BRAIN AND COGNITION 27, 147–179 (1995)

A Model and Diagnostic Measures for Response Time Series on Tests of Concentration: Historical Background, Conceptual Framework, and Some Applications

GERARD J. P. VAN BREUKELEN

Department of Methodology and Statistics, University of Limburg, Maastricht, The Netherlands

AND

EDWARD E. CH. I. ROSKAM, PAUL A. T. M. ELING, RONALD W. T. L. JANSEN, DANIËLLA A. P. B. SOUREN, AND JACK G. M. ICKENROTH

The Nijmegen Institute for Cognition Research and Information technology, Department of Psychology, University of Nijmegen, Nijmegen, The Netherlands

Based upon classical hypotheses about accumulating mental fatigue and distraction and its effect on response times, put forward in late 19th and early 20th century papers, a mathematical model is proposed for response times on tests of speed and concentration. The model assumes the random occurrence of very short distractions during information processing. It explains fluctuation and the increasing trend in response times on successive equivalent task units and leads to some simple diagnostic RT measures of speed and concentration as alternatives to the mean RT.

A review is given of several experimental applications of the model, with subjects with and without concentration problems, using cancellation and digit addition tasks. The results demonstrate the potential usefulness of the model and the diagnostic measures derived from it. As predicted by the model, prolonged task performance yields an increasing trend in RT mean and variance that can be strongly reduced by giving very short resting periods very frequently, and to a lesser extent also by task alternation, but not by simply motivating the subjects to concentrate. Some practical implications for the administration and scoring of

Part of this study was supported by Grants 560-267-003 and 560-267-031 from the PSYCHON foundation of the Netherlands Organization for Scientific Research (N.W.O.) to Edw. Roskam (project supervisor). Address reprint requests to Gerard J. P. Van Breukelen, Dept. of Methodology and Statistics, Faculty of Health Sciences, University of Limburg, P.O. Box 616, 6200 MD Maastricht, The Netherlands.

0278-2626/95 $6.00

tests of speed and concentration are discussed, as well as limitations of the present results and the complementary relation of our approach to popular ones such as "stage analysis."

INTRODUCTION

Psychological tests evaluating mental speed (Donders, 1868) and concentration are commonly used in clinical settings to detect different types of brain (dys)functioning. They are also used in schools, either to see whether a child with learning problems has an attentional deficit or as part of a test of general intelligence. In fact, correlations near .50 have been reported between measures of concentration and measures of IQ (Cornelius, Willis, Nesselroade, & Baltes, 1983; Jensen, 1982; Kaufman, 1975).

Although intuitively sensible testing and scoring procedures exist for response time (RT) tasks for the evaluation of attentional disorders, these are not founded on an explicit RT model or an unequivocal definition of concentration. The same holds for most experimental studies using RTs. In studies of sustained attention, deterioration of RT performance as a function of time on task is attributed to "loss of attention," "fatigue," or "boredom," but a formalization of these concepts is not given. Many other RT studies focus on the mean RT, simply ignoring RT variance and trend. As a result, in psychodiagnostic as well as in psychonomic literature confusion exists about what aspect of performance is referred to by "attention" and "concentration:" mean RT, RT variance, RT trend, or even response accuracy?

The present paper is an attempt to help improve the study and measurement of concentration and speed by formulating and applying a statistical model for response times obtained on a series of at least 20 equivalent task units. Examples of such tasks are cancellation, digit addition, and symbol substitution tests. The model is a mathematical formalization of some classical hypotheses about accumulating mental fatigue and distraction (see e.g. Donders, 1868; Obersteiner, 1879; Oehrn, 1895; Kraepelin, 1902; Ribot, 1902; Nayrac, 1914; Dürr, 1914; Henning, 1925; Peak & Boring, 1926; Spearman, 1927; Dumas, 1934; Bills, 1931, 1935, 1964; Mowrer & Jones, 1943; Huiskamp & De Mare, 1947; Hull, 1951; Broadbent, 1958; Foley & Humpries, 1962; Bertelson & Joffe, 1963; Sanders & Hoogenboom, 1970). It explains the presence of variation and the increasing trend in response times of a given subject on successive equivalent task units. It also makes a clear distinction between speed and concentration and thereby leads to modified administration and scoring procedures. Among others, it assumes that the RT mean is a mixture of speed and concentration and is therefore not easily interpretable. As such, our model is complementary to most current information processing approaches which start by taking the RT mean as a dependent variable, and it may illustrate the usefulness of formal models in general as an aid in studying human performance.

