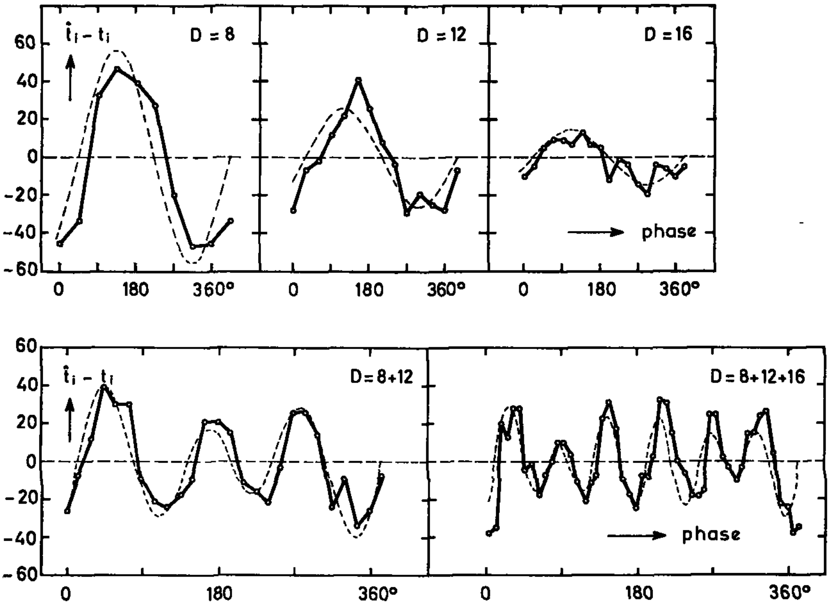


FIG. 18 – Average responses (three subjects) to composite sinusoidal inputs and their constituents. The thin dashed curves are the responses as predicted by the basic model.

terms is substantiated by our findings. Hence we are not allowed to say – as Ehrlich did – that the timing system is doing "progressively worse" when the input is not isochronic (Ehrlich 1958). Only, it does something else than passively follow the input: it actively tries to predict.

We found no significant differences in performance of the three subjects observed; which does not mean however, that there are no personal differences to be expected at all. The sinusoidal input is not the most appropriate to bring out such differences. For reasons which can be inferred from considerations put forward later in this chapter, the response to a sinusoidal input is quite resistent to variations in parameters which may be introduced in the model to account for individual differences in behavior, or the apparent lagging behind the model predictions.

6. THE STEP FUNCTION INPUT – EXPERIMENT 4

A better test to bring out fine distinctions is provided by the 'step function'. The input tested in this experiment is described by

$$t_i = \begin{cases} t_{bas}, \ i < m \\ t_{bas} + \Delta t, \ i \geqq m \end{cases} \tag{4.13}$$

The subject is presented with a series of intervals of constant duration (t_{bas}) up to an instant m, where the rate suddenly changes ($t_{bas} \rightarrow t_{bas} + \Delta t$). Also included in the experiment are negative steps ($t_{bas} + \Delta t \rightarrow t_{bas}$).

Design

Five of the regular subjects (vdV, B, vD, M and N) served in this experiment. Three values of t_{bas} were chosen (600, 1200 and 2400 msec) and three values of Δt (8, 16 and 32%). Within a single session only one value of t_{bas} was employed while positive and negative steps were presented at random for all three Δt. In addition a number of 'irrelevant' steps were included to make the situation even less predictable. Thus for instance, two positive steps, $t_{bas} \rightarrow 1.16\ t_{bas} \rightarrow 1.32\ t_{bas}$, in succession were made possible. The distance between successive steps was varied randomly over a wide range to avoid anticipation, no two steps being presented less than 9 intervals from one another.

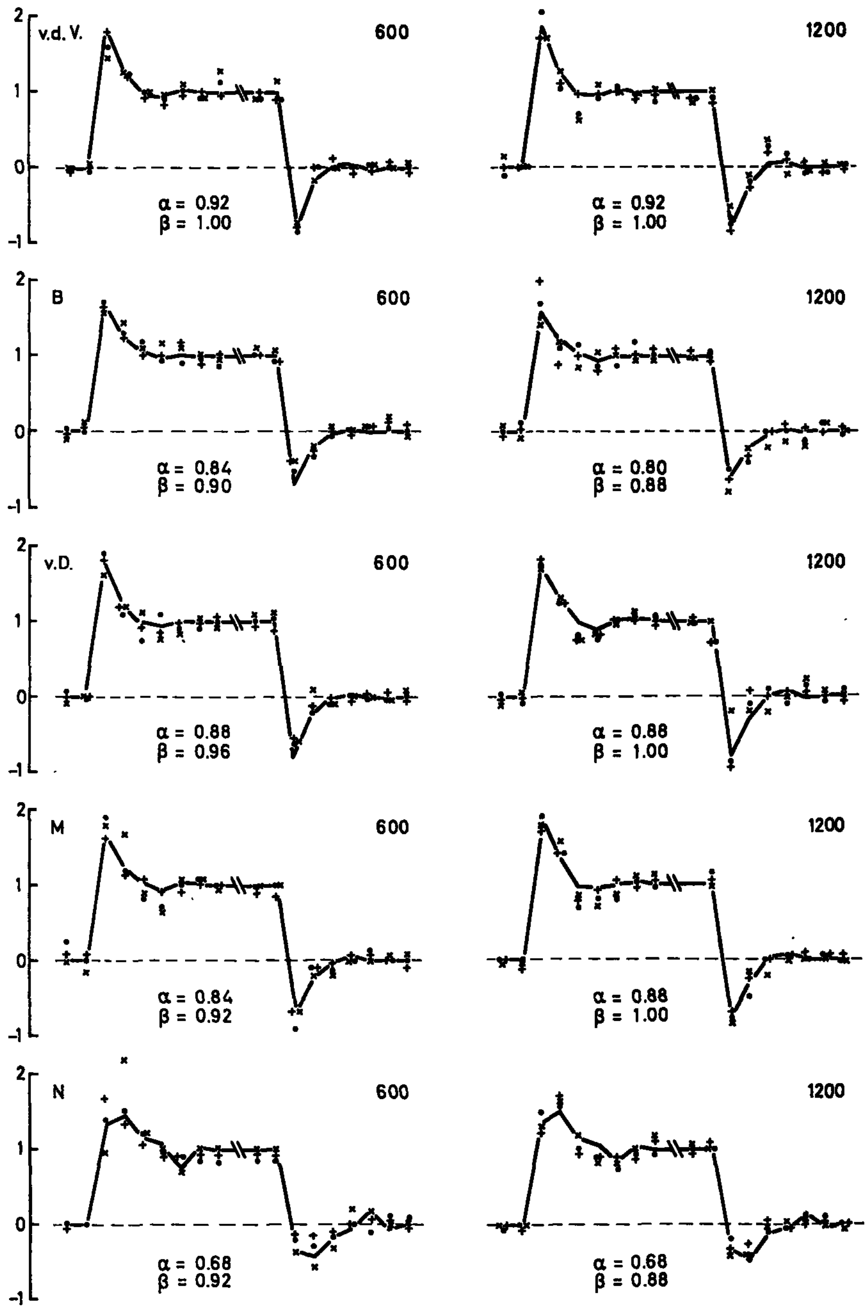
Altogether subjects produced 10 steps for each t_{bas}, Δt and step direction. The average response and standard deviations were calculated for all $\hat{t}_i$, from $m - 3 \leqq i \leqq m + 7$, at each of the 18 conditions.

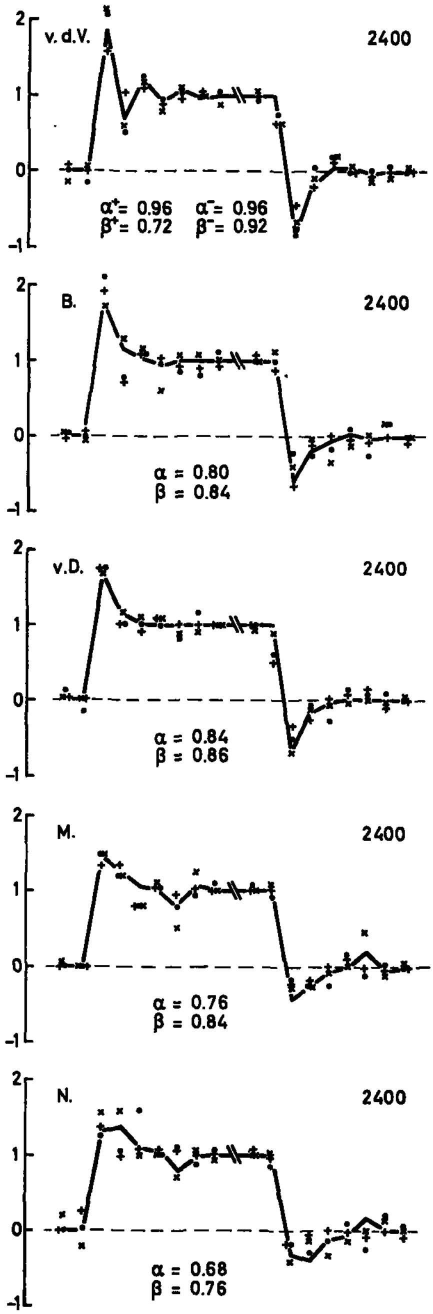
Results

The average responses of all subjects are given in Fig. 19, for $m - 1 \leqq i \leqq m + 6$. All plots are drawn to the same relative scale, for immediate comparability. Different values of Δt are plotted in one diagram, since the basic model does not predict any effect of the width of a step, a prediction which is not completely substantiated by the actual data shown in Fig. 19.

From fig. 19 we may conclude that the basic model, which is represented by Fig. 19a, provides a very good fit for some subjects and quite bad for others. Especially subjects vdV and N are extremes in this respect. Generally speaking there is certainly room for improvement of the model. In fact the solid lines in Fig. 19 represent the response as predicted by a modified model containing two parameters, which will be dealt with quantitatively in the discussion.

In order to check if, for modulated inputs, the relation between


v.d. V.
600
1200
α = 0.92
β = 1.00
α = 0.92
β = 1.00
B
600
1200
α = 0.84
β = 0.90
α = 0.80
β = 0.88
v.D.
600
1200
α = 0.88
β = 0.96
α = 0.88
β = 1.00
M
600
1200
α = 0.84
β = 0.92
α = 0.88
β = 1.00
N
600
1200
α = 0.68
β = 0.92
α = 0.68
β = 0.88



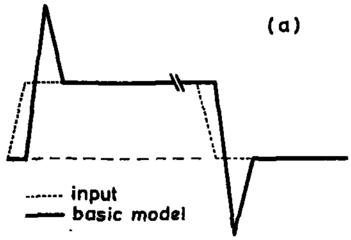


FIG. 19 – Average responses to step function inputs. Input function and response as predicted by the basic model are drawn at far right (a). All responses were drawn to the same relative scale. The solid curves are the responses as predicted by the model with parameters α and β estimated as indicated. ($\times$: $\Delta t = 8\%$; $\bullet$: $\Delta t = 16\%$; $+$: $\Delta t = 32\%$).

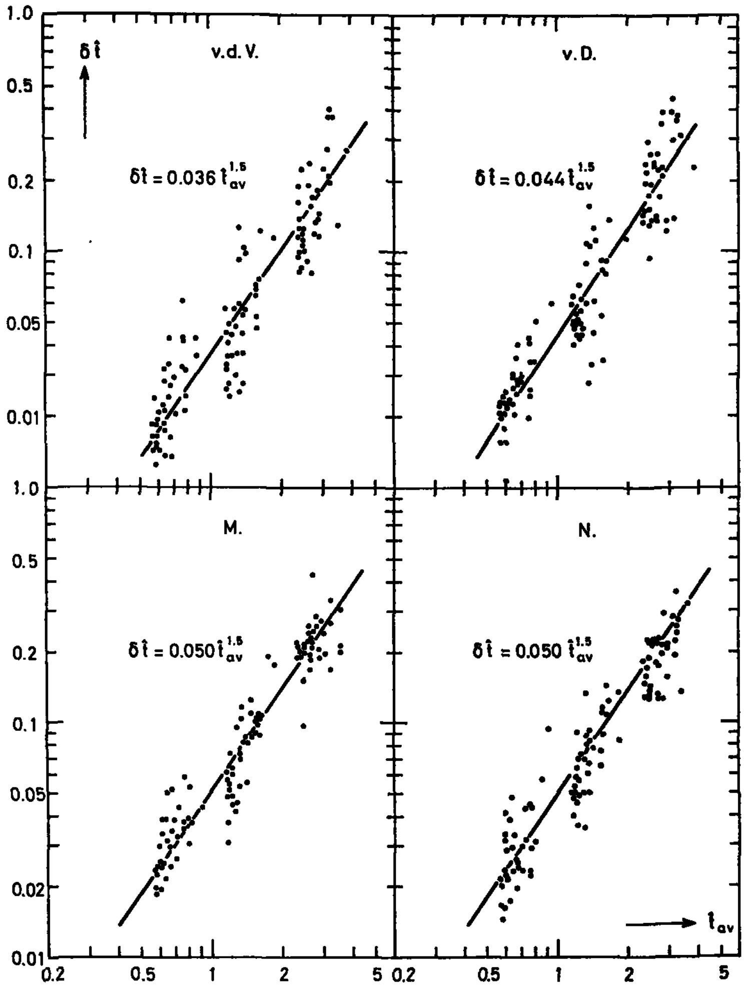


FIG. 20 – Variability of the response to a stepwise modulated input as a function of average output interval length (positive step). Time in sec.

variability $\delta\hat{t}$ and average interval length $\hat{t}_{av}$ still holds, we have plotted the relation between $\delta\hat{t}$ and $\hat{t}_{av}$ in Fig. 20, and fitted the function $\delta\hat{t} = k\hat{t}_{av}^{1.5}$, with the same estimate of k as in Chapter III (Fig. 8) for those subjects who took part in both experiments. The plots consist of all $(\hat{t}_i, \delta\hat{t}_i)$ pairs for $m-3 \leqq i \leqq m+8$ on each of the 9 positive step conditions. The finding of Exp. 1 is consolidated by the results of the present experiment. Closer inspection of the data showed that there

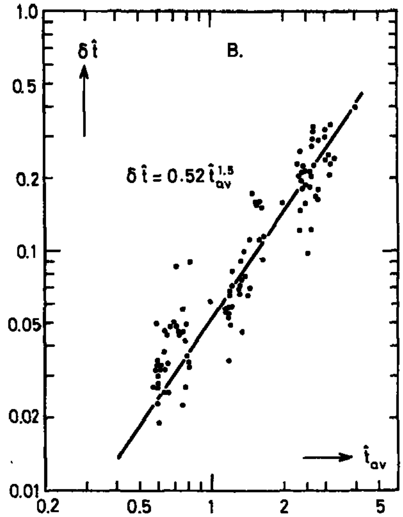


FIG. 20 (*continued*)

is a slight trend in $\delta\hat{t}$ for $i = m$ and $i = m + 1$ to be larger than expected, but this failed to be significant at the 5% level, and with a few exceptions even at the 10% level. This shows that the average response is consistent throughout and that the variability superimposed on the system's response may essentially be treated as the result of the random variations as described in Chapter III.

Discussion

The model proposed in Sec. 3 of the present chapter obviously has to be modified in order to account for the results of the experiments. The sinusoidal conditions (Exps 2 and 3) were fairly well described by the 'ideal linear predictor'. In the present experiment, the basic model seems to describe fairly appropriately the performance of the best subject, but it does not account very well for the 'worst' subject's behavior. Specifically it is found that $| \hat{t}_i - t_i | < | t_{i-1} - t_{i-2} |$, whence the error correction must extend over more than one output interval. This is obvious from the data shown in Fig. 19: it takes a subject at least 4 or 5 intervals to restore the synchrony between input and output.

There are two ways in which the model can be modified to account for these results without affecting its basic structure, or its 'psychological content'. The two alternatives are illustrated by Fig. 21.

