THE "SUPERVISOR"—
A HYPOTHETICAL MENTAL FUNCTION IMPAIRED BY BRAIN DAMAGE

By

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THE common ground between neurology and psychiatry is regrettably slight, but in either field there have been men who sought to bring about a *rapprochement* between them by evolving broad conceptions of the structure of mind. For example, Hughlings Jackson's concept of "levels" and Freud's description of the mind in terms of Ego, Super-Ego and Id are both essentially attempts to define and classify the intellectual and behavioural functions of the brain, so as to form a coherent basis for the study of the interactions and disorders of these functions.

The study of the mind at present does not suffer from a lack of empirical knowledge; there is a wealth of facts, derived very largely from psychological testing scales, as to the average performance to be expected in any number of arbitrarily devised test-situations, more or less similar to the tasks encountered in daily life. However, these tests bear no relation to the physical sciences and, as biochemistry has shown, the benefits to be gained by relating medicine to a rigorous experimental science are great.

Faced with a complex physical system—and few nowadays will object to the description of the brain as such—the reaction of the scientist is to look for measurable variables. Having found these he seeks to perform repeatable controlled experiments, in which as many variables as possible are held constant, a few are deliberately caused to vary and the response of a few others is observed and measured. In this way he builds up a composite picture of the laws which restrict and interrelate the variations of the different elements of the system as it reacts to changing external conditions.

In the case of the brain, the difficulty is to discover which are the fundamental variables; for if variables of only superficial importance are held constant, such is the flexibility of the system that it is not rendered sufficiently determinate or consistent for repeatable experiments to be possible. It will be obvious that the search for the fundamental variables of cerebral function and the search for a valid classification or "architecture" of the functions of mind are closely interlinked, if not identical.

In the present study, it has been taken as axiomatic that all the mental functions consist in the manipulation, storage and communication of information. In the lay sense of this word, such a position is unassailable, but the lay sense of the word is not accurately defined. However, a statistical definition of information exists and indeed information theory has come to rank among the foremost theoretical systems in physics or thermodynamics. The relation between information as statistically defined and information in the various senses of "news", "meaning" and the like is still debated; but if we ignore these issues and simply apply the statistical concept of information (and certain related ideas such as that of *avoidance*) to the brain, we find a degree of consistency so great as to suggest that this approach above all offers promise of revealing which are the fundamental variables of mental function.

The principal link between the everyday and the statistical concepts of information is perhaps the idea of *specificity*. When, as in the present experiments, the brain has to generate a sequence of written symbols one by one, two distinct sorts of specificity can be recognized in the utterance. The first consists in the fact that a symbol has a specific shape; the generation of such shapes is similar to numerous spatial, geometrical and constructional taks of the sort which are often impaired in lesions of the parietal lobes. The second lies in the choice and order of the shapes and this aspect of writing a sequence of symbols is more related to linguistic functions such as spelling and sentence construction. The present technique depends on the counting and the application of restrictions to certain symbol-types, without regard to their orthography so long as they are recognizable. The initial emphasis was therefore on the second type of specificity, but it has been found necessary to touch on the first type also, under the name of "script-information".

The Standard Experiment

The experimental conditions have been deliberately kept as simple as possible, not only in order that the test should be capable of being applied at the bedside but also with a view to minimizing the element of observer-interference. The principle followed has been that the subject should be left as free as possible and submitted to the smallest possible number of clearly-defined restrictions. In this way, inherent differences and similarities between different brains, which might well be masked by the imposition of more narrowly drawn and specific restrictions, have been allowed free play; and any general law of mental function revealed under these circumstances is therefore the less likely to be a mere experimental artefact.

In the standard experiment, the subject has to *write single digits at random*, for five separate "runs". The runs are all of the same duration, namely 120 sec. or 180 sec., for a given subject and he does not know the duration in advance. In practice it has been found convenient to decide the duration in the course of the first run; if the subject writes more than one line, or about 25 digits, in the first minute, he has usually been allotted two minutes for each run, otherwise three minutes. He is told to continue until given the signal to stop; he must not stop for any other reason and he must not correct or cross out any mistakes he thinks he may have made. The runs are timed with a stopwatch from the moment the subject begins to write the first digit. He is told that this is not a speed-test and that the stopwatch is merely to make sure that everyone continues for the same length of time; he must write at whatever speed the numbers come into his head.

The two most important rules are that the digits must be written one by one, not as compound numbers such as 10, 28, 934 etc.; and above all that the subject must not follow any systematic plan or formula. It should be mentioned at this point that no normal subject has ever failed to obey either of these rules after once being corrected and most normals require no correction. Brain-damaged subjects on the other hand frequently have difficulty in breaking away from stereotypies and patience may be needed to obtain five runs which do not violate the rules. When a subject is seen to be using any type of stereotypy or flagrantly disregarding the single-digit rule (the latter very rarely happens except as part of a stereotypy) he is stopped and a fresh run is started after his mistake has been explained. It occasionally happens that a patient seems unable to prevent himself writing occasional compound numbers, or lapsing into a stereotypy after the run has been satisfactorily begun; the situation is then accepted, after every effort has been made to fix the rules in his mind; but he is reminded of the rules anew before each run. A run which shows only *patches* of stereotypy is acceptable.

Two patterns of stereotypy are quite commonly shown by patients and must be watched for. The first may be called "serial perseveration" and consists in repeatedly counting up or down the numerical scale from 0 to 9. The second, which is less common, may appropriately be called "ordinal permutation" for in this case the subject still writes the digits in groups, or cycles, of ten (or nine if the zero is omitted) using each digit once only in each cycle and varying the order. In pointing out what is wrong with such utterances it is useful to stress to the patient the fact that with each digit he writes he is free to write any digit whatever. Once this principle has been grasped for the first run it is usually applied in subsequent runs. Patients vary greatly in their ability to perceive this concept of randomness; those who do so intuitively are almost always those who have been least incapacitated intellectually by their lesions and who yield the best results according to the criteria to be described below.

