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Abstract

Simple reaction time has been measured using various distributions of interstimulus intervals (ISIs), which differed both in the shape of their envelope and in their degree of discretization. For each of 7 such conditions, and for three mean ISIs (2.0, 3.3, and 5.8 s) 600 responses of two subjects have been accumulated.

Reaction times depend significantly on the shape of ISI-distributions but also on their degree of discretization. Within an experimental run they depend on single ISIs back to the third before reaction, and on sequences of ISIs. The latter effects are again influenced by the discretization of ISIs. Finally it was found that some learning of the distribution pattern (not the mere mean value) of ISIs takes place.

Our results shed some light on existing hypotheses of RT. Some inconsistencies of earlier experimental results can probably be explained by insufficient consideration of the discretization and the learning effects.

1. Introduction

Human reaction time depends on many experimental parameters (examples are cited e.g. in [15, 24, 26]), and we are far from understanding their influences. Among those parameters which can easily be varied in a serial experiment, and whose influence on reaction time can be measured, the temporal pattern of stimuli must be included.

Fig. 1. Explanation of symbols

Fig. 1 shows a sequence of stimuli ($\uparrow$) and reactions ($\downarrow$) (with no separate warning signals), and the reaction times (RTs) and interstimulus intervals (ISIs) involved. If RT_n is the reaction time under observation, the sequence of earlier interstimulus intervals $ISI_n, ISI_{n-1},$

$ISI_{n-2} \dots$ defines a *time pattern* which can be suitably chosen.

We have observed the following types of dependence of RT on the time pattern of ISIs:

(1) The distribution of reaction times characterized by their mean μ and standard deviation σ depends on the *mean interstimulus interval* (m-ISI). Within certain limits μ depends linearly on $\log$ (m-ISI). This is a well-known result [13, cf. 9, 10, 21], which has also been confirmed with good statistical accuracy in a previous paper in this journal [26], henceforth cited as Paper I.

(2) The distribution of RTs also depends – for fixed m-ISI – on the *distribution* of ISIs in the experiment. Results comparing periodic (P-) stimuli with those drawn at random from a rectangular distribution of ISIs (R-stimuli) have been presented in I. In the present work (see Section 3) we show that RT depends also on the *shape* of the ISI-distribution (rectangular or Gaussian), and on the degree of *discretization*, i.e. the number of different values of the ISI employed in simulating the ideal continuous distribution of intervals.

(3) There is a correlation of the sequence of reaction times RT_n with the *sequence* of $ISI_n, ISI_{n-1},$ and ISI_{n-2} ; i.e. an individual RT_n depends not only on the average properties of the ISIs but also on several individual ISIs just before RT_n . This has often been noticed [1, 4, 8, 10, 12, 28, cf. a. 23]; unfortunately, a programming error led us to deny this effect in I [26, p. 189f.]. After re-evaluation, our old data, and in much more detail our new data show it clearly, cf. Section 3.

Our results – which like those of I would have been impossible to obtain without our computer-controlled experimental arrangement – show that the amount of time information, which influences the “strategy” leading to a certain speed of reaction, is not small. Further discussion on this follows in Section 4b.

2. Description of Experiment

A description of our experimental set-up has been given in I, so we can keep it short here: The subject (S) sits at a table into which an oscilloscope screen has been inserted. The stimulus consists of the jump of a light-dot on the screen, the S has to follow this movement "as fast as he can" with a pencil containing 3 accelerometers. Their output is sampled every $150 \mu\text{s}$ and an acceleration larger than $g/100$ is counted as onset of the movement. A small computer controls the whole experiment; it moves the light-dot, samples the accelerometers and stores ISIs and RTs of each experiment for further analysis.

An experimental run consisted of 100 stimuli and reactions. There were no warning signals and no pauses in such a series, cf. Fig. 1. The ISIs were programmed such as to fix (1) the mean-ISI and (2) their distribution.

Fig. 2 shows the different ISI-distributions used in this study and illustrates all corresponding notations. For each of these distributions m-ISIs of 2.0, 3.3 and 5.8s were used; effects of anticipation on the one hand and fatigue on the other are small for ISIs of this size (cf. I).

For each of the 3 m-ISIs and the 7 ISI-distributions (altogether 21 different parameters) 6 different experimental runs were carried out during a period of approximately 6 weeks.