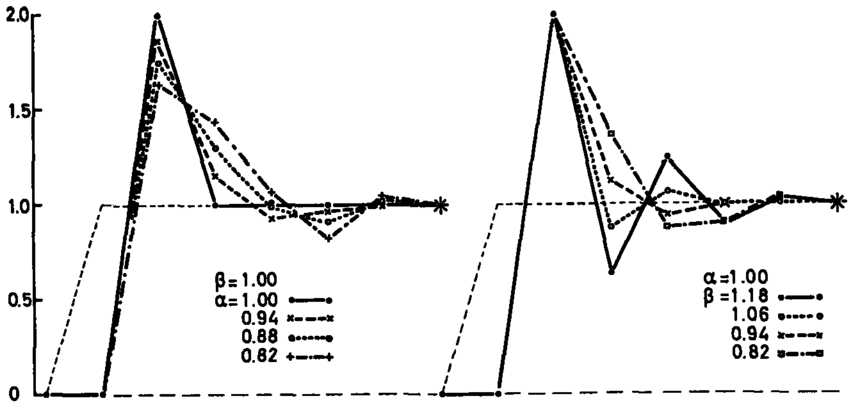


FIG. 21 – The effect of the parameters α and β on the response to a stepfunction input.

The first possibility is that an error ε_{i-1} at instant i–1 is under- or over-corrected at the next instant and is corrected further in a number of intervals to follow. The second possible course of events is that the subject corrects his error appropriately at the next instant, but then swings through and oscillates for a while around the correct synchronous relation before restoring the original synchrony. These two factors are independent but may act together.

Starting from Eq. (4.8), the z-transform of the open loop transfer function of the basic model

$$G(z) = \frac{2z-1}{(z-1)^2}, \tag{4.8}$$

we may introduce two parameters to account for the two factors. The first, being simply a matter of over- or underestimation of the size of the error, can be represented by introducing an amplification, or as the case may be, attenuation factor, α, in $G(z)$, i.e. $G'(z) = \alpha G(z)$. The second effect cannot be as easily visualized, but is brought about by splitting $G(z)$ into two partial fractions $P(z)$ and $Q(z)$, of which the first is a simple delay mechanism $P(z) = x_1/(z-1)$ and the second determines the rate at which the oscillation dies out: $Q(z) = x_2/(z-\beta)$. Power series expansion of $Q(z)$ shows that $Q(z)$ is related to the exponential decay function; in fact if $\beta = e^{-\lambda t}$, we would have $q(n) = x_2 e^{-n\lambda t}$.

x_1 and x_2 are constants which may be chosen conveniently. If $x_1 = 1/(1-\beta)$ and $x_2 = (1-2\,\beta)/(1-\beta)$, we have for $\beta \neq 1$

$$G(z) = P(z) + Q(z) = \frac{2z-1}{(z-1)\,(z-\beta)} \tag{4.14}$$

and

$$G'(z) = aG(z) = \frac{a\,(2z-1)}{(z-1)\,(z-\beta)}. \tag{4.15}$$

Thus the latter expression describes the behavior of the original model if $a = \beta = 1$, while it can further account for under- and over-correction (a) and damping of the corrective action (β). a and β should be fairly close to 1.

The transform of the closed loop transfer function derived from Eq. (4.15), by substitution in Eq. (4.5) is

$$H'(z) = \frac{a\,(2z-1)}{z^2-(1+\beta-2a)\,z+(\beta-a)}, \tag{4.16}$$

has no simple power expansion. If we substitute $a = 1 - a$ and $\beta = 1 - b$, then $a \simeq 0$ and $b \simeq 0$, and consequently we will have vanishing higher order terms in the expanded series. After this substitution expansion of Eq. (4.16) results in an expression for $\hat{t}_i$ for each $i \geqq 0$:

$$\begin{aligned}\hat{t}_i \simeq\ & (2-2a)t_{i-1} + (-1+5a+2b-4a^2-2ab)t_{i-2} + \\ & + (-4a-3b+12a^2+11ab+2b^2)t_{i-3} + \\ & + (a+b-13a^2-17ab-5b^2)t_{i-4} + (6a^2+10ab+4b^2)\,t_{i-5} + \\ & + (-a^2-2ab-b^2)t_{i-6}.\end{aligned} \tag{4.17}$$

The results of Exp. 4 are sufficiently detailed to allow an analysis in terms of the parameters a and β. Just as before, an analysis of variance was carried out to determine the fit of the model (Eq. 4.16) in comparison to the least squares fit. The values of a and β were estimated by plotting the model behavior for various values of a and β and selecting by eye the pair of values which best fitted the data; selecting an optimal set of parameters with the help of a computer would have been too costly.

The fit of the 15 sets of data to the parametrized model can be seen in Fig. 19 – and in Table 3 – together with the numerical estimates of

TABLE 3 – Summary of the analysis of the fit of the model to step function inputs.

(1) Subj.	(2) t_{bas} (msec)	(3) Parameters α	(4) Parameters β	(5) Var. red. (ILP = 100) Explicable	(6) Var. red. (ILP = 100) Exp'nd	(7) Var. red. (ILP = 100) E'nd/E'ble	(8) Sign. of further Improvement F	(9) Sign. of further Improvement p	(10) Residual least sq. variance (%)
vdV	600	0.92	1.00	76.0	52.8	0.69	4.66	<.005	6
	1200	0.92	1.00	59.5	40.3	0.68	2.71	<.05	12
	2400 +	0.96	0.72	41.4	38.0	0.92	1.29	n.s.	16[a]
	2400 −	0.96	0.92						
B	600	0.84	0.90	91.6	78.3	0.86	8.18	<.001	18
	1200	0.80	0.88	42.1	39.8	0.94	1.15	n.s.	25
	2400	0.80	0.84	42.2	24.3	0.58	2.17	n.s.	33
vD	600	0.88	0.96	67.3	52.0	0.77	2.73	<.05	11
	1200	0.88	1.00	57.0	37.5	0.65	2.78	<.05	6
	2400	0.84	0.86	62.6	58.6	0.94	1.41	n.s.	17
M	600	0.84	0.92	58.0	43.8	0.75	2.28	n.s.	10
	1200	0.88	1.00	81.0	66.7	0.82	3.93	<.005	7
	2400	0.76	0.84	84.8	70.3	0.83	6.49	<.001	21
N	600	0.68	0.92	75.8	69.5	0.92	1.98	n.s.	31
	1200	0.68	0.88	92.7	83.0	0.90	6.96	<.001	11
	2400	0.68	0.76	70.8	70.8	1.00	<1	n.s.	59

[a] To the positive and negative steps of vdV two different sets of parameters were fitted. In the analysis of variance the number of df has been reduced accordingly.

N.B. All reductions due to parameter estimates are significant, in variance with $p \ll .001$.

α and β. An analysis of variance showed that the gain in fit over the original model is considerable, even in cases where the fit to the basic model was good already (e.g. subjects vD and vdV). The analysis was carried out by splitting the total variance – i.e. the variance about the ideal model predictions – into four components: Var (total about basic model) = Var (due to step size Δt) + Var (explained by estimating α and β) + Var (not explained by the model) + Var (the irreducible least squares residual). Of the 35 degrees of freedom in the design 2 went to the step size effect – which was in all cases close to zero – and 22 to the least squares residual. Of the remaining 11, 2 were consumed by the estimation of the parameters in the model, leaving 9 for the unexplained difference between the modified model and the least squares variance.

The proportion or percentage of variance accounted for by a factor A in the analysis of variance has been estimated by calculating

$$\omega^2 = \frac{(\text{Sum of Sq. of } A) - (\text{df of } A)\ (\text{Mean Sq. of Residual})}{(\text{Total Sum of Sq.}) + (\text{Mean Sq. of Residual})} \tag{4.18}$$

(Hays 1963, p. 382).

Table 3 summarizes the results of the analysis. The percentage 'unexplainable' (least squares residual) variance is given in column (10), and is indicative of the consistency of a subject over the various step heights Δt. Column (5) represents the total variance minus this residual. The proportion that is explained as a result of the parameter estimation (assuming that each parameter consumes one df) is shown in column (6). The quotient given in column (7), in combination with the data of column (10) provide an estimate of the fit of the model.

Thus, for instance, the estimates of α and β for N2400, remove essentially all explainable variance, but this can hardly be called impressive since the least squares residual is so large. Conversely the result of vD1200, although it accounts only for 65% of the explainable variance, has to be viewed in the light of the highly consistent performance of this subject. In all instances of Table 3 the parameter estimation leads to a considerable and highly significant improvement ($p \ll 0.001$ in all cases). It can also be inferred from the table that in a number of cases no further significant reduction in unexplained variance can be obtained from additional modifications: a comparison of unexplained and explainable variance gave the F-ratios of column (8), and p-values of column (9) (9/22df; vdV2400: 7/24df).

In some sets of data further improvement appears to be possible though. To do this, we would require more extensive data, but two suggestions offer themselves readily. First we may expect further improvement from a more objective determination of α and β, although the gain would probably be of the order of a few percent only. The main source of residual variance appears to be the fact that the parameter β is a function of t_i rather than a constant, and as such introduces a non-linear aspect in the model. Since $\beta = f(t)$ namely, the system response will not only be affected by the level of the average input interval, but also by the step width Δt. Even with fairly small values of Δt this effect may be quite considerable if the rate of change of β as a function of t is high – as it is between 1200 and 2400 msec in our data. β becomes relatively small with respect to 1 for large t, which implies that for long intervals subjects have more difficulty in re-establishing the synchrony between clicks and taps, even if the original error would be correctly compensated for at the next instant after it occurred.

An analysis of the estimated values of β (Table 3) showed that about 51% of the total variance is due to the effect of interval length. Only 17% is accounted for by individual differences, which is not significant ($F = 3.01$, which for 4 and 8 df exceeds the 5% level).

On the other hand α appears to be a strictly personal parameter: 86% of the total variance in the estimates of α is due to individual differences. Subjects show – in other words – a characteristic overshoot in their response to a step function, which is independent of the interval length, and to a large extent also of the step width.

Our conclusion is that the modification of the model is a major improvement over the 'ideal linear predictor', though it is open to further refinements, first of all by introducing β as a function of t, which would make the model essentially non-linear though.

7. TWO LIMITING CONDITIONS

In this section we will conclude our exploration of the response to modulated input sequences by subjecting the 'time sense' to two limiting types of input. They are limiting in the sense that the subject will have to abandon his behaving in accordance with the model – a kind of behavior which we should perhaps consider as the manifestation of a 'least effort' principle in tapping performance – in order to meet the requirements of the experimental situation. This requirement is, by instruction, the minimization of the difference between input and output intervals.

7.1. Selftracking - Experiment 5

In this experiment we present the subject with his own output taps after a delay. If the delay is by a fixed amount T_0, synchronization will be established when the subject taps exactly at intervals of length $\hat{t} = T_0/k$, where $k \geqq 1$. We will consider only the case $k = 1$. As soon as the subject deviates so much from perfect coincidence between click and tap that he exceeds the threshold beyond which the compensating mechanism starts playing a decisive role, the subject will start to oscillate about the correct interval duration $\hat{t} = T_0$ with increasing amplitude. The same will occur when the subject is performing within his tolerance limits and the error is introduced externally by changing the delay stepwise $T_0 \rightarrow T_0 + \Delta T_0$. This is illustrated by Fig. 22a. We conclude that the model is unstable under the experimental condition and shows – within the limits set by the equipment – an ever increasing amplitude, whatever the choice of system parameters.

Fig. 22b shows the behavior that is required for an optimal adaptation to a stepwise change in delay. It consists of making a step of the correct size ΔT_0 at time $i = 1$, while neglecting the short input interval t_1. The error will be compensated, in other words, by stepping from $\hat{t} = T_0$ to $\hat{t} = T_0 + \Delta T_0$ in one single step and not changing that rate any more, irrespective of the input t_1.

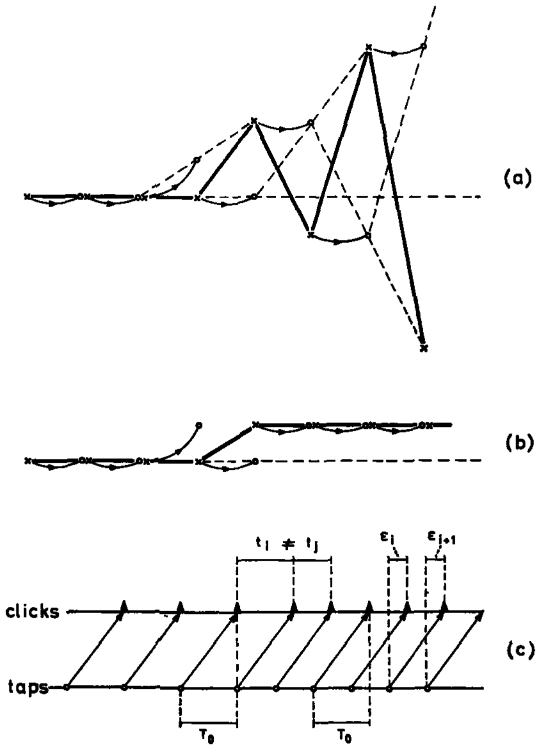


FIG. 22 – The selftracking condition. (a) Response predicted by the basic model. (b) Optimal adaptation to step function. (c) Tapping at an incorrect rate leads to a constant synchronization error, since errors do not accumulate.

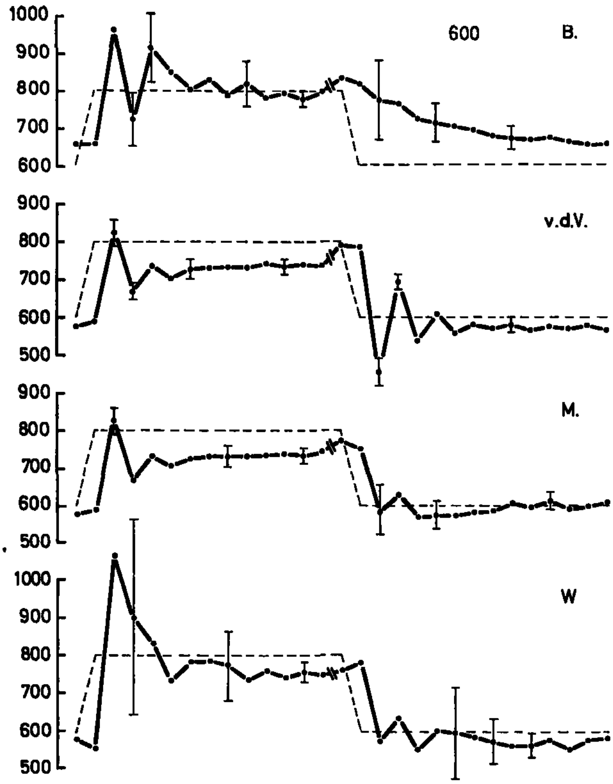


FIG. 23 – Responses to a stepwise change in delay (dashed curves) in selftracking condition. Time in msec.

This procedure may look simple, psychologically, for a trained subject, but it is essentially incompatible with the model developed thus far and requires a system which is psychologically not realistic. For, if the subject followed the optimal strategy shown in Fig. 22b, we would have: $\{\hat{t}_i\} = \{0, 1, 1, 1, \ldots\}$ as a response to $\{t_i\} = \{1, 0, 1, 1, \ldots\}$, and by Eq. (4.4a) we find

$$H(z) = \frac{\hat{T}(z)}{T(z)} = \frac{z}{z^2 - z + 1}. \tag{4.19}$$

By long division of $H(z)$ we arrive at $\{h_i\} = \{1, 1, 0, -1, -1, 0, 1, 1, \ldots\}$ which means that a single disturbance would bring the system into a state of sustained oscillation, a not very likely event to happen in a human subject.