In the first and last runs, the subject is allowed to use all the ten digits, but before each of the intervening runs he has to choose, respectively, one, two and three different digits which he is then forbidden to write. In choosing the digits to be suppressed, he is not allowed to choose the same digit in any two successive runs; the two digits suppressed in Run 3 may not be adjacent on the numerical scale and the three digits suppressed in Run 4 may not form a continuous series (such as 456). The subject is, in effect, taken round a cycle, the number of restrictions imposed in the 1st, 2nd, 3rd, 4th and 5th runs being 0, 1, 2, 3 and 0 respectively.

After the five utterances have been obtained it is desirable to go over them with the subject in order to identify any ambiguous symbols; this is particularly important in connection with those digits which are rarely used.

For each run, the number of symbols of each type must then be counted. In this investigation the following counting-rules have been adopted. When a symbol has been crossed out it must nevertheless be counted. If one symbol has been written on top of another, or if one has been changed into another, both must be counted. Wholly illegible symbols, which are rare, must be ignored. Even normal subjects occasionally break the single-digit rule by writing the number 10. Whenever it is obvious that the sequence one-zero has not come about by chance the number 10 is treated as if it constituted a single digit and the number of times 10 occurs is counted, just as for any other digit. Subjects often space their digits widely, or put a dash between them or reveal by their behaviour whether a ten is "intended". If the subject also writes sequences such as 0 1 or 1 0 0 or uses the 0 and the 1 separately, elsewhere in the same run, the sequence 1 0 does not usually seem to have been "intended" as a ten and the digits 1 and 0 are simply counted as such; the same is always done for double numbers other than 10. The main guiding principle is that the same counting-rules must be used for a given subject throughout.

Material

The object of this investigation has been to explore certain parameters of information-handling under strictly defined but relatively unrestricted conditions of performance, with the intention of identifying variables which have a recognizable "behaviour". Whenever such a variable is found, the provisional conclusion is drawn that it relates to the physiology, not necessarily of any particular neuro-anatomical structure, but rather of some *mental function*, in principle capable of being precisely defined and studied in terms of the scientifically disciplined language of information theory.

To this end it has been thought desirable to contrast and compare a reasonably homogeneous normal group with a miscellaneous group of patients with brain damage, of varying ages and pre-morbid attainments and with a variety of degrees and kinds of cerebral lesion. In order to keep the data within manageable dimensions it has been decided to present only the first ten cases of each group for whom the results were computed. The normal group comprises the first ten out of a larger group of volunteers; all were French medical students in their twenties. One student has been excluded because his utterances contained a large number of ambiguous symbols and there was no opportunity to check them with him. The brain-damaged group comprises the first ten out of about 30 patients, not selected by the writer, all of whom (save S.) were French and were attending the Centre de Langage. All showed definite clinical signs, including some dysphasia (very slight in the case of F.C.); some had spastic pareses of the writing hand but all could write sufficiently well. The first patient of all was seen before the importance of the "no-formula" rule was understood and has been excluded, because he was allowed to follow strict serial perseveration in the fifth run. The degree of disability varied greatly and if it is legitimate to speak of "overall intelligence" or "capability", using this term to mean a clinical impression of capacity to deal with new situations—such as that presented by the present technique—then one subject was conspicuously disabled (E.H.) and three or four were much less so than the rest (F.C., J.C., J.P.O. and S., in that approximate order).

It will be appreciated that the writer has played little or no part in selecting the numbers of each of the groups discussed below. Moreover, any qualitative generalizations concerning the behaviour and performance of normal or brain-damaged subjects are intended to refer not merely to the ten members of each group which are presented but to the overall experience of the writer with each category of subject.

The Rate of Spontaneous Information-Output, C

Information is defined statistically in terms of the relative probabilities of signals, or in general "events", of different types. To take a concrete example, we may imagine a situation in which M different types of letter or digit are used with varying frequencies to make up a message or "utterance". If we fix our attention on one of the M sorts of symbol and describe it as the i-th type, then supposing this type to occur n_i times in an utterance containing a total of N symbols, the statistical probability of the i-th type is defined as $\frac{n_i}{N}$ and written p_i and the information carried by each symbol of the i-th type is given by the expression $-\log p_i$. This amount increases as p_i decreases and it may be helpful to think of it as the logarithm of the rarity, or the "dilution", of the i-th type in the utterance.

A more rigorous definition of information exists which takes into account the probability of occurrence of each symbol-type *in every possible context* but for the practical purposes of this investigation so broad a definition is both cumbrous and unnecessary.

If $-\log p_i$ is the information carried by each symbol of the i-th type then the amount of information carried by *all* the symbols of this type in the utterance will be $-(n_i.\log p_i)$ since there are n_i of them. The same argument can be applied to all the M types and if we add together the M quantities computed in this way and divide the sum by the *duration* of the utterance, we obtain a measure of the rate at which information is being emitted by the source of the utterance.

Assuming that time is measured in seconds and that the logarithms employed are to base 10, this rate is expressed in decimal units of information per second, written here DU/sec. In formal notation, the average rate of information-output as measured in these experiments is given by the formula

$$-\frac{1}{T}\cdot\sum^{M}(n_i.\log p_i)$$

for an utterance of duration T seconds.

The two principal points to be made in this section are, firstly that the information-output rate is almost always lower in brain-damaged patients than in young normal adults; and secondly, that a distinct pattern, or "behaviour", can be discerned in the response of this parameter (C) to the imposition and withdrawal of restrictions.

In Table I are given, run by run in DU/sec., the values of the information-output rate for the normal and brain-damaged subjects. The lowest output-rate given in any run by any normal subject (Run 4 of J.F.) is italicized and the same has been done for all runs by brain-damaged patients which exceed this value. The various subjects have been ranked according their "personal mean" information-output rates averaged over all five runs. It will be seen that there is little overlap, either of the personal mean values or of the run-by-run values, between the two groups.