Fig. 2. Probability distribution (not to scale) of ISIs used in experiment. Discretization in QC and GS experiments was $1/500$ of ISI-range. Min ISI was 0.8s in each case, therefore $\text{max ISI} = 2 \cdot (\text{m-ISI}) + 0.8\text{s}$

Subjects were three students aged from 19–22. During the analysis it was shown, however, that one of the Ss showed extremely large fluctuations between corresponding runs. A personal inquiry confirmed these to be a result of a strongly changing disposition, so for further analysis we took only the results of the other two Ss. Clearly two Ss are not enough to be certain of the results in full generality. Since, however, the effects quoted in this paper are found in each single individual, and since a comparison with I, where it is possible, supports our new data, we have no reason to doubt that the present results are representative.

3. Results

a) The Dependence of RT on the Distribution of ISIs

As a typical example Fig. 3 shows how the RT-distribution depends on the different ISI-patterns. It can be seen that P- and GS-stimuli lead to the smallest μ and to the smallest σ . Passing from D2, D3, D5, D11 to QC experiments, the strong decrease

Fig. 3. All results of one S for m-ISI 3.3s . Each histogram consists of 600 reactions. Frequency (N) of each RT-class (width 8ms) is plotted against RT (in ms)

of σ is conspicuous. Both for μ and σ , D11 experiments are no longer distinguishable from QC experiments.

An analysis of variance for the rectangular-enveloped ISIs from the data of Fig. 3 shows that the corresponding RT-distributions cannot be derived from a uniform sample ($P < 0.001$). This high significance is also typical for all other cases.

A comparison of σ s (for the same example) by means of an F-test shows that σ for D2 experiments is significantly larger ($P < 0.01$) than the standard deviations of all other experiments except D3. This holds typically for all m-ISIs. The statistical moments of all experiments are collected in Table 1 for both Ss.

Fig. 4. Dependence of mean-RT on ISI-distributions (average of both Ss)

Fig. 4 shows the average values of μ calculated from both Ss. For rectangular ISI-distributions μ is strongly dependent on the discretization of ISIs. For a given m-ISI μ has a minimum at D2 experiments. With finer discretization it approaches the μ of QC experiments, in some cases passing a relative maximum for an intermediate situation.

These statements are valid for each S individually (except G.K. at 2.0s). Table 1 shows that RT vs. discretization behaves almost "parallel" for both Ss, the difference of μ being approximately constant (31, 37, 40 ms depending on m-ISI). The table includes also the values of the standard deviation σ . For coarse discretizations (D2, D3) σ is essentially larger than for fine ones (D11, QC). Incidentally Fig. 4 and Table 1 show the known result of larger μ and σ for increasing m-ISI, cf. e.g. [10, 12, 13, 21, 26, 28].

As can be seen in Table 1 the skewness γ remains relatively constant in all experiments (in D2 and D3 experiments γ tends to become smaller). From all R-experiments γ was calculated to be 0.85 ± 0.1 which is in accordance with I.

Table 1. Statistical moments of all experiments (m-ISI in s, RT in ms)

Subject	Type of experiment							m-ISI
	D2	D3	D5	D11	QC	GS	P	
Mean μ :								
G.K.	182	187	180	180	178	174	167	2.0
R.P.	208	216	213	215	213	194	174	
G.K.	190	197	206	198	199	183	179	3.3
R.P.	221	235	242	240	238	220	206	
G.K.	196	207	220	220	216	204	201	5.8
R.P.	236	244	252	257	262	256	245	
Standard deviation σ :								
G.K.	27.3	28.5	24.6	24.8	22.9	22.5	17.3	2.0
R.P.	30.7	28.0	25.2	23.1	26.0	24.5	31.2	
G.K.	37.4	34.3	32.3	29.7	30.7	25.5	24.2	3.3
R.P.	36.9	37.9	39.9	34.9	30.6	30.3	30.0	
G.K.	41.8	36.1	40.8	35.5	36.3	31.9	32.0	5.8
R.P.	49.4	43.3	39.7	38.7	39.6	35.5	39.6	
Skewness γ :								
G.K.	0.8	0.9	1.1	1.4	1.2	0.9	-0.3	2.0
R.P.	0.5	0.6	0.9	0.6	0.7	0.7	-0.4	
G.K.	0.8	0.6	0.9	1.2	1.1	1.3	1.3	3.3
R.P.	0.8	0.6	1.0	1.3	1.0	1.1	0.8	
G.K.	0.8	0.7	0.8	1.1	1.0	0.9	1.0	5.8
R.P.	0.7	0.9	1.2	1.1	1.0	0.8	0.6	

b) Dependence of RT on Prior ISIs

The essential notations needed for this section are explained in Fig. 1. For the following analysis the whole ISI-range was divided into 3 equal classes. This is illustrated in Fig. 5.