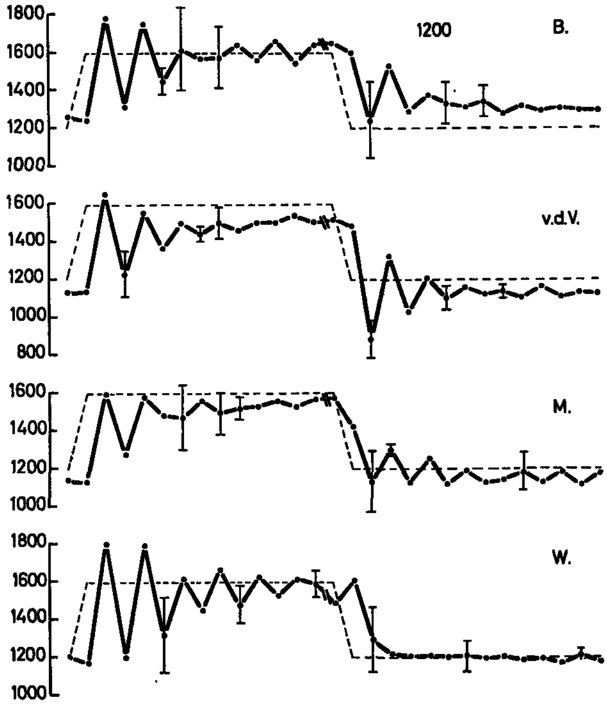


FIG. 23 (*continued*)

Comparison of the open loop function Eq. (4.15) with that derived from Eq. (4.19),

$$G(z) = \frac{z}{(z-1)^2} \tag{4.20}$$

shows that the two can never be equated whatever the choice of a and β. The following experiment was carried out to see how subjects cope with this incompatibility. If they adhere strictly to performance in accordance with the model, their response will 'explode', i.e. the oscillations in interval length will go out of bounds.

Design

Three experienced subjects from the regular pool of subjects, B, vdV and M, and an additional much less trained subject, W, produced 10 positive and 10 negative steps in response to a delayed feedback of their own output intervals. The delay T_0 ($= t_{bas}$) was either 600 or 1200 msec while the stepwise increment was 32% in both conditions. The instants at which a step up or down occurred were determined by the experimenter and were quasi-random.

Results and Discussion

In Fig. 23 the average response functions $\{\hat{t}_i\}$ of each of the four subjects are presented for $-2 \leqq i \leqq 12$. In the diagrams the largest, median and smallest standard deviations are drawn, which show how consistent subjects – at least trained subjects – are in their quite peculiar behavior.

It will come as no surprise that the subjects are able to adapt to a change in delay much better than is predicted by the model. Yet, the results show clearly that it is not an easy task. The size of overshoots is much larger than in previous experiments and they extend over more intervals. The damping of the oscillations in the average responses of Fig. 23 is in fact even flattering since in separate trials subjects generally did not reach a stable state at all (Fig. 24). Some of the apparent damping in the average response is due to sudden 180° phase shifts in the oscillation (see Fig. 24), and some seems to be due to the fact that subjects, every now and then, hit the right interval length and then proceed to tap correctly.

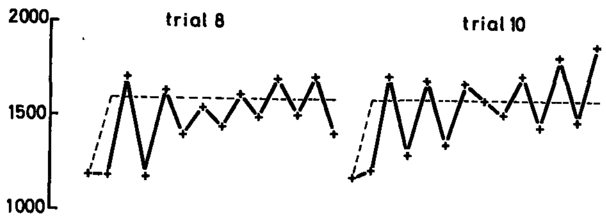


FIG. 24 – Persistence of oscillations in selftracking experiment, after stepwise change in delay (dashed curve). Time in msec. (Subject B; 1200 msec).

Not in all responses do we find sustained oscillations. The adaptation is sometimes very gradual (Fig. 23; B600). This gives us a hint as to what strategy is helping subjects to cope with their synchronization difficulties. This strategy is only applicable in the selftracking condition, since in previous experiments it would have lead to an ever increasing phase error. In the present situation namely, synchronization errors do not add and subjects are apparently able to use this property of the experimental arrangement to reduce their synchronization error gradually instead of trying to compensate for it as quickly as possible. In some cases we observe a combination of protracted oscillation and 'creeping' compensation (Fig. 23; B1200, W1200). An observable consequence of the experimental situation is also that a rest-state may be reached which differs from the actual delay interval: if the phase error is within the tolerance limits set by the subject, no further action will be taken to make the error smaller, since the time difference between click and tap will not grow with each subsequent interval (M600, vdV600). (Thus, this experiment provides a technique to study systematic errors in key tapping behavior.)

We conclude that a considerable revision of the model would be required if it were to deal with the experimental situation in an appropriate way. Obviously however, subjects also experience considerable difficulties when they try to obey the instruction to maintain the synchronization relation (Fig. 24), and this may indicate that they do not easily abandon the habitual pattern of synchronization performance that is described by the model. How difficult the situation is, can also be inferred from the results of subject W, whose average response is drowned in its huge variance.

Tapping appears to be a real skill, even if at first sight it does not seem worthy of that name.

7.2. Random modulation of the input sequence - Experiment 6

A different limitation of the timing system can be studied when it is subjected to a random gaussian input sequence, which in fact makes any predictive action invalid and consequently the use of the dynamic properties of the timing system superfluous. We may hardly expect that human subjects under such circumstances will adhere to a useless strategy, and we are interested to see whether they will alter their error-minimizing strategy; and if they do, whether all adopt the same course of action. There is a number of feasible alternatives, which have been observed under comparable circumstances in other aspects of behavior. Subjects may, first of all, start reacting instead of synchronizing with the input clicks. This will result in an average delay which is small – approximately 150 msec – with respect to the intervals under concern ($\geqq$ 500 msec). This strategy ensures a minimization of the variation in the errors. Secondly subjects may start tapping at a constant rate, with a correct or incorrect average, i.e. extracting the average of the input or not paying any attention to the input sequence at all. Thirdly subjects may try to copy the statistical properties of the input without trying to follow the exact time course of the input, a phenomenon which is well known to occur in guessing (e.g. Garner 1962, p. 220f.). There is in the fourth place the possibility that subjects do not try to compensate any error, but just 'copy' the last input interval t_{i-1}, i.e. they still use their memory for the most recent input interval, but give up the error compensating part of their behavior. And finally they may stubbornly adhere to performance in accordance with the model and content themselves with very large discrepancies between clicks and taps.

It is simple to distinguish between these alternatives. The crosscorrelation function $C(k)$ between input and output and the variance of the output sequence contain all the necessary information. $C(k)$ is equivalent to the autocorrelation function $R(k)$ (Eq. (3.3)) except that it compares two distinct series of data for lag $k \geqq 0$, instead of one series shifted along itself.

Reacting will give a high $C(0)$ since the average interval between a click and the reaction to it will be much smaller than one interval. The expected variance σ^2 will be that of the input sequence, $(\sigma^2{}_t)$, plus the noise $(\sigma^2{}_N)$ contributed by the subject while producing intervals, plus the variance of the reaction time distribution (σ^2_{RT}). The constant rate strategy will have virtually zero crosscorrelation with the input and only σ^2_N as variance; in fact it is identical to the continuation condition of Exp. 1. The 'statistical copy' will show

TABLE 4 – Predicted crosscorrelation coefficients and variance of response function $\{\hat{t}_i\}$ for various response strategies, if the input sequence has a standard normal distribution.

Strategies	Predicted Values			
	$C(0)$	$C(1)$	$C(2)$	$\sigma^2_{\hat{t}}$
Reacting	high +	0	0	$\sigma^2_t + \sigma^2_{RT} + \sigma^2_N$
Constant Rate	0	0	0	σ^2_N
Statistical Copy	0	0	0	$\sigma^2_t + \sigma^2_N$
Reproduction of t_{i-1}	0	high +	0	$\sigma^2_t + \sigma^2_N$
Basic Model	0	high +	high —	$3\sigma^2_t$

no correlation with the input either, but will copy the input variance, added to σ_N^2. Reproduction of t_{i-1} will show a very high crosscorrelation for lag $k = 1$, and have a variance equal to $\sigma^2{}_t + \sigma^2{}_N$. The model-strategy finally, has a high correlation with t_{i-1}, and a high negative correlation with t_{i-2} since $\hat{t}_i \simeq 2t_{i-1} - t_{i-2}$ (Eq. (4.6)). It can be shown that in this case $\sigma^2{}_{\hat{t}} = 3\sigma_t^2$. These points have been summarized in Table 4.

The following experiment was carried out to see which – if any – of these strategies is actually adopted by the subjects, when confronted with a random input sequence.

Design

Three subjects, M, N and vdV, of the regular pool and two naive subjects L and Bo, took part in the experiment. Each produced a series of 200 intervals in response to a random sequence of intervals

TABLE 5 – Crosscorrelation coefficients and standard deviations of response to random normal input sequences.

Subject	t	$C(0)$	$C(1)$	$C(2)$	$s_{\hat{t}}$
M	600	.092	.382	.374	91.7
	1200	.041	.849	.036	168.5
	2400	.192	.692	.116	286.5
N	600	.015	.844	.242	53.7
	1200	.086	.540	.088	131.8
	2400	.079	.672	.052	301.1
vdV	600	—.017	.903	.056	73.9
	1200	—.013	.935	—.145	186.8
	2400	.020	.870	—.010	300.2
L	600	.248	.456	.021	86.7
	1200	.094	.278	.137	231.5
	2400	.032	.247	.140	459.9
Bo	600	.192	.066	.088	111.1
	1200	.100	.724	.047	167.0
	2400	.075	—.039	—.072	265.4

$C(k)$ for $p = 0.01$: $\pm$ 0.181 ($n = 200$)

at each of three values of t_{av} (600, 1200 and 2400 msec). A χ^2 – test for normality gave $\chi^2 = 10.91$, for 10 df ($0.50 < p < 0.75$), and the range of the autocorrelation function $R(k)$ of the sequence, varied between 0.120 and -0.130 for $0 \leqq k \leqq 15$, which is nowhere significantly different from zero (but see note 2 on p. 34). The distribution of the input sequence was truncated at $t_{av} \pm 0.20 t_{av}$, i.e. at $t_{av} \pm 2\sigma_t$. The actual standard deviations (s_t) of the input sequences were 58.6, 117.2 and 234.4 for $t_{av} = 600$, 1200 and 2400 msec respectively.

Results and discussion

The relevant data, the crosscorrelation functions $C(k)$ for $k = 0, 1, 2$ and the actual standard deviations $s_{\hat{t}}$, were calculated for each of the three series of each subject and have been collected in Table 5.

The only tapping strategy which can account for the results, at least those of the trained subjects, is the 'reproduction of t_{i-1}': $C(1)$ is high and positive, $C(2)$ is virtually equal to zero except in one case where it is positive. The basic model in fact predicted $C(0) = -0.13$, $C(1) = 0.93$ and $C(2) = -0.67$ on the basis of the input sequence presented.

The variance of the response sequence is assumed to be a composite of the variance of the input plus the noise of the 'time sense' itself. The two may be treated as additive since both are based on (quasi-)normally distributed events. The input sequence was constructed that way and in Chapter III the internal noise component was shown to be approximately normally distributed. Hence we can make an estimate of $s^2{}_N$, which should be proportional to t^3, since $s_N \propto \delta\hat{t} \propto \hat{t}^{1.5}_{av}$. This estimate is of necessity very rough since the data are quite variable. We have therefore averaged over subjects M, N and vdV. The naive subjects were left out of consideration: their performance clearly follows a different pattern, possibly affected by a learning effect.

TABLE 6 – Observed and predicted values of $\delta\hat{t}$, in msec, under the hypotheses $\sigma_N \propto \hat{t}_{av}$ and $\sigma_N \propto \hat{t}^{1.5}_{av}$ (Weber).

$\hat{t}_{av}$	$s_{\hat{t}}$ (observed)	$\sigma_{\hat{t}}$ (predicted)	$\sigma_{\hat{t}}$ (pred. Weber)
600	73.1	65	74
1200	162.4	138	148
2400	296.1	325	296

It turns out, that the additive relation $s^2{}_{\hat{t}} = s^2{}_t + s^2{}_N$ does not give a particularly good fit, when the 1.5-power relation is applied, not even when we assume on the basis of the results displayed in Figs 7 and 8, that there is some negative correlation between $\hat{t}_i$ and $\hat{t}_{i-1}$. Instead, if it is assumed that a normal Weber relation holds, a much better fit is obtained, as can be seen by comparing the two relevant columns of Table 6.

We can offer no reasonable explanation for this evident deviation from the quite firmly established relation $\delta\hat{t} \propto \hat{t}_{av}^{1.5}$.

With respect to our main objective, we conclude that the way in which subjects try to synchronize with a randomly modulated series turns out to be a fairly faithful following of the input, with a lag of one interval. The naive subjects seem to have followed a much more random 'strategy', which was also confirmed by the calculation of the autocorrelation functions of the response sequences: no systematic sequential dependency was found in any of the series of data: $R(k)$ unsystematically varied between $+ 0.200$ and $- 0.221$ for $0 \leqq k \leqq 15$.

CHAPTER V - QUANTIZATION IN TAPPING

1. INTRODUCTION

In this chapter we shall deal in some detail with two points which were raised earlier and which might be interpreted as evidence for the quantal structure of psychological time. The type of experiments reported in this study is not suited to provide direct evidence for the existence of a basic unit of time; this seems to be at least one point where "the psychologist should yield his seat to the neurophysiologist" (Ehrlich 1958). We are interested in the phenomenon in view of our aim of providing a descriptive framework of timing behavior, which ought to include any quantization of the output, whatever its source.

A quantized signal is characterized by the property that it may assume only a finite number of values. Changes from one level to another occur stepwise and abruptly. By quantization of time intervals we usually mean that intervals can be described as integral multiples of some basic interval τ, which is mostly said to lie in the range between 50 and 200 msec, (Stroud 1955) although shorter 'time quanta' have been reported (see for instance Latour 1961, 1966). The evidence for the quantal structure of time has become quite weighty over the past 15 years (see Hirsh and Sherrick (1961); Lansing (1957); Latour (1966); Lichtenstein (1962); Mundy-Castle and Sugarman (1960); Stroud (1950, 1955); Venables (1960); White (1963); Whitrow (1960) and numerous other authors). The problem is clearly waiting for a thorough, critical evaluation.

In our opinion this wealth of evidence has reduced rather than enhanced the likelihood of finding a unit of psychological time. Instead it has become increasingly clear that perceptual and motor behavior are necessarily quantal in character in order to make their 'cortical control' possible. The analogy with the 'cycle time' of a digital computer readily suggests itself (Latour 1966). In this setting any time unit which is functionally appropriate will, under certain conditions, take the role of a 'time quantum' whether it be 20 or 120 msec long. The complexities with respect to the fundamental constituent periodicities appear at present to lie beyond our comprehension (Latour 1966).

We have found two manifestations of quantization in time intervals produced by key tapping: distributions of intervals produced by synchronization or continuation show multimodalities which at first sight seem to be periodic (Exp. 1; Fig. 10); and the adaptation to small average rates of change in sinusoidal input sequences shows indications of stepwise compensation of synchronization errors (Exps 2 and 3). These two effects will be dealt with in the two sections to follow.

2. THE MULTIMODALITY OF TAPPING INTERVAL DISTRIBUTIONS

Periodicities in the distributions of interval estimates have not been reported in the literature. Multimodality has been found however in the distribution of reaction times (Lansing 1957; Mundy-Castle and Sugarman 1960; Venables 1960; Woodworth 1938). Distributions of search times in detection tasks were also found to be periodic (Augenstine 1955). Generally the periods reported are of the order of 100 msec or bear a simple relation to that duration, which might be related to the alpha-rhythm of the brain. Most authors have been hesitant to formulate such a connection in terms of cause and effect. So much seems clear however, that the observed multimodality is not a simple artefact caused by the tremors of the extremity with which the reactions are executed: the frequency band of the latter is much wider than was reported, for instance, for decision times by Augenstine (1955).

The reasons why no periodicities in the distributions of time intervals have been reported before seem to be simple: apparently nobody looked for them and hardly any author has collected enough data to enable him to undertake a periodicity analysis of some kind.

The following analysis of the distributions of Exp. 1 was carried out to verify whether the observed fluctuations are periodic, and if they are, to see to what extent they are stable over trials and conditions.