It is clear that the information-output rates of the brain-damaged group are in general considerably below those of the normal group. The two groups were not matched in any way; the normals were all young adult medical students but

TABLE I

Information Output Rates for Normal and Brain-Damaged Subjects

Normal Subjects	*Run 1*	*Run 2*	*Run 3*	*Run 4*	*Run 5*	*Personal Mean*
P.M.	1·883	1·825	1·227	1·066	2·029	1·646
R.J.	1·338	1·200	0·975	0·669	1·493	1·135
H.R.	1·055	1·037	0·927	0·919	1·584	1·104
D.B.	0·821	1·131	0·991	1·036	1·253	1·046
S.L.C.	0·893	1·024	0·972	0·733	1·210	0·966
C.R.	0·890	0·898	0·921	0·706	1·289	0·941
M.B.	0·908	1·069	0·711	0·562	1·114	0·873
G.	0·855	0·814	0·587	0·731	1·002	0·798
M.A.	0·653	0·544	0·574	0·636	0·796	0·641
J.F.	0·712	0·591	0·503	*0·419*	0·950	0·635
Group Means	1·001	1·013	0·839	0·748	1·272	0·979
Patients						
J.C.	*0·855*	*0·905*	*0·582*	*0·484*	*0·697*	0·705
F.C.	*0·617*	*0·610*	*0·542*	*0·508*	*0·946*	0·645
S.	*0·496*	*0·565*	*0·441*	*0·535*	*0·547*	0·517
J.P.O.	0·397	0·392	0·399	0·371	*0·466*	0·405
Le R.	0·237	0·287	0·238	0·146	0·300	0·302
R.M.	0·281	0·206	0·159	0·126	0·307	0·216
M.D.	0·205	0·200	0·182	0·122	0·295	0·201
G.B.	0·157	0·172	0·207	0·190	0·238	0·193
J.R.	0·134	0·094	0·087	0·203	0·139	0·132
E.H.	0·181	0·136	0·107	0·071	0·088	0·117
Group Means	0·356	0·357	0·294	0·276	0·402	0·342

the patients ranged in age from 23 to 60 and were very diverse in the probable levels of pre-morbid intellectual capacity. However, youth and a high native intelligence are generally agreed to be factors which mitigate the effects of cerebral lesions and it seems possible that the spontaneous information-output rate may be an overall measure of residual mental capacity, taking all factors into account.

Turning to the "behaviour" of this parameter, it will be seen that while the imposition of one restriction (Run 2) has little effect on the group mean output-rate, two and three restrictions (Runs 3 and 4) progressively reduce it; and on the withdrawal of restrictions (Run 5) there is a pronounced "rebound", the output-rate rising above its initial value. This collective behaviour is the same for both groups but the rebound is more marked for the normals. The rebound is seen in every normal subject without exception and also in every patient save J.C., who gave exceptionally high output-rates in Runs 1 and 2.

The rebound appears to be in the nature of a compensation for the reduced output-rates in the intervening restricted runs, for if the group mean for Run 1 is compared with the group mean averaged over all five runs, there is agreement to 1·7 per cent. for the normal group and to 4·2 per cent. for the brain-damaged group. Indeed, if for each subject of both groups the personal mean output-rate is plotted against the output rate in Run 1, a high degree of correlation is obvious, especially for the lower output-rates. This collective and individual tendency for the overall mean rate for all five runs to agree with the rate in the initial run, suggests strongly that the spontaneous rate of emitting information *tends to be a constant for a given brain* over a period of time, so that if conditions operate temporarily to reduce it there will be a compensatory rebound when these conditions are relieved. If this finding is applicable to other forms of information-output than the utterance of digits at random, it may have a bearing on a variety of practical problems in psychology.

Information-Output Rate (C) *and Symbol Rate* $\left(\frac{1}{t}\right)$

For brevity, the average rate of writing digits will be termed the symbol rate. If N digits are written in a run lasting T seconds, then putting $t = \frac{T}{N}$ for the average time per symbol, the symbol rate is $\frac{1}{t}$.

It might reasonably be anticipated that since symbols are normally used to convey information (in the lay sense) there would be some kind of relation between the symbol rate and the information-output rate, defined as above. However, this is not logically inevitable, because the average amount of statistical information conveyed by each symbol of an utterance depends on the relative frequencies of the different symbols and on the number of different symbol-types represented. It is quite possible to vary the total number of symbols in an utterance without affecting its total information content, and *vice versa*. The average information per symbol, according to the definition of the previous section, is

$$-\frac{1}{N}.\sum^{M}(n_i.\log p_i)$$

and this has its maximum value of log M when all M symbol-types occur equally often. It follows that the average information per symbol can be varied both by altering M and by favouring some symbol-types at the expense of others and that the information-output rate can in theory vary independently of the symbol rate. None the less a close relation between the symbol rate and the information-output rate has been found in these experiments, for almost every subject, whether normal or brain-damaged, and it is obeyed with precision in many cases. It follows that the systematic relation between these two parameters, which could not have been predicted on theoretical grounds, must be a reflection of the functional organization of the brain.

In 17 out of the 20 subjects considered here the information-rate increases linearly with the symbol rate for all five runs; therefore the presence or absence of restrictions does not affect this relationship. The general equation is:

$C = s\left(\frac{1}{t} - \frac{1}{t_o}\right)$, where s is the slope of the straight line relating the output-rate and the symbol rate and $\left(\frac{1}{t_o}\right)$ is the value which the symbol rate would have if the information-output rate were imagined to drop to zero. (This last situation is by no means impossible; it would be the case if the symbols uttered were all of one type, *i.e.* if $M=1$).

In nine of the ten brain-damaged subjects and in eight of the ten normals, this law is obeyed with varying degrees of accuracy, the main variations from subject to subject being in the values of the two constants s and t_o and in the range over which the two rates vary. The values of the two constants, and of their product (written C_o) are given in Table II. There was considerable uniformity among the normals, for whom the overall range of s was 1·10–1·22 (mean 1·16) and of t_o, 3·1–7·1 sec., (mean 5·5 sec.). For the brain-damaged subjects, s was still fairly uniform with an overall range of 0·96–1·25 (mean 1·10) but the values of t_o were much more variable.