The results are the following: RT_n is influenced by prior ISIs back to ISI_{n-2} . ISI_{n-3} and earlier ones do not lead to a measurable difference between the ISI-classes.

(1) There is a tendency for a monotonous increase of RT with increasing ISI_{n-2} ; in any case (supported by high significance of a binomial test) RT after a short ISI_{n-2} is smaller than after a long ISI_{n-2} . The size of this effect amounts to about 6 ms and does not depend specifically on m-ISI or on the discretization of the ISI-distribution.

Fig. 5. Explanation of symbols

Fig. 6. Dependence of RT_n on ISI_{n-1} (same S as in Fig. 3). Each ISI-distribution is divided into 3 classes (s, m, l, cf. Fig. 5). Broken horizontal lines indicate total mean μ

Fig. 7. Dependence of RT_n on ISI_n (same S, and same notation as in Fig. 6)

(2) With respect to ISI_{n-1} , binomial tests show with very high significance that the increase of RT from short to long ISI_{n-1} is monotonous. This is shown in Fig. 6 for one S. For all m-ISI, and all ISI-distributions under consideration this effect is similar; nevertheless it seems that the effect is smaller for D2 experiments (ca. 5 ms increase of RT) than for QC or GS experiments (ca. 9 resp. 11 ms).

(3) Fig. 7 shows the variation of RT_n with increasing ISI_n , the one immediately before RT_n . The effects of ISI_n on RT are much stronger than those of earlier ISIs (cf. Table 2). A predominant feature is the different kind of dependence of RT on ISI_n for the different ISI-distributions. For D2 experiments RT belonging to a short ISI is smaller than RT after a long one; for D3 experiments $(RT(s) < RT(m) \approx RT(l))$ holds. Mutual t-tests give high significance to all these statements ($P < 0.001$).

Table 2. RT difference (short ISI_n minus long ISI_n in ms)

Type of experiment	Subject	Mean ISI (s)			Average
		2.0	3.3	5.8	
D2	G.K.	-29	-46	-56	-46
	R.P.	-37	-44	-64	
D3	G.K.	-22	-29	-27	-29
	R.P.	-23	-25	-45	
D5	G.K.	3	-6	-9	-5
	R.P.	-5	2	-16	
D11	G.K.	7	12	13	8
	R.P.	5	10	1	
QC	G.K.	3	14	20	11
	R.P.	14	6	9	
GS	G.K.	21	25	17	22
	R.P.	19	24	27	

For D5 experiments a *reversal* of the effect is noticeable and the variation of RT as a function of ISI-class is unsystematic. For D11 experiments the reversal is complete and is even more distinct for QC and GS experiments; RT is now decreasing with increasing ISI_n . A non-parametric Friedman analysis of variance [25] yields significant differences of ranks for D11 and finer distributions ($P < 0.0055$ at least), whereas D5 experiments yield no systematic ranks.

The effects are similar for all m-ISIs under consideration; only for D2 experiments the difference $RT(l) - RT(s)$ increases with increasing m-ISI. Note that in this case the short ISI is always 0.8 sec, whereas the long one is 3.2, 5.8 and 10.8 s respectively. It is evident that RT after the short ISI is practically constant, whereas RT after the long ISI increases for longer m-ISI. This explains the bimodal RT-distribution (cf. the corresponding histogram in Fig. 3) and the extremely large standard deviation for D2 experiments.

c) Learning Effects

The effects mentioned under 3b) are averages over serial experiments of 100 stimuli. An analysis of the first tenths or thirds of such series shows that the behaviour depicted in Fig. 7 is the result of some "learning" of the temporal structure of stimuli presented. During the first 10 reactions of an experimental run RT_n has a *minimum* for an ISI_n of *medium* length: a typical "V"-shaped curve develops (cf. Fig. 8). This wellknown effect [2, 5, 11, 19] is the result of an adaptation to the m-ISI of the series presented: at this stage, however, the different ISI-distributions