Method

The technique of autocovariance spectral analysis on discrete data was used, as described by Blackman and Tukey (1959). This technique consists essentially of two steps. First the autocorrelation function $R(k)$ of the time series to be studied is determined (Eq. 3.3). The next step is to fit cosine functions of increasing frequency ν, to $R(k)$. If

ΔT is the class- or sampling interval of the time series, then $0 \leqq \nu \leqq 1/2\,\Delta T$. The index of the fit of a particular cosine function is the sum of the cross products of $R(k)$ and the function $y = \cos\left(\frac{\pi p}{m}\, k\Delta T\right)$ in which $p/2m\Delta T$ is the frequency ($0 \leqq p \leqq m$, and $m \leqq k$). The expression

$$V(p) = \{R(0) + 2 \sum_{k=1}^{m-1} R(k) \cos \frac{\pi p}{m} k + R(m) \cos \pi p\}\, \Delta T \tag{5.1}$$

for $0 \leqq p \leqq m$, is called the raw spectral density at frequency $\nu = p/2m\Delta T$. For example, the autocovariance spectrum will be flat – within certain statistical limits – if the original time series originates from a random gaussian noise, the 'density' being a function of the variance (bandwith) of the data. If on the other hand, the time series is a pure simple sinewave, $R(k)$ will be a pure cosine function, and consequently $V(p)$ will consist of a single peak at a particular frequency.

Usually the spectrum is smoothed, using a relation like

$$U(p) = 0.54V(p) + 0.23\ \{V(p+1) + V(p-1)\}, (0 < p < m). \tag{5.2}$$

There are no completely satisfactory tests to determine whether a particularly high peak in $U(p)$ indicates a significant periodic trend in the data. Blackman and Tukey (1959) proposed a χ^2-test which is based on the probability that a peak value in the spectrum is due to chance variations, given the overall variability of the spectrum. This test provides at least a reasonable indication of the importance of the peaks in a spectrum.

Data

$U(p)$ was calculated for all 32 series with interval length $\hat{t}_{av} = 1667$ and 3333 msec of Exp. 1. Series with smaller values of $\hat{t}_{av}$ could not be used since the total range of their distributions was much less than the required value of approximately 10 times the expected largest period in the data. Even some of the 1667 msec series did not meet this requirement, but in no case was a sample less than 800 msec wide. The intrinsic difficulty is that collecting more data will not appreciably increase the range of their distribution. We are helped however by having an estimate of $U(p)$ from two independent samples on each condition. It should be realized though that we are stretching the requirements of the method to some extent, and that the results of the analysis are suggesting rather than establishing facts.

The sampling interval ΔT was set at 25 msec. Preliminary checks made it clear that little information could be gained by taking a shorter, 10 msec, sampling unit (which in addition increased computing time roughly by a factor of 10). Since spectral analysis requires stationarity of the data, the distributions were modified in advance by subtracting the expected frequency derived from Eq. (3.8) from the observed frequency in each sampling interval.

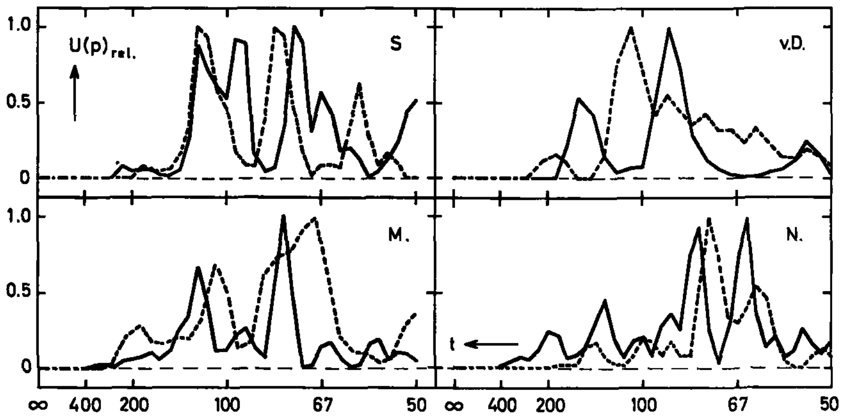


FIG. 25 – Autocovariance spectra of the multimodal interval distributions of Exp. 1 (3333 msec synchronization sequences).

Results and discussion

The smoothed spectra $U(p)$ and the significant peaks in $U(p)$ were determined for each of the 32 series. The χ^2-tests were based on 4 degrees of freedom.[1] The results have been summarized in Figs 25 and 26. Fig. 25 provides examples of the smoothed autocovariance spectra. It incorporates $U(p)$ for all synchronization sequences of $t_i = 3333$ msec for all four subjects. It is clear that there are peaks in the spectra which are significant. Accordingly there are periodic

[1] The number of degrees of freedom, df, has been estimated from $df = 2\,(D_n - D_m)/3D_m$, in which D_n is the number of data points, and D_m is the maximum lag. In our case this amounts to 3 df, to which 1 df has been added as a (conservative) estimate of additional degrees of freedom due to peaks in the spectrum (Blackman and Tukey 1959).

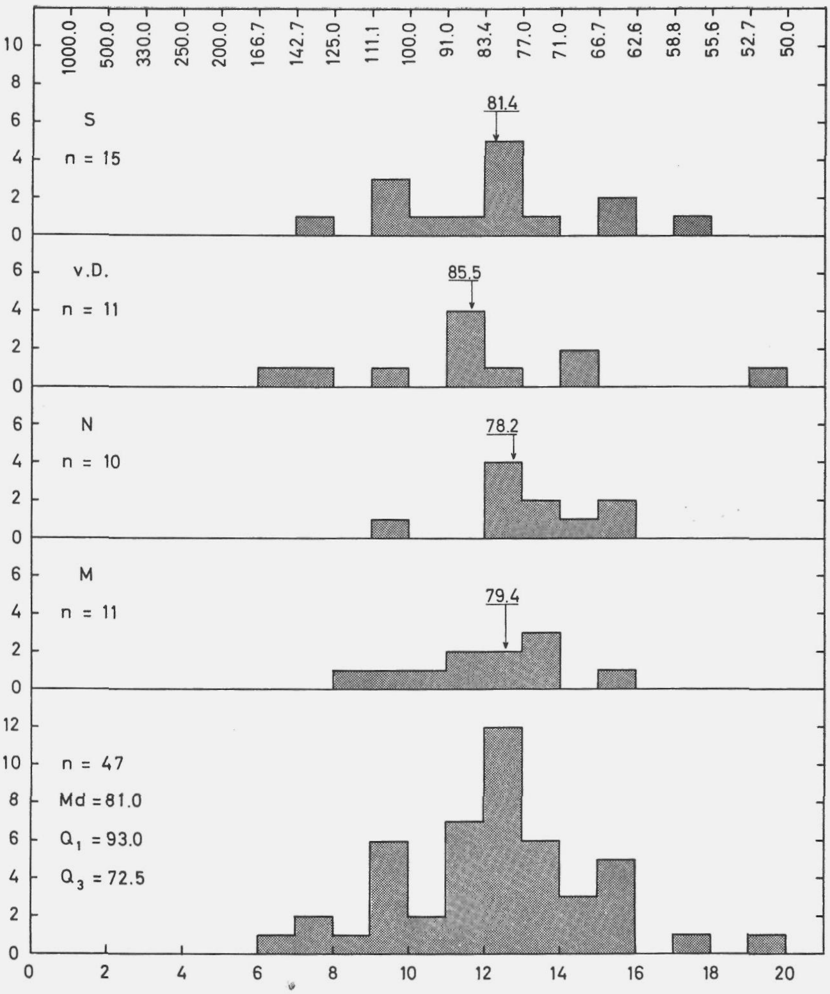


FIG. 26 – Distributions of significant peaks in the autocovariance spectra of the interval distributions of Exp. 1.

fluctuations in the distributions of the longer intervals of Exp. 1. However, there are frequently peaks at more than one point and in some cases there is a fairly high spectral density over a quite broad part of the frequency range. In the third place it looks as if in some cases the spectrum of the second series is shifted slightly with respect to the first (Fig. 25).

Since the spectral densities were estimated from very short samples we can base no firm conclusions on these observations. It is clear however that he who wants to find a singular unit of psychological time will look in vain. Depending on the momentary situation different period lengths may be observed, suggesting that the time quantum is a functional rather than a deterministic entity.

Notwithstanding the variation in the values of the 'time quantum', we can see in Fig. 26 that there is a quite marked central tendency for the significant peaks (5% level or better). They cluster around a median value of 81 msec, with an inter-quartile range of 20 msec. Fig. 26 shows the distribution of these peaks for each subject and for all subjects together. Of the 47 significant peaks 27 fall within $\pm$ 10 msec from the median. Furthermore subject S showed consistently a second peak at approximately 105 msec, thus contributing most to the peak at that value in the combined graph. Neither in this, nor in any other case, was there any indication that the peaks in one and the same spectrum bear a simple relation to one another: peaks do not show at integral multiples of a particular frequency. We did not find, finally, any significant differences in the distribution of the peaks between the continuation and synchronization series (medians 82.5 and 78.3 msec respectively), or between the 1667 and 3333 msec interval lengths (medians 78.0 and 81.7 msec respectively).

It was suggested earlier that the size of the time quantum depends on the prevailing circumstances. If this is so, neither the length of the input intervals, nor the input mode, seem to be determining factors. The following section will give some indications as to what kind of factors is important.

3. STEPWISE ADAPTATION TO A MODULATED INPUT – EXPERIMENT 7

Quantization of time intervals should be observable in the responses to modulated input sequences. To the extent that adaptations to a constant rate seem to be carried out stepwise, we may expect that such steps can also be observed if the length of the input intervals varies slowly enough. Sinusoidal modulation provides low rates of change but tends to have any quantization effect wiped out, since the steps will become desynchronized in absence of clearly marked anchor points in the input sequence. Experiment 7 was designed to provide such anchor points and to enhance quantization effects if present at all.

Design

Two subjects, M and vdV produced two series of 10 accelerated and 10 decelerated sequences of the 'ramp functions',

$$t_i = \begin{cases} t_{bas}, \; i < 0 \\ t_{bas} + k\Delta t, \; i \geqq 0 \end{cases} \tag{5.3}$$

and

$$t_i = \begin{cases} t_{bas} + 200, \; i < 0 \\ t_{bas} + 200 - k\Delta t, \; i \geqq 0 \end{cases} \tag{5.3a}$$

in which $t_{bas} = 600$ or 1200 msec, $\Delta t = 10$ or 20 msec and $k = 20$ or 10 respectively ($k\Delta t$ being maximally 200 msec.). The results of each series of 10 trials were averaged, whence two average responses on each of the 8 conditions were obtained. Steps in the adaptation to the changing rate were determined graphically, a step being identified by two conditions of the first differences between any two successive intervals: $|\Delta\hat{t}_i| > |\Delta\hat{t}_{i-1}| \cap |\Delta\hat{t}_{i+1}|$, and $\Delta\hat{t}_{i-1} \simeq \Delta\hat{t}_{i+1} \simeq 0$. At very few points did this decision criterion fail, although some arbitrariness could not always be avoided (see Fig. 27).

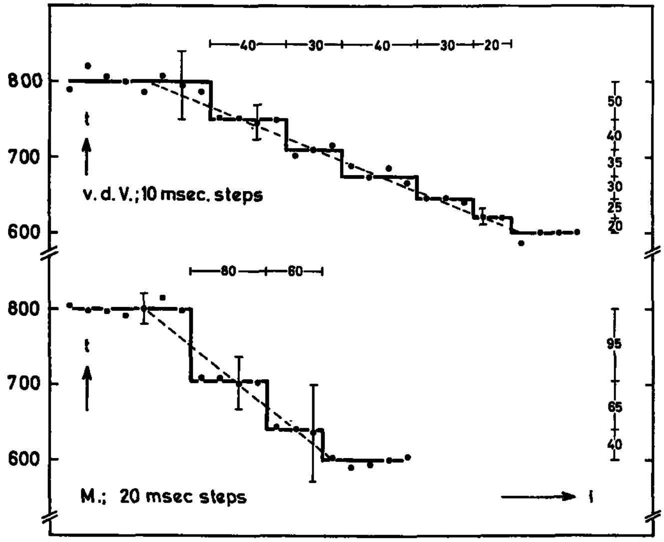


FIG. 27 – Examples of responses to ramp function input with low rates of change. Time in msec. The dashed line represents the input function.

Results and discussion

Quantization or stepwise adaptation was very prominent in virtually all of the records. There were one or two exceptions in the 600 msec condition only. The steps can be characterized by two measures, their heights and widths, which need not be completely reciprocal, though they are closely related. Height and width of each step in the records were estimated and are represented in summary in Table 7. Since there were no significant differences in performance between the two subjects, their results have been combined.

TABLE 7 – Average height (msec) and width (number of intervals) of steps in stepwise adaptation to ramp function input with small Δt. (Means and standard errors).

Δt (msec)	t_{bas} (msec)			
	600		1200	
	Width	Height	Width	Height
10	3.73 ± 0.15	36.7 ± 1.53	4.03 ± 0.38	46.3 ± 2.35
20	3.18 ± 0.24	66.9 ± 4.75	3.19 ± 0.22	67.0 ± 4.72

The outcome is consistent with the findings reported earlier, in one important respect: the step height is approximately the same for the two values of t_{bas}. This indicates that the adaptation is essentially carried out on the basis of the prevailing error rather than on the average length of the intervals. The difference of a factor of two in step height – and accordingly the identical width of the steps – in the 10 and 20 msec conditions is less obviously related to our earlier findings. The only explanation which is consistent with the observations, is that subjects maintain approximately a constant rate of tapping, and update their response after a more or less fixed number of intervals, irrespective of the actual synchronization error ε, as long as that error is not large in comparison with the fluctuations ($\delta\hat{t}$) in the estimates of t. This kind of behavior is not unusual in psychophysics. Subjects seem to postpone a decision as to what action they will take, until they have accumulated sufficient evidence about the nature of a stimulus – in our case the synchronization error.

If on the other hand the difference between click and tap is far above threshold, the uncertainty of the subject will be reduced instantaneously, and a much more continuous adaptation to the input sequence will result, as we saw in most of the preceding experiments. Further experiments may reveal in greater detail the properties of the decision process which underlies the 'intermittent adaptation' to slowly changing input rates.

4. CONCLUSIONS

The question if there is a universal time quantum of virtually fixed size τ, does not appear to be any closer to an affirmative answer than it was before. We have found step effects in a range between 25 and 125 msec, with only one characteristic in common: the step size remained fairly constant within an experimental condition. This supports the view, expressed earlier, that each specific situation may have its own functional 'processing time unit' which may vary widely from situation to situation. Yet, we predict that steps much smaller than 25 msec are unlikely to occur in the type of behavior under investigation, even if the motor system is able to produce finer adaptations. Below 25 msec we are in the range of durations where the order of two successive events cannot be determined any more (Hirsh and Sherrick 1961). Even if the size of the error could be estimated reliably, the subject would not be certain as to whether he should increase or decrease his rate of tapping. Consequently he would wait for additional information during later intervals, before correcting his rate.

Finally, it seems that most of the quantization phenomena in our experiments are a result of the effect of a threshold mechanism of some sort (perceptual or cognitive) on the dynamic 'time sense'. At the same time, it is not entirely clear how the periodicities found in the interval distributions of Exp. 1 tie in with the concept of such a threshold. Whether these periodicities and the 'intermittent correction' derive from the same process remains open for further investigation.

CHAPTER VI
THE INFLUENCE OF NON-TEMPORAL INFORMATION ON TIMING

1. INTRODUCTION

In Chapter I some of the work pertinent to the effects of non-temporal factors on time perception and timing was reviewed. We will conclude the experimental part of this study with three exploratory experiments, dealing with the influence of what we named 'information processing load' on the timing system. This problem is not only theoretically of interest but has considerable practical importance as well. Since transmission of information is gradually replacing transmission of energy in human jobs, there has been a growing concern for the extent to which the information transmitting channels of industrial and military personnel are occupied by the requirements of such tasks as, for example, process controling in an automatic factory.

It is possible to measure how far the processing channel is occupied by a particular task, by means of an extra task which has to be performed concurrently with the main task. Some index of deterioration of performance on the secondary task is then used to classify tasks in order of the load they impose on the worker (see e.g. Bartenwerfer, Kotter and Sickel (1962); Bertelson *et al.* (1966); Knowles (1963); Koster and Taverne (1966); Schouten, Kalsbeek and Leopold (1962).) The present author demonstrated elsewhere (Michon 1964a, 1966a, b) the usefulness of an index of irregularity of tapping at the 'personal rate' as a measure of information processing load.