When looking back at studies on attention and disorders of attention as described in the literature at the end of the 19th century and at the beginning of the 20th century, one may distinguish between studies on "apperception" and those investigating "fluctuations" or oscillations of attention. The former may be regarded as studies on selective attention and processes that may be subsumed under the heading "perception." The latter can be regarded as investigating what current authors would probably refer to as sustained attention, vigilance or (tonic) alertness. Today we tend to associate the notion of attention more closely with selective attention, the apperceptive aspects. However, the reader should keep in mind that in the 19th and early 20th century literature "Aufmerksamkeit" or "concentration" primarily referred to a subject's capacity to perform a task for a relatively long period, and in these studies frequently cancellation tasks were used. "Being concentrated" was similar to "keeping a particular idea in consciousness," and "distracted" referred to the situation that a particular idea in consciousness was replaced by another, which was assumed to be a normal phenomenon: "There is no such thing as voluntary attention sustained for more than a few seconds at a time," James (1890) remarked. The present paper concerns this sustained attention or "concentration," not the issue of selective attention.

The structure of the paper is as follows: First, a sketch is given of a particular test of concentration used in several of our experiments. With this test in mind, a historical survey is given of papers that already contain the basic ideas behind the present model. Second, the model itself is explained and simple diagnostic RT measures are derived from it. Third, a review is given of several experimental applications of the model and the measures. Finally, the empirical support for the model is summarized and discussed, as well as some practical implications for testing speed and concentration, some limitations of the present results, and the complementary relation of our approach to popular ones.

THE BOURDON TEST AND SOME HISTORY

In Dutch hospitals and schools, concentration is often assessed with the "Bourdon" cancellation test, named after the French psychologist Bourdon (1860–1943), who used letter cancellation tasks to study visual discrimination (Bourdon, 1895). However, the Dutch Bourdon tests are based on the dot pattern task described by Abelson (1911), introduced in Holland by the psychiatrist Wiersma in his studies on attention in epileptic and psychiatric patients (Wiersma, 1910). In these tests, patterns of three, four, or five dots are presented and the subject has to cancel all patterns of four dots but ignore the other types. Figure 1 shows a sample

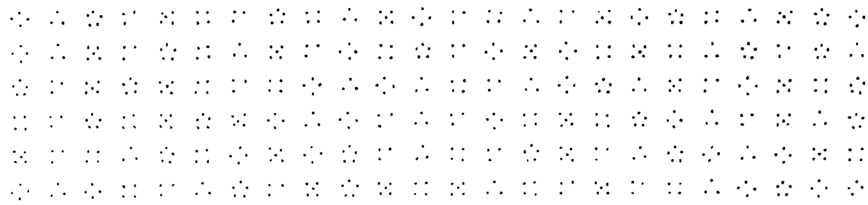

FIG. 1. Sample of a parallel test version of the Bourdon–Vos concentration test for children.

of the Bourdon–Vos test for children (Vos, 1988). In Germany a similar test is known, the "d2 test" of Brickenkamp (1962). This test consists of sequences of the letters p and d, with 1, 2, 3, or 4 bars above and/or below the letter. The letters d with two bars are the targets to be crossed, hence the name d2 test. The studies reviewed in the present paper were limited to the Bourdon–Vos test and a digit addition task, but the model, experimental design, and statistical analyses can be applied to other tests, such as the d2 test, just as well, provided that response times are recorded.