Fig. 8. Learning effects observed for the dependence of RT_n on ISI_n (same S, m- ISI 5.8 s)

cannot yet be distinguished by the Ss. A second stage of adaptation or "learning" develops later on after about 20 or 30 trials.

d) Dependence of RT on Sequences of Prior ISIs

For this analysis the ISIs are divided in the same way as explained in Fig. 5. The influence on RT of the sequences $ISI_{n-2} - ISI_{n-1}$ and $ISI_{n-1} - ISI_n$ is examined separately for the ISI-sequence classes short-short (s-s), short-long (s-l), long-short (l-s) and long-long (l-l).

(1) Sequence $ISI_{n-2} - ISI_{n-1}$: The small ISI_{n-2} - and ISI_{n-1} -effects suggest (cf. Section 3b) a weak sequential dependence. In all cases the sequence s-s yields shorter, the sequence l-l yields longer RTs than the total mean-RT, μ .

Fig. 9. Dependence of RT on the sequence $ISI_{n-1} - ISI_n$ (same S, m- ISI 5.8 s)

(2) Sequence $ISI_{n-1} - ISI_n$: Fig. 9 shows the typical effect. Again the opposite behaviour of D2 and D3 experiments on the one hand, and QC and GS experiments on the other is evident. For the D2, D3, QC and GS experiments a nonparametric Friedman analysis of variance shows significant differences between the reaction time of the different classes ($P < 0.01$ for D2 and D3 experiments, $P < 0.05$ for QC and GS experiments). No significant ranks between different classes are found for D5 and D11 experiments.

4. Discussion

a) Comparison with other Work

With respect to mean, standard deviation and shape of RT-distributions we refer to Paper I [26]. In the present study emphasis is laid on three effects: (1) The dependence of RT on the shape of the ISI-distribution. This has been studied in a few cases [1, 2, 27]. (2) The dependence of RT on the prior ISI and on sequences of prior ISIs, which has been studied in many cases [1, 3, 5, 8, 10, 11, 17, 19, 28]. (3) The dependence of RT on the discretization of ISI-distributions. To our knowledge this has never been systematically studied, and the parameter "discretization" has been left more or less uncontrolled in previous work. Since we have seen that effects (1) and (3) interfere with (2), and because of many other differences of method, where we do not know how much the S's sensitivity to temporal patterns interferes, our possibility to compare our results to other authors' work is limited.

Inconsistencies with previous work can especially arise from the following:

(1) In Section 3c) we showed that the time pattern is "learned" somehow. If a single series of reaction tasks is too short, or if long intertrial intervals (ITIs) are interspersed, the stationary state of reaction on a time pattern may not be reached.

(b) In experiments with warning signal, the ITI is part of the time pattern. Many authors do not even mention its size in their paper. But in view of what we found, it seems obvious that the influence of ISI_{n-1} will depend also on the length of the ITI between ISI_n and ISI_{n-1} .

In what follows some specific results are discussed in their relation to former work:

D2 Experiments. Zahn and Rosenthal [28] working with optical warning, acoustic stimulus and an ITI of 7 s found that RT_n after a short ISI_n is longer than after a long one. Also they found another influence of ISI_{n-1} than we do. We have no explanation for the inconsistency except what has just been mentioned.

D3 Experiments. Kellas, Baumeister and Wilcox [11] worked with optical warning and acoustic stimulus. Their ITI is not given. Their Fig. 3 shows a D3, $\mu = 8$ s experiment in perfect check with ours (cf. Fig. 8) including the learning effect.

In the experiments of Näätänen [19] only series III has a discretization comparable with ours in number *and with* of quanta, while in his series I and II as well as in series "V" of Karlin [10] the relative discretization (minimal distance between two possible ISI-values divided by mean-ISI) is similar to what we would call a D6 not D3 experiment. This may explain different results. Moreover most of the authors curves are V-shaped indicating the possibility of effect (a) mentioned above, i.e. incomplete learning of the time pattern.

Rather different and also inconclusive are the D3 results of Leplat [17].