In the literature we find some disagreement as to whether the performance decrement of the secondary – and frequently the main – task is due to interference between parts of the simultaneously presented information or to intermittent processing of information from the two tasks. Of the two possibilities the latter seems to be the most attractive alternative. Much evidence has been accumulated in support of the 'one channel hypothesis' of human information transmission on which it is based. According to this view – put forward by Hick (1948), Broadbent (1958) and other British psychologists (Davis 1957; Welford 1959, 1960; see also Sanders 1963, 1967a, b), – human operators can extract information from only one source at a time. Multiple sources have to be dealt with by 'switching' more or less frequently from one source to another, i.e. by intermittent processing. The process of switching (see Egeth 1967; Sanders 1963, p. 26f.; 1967b) was originally thought of as peripheral or 'sensory 'switching, but seems gradually being replaced by a more 'functional' switching concept, in which the nature of the information source is entirely determined by the characteristics of the task. We might have, for instance, switching between a meaning-source and a spatial location source. The most up to date review of the various problems of the one channel hypothesis can be found in Welford (1967) and other papers in Sanders (1967a).[1]

The use of key tapping as a secondary task is based on the assumption that temporal information has to be processed like any other kind of information: the duration of intervals has to be stored, retained and retrieved, and it has to be compared with other stored intervals or with running clock time. By stressing the timing aspects of work, the use of tapping as a measure of information processing load brings us close to the research in which response latencies and decision times are described in terms of queuing models (Kaufmann 1963; McGill 1963; McGill and Gibbon 1965; Restle 1961; Restle and Davis 1962). The psychological applications of queuing theory do, however, not include multiple source models thus far.

The aim of the following three, minor, experiments is to gain some preliminary insight into the effect of non-temporal information on the timing system. One point is of particular interest in this context. As we said before, the regularity of timing performance is affected markedly when it is measured under the 'double task' condition, i.e. when key tapping is given as a secondary task. In that case the two tasks are presumably functionally independent, and carried out alternately. In most practical circumstances however, the timing aspects of a task will be integrated with its non-temporal aspects. In musical performance, for example, timing or rhythmical information is coded

[1] It should be stressed incidentally that in the work on human information processing which makes use of computer simulation, the one-channel hypothesis is an implicit postulate. The design of present day computers embodies only one 'accumulator' through which all information is manipulated. The accumulator is unable of "doing two things at once". In this kind of research little explicit attention has been paid thus far to the properties of the human 'accumulator' processes, like attention and short term memory.

together with information about melody, accentuation and intensity. Although it is likely that the latter will exert appreciable influences on the former categories, the major switching problem, which would arise if we tried to play the piano and to recite an entirely disconnected piece of prose simultaneously (Pauli 1937), is absent under the 'integrated task' condition.

2. SEPARATE VS. INTEGRATED PROCESSING OF TEMPORAL AND NON-TEMPORAL INFORMATION – EXPERIMENT 8.

The following experiment was carried out to see if the synchronization response is affected differently when extra information is processed under double task conditions than it is under integrated task conditions.

In this experiment – and also in the following two – the temporal stimuli, sequences of auditory clicks at 45 db above threshold, were presented as before. In addition visual stimuli were presented which were selected randomly from sets of up to eight alternatives. The stimulus arrangement consisted of a horizontal row of eight green signal lights which lit up, one at a time, in a random sequence which had been prepared on punched tape. The punched tape reader was in turn activated by a signal from any one key of the set of response keys in front of the subject. The schematic diagram of the arrangement is shown in Fig. 5 (see p. 25). Upon pressing any of the keys of the set, a new stimulus was presented without delay. Subjects were instructed to watch the stimulus, select the appropriate response key – always with full left to right compatibility – and to press the selected key in synchrony with the clicks presented through the headphone, in one condition (integrated task). In the second condition they did not synchronize by means of the set of response keys, but tapped a Morse key, as in the earlier experiments and responded to the visual stimuli between successive taps. The tapping was performed with the right hand, the reaction keys were pressed with the left hand.

Design

Three of the regular subjects (vD, B and M) took part in this experiment. One, vD, may be considered a very consistent performer, while B did show the largest variances throughout the experiments. M took an intermediate position in most experiments.

Each subject was presented with two series of 10 positive steps with

$t_{bas} = 1200$ msec and stepwidth $\Delta t = 192$ msec (16%). Non-temporal information consisted of randomly selected lights from a set of four (the central four of the row of eight), which is equivalent to an event uncertainty of 2 bits.

Results and discussion

The average responses were determined for each series of 10 steps. The results are shown in Fig. 28, separately for all three subjects.

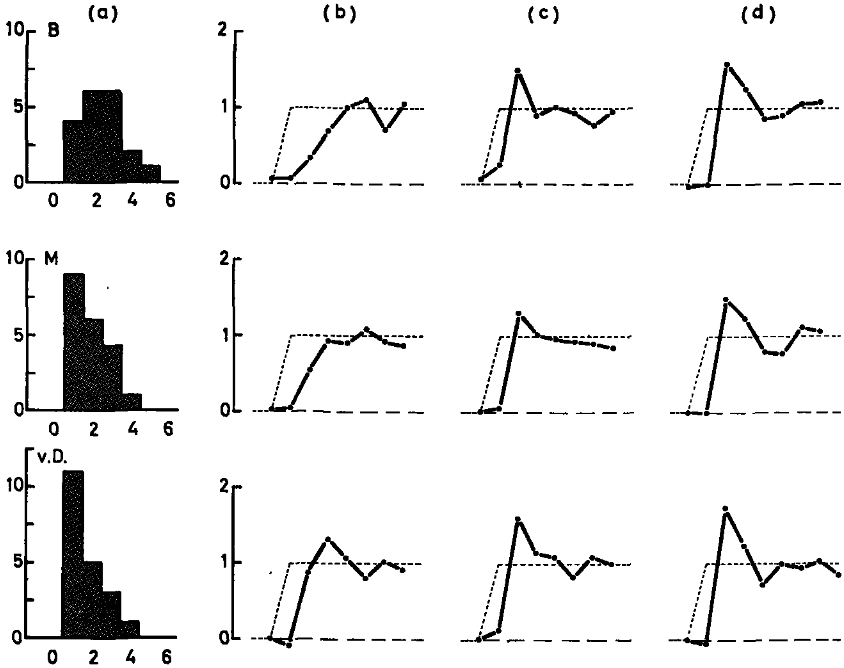


FIG. 28 – Average response to positive step function input under influence of non-temporal information in the double task condition (b), and integrated task condition (d). (a) represents distribution of the instants at which response steps are initiated with respect to the input step. (c) shows the result of rearranging the response trials on the basis of (a).

Three conclusions may be drawn from the results. Although, in the first place, there is a considerable difference between the average responses in the two conditions (Fig. 28 b and d respectively), much of the difference can be explained from the variable delay in onset of the compensatory action. In the double task condition our subjects did not necessarily compensate for the change in rate at instant $i = 1$, (the step being presented at $i = 0$) but the adaptation could occur at any instant $i = 1, \ldots, 5$, as is shown in Fig. 28 a. If we rearrange the separate trials is such a way that the points at which the actual transition in the response is made coincide, we obtain the average response curves shown in Fig. 28 c. The latter curves come much closer to those depicted in Fig. 28 d, which suggests that the system response in itself is not too different under the two experimental conditions but that in the double task condition subjects have to surmount a higher threshold or level of uncertainty before they decide to adapt to a new rate. (see Sec. V. 4).

A second conclusion to be drawn from the results is that in the integrated task condition the responses of the three subjects compare very well with the responses produced in absence of non-temporal information (see Fig. 19). Hence we can conclude that the effect of the non-temporal information is on the variability of the results, rather than the average response; in fact we may attribute the shift in the point of transition to increased variability as well. The variations in the average response were found to be of the order of $\delta\hat{t} \simeq 0.090$ for $\hat{t}_{av} = 1200$ and $\delta\hat{t} \simeq 0.120$ for $\hat{t}_{av} = 1400$, averaged over the three subjects. Comparable results for performance in a comparable situation without non-temporal information can be derived from Fig. 20, where we find $\delta\hat{t} \simeq 0.060$ and $\delta\hat{t} \simeq 0.075$ for $\hat{t}_{av} = 1200$ and 1400 respectively.

Thirdly, we find that subjects differ considerably from one another as to the extent to which they are affected by extra information (Fig. 28a, for instance, shows this), which is a common finding in studies about 'information processing capacity'.

3. INVARIANCE OF THE AVERAGE RESPONSE – EXPERIMENT 9

This experiment is intended as a further check on the response invariance of synchronous tapping in the integrated task condition. If such response invariance exists, irrespective of variations in the amount of non-temporal information, we may assume that the timing system is not directly affected by extra information – in the sense that the system parameters change – but that momentary fluctuations, mainly those which may affect the memory for intervals or the appreciation of synchronization errors, are increased. In other words: if the average response is invariant, the non-temporal information affects those components which manifest themselves as (quasi-)noise.

Design

Each of four subjects, vD, B, M and vdV contributed two series of 10 steps up and down at $t_{bas} = 1200$ msec and $\Delta t = 192$ msec (16%), with 2, 4 and 8 alternative choices (see Exp. 8) as extra information, under the integrated task arrangement. As before, the occurrence of the steps was randomized to preclude anticipation by the subject.

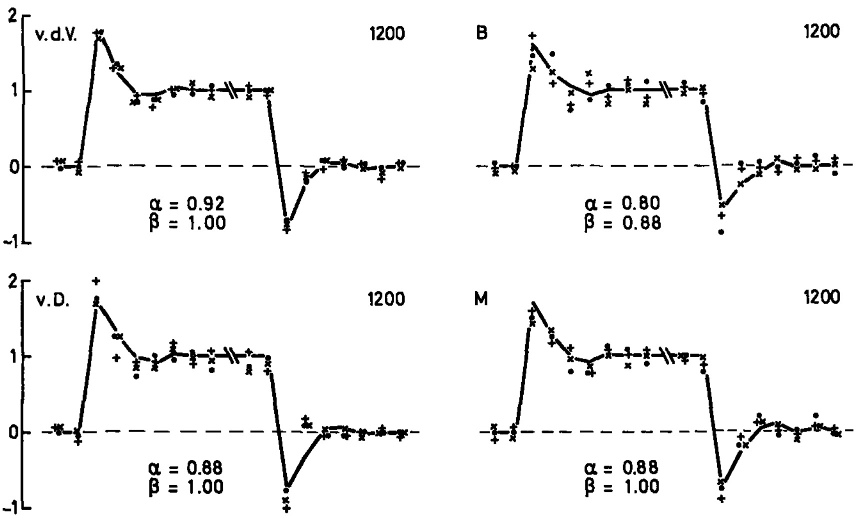


FIG. 29 – Average responses to a step function input under influence of non-temporal information in the integrated task condition. (2 (×), 4 (•) and 8 (+) alternative choice task).

Results and discussion

The response functions are shown in Fig. 29, which makes it evident that there is no effect whatsoever of the amount of extra information on the average response, and consequently on the system parameters. The only exception seems to be subject B, who displays a decrement in overshoot with increasing extra information, and a corresponding increment of the overshoot at a later instant ($i = 2$). Unlike the effect observed in the previous experiment (Fig. 28 a), this shift in response is not due to variations in the instant at which the change in tapping rate is effectuated: in all trials except two, the step in the response occurred at instant $i = 1$.

TABLE 8 – Analysis of the fit of previously estimated parameter values (Exp. 4) to data of Exp. 9 (see Table 3).

Subject	Parameters		Var. Red. (ILP = 100)			Sign. of improvement		Residual least sq. variance
	α	β	Expli-cable	Exp'nd	Exp'nd / Exp'ble	F	p	(%)
vdV	0.92	1.00	79.2	64.8	0.82	6.32	<.001	2
B	0.80	0.88	52.5	35.3	0.67	3.68	<.01	6
vD	0.88	1.00	—54.0	—41.3	0.77	3.78	<.01	3
M	0.76	0.84	61.9	49.5	0.80	3.33	<.01	3

The response curves (solid lines) which were drawn in Fig. 29 are the same as the curves drawn in Fig. 19 for $t_{bas} = 1200$ msec. This enhances, in a way, the response invariance: all curves give a quite good fit for the data of the present experiment. The amounts of variance explained by the parameters estimated in the earlier experiment (Exp. 4) are given in Table 8, and compare excellently with those of Table 3, at least for three of the four subjects. The performance of vD was explained more adequately by chosing $\alpha = \beta = 1$, i.e. by the basic model. It seems likely that a substantial improvement of the fit might be achieved – like we suggested in the discussion of Exp. 4 – only by modifications in the model rather than by a better estimate of the two parameters.

Further comparison of Figs. 19 and 29, and of Tables 3 and 8, shows that the effect of the step width (Exp. 4) is more detrimental to the invariance of the response function than is the amount of non-temporal information – at least within the modest range of the conditions studied.

4. THE EFFECT ON THE RESPONSE TO ISOCHRONIC INPUT SEQUENCES – EXPERIMENT 10

In this experiment we have tried to determine what the effect is of non-temporal information on the noise components of the timing response. Thus, we return to the input conditions of Exp. 1 (Chapter

III), where the responses to stationary input sequences were analyzed which, as we argued, offer insight into the spontaneous activity of the 'time sense'.

Some of the parts of the analysis carried out in Chapter III are used in the analysis of the data of the present experiment, in which extra information was presented by means of the 2, 4 and 8 alternative choice task.

Design

Four subjects, vD, B, M and vdV took part in this experiment. Each produced a series of 200 intervals under each of 9 conditions. The input intervals were either 600, 1200 or 2400 msec in length, and either 2, 4 or 8 alternative visual stimuli were presented. The series were given in a random order, two per session.

Results and discussion

The results were analyzed as in Chapter III, with the exception of the trend elimination, which would have had no appreciable effect on the remaining parts of the analysis since all series were obtained under the synchronization condition.

Short term variations The autocorrelation function $R(k)$ of each series, based on 195 intervals of the series this time, because in some series the number fell just short of 200, was determined up to lag $k = 10$. Only values of $R(1)$ turned out to be significant – with one exception in $R(2)$ – and these are summarized in Table 9.[1]

TABLE 9 – Average $R(1)$ of the nine conditions of Exp. 10 (Average of four subjects).

$t_{bas.}$	2	4	8	Mean
600	—0.177	—0.117	—0.111	—0.135
1200	—0.292	—0.299	—0.302	—0.296
2400	—0.329	—0.353	—0.339	—0.340
Mean	—0.266	—0.256	—0.251	—0.258 = grand mean.

[1] See note 2 on page 34.

An analysis of variance on the complete set of values $R(1)$ confirmed the conclusion to be drawn from Table 9 that no significant differences between the 2, 4 and 8 alternative conditions exist. There are significant differences, however, between the various t_{bas}, a tendency which was not obviously present in the data of Exp. 1, and which was consequently not explicitly analyzed in Chapter III.

The grand mean of the $R(1)$ of all 36 series is $R_{av}(1) = -0.26$, with a standard deviation of 0.131. This is not significantly different from the mean of the $R(1)$ of the autocorrelation functions in Exp. 1 (Fig. 7) which was -0.20 (with standard deviation 0.073). A Student t-test gave $t = 1.80$ for 23 degrees of freedom.

The conclusion from these results is that a produced interval is neither more, nor less, dependent on preceding intervals as a result of extra information than we observed in Exp. 1. This may be taken as additional support for the conclusion drawn in the discussion of Exp. 9, that the system parameters are not affected by non-temporal information.

Extreme deviations. The analysis of extreme deviations, carried out on all 36 series, leads us to another piece of evidence for this contention. The results are summarized in Fig. 30, which is directly comparable to the contents of Fig. 8. The response curves for the local behavior around deviations which exceed two standard deviations with respect to the local mean, are self-evident: again we do not find any significant difference between the 2, 4 and 8 alternative conditions, a result also confirmed by an analysis of variance.

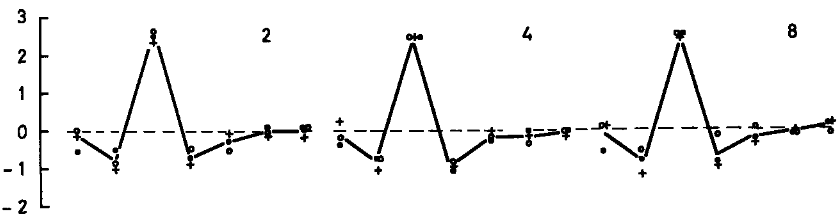


FIG. 30 – Compensation of extreme deviations under influence of 2, 4 and 8 alternative choice task in the integrated task condition. (600 (o), 1200 (•) and 2400 (+) msec intervals).