The Bourdon–Vos test consists of 33 lines containing 24 dot patterns each that are equivalent with respect to the frequency of each dot pattern. Response times (RTs) are recorded per line, which yields 33 RTs per subject. Accordingly, in the present paper RT does not refer to the latency of a single response to a stimulus such as a dot pattern, but to the time to perform a task unit of, for instance, 24 dot patterns. The rationale for measuring RTs per task unit instead of per stimulus is given in the quotations below and under the General Method section of our paper.

The minimum time needed by a given subject to process a test line can be assumed to be roughly constant across successive lines, and the RT variance across lines, which is one of the test scores, is assumed to reflect fluctuations in concentration. This is clearly illustrated by Huiskamp and De Mare (1947):

> . . . to obtain an impression of the subject's ability to concentrate. This ability is reflected by the regularity of the times needed to complete each test line. (p. 75, translation by the authors)

These authors also acknowledged the importance of equivalent task units, such as equivalent test lines rather than single dot patterns or randomly constructed lines.

> . . .we must be sure that the observed RT fluctuations are solely due to changes in the subject's concentration . . . it is necessary that we use material that in itself does not cause fluctuations in the response time per line. Each line must make the same demands on the subject. (p. 75)

The relation between *RT variance* and lack of concentration was already recognized in the 19th century by Donders (1868) and by Obersteiner (1879). In his classical study of the duration of mental processes, Donders (1868) observed

> For the duration of the mental processes I attached particular value to the minima found [i.e., the lowest RT of a given subject on a given type of stimulus, the authors].
>
> Distraction during the appearance of the stimulus is always punished with prolongation of the process. In this connection, however, it is clear that the *minima found are the purest values:* they represent the smoothest and most undisturbed course of the process. (p. 428)

A few years later, in a study of attention, Obersteiner (1879) wrote

> In the following experiments we seek to determine the *minimum period necessary for a given psychical act* in different persons, and next to ascertain under what conditions a distinct retardation is observed. This retardation stands in inverse proportion to the intensity of attention. . . . these differences in the reaction-period which may serve directly as the measure of attention. . . . (p. 444).

Obersteiner (1879) made a very clear distinction between this *minimum RT* on the one hand, which he thought would be affected by grave organic degeneration of the brain, and intra-individual *deviations* from this minimum time on the other hand, which he attributed to attentional problems due to internal causes like headache and external distractors like music.

The experiments on which Donders and Obersteiner based their theories were very original, but admittedly somewhat primitive according to present standards, being limited to only a few subjects, small numbers of RTs, and 19th century devices for transmitting signals and recording responses.

Obersteiner studied signal detection RTs of subjects, who had to react by finger movement to the perception of a sound. He used an apparatus devised by the famous neurologist Exner and himself, called the Psychodometer. The subject had to indicate by a movement of his finger the exact moment at which he perceived a sound emitted by the apparatus. The instrument was capable of registration of intervals of time up to 1 msec. In what he calls experiments he typically registered 6 to 14 responses and determined the minimum and mean RT. In his review he reports these responses and describes results obtained in, for instance, a woman with severe headaches, his servant, and a colleague, who is tested while simultaneously a "tolerably strong induction current to the left arm" is applied or while an additional auditory, optical or cutaneous stimulus is presented. He reports that a practised scientific observer seldom exceeded the minimum reaction time by more than 40 msec, but also that RT mean and variance increased in the presence of external distractors such as soft music or the changing images of a kaleidoscope. He also reports a few clinical results: two patients in varying stages of general paralysis showed elevated minimum RTs, while a patient suffering from hallucinations showed normal minimum RTs but a larger RT variance.

Donders introduced his famous subtraction method for estimating the duration of the central processes of stimulus identification and response selection from differences between simple and choice RTs. Stimuli were electric impulses to the feet, red and white lights, and the sound of vowels. Responses were given by hand or by voice. For his RT recordings, Donders used ingenious devices of which details are given in the appendix to his paper.