TABLE II

Information Output Rate (C) and Script-Information Output Rate (C_o). Values of the personal constants s, t_o and $\frac{C_o}{C}$ —see text

	Normal Subjects					*Patients*			
	s	t_o	C_o	C_o/C		*s*	t_o	C_o	C_o/C
M.A.	1·15	6·7	0·17	0·27	S.	1·17	5·9	0·20	0·39
J.F.	1·22	7·1	0·17	0·27	M.D.	1·25	17	0·07	0·35
M.B.	1·17	5·0	0·23	0·26	J.P.O.	1·20	10	0·12	0·30
G.	1·20	5·6	0·21	0·26	J.R.	1·05	40	0·03	0·23
S.L.C.	1·17	5·0	0·23	0·24	J.C.	1·10	8·0	0·14	0·20
P.M.	1·16	3·1	0·37	0·23	R.M.	1·14	29	0·04	0·19
H.R.	1·12	5·3	0·21	0·19	F.C.	1·02	13	0·08	0·12
R.J.	1·10	5·9	0·19	0·17	Le R.	0·99	33	0·03	0·10
					E.H.	0·96	300	0·003	0·03
Group Means	1·16	5·5	0·23	0·25		1·10	50·7	0·08	0·21

In general, t_o is larger for the brain-damaged subjects than for the normals; the only patient to give a value in the normal range was S. This patient, one of the least seriously incapacitated, was a young American whose only neurological signs were of slight nominal aphasia and perseveration, when seen two weeks after the aspiration of a subdural haematoma. His progress had been so rapid that his family regarded him as normal, and within ten days of the date of the test he was considered normal on neurological examination. At the opposite

https://doi.org/10.1192/bjp.108.454.329 Published online by Cambridge University Press

extreme, with a t_o of 300 sec., is E.H., an ex-Foreign Legionary of the same age as S. who had a severe post-traumatic amnesia of ten months' standing. Even excluding E.H., the mean value of t_o (19·5 sec.) is well above the normal range. There is evidently a strong tendency for brain damage to increase t_o.

Table II also shows values of the product of s and $\frac{1}{t_o}$. If we write this product C_o the usual equation can be rewritten: $\frac{1}{t} = \frac{1}{s}(C+C_o)$. This form suggests that the symbol rate may be physiologically determined by the sum of the information output-rate, defined in the usual way, and another rate of uttering information, C_o, which is independent of the variables altered in this experiment. Now C is computed by counting the number of times each symbol-type occurs; it is concerned with the relative frequencies of choice of the various types and has nothing to do with the complexity of the symbols themselves. However, symbols such as digits are specific patterns and not merely random marks on the paper, so that some information must be intrinsically vested in them, quite apart from the specificity of the utterance which arises out of the diversity and choice of the symbols it contains. It is possible, in short, that C_o is a measure of the rate—constant throughout the experiment for each subject—at which the intrinsic *script-information* is being uttered.

Now s is little affected by brain damage and formally, the low values of C_o in this group are explained by the high values of t_o, since $C_o = \frac{s}{t_o}$. Physiologically, however, it is likely that brain damage primarily reduces the script-information output rate, so that the rate of uttering symbols when only one type is being uttered and the symbol-choice information output rate (C) is zero, will be low and t_o high. Table II shows to what extent C_o is reduced by brain damage.

Comparing the two groups collectively, C_o is in fact reduced to about the same extent by brain damage as was C. Excluding C.R. and D.B. (who did not show the usual law relating C to $\frac{1}{t}$) the group mean values for these parameters, in normal subjects, were respectively 0·23 DU/sec. and 0·975 DU/sec. For the patients the corresponding figures were 0·08 DU/sec. and 0·360 DU/sec., excluding G.B. for the same reason. The ratio $\frac{C_o}{C}$ for the normal group was therefore 0·24 and for the patients, 0·22. Similarly if these 17 subjects are taken individually and C_o is plotted against the personal mean C, the points lie symmetrically scattered about the approximate line $C_o = 0{\cdot}23$ C. Looking at the collective figures another way, for C_o the ratio between the patients' and the normals' group means is $\frac{0{\cdot}08}{0{\cdot}23} = 0{\cdot}35$ and for C, averaging over all five runs, it is $\frac{0{\cdot}360}{0{\cdot}975} = 0{\cdot}369$. Thus in the two groups considered, both C_o and C are reduced by miscellaneous brain lesions by about 64 per cent.

However, the ratio $\frac{C_o}{C}$, which is relatively constant for normal subjects

(0·17–0·27, mean 0·25) varies widely from one patient to another (0·03–0·39, mean 0·21) and this appears to indicate that if, as is likely, C_o measures the rate of uttering script-information, different brain lesions affect to differing extents the capacity to handle "shapes" and the capacity to utter information vested in the *choice* of these shapes. We should, in this case, expect a low ratio $\frac{C_o}{C}$ from patients with constructional apraxia and spatial disorientation. Several of the patients in this study showed minor degrees of finger-agnosia, inability to draw clock-faces and arrows and the like and E.H. was markedly disorientated. In particular F.C., who ranks high in every other performance-test described in this paper, ranks low with respect to the ratio $\frac{C_o}{C}$; this patient was recovering from the removal of an angioma from the left *gyrus angularis*, had suffered from typical "parietal" symptoms postoperatively and still showed a slight tendency to neglect the right hand.

"*Reversibility*"

In most psychological testing, allowance has to be made for various "learning" or "practice" effects. In this respect the brain appears to lack *reversibility*, an important property of conventional physical systems, which behave in constant and repeatable ways whenever the same set of experimental conditions is imposed. However, when the brain is performing "at random" there should be nothing to learn; it is perhaps for this reason that with the present technique, reversibility in certain respects can be shown to be a property of the normal brain—and sometimes of the damaged brain also.

By this is meant simply that for any given normal subject, at least one statistical parameter can be found which returns in the last run to within narrow limits of its value in the first run. Apart from the number of forbidden digits, or "restrictions", which is varied successively through the values 0, 1, 2, 3 and 0, the conditions remain constant throughout; consequently all the imposed conditions are the same for the first and last runs and if in these two runs the brain gives the same performance with respect to one or more criteria, it is behaving to that extent like a reversible physical system.

In Table III are given the run-by-run values, for each normal subject, of some parameter for which he was judged to be reversible. We shall not be further concerned with these parameters in the present paper and they are given here merely to illustrate the phenomenon of reversibility. It will be seen from the last column of the Table—which gives the difference between the initial and final values as a percentage of their mean—that the differences are small. (If they are expressed as percentages of the range over which the parameter varies in the course of the five runs, i.e. of the "span", they become very small indeed.) The value in Run 5 is sometimes greater and sometimes less than the value in Run 1; the average change for those cases which show an increase is 1·6 per cent. and for those which show a decrease it is 1·5 per cent. which suggests that unimportant random factors are responsible for the slight deviations from reversibility which occur.