The distribution of response intervals under various information loads. Under this heading the remaining part of the analysis in analogy with that of Exp. 1 will be subsumed. A summary of those results which are of interest to the problem tackled in the present chapter is given in Fig. 31 and Table 10.

With respect to the shape of the distributions we find again that there is a reasonable closeness to normality. Although no complete set of χ^2-tests was carried out on all 36 series, it appears from the χ^2-estimates that were made, that about 30 distributions will not deviate significantly from a normal distribution, when the number of class intervals is approximately 20.

The interval distributions show a much less pronounced tendency to periodicities superimposed on the main shape, and accordingly the spectra were much less peaked. Again, the amount of data on which the spectra were based was too small to give more than a rough impression, but the result of the extra information seems to be twofold: the peaks are much broader and their maxima vary over a wider range (the interquartile range being of the order of 45 msec, as compared to 20 msec for the results obtained in Sec. V.2.). We will not go into any detail with respect to these data, but they are, to say the least, not in contradiction with our earlier supposition that much of the quantization effects in timing may result from an interaction between the intrinsic noise of the tapping response and the evidence a subject needs for a proper functioning of his compensating mechanisms.

The relation between the standard deviation and the average length of the response intervals is illustrated in Fig. 31, which shows that the effect of non-temporal information on the variability of the results is quite noticeable, with two restrictions though. Only at 600 and 1200 msec do we find an effect (this is not an artefact of the logarithmic grid of Fig. 31).

Not all four subjects show an equally large effect. As we might expect, subject B showed a considerable deterioration, whereas vD and especially vdV generated a much smaller increase in their variability. This was confirmed by an analysis of variance on log-transformed data, showing that the overall effect of the number of alternatives is significant ($F = 12.62$, $2/12$ df, $p < 0.001$) but also that the size of the effect is significantly different for different subjects ($F = 3.23$, $6/12$ df, $p < 0.05$).

In order to see if the general trend of decreasing (relative) effect of extra information at longer intervals, on the variability can be explained by assuming that the processing of temporal and non-temporal information is serial, the variance of the response intervals was compared

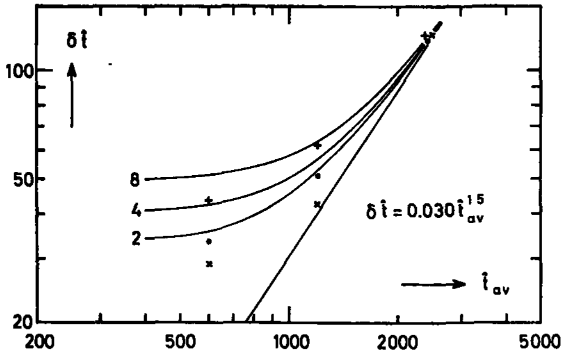


FIG. 31 – Variability of the response to isochronic input sequences as a function of the average output interval length, for different amounts of non-temporal information (2 (×), 4 (•) and 8 (+) choice task. If variances would be additive, the data points would lie on the curves 2, 4, and 8 respectively.

with that of the interval distributions produced without extra information and the variance of the reaction time distributions of the 2, 4, and 8 alternative choice task. The assumption – undoubtedly an oversimplification – was that the variance of the choice reaction times proper and the variance of the response intervals proper, will simply add to the variance of the integrated task results, if the processing of the two kinds of information is completely independent, i.e. serial. A presupposition, in that case, is that much of the preparatory action to the actual processing – i.e. the conduction to an from the central parts of the nervous system – occurs simultaneously. Otherwise it would be impossible that the time to deal with both tasks is much less than the sum of the average response times for the separate tasks. In other words it is supposed that most of the variance is contributed by processes which have very short average latencies but high variability.

A test of the extent to which the variances of the response intervals and the reaction times of the choice tasks add has been summarized in Fig. 31, which in part is based on the data presented in Table 10. Table 10 derives from the reaction times of the four subjects who took part in Exp. 10, in response to random sequences of stimuli. 50 reactions were obtained in the 2, 4 and 8 alternative conditions, under each of two instructions. Subjects produced these reactions in a self paced situation, either under the instruction of working as fast as possible without making errors (Quality), or with an instruction to work as fast as possible, not paying attention to errors (Speed). The

TABLE 10 – Means and standard deviations of reaction times of 2, 4 and 8 choice reaction tasks. (Average of four subjects).

Altern.	Instruction	% Errors	Mean RT (msec)	s_{RT}
2	Quality	3.5	463	32
	Speed	17.5	418	35
4	Quality	1.0	582	36
	Speed	18.0	481	45
8	Quality	2.0	702	48
	Speed	18.5	582	50

results of the four subjects were combined and are shown in Table 10, which reveals that the variance is not much affected by the two instructions, whence they are combined in the following calculation.

The straight line with slope 1.5 shown in Fig. 31 represents the expected relation between $\delta\hat{t}$ and $\hat{t}_{av}$ in case there were no effect of the extra information. The curves identified by numerals 2, 4 and 8 show the relation that would hold if the variance of the response intervals and the reaction times would be simply additive. The actual results fall in between these two limits. A rough estimate of the correlation which is indicated by the data points in Fig. 31 was obtained from the relation for the sum of the variances of two normal stochastic variables:

$$\sigma_{12}^2 = \sigma_1^2 + \sigma_2^2 + 2r\,\sigma_1\sigma_2. \qquad (6.1).$$

We find that the correlation between the two variables is of the order of $r = -0.25$, which suggests that there is at least a moderate interaction between the processing of temporal information and non-temporal information. The precise nature of this interaction remains to be uncovered by further experiments.

5. CONCLUSIONS

This exploratory survey of the relation between non-temporal information and synchronization or timing has opened up many questions about the quantitative relations between temporal and non-temporal information, of which the previous sections offered only a provisional outline.

We found that timing performance is different when the relevant aspects of a task can be integrated with the processing of temporal information, than when that second task is executed as a secondary task. In the former case the extra load is easily disruptive of the timing response, while in the latter case such an influence is virtually absent. With respect to the practical problem of measuring information processing load this confirms that the use of extra load in the form of a secondary task is something fundamentally different from adding a dimension within a task. The latter is in fact the approach of, among others, Conrad (1955) and Sanders (1963), as was pointed out by the present author (Michon 1966b).

Looking at the response to the isochronic input sequences, again little effect of non-temporal information was found on the dynamic aspects of the timing system. Those parts of the analysis which were intended to bring to light any sequential or compensatory aspects of the response, as expressed in the systems parameters, were negative. The only effect of the extra information appears to be on the 'noise' generated by the subject. Incidentally it should be stressed that this finding does not necessarily allow extrapolation to very high levels of extra load.

A simple essay to account for the effect of extra information on the variability in the isochronic response intervals makes it likely that the temporal and non-temporal sources of information do interact to some extent. A correlation, $r \simeq -0.25$, obtained from the data indicates that processing is in part serial, in part integrated.

CHAPTER VII - RECAPITULATION AND CONCLUSION

1. INTRODUCTION

In this final chapter we shall provide a summary of the various aspects of the timing system as it emerged in the preceding pages, by stating it in the form of an information processing model. By doing so we reach back to the preliminaries of Chapter I, where we stressed the feasibility of applying the information processing approach to the present problem area. The basic, non-sequential, constituents of the 'time sense' were put together in de diagrams of Figs. 1, 2 and 3, but we postponed the incorporation of a dynamic error compensating component in these simple diagrams for lack of relevant data. Building on the arguments of Chapter I we will complete our model now.

In its final form it is put to a test by implementing it as a simple program for a digital computer. Computer simulation has added a powerful new dimension to psychological methodology because it provides a means of testing the logical consistency of a model or theory and of checking if it functions in accordance with the intention of the theorist (Feigenbaum and Feldman 1963; Newell and Simon 1963; Reitman 1965). We should consider the simulation of the 'time sense' solely as a formulation of the model in terms of a set of instructions to the computer and not as an attempt to simulate the actual processes going on in the living organism. Writing a program only means: specifying our model in unambiguous terms, hence leaving open the possibility of evolution out of its current state as well as the possibility of falsification. The strength of computer simulated models is that they are particularly vulnerable with respect to the latter point.

2. FIVE FEATURES

This section is a summary of five main features of the experimental results.

(*a*) *Memory for previous input intervals.* It was found that subjects act on the basis of knowledge about the sequence of input intervals.

This applies – *mutatis mutandis* – to external as well as internal standards. In the latter case we may conceive of the standard as a 'running average' of a small number of intervals previously produced by the subject, though it was not possible to determine just what number.

(*b*) *Memory for previous synchronization errors.* Phenomenologically there is a second aspect involved in synchronization. Subjects actively match their taps with the clicks they hear and try to minimize the time difference between click and tap – which, in fact, is exactly what they were instructed to do. The experimental results have added substantial evidence for this compensatory aspect in timing behavior.

From the interaction between these two factors, essentially the retention of intervals and the concurrent retention of synchronization errors, results the behavior which is described by the dynamic model developed in Chapter IV.

It is immaterial to the mathematical model how the contributions of each of the two components of the 'time sense' are weighed in the equations which describe the behavior of the system. Expression Eq. (4.17) for instance gave the values of $\hat{t}_i$ for any $i \geqq 0$, as a function of preceding intervals, $t_{i-1}, t_{i-2}, \ldots, t_{i-5}$, but $\hat{t}_i$ can equally well be expressed in terms of a weighed error term, as in Eq. (7.1):

$$\begin{aligned}\hat{t}_i \simeq t_{i-1} + \{&(1-2a)\,\Delta t_{i-1} + (3a + 2b - 4a^2 - 2ab)\,\Delta t_{i-2} + \\ &+ (-a - b + 8a^2 + 9ab + 2b^2)\,\Delta t_{i-3} + (-5a^2 - 8ab - \\ &- 3b^2)\,\Delta t_{i-4} + (a^2 + 2ab + b^2)\,\Delta t_{i-5}\}. \end{aligned} \tag{7.1}$$

Hence it seems to be a matter of some arbitrariness when we decide to attribute to the interval-memory *sub* (a), only the power to retain the last input interval. This is consistent with some of the subjects' behavior however. In Exp. 6, and to some extent also in Exp. 5, we found that the intervals produced by experienced subjects were a fairly faithful copy of the immediately preceding input interval in those circumstances where error compensation was not an appropriate strategy anymore, to obtain a maximum of synchronization. Moreover, when we deal with isochronic series of intervals there is no distinction between keeping one interval in memory and retaining any number of input intervals, since all are identical. Finally, in those conditions where the 'ideal linear predictor' (Sec. IV.3) provides a more or less adequate description of behavior, it is only the last input interval t_{i-1} and the last synchronization error ε_{i-1} which determine the response of the system.

It should be stressed once more though, that finally the choice of weights is a matter of psychological interpretation of a psychologically indifferent, formal model.

(*c*) *Random fluctuations vs. average response.* The first two features of the 'time sense' refer to the average response of a subject, based on a number of independent trials with the same input function. Fluctuations in the response during a particular trial were neglected in the dynamic model and were not expressed in the model parameters. We found the short term fluctuations to be very nearly normally distributed with a standard deviation which is proportional to the 1.5 power of the average interval length $\hat{t}_{av}$. This relation can be inferred also from a number of older studies (e.g. Stott 1933; Woodrow 1932; see also Michon 1964b, Fig. 1).

It was hypothesized – in a very preliminary way – in Sec. III.3 that this 'noise' may be due to a degradation of the 'internal representation' of an interval stored in memory. This memory decay would be proportional to the time elapsed since the moment of storage and by amounts reflecting a constant relative sensitivity (Weber's law).

In terms of information processing the random factor affecting the memory for temporal information represents a complex of factors about which we are ignorant. The results of Chapter VI suggest that the variability in synchronization may be caused by intermittent processing of temporal and non-temporal sources of information. This might also apply when no specified extra information is presented to a subject. We find that attention will wander during an experimental session, even with the most reliable of our subjects, and there is no *a priori* reason to make a distinction between externally and internally generated information with respect to intermittent processing.

Hierarchically the noise factor seems to be very much subordinate to the essential activity of the timing system. In particular, subjects were frequently disturbed about their obvious inability to cope with the quite considerable deviations they generated spontaneously while they were trying to track an isochronic input sequence.

(*d*) *Thresholds and decision criteria.* A fourth group of factors, found active in the timing behavior of our subjects, consists of two psychologically distinct but functionally equivalent types of entity.

There are lower limits on performance, usually set by the physiological limitations of the subject, and other limits whose transgression may drastically alter observable behavior but which are not thresholds in the usual sense of the word. Frequently limits of the second kind will even be quasi-cognitive. An example of the first category is the threshold for perception of order, which plays a role in the stepwise adaptation to very small changes in the rate of input (Exp. 7). Continued error sampling in the case of small errors in synchronization and the decision to abandon error compensation altogether when the input modulation becomes essentially unpredictable, belong to the second category.

Such decision rules are crucial elements in information processing models; they determine the 'transfer of control' between parts of the model on the basis of the results of operations carried out by those parts. Their number is in principle unlimited since they are established or at least influenced by all kinds of environmental, motivational and instructional factors. Some will be inherent to the human organism and show up in some form in all subjects, others may be strictly personal. Their number is ultimately restricted only by the level of analysis set by the investigator.

(*e*) *The influence of non-temporal information.* We have found support for our contention that the actual performance of the timing system (as determined by the basic properties of the model and the parameter values) is not easily affected by non-temporal information. It seems to be primarily the quality of the retention of intervals which is affected.

The precise relations between the – intermittent ? – processing of temporal and other information remain to be established. Since we did not arrive at quantitative formulations about these relationships, we will refrain from incorporating them in the present formulation of our model.

3. AN INFORMATION PROCESSING MODEL OF THE 'TIME SENSE'

The final formulation of the model describing the timing behavior of subjects in a key tapping situation embodies the first four constituent factors listed in the previous section. The present description adheres closely to the simple processing models depicted in Figs 1, 2 and 3 of Chapter I, in addition to being a description of a computer program, written in the Digital Equipment Corporation version of FORTRAN II, and run on a DEC PDP–7 computer with an 8000 word core memory.

As before, it is possible to make a distinction between the functional structure of the model and the actual flow of information between the components.

3.1. The functional structure

The functional layout of the model is given in Fig. 32. The part at the right represents the 'time sense' of the subject, the part at left stands for the essential elements of the experimental situation, the stimulus presentation and recording equipment, and a 'physical clock'. The subject monitors the clicks presented to him and the taps which he generates himself on the basis of his 'internal representation' of the interval to be produced (his prediction). This internal representation is more complex than the interval memory of Figs 1 and 2, since it incorporates the compensation of errors. In fact it is composed of the stored duration of the previous input interval and the weighed error score as given in Eq. (7.1).

The experimental environment consists of a clock-routine (CLOCK in Fig. 32) which serves as a physical time reference throughout an experimental run. At the start of a run it is set equal to zero. Parameters defining the subject and the experimental conditions are specified together with the input sequence to be presented to the subject. Also at this point, the 'subject' is given a warning signal which implies that all internal variables – otherwise inaccessible to the experimenter – are set. Finally the first click and first tap are given in synchrony and the clock is started, after which the following chain of actions results.

After the clock has been started, it is current reading is checked against the input function and if the two match a click is produced (CLICK-routine). The occurrence of a click can be detected by the 'subject', who counts time base pulses between two clicks, and stores the count of this interval immediately upon completion (T-STORE). (Before a run is started one arbitrary interval $\neq 0$ is preset in this store). At the same time the subject samples information about the time difference between tap and click. (The first tap is given at the same time as the first click and consequently the result is a zero error reading.) Sign and magnitude of an error are determined as long as they exceed a certain lower limit (E-COUNTER) and a weighed error term is then stored in memory (E-STORE). The two stored values are then transferred to a third storage, which is a deteriorating 'internal representation' of the interval as it will be produced by the subject (INTREP). The deterioration is proportional to the 1.5 power of the interval last presented. If the time elapsed since the previous tap is equal to the 'internal representation', a tap is produced (TAP). The tap is made available to the E-COUNTER, which closes the feedback loop. At the same time the program proceeds to the recording routine (RECORD). This routine is part of the experimental environment again. It can be operated in two ways by setting a program parameter; it will either produce a linear record of input and output sequences during a run of the program, which is equivalent to the output normally obtained in timing experiments, or it will print a full 'tracing' of the eleven most important variables in the model such as the values of T-STORE, E-COUNTER and INTREP.