Later studies became increasingly sophisticated, relying upon somewhat larger numbers of subjects, much larger numbers of RTs, and—after World War II—stimulus presentation and response recording by means of computers. But these studies supported the basic notions of Donders and Obersteiner about distraction. Of particular interest are the studies by Kraepelin and his associates. In his chapter "Die Arbeitscurve" ("The performance curve") in the Festschrift for Wundt (1902), Kraepeling clearly shows his awareness that the time a subject needs to perform a certain task may be decomposed into several factors. In his studies Kraepelin typically asked subjects to do simple additions written on sheets of paper for approximately 90 min. He plotted the number of sums completed per 5 min. In the final part of his paper he claims that the observed curve is influenced by practice (Übung), adaptation (Gewöhnung), stimulation (Anregung), fatigue (Ermüdung), and will power (Willenspannung). He even estimates specific functions for these factors in such a way that added together, they produce the observed curve.

Voss (1899) observed that with prolonged work on a digit addition task the frequency of long RTs increased, whereas there was no change in the fastest RTs. He attributed this to attentional fluctuations in central processes. Oehrn (1895) also regarded RT variability as a measure of (lack of) attention. He believed that RT performance is mainly affected by practice on the one hand and mental fatigue on the other hand. Using tasks like digit addition and letter search, he showed that rest pauses allowed the negative effects of fatigue on RTs to disappear while the positive effects of practice remained. Kraepelin (1913) and Hutt (1910) later reported this effect of rest to be smaller in psychotic patients than in healthy subjects (for a review of the work of Kraepelin, Oehrn, and Voss, see Eysenck & Frith, 1977).

In the present century, similar results were reported in studies of "mental blocks" during sustained task performance (Robinson & Bills, 1926; Bills, 1931, 1935, 1964; Broadbent, 1958; Foley & Humpries, 1962;

Bertelson & Joffe, 1963; Sanders & Hoogenboom, 1970). Mental blocks were roughly defined as RTs longer than twice the mean (or the median) RT of a given subject on a given task. The main results of these studies can be summarized as follows:

(i) During prolonged task performance of a given subject the short RTs remain the same, but long RTs appear with increasing frequency as a function of time on task;

(ii) This RT deterioration can be prevented, or at least reduced, by resting pauses as well as task variation.

These mental blocks were believed to be "brief involuntary resting pauses, necessitated by the accumulation of fatigue, or reactive inhibition" (Bills, 1964). This belief was clearly influenced by Hull's (1951) theory of reactive inhibition:

> Whenever a reaction (R) is evoked from an organism there is left an increment of primary negative drive (I_R) which inhibits to a degree according to its magnitude the reaction potential to that response. . . . With the passage of time since its formation I_R spontaneously dissipates. . . .

Similar ideas had already been expressed by Ribot (1902) and Spearman (1927). For instance, Ribot (1902) stated that

> Attention is an exceptional, abnormal, state that cannot last very long, because it contradicts the fundamental condition of psychic life: change. (p. 4, translation by the authors)

And

> Everyone knows by experience that voluntary attention is always accompanied by a feeling of effort that is proportional to the duration of the attention and of the difficulty in maintaining it. (p. 95, translation by authors)

Spearman (1927) looked upon RT fluctuation, or "oscillation" as he called it, as a new universal factor in addition to his general intelligence factor *g*, and associated it with attention and mental fatigue (pp. 326–327). The following words of Spearman show a striking resemblance to those of Ribot and Hull:

> . . . the occurrence of any cognitive event produces a tendency opposed to its occurrence afterwards. (p. 308)

and

> Usually hard work, we may suppose, produces an increased consumption of this energy, and thereupon a corresponding increase in recuperation. (p. 327)