The parameters which were found to be reversible will be seen, although moderately complex at first glance, to be made up of only a small number of measured or computed elements, namely, T, N, M, C, ΔA and ΔH. All of these, together with certain combinations of some of them, appear to be of physiological importance, especially

$$\Delta A \text{ and } \frac{\Delta H}{N} \text{ and } \frac{M}{\Delta A}\cdot\frac{\Delta H}{N}.$$

The second of these is the redundancy. The evidence that they relate to important functions of the brain is of the sort given in the discussion of the symbol rate, namely, that these quantities are often found to be systematically related by simple laws to others, such as C, or $\frac{\Delta A}{\theta}$ or θ (q.v.) to which, as we shall see below, it is possible to assign a precise neurophysiological meaning with a fair degree of confidence.

TABLE III

Various Parameters for which Normal Subjects were "Reversible"

Subject	*Parameter*	*Run 1*	*Run 2*	*Run 3*	*Run 4*	*Run 5*	Change, % of mean
P.M.	C.t	0·995	0·948	0·926	0·842	0·986	−0·91%
R.J.	$\frac{M}{\Delta A}\cdot\frac{\Delta H}{T}$	1·351	0·823	0·627	0·378	1·338	−0·97%
H.R.	$\frac{M}{\Delta A}\cdot\frac{\Delta H}{N}$	0·995	0·520	0·484	0·645	0·999	+0·40%
D.B.	$\Delta A.\frac{1}{t}$	0·221	0·125	0·035	1·178	0·223	+0·90%
S.L.C.	$\frac{M}{\Delta A}\cdot\frac{\Delta H}{N}$	0·584	0·905	1·088	0·506	0·567	−2·95%
C.R.	$\frac{\Delta A}{M}\cdot\frac{\Delta H}{T}$	·000638	·001200	·000798	·000000	·000640	+0·31%
M.B.	$\Delta A.$	0·198	0·035	0·748	0·019	0·195	−1·53%
G.	$\frac{M}{\Delta A}\cdot\frac{\Delta H}{T}$	0·861	0·780	0·390	0·643	0·898	+4·21%
M.A.	$\frac{\Delta A}{M}.t$	·000759	·001888	·000212	·001955	·000741	−2·40%
J.F.	$\frac{M}{\Delta A}\cdot\frac{\Delta H}{N}$	0·915	0·979	0·650	1·021	0·908	−0·77%

Theta (θ)

In the course of investigating the reversibility of various parameters it was found that one in particular, which will be termed *theta*, showed a fairly high degree of reversibility for some normal subjects (P.M., G., J.F.) and a marked tendency to reversibility for all but one of the normal subjects. Three of the brain-damaged patients also showed a fairly high degree of reversibility (F.C., Le R., R.M.). Taking the collective average values of *theta*, run by run, for the normal group excluding this exception (C.R.) the difference between the group mean value in Run 1 and the group mean value in Run 5 was 2·3 per cent. of the "span" between the highest group mean value (1·061 in Run 3) and the lowest (0·209 in Run 1). It was concluded that *theta* would repay investigation as a parameter of physiological significance.

The importance of *theta* was also suggested strongly by the fact that for the exception in the normal group (C.R.) *theta* again showed a systematic "behaviour", albeit a different behaviour from the reversibility seen in the majority of cases. For the subject C.R. it was found that the reciprocal of *theta*, $\frac{1}{\theta}$, increased linearly in relation to the number of runs performed, that is, to the length of time spent in writing digits, with or without restrictions. This same linear increase of $\frac{1}{\theta}$ with practice has been found in several other normal subjects, in experiments where the subject writes ten or more runs (all of the same duration, 60 or 120 sec.) of which the first four or five are written under the same conditions as Run 1 and Run 5 of the standard experiment. In subsequent runs certain additional conditions were imposed which sometimes but not always obscured the linear rise of $\frac{1}{\theta}$ with practice.

It seems clear that *theta* may behave in at least two different ways although it relates to some definite mental (i.e. cerebral) function. Inspection of the formal expression which defines *theta*, namely:

$$\theta = \frac{t}{M}.\text{antilog}\Delta A \textit{ or } \frac{T}{N.M}.\text{antilog}\Delta A$$

has suggested a possible theoretical model for this function, which will be presented below.

TABLE IV

Reversibility with respect to Theta in Normal and Brain-Damaged Subjects

Normal Subjects	*Run 1*	*Run 2*	*Run 3*	*Run 4*	*Run 5*	Change, % of span
P.M.	0·054	0·685	1·000	0·119	0·068	+ 1·5%
R.J.	0·080	0·207	1·476	1·860	0·130	+ 4·7%
H.R.	0·101	0·603	0·670	0·552	0·079	− 3·7%
D.B.	0·221	0·118	0·136	0·933	0·117	− 12·7%
S.C.L.	0·573	0·108	0·128	0·891	0·671	+ 12·5%
C.R.	*0·484*	*0·308*	*0·218*	*0·182*	*0·130*	*−100* %
M.B.	0·171	0·107	0·795	0·224	0·138	− 4·9%
G.	0·156	0·180	3·461	0·401	0·177	+ 0·6%
M.A.	0·301	0·793	0·226	0·836	0·282	− 6·2%
J.F.	0·220	0·212	1·655	0·493	*0·240*	+ 1·4%
Mean (excluding C.R.)	0·209	0·335	1·061	0·701	0·211	+ 2·3%
Patients						
J.C.	1·39	0·185	1·21	1·41	3·31	+ 62 %
F.C.	0·301	0·442	1·70	5·46	0·209	− 1·8%
S.	19·8	9·82	3·88	3·31	8·10	− 71 %
J.P.O.	0·502	0·528	0·913	3·84	0·939	+ 13 %
Le R.	1·19	0·503	0·556	24·4	0·419	− 3·2%
R.M.	0·439	0·549	2·01	1·09	0·352	− 5·2%
M.D.	3·41	1·28	0·818	1·46	0·484	−100 %
G.B.	1·26	1·30	3·41	1·07	15·5	+ 99 %
J.R.	4·53	2·33	4·16	1·47	1·27	−100 %
E.H.	0·694	1·32	8·49	3·18	1·87	+ 15 %
Mean	3·35	1·82	2·72	4·67	3·25	− 3·5%

https://doi.org/10.1192/bjp.108.454.329 Published online by Cambridge University Press