When the state of the system has been recorded, the clock is advanced one unit step and the complete cycle repeated until a halt instruction is provided externally.

It should be stressed, incidentally, that not all variables are recalculated in each cycle of the program; the model is activated only upon the occurrence of a click or a tap, except for the time counting activities which are continuously updated.

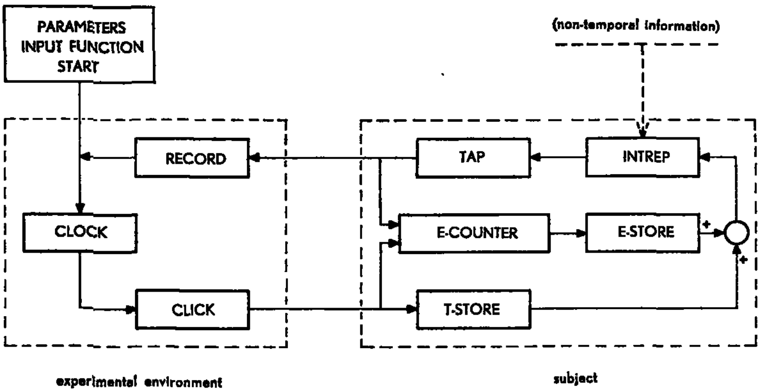


FIG. 32 – Functional diagram of the final version of the 'time sense' model.

3.2. Decision structure

The diagram, shown in Fig. 33 is comparable to the right halves of Figs 1, 2 and to Fig. 3. It shows the essential details about the 'transfer of control' in the model. The course of action taken during the first few intervals of a run, when the subject tries to establish synchrony between his taps and the input sequence, has been left out for reasons of simplicity.

There are essentially two possible events to be detected: a tap and a click. If neither of the two occurs during a particular sampling instant, the counters for t_i and – depending on the state of the 'error flag' (see below) – the current synchronization error, are updated and a decision

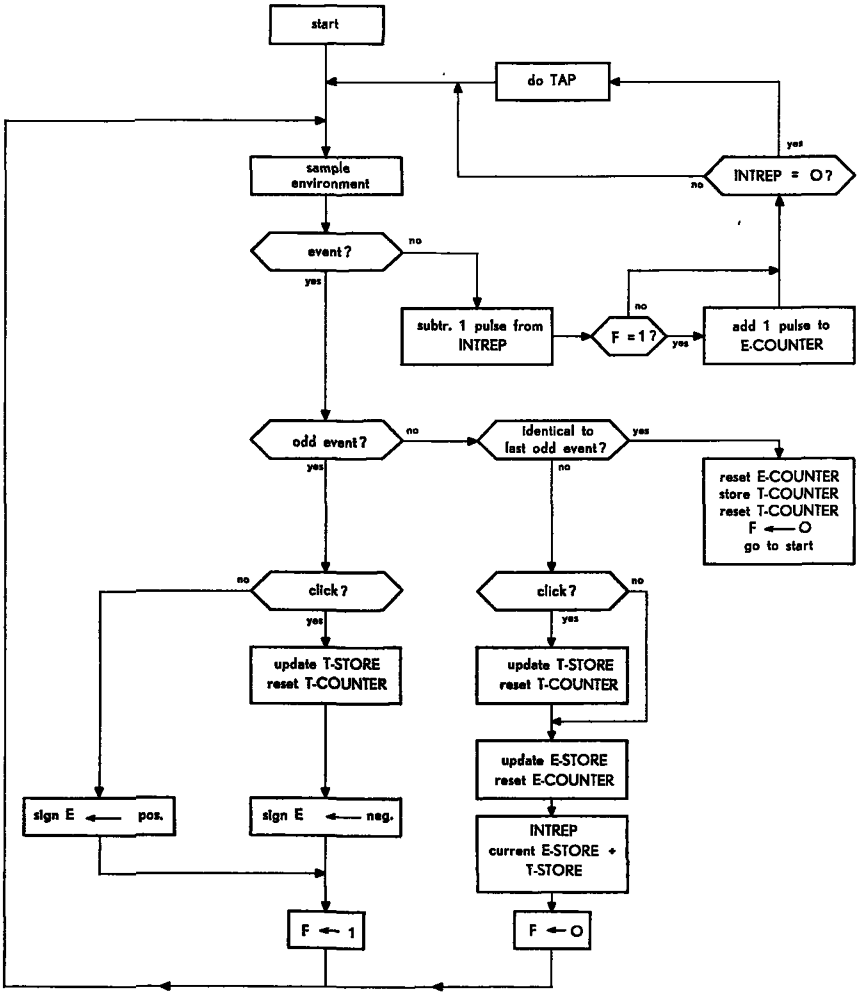


FIG. 33 – Flow diagram, showing the decision structure of the 'time sense' model.

is taken whether or not a TAP is to be given at this instant. If no tap is given, the next sample of information is taken. When an event occurs, it is determined whether the event is odd or even in the series of all events by means of a binary 'error flag' which changes its value on each event (tap or click) in an experimental run. Synchronization errors are measured only between an odd and the next even event, unless both are clicks or taps. The distinction between even and odd events is seemingly not given phenomenologically, but subjects are in fact pairing events, each pair being composed of a click and a tap irrespective of their order. The distinction between odd and even which is made by the program is simply a formalization of this implicit pairing. If for some reason this relation is disturbed, as may happen when the rate of change of an input sequence becomes very large, a new start will be made after resetting of all memory stores. Such fresh starts could be observed in real subjects, when they occasionally lost track of the input and omitted a tap or two.

The lower part of Fig. 33 is largely self-explaining. It determines when the storage of the previous input interval will be accomplished (after each click), when the internal representation based on input interval and synchronization error is updated (after each even event), when the error-counter is started (after the odd events), etc.

For the sake of clarity we have left out all secondary details which may be built into the model to account for threshold and decision effects. To three points – already mentioned in the previous section – we will refer briefly.

First, the threshold for errors of synchronization, depending on the perception of the order of events, would cut off most of the lower half of Fig. 32 thus shunting all compensatory action. The subject will continue tapping on the basis of the internal representation already available – in fact an internal standard – until the accumulated error becomes large enough to induce once more a corrective action.

In the second place, a comparable course of action will be taken if performance in accordance with the model does increase the average synchronization error instead of reducing it (Exp. 6). Shunting occurs at a different place in the model this time, since performance is not based on a non-changing internal representation, but on an internal representation which is a copy of the latest input information.

The effect of intermittent adaptation found in Exp. 7 may be thought of as being due to an information sampling strategy, in which the subject postpones a decision about compensatory action until he is sufficiently informed about direction and magnitude of the synchronization error, which has to be extracted from the 'noise' in the experimental situation.

Since the model is a summary rather than a first statement of our conceptions, we will not elaborate on the agreement between data and model. As a matter of fact the theoretical curves in Figs 15, 17 and 19, among others, were generated with the aid of an early version of the model.

Two minors points may suffice here to illustrate some of the implications of the model. The first example refers back to Fig. 18 (p. 56) where it was found that the actual response to sinusoidal inputs tend to lag behind the predicted response of the basic model. This was attributed, rather loosely, to smearing of the error compensation over several instants. The formal demonstration of this effect is given in Fig. 34, which shows the influence of the parameters α and β on the response to a simple sinewave input with a period $D = 12$.

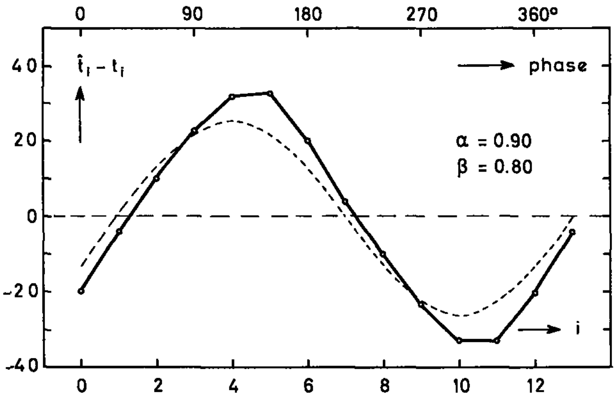


FIG. 34 – 'Phase lag' with respect to the basic model average response (dashed curve), due to parameters α and β. Simulated data.

In Fig. 35 a second example is given. It shows the response of the computer-implemented model to a slowly decelerating input sequence (dashed line). The graph at right shows the performance that results from the assumption that the error counter is completely reset each time the synchronization error is too small to be perceived; at left Fig. 35 displays the behavior which results when a very small error is allowed to contribute to the stored error term, although it is not compensated for in the next interval but only when the accumulated error becomes large. It can be seen that the two storage modes are not essentially different, at least in the range in which the system parameters were found to be in Exp. 4.

A concomitant result which stands out clearly in the simulated data, is that for suitable parameter values (especially $\alpha = 0.8$, total reset) the size of the steps in the adaptive pattern gradually becomes smaller. This result was also found frequently in Exp. 7, but was originally thought of as coincidental. Fig. 35 however, brings out quite clearly that it is an intrinsic property of the model.

The current version of the program is very elementary like we said before. Yet it is open to all sorts of additions and offers complete data on the effect of any alteration. Conversely such alterations may provide valuable suggestions for further experiments which may contribute to the solution of the problems of timing in skilled behavior.

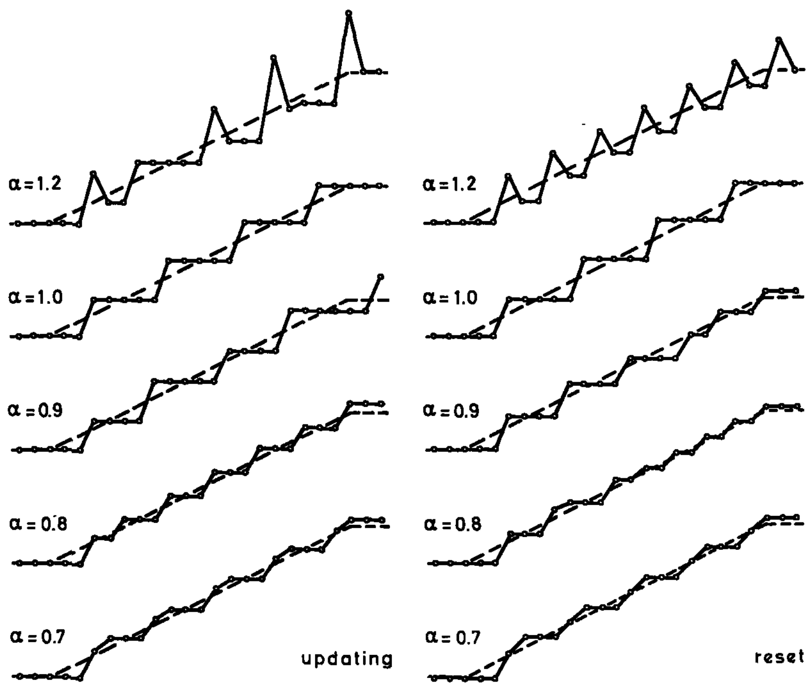


FIG. 35 – Examples of responses to a ramp function input produced by the computer version of the 'time sense' model. $\beta = 1.0$ in all cases.

Titchener (1905, quoted by Creelman (1962)) looked upon the psychology of temporal discrimination as a 'microcosm, perfect to the last detail". His enthusiasm is not shared by many psychologists today. Yet time and rhythm were major topics in experimental psychology until approximately 1930, when they gradually slipped out of the focus of interest. The consequence was that even a contemporary reviewer was able to write: "time perception is a venerable, tired topic in psychology that interests very few active investigators any more, perhaps because no one bothered to explore the mechanisms of time perception and how it might enter into meaningful interaction with other mechanisms" (Adams 1964, p. 197). A further important criticism has been that, whatever remained of the glorious microcosm, has developed off "the main stream of empirical research on sensory capacities" (Creelman 1962, p. 582). As a result most modern handbooks of experimental psychology contain no chapters on time perception. An exception is Woodrow's article (1951) in Stevens' handbook.

The turn of the tide came around 1958. An important factor was Fraisse's monograph (1957, 1964), which provided the essential review of a hundred years of experimental time psychology. At the same time other aspects of time in psychology and other life sciences attracted the interest of many investigators (Whitrow 1960; Bünning 1963; Fraser 1966).

Within the field of time perception proper, the crucial innovations have been – in our opinion – Frankenhaeuser's (1959) study on the relation between time perception and retention and Creelman's (1962) doctoral dissertation, both of which introduced new methodological approaches. Especially the latter has paved the road to re-establishment of the contact between classical time psychology and the study of other kinds of temporal relations in perception and motor behavior. In the present study we took another step in this direction. The available technical facilities made it easy to achieve a high level of precision in presentation of stimuli and recording of responses, and to collect more data than were obtained in most earlier studies. Moreover we have dealt explicitly with the variations in the subject's response and not only with its 'central tendencies'.

These factors are only of secondary importance however. The principal aim was to provide a formal framework and a technique for the sequential analysis of temporal relations in behavior. Both the framework suggested and the technique employed stand in close relation to at least two topical areas of psychological endeavor: information psychology and skilled behavior (tracking).

The establishment of such a descriptive frame has imparted an exploratory flavor upon this investigation, at the cost of many interesting details which could not be worked out. Another consequence is that we had to refrain from connecting our inquiry to the extensive work on topics which are in a sense related to the problem of timing, like immediate memory, response latencies, the psychological refractory period, etc. Even a more directly related problem – the alleged distinction between single presentation experiments and serial experiments remains to be charted.

We are convinced that temporal relations – with which man is confronted in several ways – provide him with information which must be processed in a way that is not essentially different from the way any other kind of sensory, symbolic or proprioceptive information is handled. In this respect the psychology of time does not deal in any sense with a 'microcosm' but on the contrary with a very essential part of all human behavior.

SUMMARY

In this experimental study a framework is developed for the description of the temporal relations between the elements in a chain of actions. The behavior of subjects in several key tapping situations is studied in a way which can in principle be extended to more complex forms of timing.

A review of the literature relevant to this problem area – discussed in Chapter I – shows two major defects of earlier studies.

(a) There is a wealth of very specific physiological and psychological theories about the nature and localization of the mechanism responsible for subjective time evaluation – metaphorically: the 'time sense' – but practically none of these theories can serve as a descriptive basis for empirical observations.

(b) No studies are available which give an analysis of the interactions between successive intervals in a chain of time evaluations, while it is plausible that there are such sequential dependencies if the intervals are not too far apart in time.

The goal of the present investigation is to provide an outline of a formal model of timing, which accounts for sequential dependencies that may be present in certain conditions. The approach adopted is related to the systems analytic models of spatial (manual) tracking, since serial production of intervals (key tapping) may be considered, in several respects, as the temporal analogue of spatial tracking performance.

In Chapter II some definitions and the technical preliminaries to the later chapters are presented. The basic experimental arrangement was that subjects tried to synchronize taps on a key with a series of clicks, presented to them through earphones.

The simplest input function – studied in Chapter III (Exp. 1) – is the isochronic sequence, which is the equivalent of the constant input signal in spatial tracking. It provides data on the spontaneous activity of the timing system.

The major part of the spontaneous variations – which are found to

be proportional the 1.5-power of the average interval length of the response intervals – may be considered as normally distributed random fluctuations. Only for extreme deviations there are signs of compensatory action. The same result is obtained when the subject tries to reproduce a particular interval length after the presentation of a standard is discontinued. The random part of this behavior is identical with that of the synchronization condition. Only the pattern of compensation is different and suggests an 'internal standard' which is a weighted average of a number of preceding response intervals.