D5 Experiments. As Fig. 7 shows D5 experiments are at a point of transition from D3 to D11 behaviour. This may be the reason why several other investigators found inconclusive results even within their own series of experiments, see e.g. [3, 8, 18, 27].

D11 Experiments. Here we must mention Klemmer [12] who performed P and D11 experiments, the latter with different widths of the distribution. Some other conditions were different from ours (warning click, ITI 11 s). The result with respect to ISI_n matches ours, but not that concerning the sequence $ISI_{n-1} - ISI_n$, where Klemmer's result is more similar to our QC series. But note that the ITI makes comparison doubtful anyhow.

QC Experiments. Drazin [4] has reported the use of a "continuous distribution" of ISIs, though it is not quite clear how continuous it was. His results, where comparable, are in agreement with ours.

b) General Remarks

There exist many hypotheses about what mechanisms are involved in RT (cf. [15]) and we do not intend to deliver a further one. Rather, the following remarks tend to support the view that man's response to time patterns (as measured by RT) is too complex for simple theories, and his behaviour – even in such primitive tasks – is best described in terms of "strategies" (cf. [16]).

Time uncertainty. One of the most appealing concepts for the explanation of the variability of RT is Klemmer's notion of "time uncertainty" [13]. He assumes that time uncertainty can be expressed as the variance σ_t^2 , which is the sum of the S's uncertainty of time prediction, σ_s^2 , and the objective variance σ_0^2 of the distribution of ISIs. Time prediction experiments led Klemmer to assume that σ_s is proportional to the time interval Δt involved.

In his RT experiments he finds that RT is a linear function of $\log \sigma_t$. But unfortunately he does not really test his assumptions. For he uses only GS-distributions for his ISIs, for which σ_0 is proportional to m-ISI. Since he has found $\sigma_s \propto \Delta t$, his experimental result $RT \approx a + b \log \sigma_t$ (with a and b constant) does not mean any more than the well known statement $RT \approx a' + b' \log(\text{m-ISI})$. Particularly, the additivity of the uncertainties σ_s^2 and σ_0^2 is not at all tested.

Fig. 10. Dependence of RT on normalized standard deviation of ISI-distribution (average of both Ss). On each curve the points are from left to right P, GS, QC, D11, D5, D3, and D2 experiments

In our experiment the ratio of σ_0 to m-ISI is not fixed but varies, e.g. for m-ISI = 5.8 s from 0 (P-exp.) via 0.22 (GS-exp.) etc. to 0.86 (D2-exp.). Fig. 10 shows the dependence of RT on σ_0 at the three fixed m-ISIs. This picture would not be markedly changed if one took into account σ_s (except for the P-experiments). We must therefore conclude that a logarithmic dependence of RT on "time uncertainty" defined after Klemmer does not exist.

We could, however, also use Nickerson's [20] definition of the "a priori uncertainty" of the duration of ISI. He computes it as the information H , which for our D-experiments with discretization k comes out to be $\log_2 k$. From our data RT is *not* proportional to $\log_2 k$. We refrain from counting this as an evidence against a general Information Hypothesis (cf. [9, 14]) since we believe that any definition of the information content of time *must* contain a model of the "time receiver". In our problem, however, an unambiguous model for this does not exist.

Expectancy and the Like. The discussion under 3c) shows that the adaptive behaviour described with the word "expectancy" is not so simple as some authors believe. We see at least 2 stages of adaptation to ISI time series, the second of which we prefer to call a "learning" process. If we want to use the word "expectancy", the experiments show that expectancy is structured. The structured expectancy leads to "strategies" devised to meet the overall goal of fast reaction.

Periodicity of RT Distributions. The existence of an internal oscillator leading to some quantization of RTs has recently been promoted again by Harter [6, 7] and Pöppel [22]. In view of our large material (≈ 25000 reactions) it may be worthwhile to perform a detailed search for such periodicities. For the moment

we can only state that inspection of our histograms like those of Fig. 3 does *not* support the periodicity hypothesis. Typically the histograms are unimodal even for single runs of 100 reactions. The fact that the D2 and D3 curves look like multimodal is easily explained: In view of the large difference in RT to individual short, mean, or long ISIs (displayed in Fig. 7), these curves are a superposition of two resp. three unimodal distributions belonging to the two or three ISIs employed.

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