The definition of the parameter ΔA is as follows. Supposing that any given symbol-type, which in general we may call the i-th type, has a statistical probability p_i in a given utterance, then the *avoidance* of this type is defined as $-\log p_i$. There is evidence from the phenomenon of "strategy" in verbal and numerical utterances (Thomas, 1960a,b) that avoidance is an important parameter of cerebral function. Computing the avoidances for each of the M types represented in the utterance and adding them together we obtain

$$-\sum^{M}(\log p_i),$$

a positive quantity which has its minimum value of M. log M when all the probabilities are equal. The difference between the observed sum of avoidances and the quantity M. log M, for a given utterance, is written ΔA and may be termed the Excess Avoidance. Thus

$$\Delta A = (-\sum^{M}(\log p_i) - M.\log M).$$

The Supervisor

The function which the writer believes to be reflected in the behaviour of *theta* is that of monitoring the output. It is, of course, known that some kind of monitoring or "feedback" activity accompanies most if not all forms of behaviour and the simplest imaginable way in which the utterance of symbols could be monitored would consist in registering how many of each sort were being uttered. The word "supervisor" has been coined to denote the mental function which must comprise one phase of this process, namely that of *matching each symbol uttered against one or other of the M different symbol-types which are being uttered* by some cerebral source independent of, or at any rate other than, the supervisor.

No assumptions are intended as to the topographical localization or dispersion of the neurones responsible for the supervisor function or for the generation of the symbols. It is, however, assumed that the supervisor has no "memory", so that its response to symbols presented "now" is not affected by the relative frequencies with which the different symbols have been uttered in the past. It is also assumed that the supervisor has a limitation, in the form of a finite reaction-time given by *theta*. In other words, *theta* is assumed to be the time required for one "supervisory act", i.e. for the supervisor to register the utterance of one symbol of a specific type. Since the supervisor can only respond once in every *theta* seconds, *ex hypothesi*, it is only a small additional assumption to say that when the symbol rate is such that more than one symbol is presented to the supervisor in the space of each reaction time, these serial events are not distinguished as to their order but are treated as if simultaneous. A similar limitation has been postulated in other domains of perception by Moles and to borrow a phrase (Moles, 1958) we may look upon *theta* as the duration of the moment "now" for the supervisor.

The situation may be visualized by imagining that the symbols are being uttered on a moving ticker-tape with M tracks (one for each type of symbol) at the rate of $\frac{1}{t}$ per second. In each time-epoch θ, the supervisor views simultaneously a length of tape bearing $\frac{\theta}{t}$ symbols, each in its appropriate track, spaced out along it at intervals corresponding to t seconds.

For a normal subject in the unrestricted conditions (Runs 1 and 5) *theta* is always less than or equal to t; consequently not more than one symbol is present on the imaginary length of tape viewed in each reaction time. Taking the special case where $\theta = t$ and exactly one symbol is viewed, it will be seen that the registering of this symbol consists in "recognizing", "selecting" or otherwise responding specifically to the particular track on which this symbol lies. Since there are M tracks and since the supervisor—having no "memory"—has no means of anticipating which track will be occupied by any symbol uttered, the information handled in each supervisory act will be log M units, for it is an axiom of information theory that in choosing one out of X equiprobable alternatives the information handled is log X.

Otherwise expressed, we may say that for each symbol on the tape, there will be M positions, all equally likely as far as the supervisor is concerned, which it might occupy and the supervisory act consists in identifying which of the M it does occupy. In the case where θ is greater than t the supervisor *views* more than one symbol on the tape in each reaction time but can only *register* one. Since the tape has M tracks and $\frac{\theta}{t}$ symbols are viewed in each reaction-time, the number of *positions* viewed will be $M.\frac{\theta}{t}$ and the supervisory act consists in identifying one of these. As all the positions are simultaneously viewed and as all the tracks are equally likely to contain the symbol registered, the information handled in the supervisory act will be that required for the selection of one out of $M.\frac{\theta}{t}$ equiprobable alternatives, i.e. $\log\left(M.\frac{\theta}{t}\right)$ units. This quantity reduces to log M for the special case where $\theta = t$.

At this point we make a single wholly arbitrary assumption; it is that the parameter ΔA measures the information handled in each supervisory act. The sole justification for this assumption is that it is fruitful in practice. Putting ΔA equal to $\log\left(M.\frac{\theta}{t}\right)$ and rearranging, we obtain

$$\theta = \frac{t}{m}.\text{antilog}\Delta A.$$

Since $t = \frac{T}{N}$ a more convenient expression for some purposes is:

$$\theta = \frac{T}{N.M}.\text{antilog}\Delta A.$$

In terms of this model we need only note at this stage that whenever θ is greater than t, the supervisor "views" in each reaction-time $\frac{\theta}{t}$ symbols (distributed among $M.\frac{\theta}{t}$ positions on the imaginary tape) but registers only one. Consequently, only one in every $\frac{\theta}{t}$ symbols of the utterance can be monitored and the supervisor is failing to perform its function satisfactorily, by definition.

The Supervisory Rate $\left(\frac{1}{\theta}\right)$ *and Information Feedback Rate* $\left(\frac{\Delta A}{\theta}\right)$

Several assumptions have been incorporated in the working hypothesis just put forward and their validity must rest in part on whether the hypothesis proves to be fruitful. Space does not allow all the evidence which indirectly supports the hypothesis to be considered here but two main lines of development must be touched upon.

The hypothesis sheds some light upon the behaviour of *theta*. If this parameter (which has the physical dimensions of time, since M, N and ΔA are pure numbers) relates to the reaction-time of a neurophysiological system without a "memory" then it is not surprising that it should show reversibility. On the other hand, the linear rise which $\frac{1}{\theta}$ sometimes shows with practice is also intelligible since $\frac{1}{\theta}$ is the rate of performing supervisory acts, or the rate at which the supervisor registers uttered symbols; we may call it the *supervisory rate* and express it in units of SA/sec.