In Chapter IV the synchronization response to modulated input functions of several types is studied. The input functions were simple sine waves (Exp. 2), composite sine waves (Exp. 3) and step functions (Exp. 4). The analysis of the results and the formulation of the model are based on some simple techniques borrowed from systems analysis, notably that of the 'generating function', which makes it possible to deal with sequential dependencies in series of intervals The proposed model is based on the simplest predictive system, the so-called 'ideal linear predictor'. On the basis of the discrepancies observed between model and data, a modification is proposed which gives an improved fit. This modification requires the introduction of two parameters, one of which is identified as a strictly personal parameter, while the other is a function of the average interval length (essentially a factor which makes the model non-linear). The model explains roughly between 60 and more than 90% of the explicable variance, depending on the experimental situation and the subject.

It is likely that human beings will change the behavior, displayed in normal tapping conditions and described by the model, if the strategy followed introduces a larger mean synchronization error than is acceptable to them. Two experiments, devised to bring the subjects forcedly beyond their limit of acceptance, indicate that in such conditions the compensation effect is practically lost (Exps 5 and 6).

Chapter V deals with the well known problem of the 'perceptual moment' or 'time quantum' in psychological processes. A further analysis of the data of Exp. 1 supports earlier findings of periodicities in response latencies: estimates of time intervals tend to cluster around integral multiples of 80 msec. This finding adds hardly any further insight into the nature of this quantization effect, however.

A second quantization phenomenon present in tapping behavior may offer a more helpful hint. This effect is analyzed in Exp. 7, where it is found that subjects adapt their tapping rates to slowly changing input rates in a stepwise fashion. This behavior suggests a threshold – which may probably be identified as the threshold for order of events – on which an additional effect from the interaction of random fluctuations and the error compensating mechanism is superimposed.

It is not clear yet, how the two quantization phenomena, which obviously are characteristic for subjective time evaluation, are related. It is doubtful though, whether a more or less deterministic 'time quantum' is needed as an explanatory principle.

Non-temporal factors are known to exert an appreciable influence on the subjective experience of time. In Chapter VI three exploratory experiments are reported, which give some insight in the effect of extra information on timing. In this context we must distinguish two basic possibilities: the non-temporal information may be integrated with temporal information (as in musical performance) or it may be functionally separate (double task situation: e.g. playing a piano and reciting prose). Exp. 8 demonstrates that subjects experience timing difficulties in the double task situation, but have hardly any in the integrated task situation. In Exp. 9 additional support is found for the latter part of the previous statement. Obviously the extra information, at least in the integrated task condition, does not affect the 'time sense' in the sense of affecting the system parameters. Finally in Exp. 10, the influence of integrated non-temporal information on isochronic input sequences is studied. An effect is found on the variability which makes it plausible that the information – temporal and non-temporal – is partly processed in series.

In Chapter VII a recapitulation is given, in the form of an information processing model which has been implemented as a simple FORTRAN program for a digital computer. A number of silent implications of the mathematical model and partly hidden arguments of the previous chapters are made explicit by computer simulation. This formulation also provides a rigorous frame of reference for future modifications or – possibly – refutation of the theory underlying it.

SAMENVATTING

Het juist uitvoeren van een samengestelde handeling vereist dat de temporele relaties tussen de onderdelen van de handeling nauwkeurig in acht genomen worden. Een overzicht van de literatuur – verwerkt in Hoofdstuk I – openbaart het bestaan van enkele markante lacunes in het denken over deze 'tijdstiptheid' (*timing*) in waarneming en gedrag. Zo vindt men een groot aantal specifieke fysiologische en psychologische hypothesen omtrent de aard en localisatie van de 'tijdzin' als mechanisme dat aan het vermogen tot stiptheid ten grondslag ligt. Geen van deze hypothesen kan evenwel dienen als formele basis voor de kwantitatieve analyse van empirische gegevens. In de tweede plaats wordt in de literatuur een nauwelijks geargumenteerd onderscheid gemaakt tussen situaties waarin de proefpersoon moet reageren op een enkelvoudige prikkel (tijdperceptie-experimenten) en die waarin een reeks intervallen in serie wordt aangeboden (tempoperceptie, ritme). Om verschillende redenen moet aan deze tweede aanbiedingswijze de voorkeur worden gegeven, niet in de laatste plaats omdat bij enkelvoudige aanbieding de 'tijdzin' geobserveerd wordt in een overgangstoestand.

Het belangrijkste bezwaar van de in de literatuur beschreven onderzoekingen hangt hiermee samen. Nimmer is getracht, systematisch de relaties tussen opeenvolgende intervallen in een reeks tijdschattingen te analyseren, terwijl het alleszins aannemelijk is dat zulke afhankelijkheden eer regel dan uitzondering zijn.

Het doel van deze experimentele studie is, een kader te verschaffen voor de kwantitatieve beschrijving van tijdstiptheid als manifestatie van een tijdzin. Daarbij is uitgegaan van een zeer simpele vorm van temporeel gestructureerd gedrag, namelijk het drukken op een seinsleutel met al of niet regelmatige tussenpozen. Hoewel niet expliciet verwezen wordt naar de relatie met andere aspecten van de tijd in ervaring en gedrag, kan het sleutel-tikken beschouwd worden als exemplarisch voor meer complexe vormen van tijdstiptheid, zoals musiceren of montagearbeid aan de lopende band. Het hier geschetste model houdt rekening met de dynamische relaties tussen opeenvolgende intervallen, en in het onderzoek is dan ook steeds gebruik gemaakt van meervoudige stimuli, reeksen van al of niet isochrone intervallen.

Het experimentele onderzoek wordt ingeleid in Hoofdstuk II, met een overzicht van de gebruikte terminologie en een beschrijving van de apparatuur en de toegepaste methoden.

De in de Hoofdstukken III tot en met VI beschreven experimenten waren alle gebaseerd op eenzelfde opdracht: de proefpersoon moest trachten het indrukken van de sleutel te synchroniseren met een reeks klikken die via een hoofdtelefoon werd gepresenteerd. De eenvoudigste stimulus is in dat geval de isochrone reeks, bestaande uit intervallen van volstrekt gelijke duur. De reactie op isochrone reeksen van verschillende intervallengte (0.3 tot 3.3 sec) wordt onderzocht in Hoofdstuk III (Exp. 1). Aangezien de stimulus hier het karakter bezit van een 'rustniveau', verschaft de reactie erop inzicht in de spontane activiteit van de 'tijdzin'.

De nauwkeurigheid waarmee synchronisatie tot stand komt blijkt evenredig te zijn met de 3/2-de macht van de gemiddelde lengte der geproduceerde intervallen. Deze relatie werd ook in andere experimenten teruggevonden en bevestigt de oude bevinding dat Weber's wet niet geldt voor tijd. De variaties in de geproduceerde intervallen mogen in het algemeen opgevat worden als toevalsvariaties. Hun verdeling is bij benadering normaal en sequentie-afhankelijkheden zijn verwaarloosbaar klein. Slechts voor extreme afwijkingen van synchroniteit is er een merkbare compensatie van de opgetreden fout, in de vorm van negatieve terugkoppeling.

Indien de proefpersoon een isochrone reeks tracht voort te zetten na het stoppen van de stimulusklikken, blijkt er een grote mate van overeenstemming te bestaan met de prestatie onder eerstgenoemde conditie. De toevalscomponent is identiek in beide situaties en het verschil blijkt uitsluitend uit de wijze van compenseren, die bij het ontbreken van externe referentiepunten uiteraard afwijkt. Toch kan men in de continuatie-conditie spreken van compensatie, en wel met betrekking tot een interne standaard, die opgevat kan worden als het gewogen gemiddelde van een aantal eerder geproduceerde intervallen. Over de eigenschappen van deze interne standaard is de informatie nog ontoereikend.

In Hoofdstuk IV wordt het gedrag in reactie op gemoduleerde intervalreeksen geanalyseerd. Van een gemoduleerde reeks varieert de lengte van opeenvolgende intervallen volgens een bepaald patroon. In het bijzonder zijn sinusvormig en sprongsgewijs gemoduleerde reeksen onderzocht.

Bij de analyse der resultaten en de formulering van het model dat deze resultaten beschrijft is gebruik gemaakt van de mathematische techniek der 'voortbrengende functies', waarmee het mogelijk is de betrekking tussen aanbiedingsreeksen en geproduceerde reeksen te vinden. Deze geldt ongeacht de feitelijk aangeboden reeks en dient dus tevens als een predictief model waarmee de reactie op een willekeurige aanbiedingsreeks voorspeld kan worden.

De eenvoudigste aanname, gekozen als uitgangspunt voor het in Hoofdstuk IV ontwikkelde en getoetste model, is dat een op een bepaald moment optredende synchronisatiefout (het tijdsverschil tussen een klik en de bijbehorende tik op de seinsleutel) met het eerstvolgende interval geheel gecompenseerd wordt. Een dynamisch systeem dat zulk een gedrag vertoont, noemt men een 'ideale lineaire predictor'. Uitgaande van dit zeer eenvoudige basismodel, blijkt het vrij goed mogelijk het synchronisatiegedrag bij het aanbieden van simpele sinusfuncties (Exp. 2) en combinaties daarvan (Exp. 3), te beschrijven. Er blijft echter een gering faseverschil onverklaard dat erop wijst, dat de compensatie van een fout niet volledig geschiedt met het eerstvolgende interval, maar over verscheidene intervallen wordt uitgesmeerd. Mede op grond van andere overwegingen, met name op basis van de reactie op sprongsgewijs gemoduleerde reeksen, is een verfijning van het model mogelijk, door het invoeren van een tweetal parameters (Exp. 4). Eén daarvan draagt het karakter van een persoonlijke parameter, de andere is bijkans uitsluitend een functie van de lengte van de aangeboden intervallen.

Het model verklaart in zijn uiteindelijke vorm een aanzienlijk deel van de niet als 'ruis' aan te merken variantie – ruwweg tussen 60 en 90%, afhankelijk van de condities en de proefpersoon.

Het is niet aannemelijk dat de mens zich automatisch van het in dit model beschreven 'systeem' zal blijven bedienen wanneer hij daardoor aanzienlijk slechter aan de opdracht tot synchroniseren zou gaan voldoen dan hij in beginsel zou kunnen. Dit is getoetst in een tweetal experimenten waarbij inderdaad een duidelijke verandering in de strategie optreedt, in die zin dat het compensatie-effect in het gedrag min of meer verloren gaat. In de eerste conditie waarin dit geconstateerd is, werd de door de proefpersoon geproduceerde tiksequentie met een vertraging teruggevoerd naar de hoofdtelefoon als kliksequentie

(Exp. 5). In het tweede geval was de lengte van de aangeboden intervallen een stochastische variabele met een normale distributie (Exp. 6).

In de experimenten met isochrone aanbiedingsreeksen (Exp. 1) werd geconstateerd dat de distributies van de geproduceerde intervallen uitgesproken veeltoppig zijn, althans voor de grotere intervallen. In de modulatie-experimenten werd somtijds een stapsgewijze aanpassing aan het zich wijzigende tempo geconstateerd. Deze beide verschijnselen duiden op een quanteus karakter van de subjectieve tijd. Een nadere discussie wordt in Hoofdstuk V gegeven.

Bij tijdschattingen zoals in deze studie onderzocht worden is, anders dan bij reactietijd-distributies, multimodaliteit van de intervalverdeling niet eerder vastgesteld. De evidentie voor een 'tijdquantum' wordt door onze gegevens in zoverre gesteund, dat de geproduceerde intervallen een voorkeur vertonen voor veelvouden van 80 msec. Opheldering over de aard van het tijdquantum wordt daarmee natuurlijk niet verschaft – daarop waren de beschreven experimenten niet afgestemd.

De stapsgewijze aanpassing aan een langzaam veranderend tempo (Exp. 7) blijkt zeer duidelijk een functie te zijn van de eigenschappen van de aangeboden reeks, hetgeen de uniekheid van een periode van 80 of 100 msec als min of meer deterministisch tijdquantum ondermijnt. De grootte en frequentie van stapsgewijze aanpassingen is naar de ondergrens beperkt door het onvermogen de volgorde van twee gebeurtenissen (klik en reactie) aan te geven wanneer deze minder dan 20 à 30 msec uit elkaar liggen, terwijl daarboven de zekerheid omtrent richting en grootte van de te volgen verandering een belangrijke factor in het ontstaan van de stappen lijkt te zijn. Deze subjectieve zekerheid is een functie van de variaties tengevolge van de 'ruis'-componenten in het tijdschattingsmechanisme.

Het is bekend dat de subjectieve ervaring van een tijdsverloop sterk wordt beinvloed door bijkomstige informatie van niet-tijdelijke aard. Een groot aantal van deze factoren is in de literatuur beschreven. Eén van deze factoren is de informatie per stimulus (stimulus-onzekerheid). Het doel van Hoofdstuk VI is, enig inzicht te verschaffen in de wijze waarop tijdstiptheid wordt aangetast door zulke extra informatie.

Als aanbiedingsreeksen werden, als tevoren, de sprongfunctie en de isochrone reeks gebruikt.

Uit de experimenten blijkt dat de gemiddelde reactie nauwelijks wordt aangetast indien de extra informatie een functioneel geheel vormt met het sleuteltikken (Exp. 8). Bij functionele scheiding – de zogenaamde dubbeltaaksituatie – vinden we een duidelijk veranderde gemiddelde responsie, voornamelijk als gevolg van de variaties in het moment waarop de sprong in de aanbiedingsreeks wordt gecompenseerd, hetgeen in de dubbeltaaksituatie dikwijls twee, drie of zelfs vier intervallen kan worden uitgesteld.

Uit de resultaten valt voorts af te leiden, dat in de geintegreerde taaksituatie de verwerking van temporele en niet-temporele informatie grotendeels in serie verwerkt wordt, hoewel enige correlatie aanwezig is (Exp. 10).

De gedaante der gemiddelde reactie op een stapsgewijze verandering in de aanbiedingsreeks tenslotte, wordt niet of nauwelijks beinvloed door met de sleuteltik-taak geintegreerde extra informatie (Exp. 9), waaruit we mogen concluderen dat de aangeboden extra informatie geen systematische invloed uitoefent op het functioneren van de 'tijdzin', maar daarentegen de momentane variatie doet toenemen, hetgeen toegeschreven zou kunnen worden aan 'schakelprocessen' in de informatieverwerking door het brein.

In Hoofdstuk VII wordt een samenvatting gegeven van de empirische bevindingen uit de voorafgaande hoofdstukken, in de vorm van een informatie-verwerkingsmodel dat werd gerealiseerd als een programma voor een digitale computer. Hoewel het in deze vorm geen nieuwe gezichtspunten oplevert ten opzichte van de voorafgaande mathematische formulering, biedt het twee belangrijke voordelen. Een programma stelt een aantal aspecten van een model expliciet, die in het mathematische model slechts impliciet gegeven zijn, en in de tweede plaats verschaft het de waarborg dat een model in feite functioneert en dat het doet wat het zegt te doen. In die hoedanigheid ligt het model vast, en kunnen toekomstige uitbreidingen, amendementen en toetsingen expliciet op de in deze studie ontwikkelde gedachten betrokken worden.

n	number of intervals in a sequence
i	rank order index; instant $(1 \leqq i \leqq n)$
T	continuous physical time
T_0	zero point of time scale; start of experimental run
T_i	time since T_0 at the instant at which i^{th} interval is completed
t	duration (length) of input intervals
$\hat{t}$	duration of output intervals
t_i	length of i^{th} interval in input sequence; $t_i = T_i - T_{i-1}$
$\hat{t}_i$	length of i^{th} interval in response sequence
$\{t_i\}$, $\{\hat{t}_i\}$	sequence of intervals expressed as a vector
t_{av}, $\hat{t}_{av}$	average length of the intervals of a sequence
t_{bas}	base line of interval sequence = shortest interval; equivalent to DC-level in electric systems
Δt_i, $\Delta \hat{t}_i$	first difference $(t_i - t_{i-1})$ or $(\hat{t}_i - \hat{t}_{i-1})$
Δt	increment in modulated sequences, e.g. $\Delta t = 0.1t^2$
$\delta\hat{t}$	differential threshold; $\delta\hat{t}/\hat{t}_{av}$ is the Weber fraction
τ	time quantum; duration of one element of discrete psychological time
$\pm\varepsilon$	interval between input click and corresponding response tap; the sign of ε is positive if tap precedes click and negative if click precedes tap
D	length of period (number of intervals per cycle) of periodic input sequences.

Other symbols used throughout the text are in accordance with mathematical or statistical conventions.

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