There is no real contradiction involved in postulating that the same parameter of a cerebral system should have two distinct behaviours. In the strategy phenomenon (Thomas, 1960a, b) the avoidance may be found to vary in several different ways with respect to some other parameter, in different subjects or in the same subject at different times. The hypothesis of the rate-limiting process, put forward originally to account for "strategy", but probably applicable also to the study of calculation, suggests that two different aspects of the supervisor function may be rate-limiting in different circumstances, so causing *theta* to show more than one behaviour. The supervisor being an information-handling system, there must be at least two points at which a "bottle-neck" could dominate its performance—the input and the output. The former might, for example, correspond to the perceptual process involved in recognizing the monitored symbol and the latter to the secondary process of counting the symbols classified in this way.

Another aspect of the supervisor hypothesis is the following. If the fact ΔA is the amount of information handled in each supervisory act, then since each supervisory act required θ seconds, the rate at which the supervisor handles information will be $\frac{\Delta A}{\theta}$ DU/sec. This is, in the strictest sense, a "feeding-back" of information and for this reason $\frac{\Delta A}{\theta}$ has been provisionally termed the *information feedback rate*. This parameter shows several interesting features which are compatible with the meaning assigned to it in the supervisor hypothesis.

In the first place, it is reduced by brain damage, as may be seen from Table V. In this Table, as in Table I, the lowest value given in any run by a normal is italicized and so are all those values by patients which exceed this lowest normal rate. There is marked overlap of the two groups according to this test, but despite this fact the information feedback rate of the brain-damaged group, taking the overall group mean for all five runs, is only 30 per cent. of the group mean rate for the normals. The information feedback rate is therefore reduced by 70 per cent. for the present groups, by brain damage, which agrees fairly closely with

TABLE V

Information Feedback Rates for Normal and Brain-Damaged Subjects $\left(\frac{\Delta A}{\theta}\right)$

Normal Subjects	*Run 1*	*Run 2*	*Run 3*	*Run 4*	*Run 5*	*Personal Mean*
P.M.	1·589	1·635	1·123	0·206	2·143	1·339
C.R.	1·319	1·474	1·327	0·195	1·800	1·223
R.J.	0·365	1·960	0·806	0·594	2·315	1·208
H.R.	0·268	1·351	1·757	1·231	1·291	1·180
D.B.	1·201	0·883	0·590	1·030	1·498	1·040
M.B.	1·160	0·331	0·941	0·835	1·413	0·936
G.	0·849	0·819	0·382	1·147	1·459	0·931
M.A.	1·022	0·854	0·289	0·838	1·287	0·858
S.L.C.	1·308	*0·180*	0·355	0·882	1·360	0·817
J.F.	0·922	0·358	0·560	0·568	1·553	0·792
Group Mean	1·000	0·985	0·813	0·753	1·612	1·033
Patients						
F.C.	*0·801*	*0·958*	*0·574*	*0·260*	*1·366*	*0·792*
J.C.	*0·810*	*1·120*	*0·704*	*0·589*	*0·419*	0·728
J.P.O.	*0·622*	*0·528*	*0·613*	*0·306*	*0·707*	0·555
S.	0·104	*0·185*	*0·326*	*0·392*	*0·211*	0·244
G.B.	*0·244*	*0·280*	*0·258*	*0·297*	0·105	0·237
M.D.	*0·258*	*0·310*	0·157	0·103	*0·335*	0·233
Le R.	*0·374*	*0·226*	0·076	0·063	*0·186*	0·185
J.R.	0·180	0·120	0·123	*0·319*	*0·184*	0·185
R.M.	*0·216*	0·053	*0·249*	0·055	0·103	0·135
E.H.	0·112	*0·200*	0·119	0·109	0·108	0·110
Group Mean	0·372	0·398	0·320	0·249	0·372	0·341

the 65 per cent. reduction in the script-information output rate (C_o) and the 63 per cent. reduction in the symbol-choice information output rate (C).

Secondly, the behaviour of $\frac{\Delta A}{\theta}$ in response to the imposition of restrictions in Runs 2, 3 and 4 is qualitatively very similar to that of the (symbol-choice) information output rate. For both groups, the collective mean value of $\frac{\Delta A}{\theta}$ is only slightly affected by the first restriction, is progressively decreased by two and three restrictions and rebounds above its initial value in Run 5. This rebound is seen in every individual normal subject and in five of the ten patients. Furthermore, the group mean values of $\frac{\Delta A}{\theta}$ for all five runs (1·033 DU/sec. for normals, 0·341 DU/sec. for patients) agree quite closely with the group mean values for Run 1 only (1·000 DU/sec. and 0·372 DU/sec. respectively) implying that the "rebound" phenomenon is once again compensatory in nature, although the rebound is evidently rather less brisk in the brain-damaged group, and that the hypothetical information feedback rate, like the information-output rate, tends to be held constant over a period of time.

The various correlations and parallels which have been described between the three information-handling rates

$$C, C_o \text{ and } \frac{\Delta A}{\theta}$$

seem to suggest that inherent and acquired differences in cerebral capacity tend broadly to be reflected to the same extent in all the information-handling functions of the brain, although as the last column of Table II shows, one function may nevertheless be impaired more than another by a brain lesion. This may mean that a given function is carried on by neurones dispersed very widely over the brain but centred on a focal region, a view with which many clinicians would agree.

Many other observations might be quoted to show that when

$$\theta, \frac{1}{\theta} \text{ or } \frac{\Delta A}{\theta}$$

are plotted against other parameters of known or probable physiological importance, such as $\frac{\Delta H}{N}$ (the redundancy) or against each other, systematic relationships frequently emerge, indicating a structuration or pattern of organization of cerebral function. However the fertility of the supervisor hypothesis may be illustrated in another manner, for it has led to the evolution of a test which discriminates sharply between brain-damaged and normal subjects.

Cerebral Hysteresis (Y)

According to the supervisor hypothesis it is clearly undesirable for *theta* to be large, since a large *theta* means either that the symbol-rate must be correspondingly reduced or else that the utterance cannot be fully monitored. From their behaviour in these experiments, brain-damaged patients seem less able to monitor their utterance than normals; patients often seem genuinely surprised to learn that they have needlessly ignored certain digit-types, or written forbidden digits, or that they are adopting a stereotypy. They show a lack of insight into their own performance, which is, of course, in keeping with the fact that some degree of anosognosia is very commonly present in brain-damaged patients.

It is therefore compatible with the supervisor hypothesis that the values of *theta* given by brain-damaged patients are on the whole higher than those of normals (Table IV) and that, despite the lower symbol rates shown by patients, θ exceeds t far more often and to a much greater extent in brain-damaged subjects than in normals. Again, the degree of reversibility of θ in individual patients is much less than in normals and it seems that, whatever the reason, the mutual adjustment of *theta* and the symbol rate is impaired by cerebral damage.

A simple graphical technique was therefore developed by which the degree of this mutual maladjustment might be measured. This consists in plotting θ against t, for the subject in question, joining the five points together in the order of performance of the corresponding runs and finally joining the point for Run 5 to the point for Run 1. The area enclosed—which may be in one or more segments—is then measured by the method of counting squares.

If θ and t are closely adapted to each other so that changes in the one cause the other to change by a corresponding amount in the same direction the enclosed area will be small, even if θ and t vary over a wide range. On the other hand, a large area will mean either that θ and t vary independently, or that the one only follows the other after a time-lag. The second interpretation is suggested by the fact that *theta* tends to show a lower degree of reversibility in brain damage, which is also associated with large areas according to the present test. For this reason, it may perhaps be thought appropriate to apply the term "hysteresis", borrowed from physics, with its implication of *sluggishness*, to the maladaptation of *theta* and the symbol rate which a large area denotes. Since θ

and t are both times, the area will have the units of (sec.^{2}) and it will be convenient to assign to it the symbol Y.

Table VI shows the values of Y in sec.^{2} for each of the two groups and it will be seen that a striking discrimination between the normal and brain-damaged subjects is achieved, with respect to this parameter. It is evidently the most delicate test for brain damage of any presented in this paper.

TABLE VI

The Cerebral "Hysteresis" (Y) in Normal and Brain-Damaged Subjects

Normal Subjects	*Y sec.^{2}*	*Patients*	*Y sec.^{2}*
G.	0·030	J.C.	0·86
C.R.	0·045	R.M.	1·1
S.L.C.	0·045	S.	1·3
D.B.	0·060	F.C.	1·5
H.R.	0·075	M.D.	1·6
M.A.	0·095	J.P.O.	1·6
R.J.	0·16	J.R.	3·0
M.B.	0·18	Le R.	3·5
P.M.	0·19	G.B.	7·0
J.F.	0·19	E.H.	21

N.B. To 2 significant figures.

Several points arise from this result. For example, the patients of the brain-damaged group were by no means all clinically alike, yet every one gives a value for Y which is well above the normal range. Apparently this form of impairment of supervisor function occurs with many, if not all, kinds of cerebral lesion, a conclusion which agrees with the way in which C, C_o and $\frac{\Delta A}{\theta}$ are all reduced to about the same extent in the patient-group as a whole, since it tends to confirm the notion that different cerebral functions are dispersed widely over the brain.

Secondly, the two highest values of Y were given by G.B. and E.H., who were the only cases of post-traumatic syndrome in the group. Both showed to a marked extent the behaviour commonly seen in this condition, which is often labelled "hysterical overlay". Now the essence of true conversion hysteria is an absence of insight into the mental processes and motives which give rise to the hysterical symptom; if the supervisor function revealed by the study of parameters such as θ, $\frac{\Delta A}{\theta}$ and Y is the same as that which is responsible for "insight" into other and more complex forms of behaviour than the utterance of symbols at random, it may be that a high value of Y or a low value of $\frac{\Delta A}{\theta}$ denotes an impairment of insight in the broader sense. If this view is correct it means that organic lesions can cause a genuine disorder of cerebral function which shows itself as a tendency towards the "hysterical" pattern of behaviour—a belief which is already held by many, especially in connection with encephalitis.

Finally, it must be stressed that the validity of the hysteresis technique depends on the validity of each of the five runs; if any one of them is vitiated the value of Y is meaningless. The one patient who has been excluded from this study, as already explained, obeyed strict serial perseveration throughout Run 5 and his value for Y was well *below* the normal range.

6A

Summary

A simple paper-and-pencil technique is described in which normal and brain-damaged subjects write digits one by one, at random, in five timed runs. Restrictions are imposed in Runs 2, 3 and 4, where the subject is forbidden to use certain digits.

Several statistical parameters of the resulting utterances are defined, shown to have characteristic "behaviours" and interpreted in terms of information theory. The *information output rate* (C) increases linearly with the *symbol rate* $\left(\frac{1}{t}\right)$ in 85 per cent. of all subjects, and the *script-information output rate* (C_o) can probably be deduced from this relationship. Restrictions reduce C and their withdrawal causes a "rebound" in every normal subject.

"Reversibility" is illustrated. The parameter *theta* (θ) is defined and shown to have a "behaviour". It is substantially reversible for most normals and some patients.

The "Supervisor" is postulated as a specific mental function—that of monitoring the output—and *theta* is interpreted as the reaction-time of the Supervisor. Certain implications are discussed and the *rate of information feedback* through the Supervisor $\left(\frac{\Delta A}{\theta}\right)$ is shown to react to restrictions in qualitatively the same manner as the information output rate (C).

Comparing the two groups of subjects, brain damage reduces C, C_o and $\frac{\Delta A}{\theta}$ by 63 per cent., 65 per cent. and 70 per cent. respectively. Subject by subject, combining both groups, there is obvious correlation between each pair of these three information-handling rates, taking personal mean values of $\left(\frac{\Delta A}{\theta} \text{ and } C\right)$ but the ratio between any two rates may vary; the ratio $\frac{C_o}{C}$ varies more widely among this miscellaneous group of patients than among the normals.

Brain damage also increases θ, reduces the reversibility of θ and tends to make θ exceed t. It is argued that impairment of the Supervisor is reflected in a maladaptation of θ and t. The "hysteresis" (Y) which measures this maladaptation is shown to discriminate very sharply between normal and brain-damaged subjects.

Acknowledgements

This investigation was assisted by the award of an M.R.C. Exchange Scholarship and was carried out at the Centre de Langage, Hôpital de la Salpêtrière, Paris. My thanks are due to Prof. F. Lhermitte, who provided every facility, and to Dr. Tissot, who selected the patients, for many fruitful hours of discussion.

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