In summary, it may be concluded that from Donders (1868) to Bills (1964), several authors translated concentration into RT variance and deterioration and made a distinction between the minimum RT and deviations from it, attributing these deviations to involuntary resting periods, necessitated by the accumulation of mental fatigue or "inhibition." Unfortunately, these old ideas were never formalized into an explicit RT model that could lead to unequivocal diagnostic measures. On the contrary, many psychologists nowadays appear to identify attention with speed and with the mean RT, regarding RT variance as a nuisance, and ignoring minimum RTs and non-stationarity of RT series, that is, RT trend. This paper tries to restore the old approach by introducing a mathematical formalization of it and deriving theoretically based RT measures from this formalization. Although this mathematical model is only an approximation of real test performance, and not a panacea, it helps to make notions about concentration more explicit. In this way, it may contribute to an improvement of testing and scoring procedures, and to a well-considered choice of RT summary measures in experimental and clinical studies of task and subject factors. As such, it is also an illustration of the merits of formal models in general.

Before discussing our "Inhibition model," however, we first want to prevent any possible misunderstanding about our use of the concept of "inhibition." It is obvious that the notion of inhibition plays an important role in a wide variety of current theories and studies of cognitive functions, in healthy subjects as well as in patients with brain dysfunctions. For instance, in the literature on the "attentional deficit disorder with hyperactivity," a problem with suppressing activity at almost every level of neurophysiological or neuropsychological organization has been assumed (Eling & Renier, 1981). In line with the views of David Ferrier (1876; for a historical analysis of the notion of inhibition up to that time see MacMillan, 1992), Luria (1973) conceived of the frontal lobes as the system that suppresses inappropriate behavior and therefore lesions to the frontal lobes lead to disinhibited or stimulus-driven behavior. Shallice's model of the supervisory system (Shallice, 1988) also makes use of both activation and inhibition, in a way that resembles its usage in neural networks in artifical intelligence studies. The work of Tipper (1985) on "negative priming"—in which he showed that in a visual selective attention task, naming of a picture was delayed when that stimulus had been an irrelevant stimulus on a preceding trial—is also based on a particular notion of inhibition.

As the notion of inhibition has been used in so many different contexts, the reader should be careful in transposing a particular conceptualization of the notion of inhibition to another research area. It is particularly in view of these semantic and conceptual ambiguities that we want to argue that a formal theory may be a better means to making progress in the area of attention. In the present model, Inhibition is simply the verbal label for a certain mathematical function.

THE INHIBITION MODEL

The core of the Inhibition model of Van der Ven, Smit, and Jansen (1989) (see also Van Breukelen, Jansen, Roskam, Van der Ven, & Smit, 1987) consists of two hypotheses that are closely related to the classical ideas summarized above.

1. DISTRACTION HYPOTHESIS. Response times consist of two components, mental processing time and distraction time. Distractions occur intermittently and at random while the subject is processing test times.
2. OVERLOAD HYPOTHESIS. Distractions are necessary resting periods that prevent an accumulation of mental overload. An increase of processing time will therefore lead to a simultaneous increase of distraction time.

The Inhibition model formalizes both hypotheses for the domain of routine mental tasks, such as concentration and speed tests. This formalization consists of a statistical model of which the parameters can be estimated for each individual test administration. Subject and task effects can then be studied at the level of these parameter values instead of the mean RT. Some of these paramaters are very closely related to the RT measures suggested by Donders (1868) and Obersteiner (1879). More specifically, the inhibition model assumes that

(a) The total RT of a subject on a task unit (such as a Bourdon line) is the sum of two components, processing time and distraction time. Distractions occur at random during the processing, and so each RT is the result of an alternation of processing and distraction periods (although some RTs may be distraction-free by chance);

(b) For a given practiced subject the total processing time needed to perform a particular cognitive procedure, such as the completion of one Bourdon–Vos line, is fixed in length and will be denoted as A;

(c) The incidence and the duration of distractions depend on two hazard rates,[1] or loosely speaking, tendencies:

(1) The tendency to switch from processing to distraction increases with rate μ_1 during processing (due to the accumulating overload), and decreases with rate μ_2 during distractions (which serve as resting periods). After a time t since the start of the test this tendency equals

$$\lambda(t) = \lambda(0) + \mu_1 T_p - \mu_2 T_d, \tag{1}$$

where $\lambda(0)$ is the initial value of the hazard rate or tendency at time 0,

[1] The hazard rate is defined as: $\lambda(t) = f(t)/[1 - F(t)]$, where $f(t)$ is the probability density function and $F(t)$ the cumulative distribution function of the duration of the current processing period (in case of $\lambda(t)$) or distraction period (in case of δ). For small Δ, $\lambda(t)\Delta = P(t < T < t + \Delta | T > t)$, the probability that a shift from processing to distraction occurs in the next time interval Δ, given that it has not occurred yet.

and T_p and T_d represent the total processing time and distraction time preceding time t;

(2) The tendency to switch back from distraction to processing is constant throughout all processing and distraction periods and will be denoted as δ.

The whole process is visualized in Fig. 2. The Inhibition model derives its name from the tendency $\lambda(t)$, which is the inhibition to continue the processing.

In summary, the Inhibition model contains five paramaters:

A = the processing time per task unit (the reason for not using a greek symbol for this parameter will become clear in the next section)
$\lambda(0)$ = the initial inhibition or tendency to stop processing
δ = the tendency to resume processing
μ_1 = the rate of inhibition increase during processing
μ_2 = the rate of inhibition decrease during distraction

The model assumptions listed above may need some clarification.

Assumption (a) implies an all-or-none process, which may be a simplification, but is completely in line with the ideas of Donders (1868), Obersteiner (1879), Bills (1931), and others. Moreover, a good strategy is to start with a simple model, and only modify it if there are strong empirical reasons to do so.

Assumption (b) implies that a practised subject will need roughly the same amount of processing time (not RT!) for each unit in a series of equivalent task units, such as the Bourdon lines. It can be shown mathematically that this processing time is well approximated by the subject's

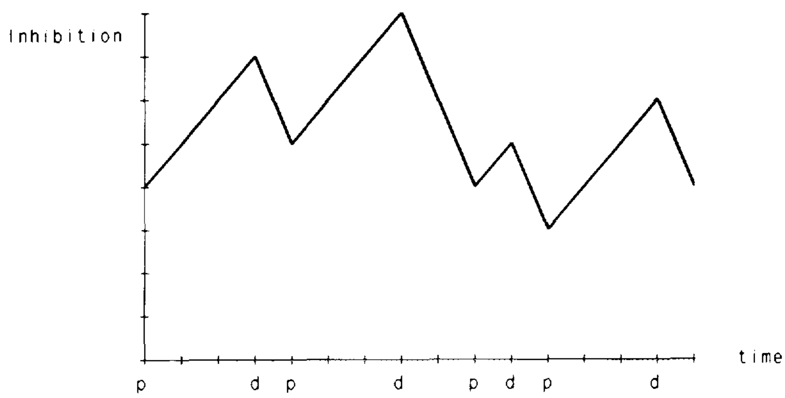

FIG. 2. The Inhibition process. Alternation of inhibition increase during processing (p) and inhibition decrease during distraction (d).

minimum RT in the total RT series if the series is long enough (say at least 30 RTs). The RT variance across successive lines is attributed to distractions, that is, to a lack of concentration (compare Donders, 1868; Obersteiner, 1879; Spearman, 1927; Huiskamp & De Mare, 1947). In the next section we return to this assumption and the necessary experimental conditions for its validity. Incidentally, a generalized model allowing processing time variability already exists (Van Breukelen, 1989a), but the problem of parameter estimation, in particular the mean processing time, has not been solved yet.

Assumption (c1) reflects the idea of accumulating overload that was already present in the work of Oehrn (1895), Ribot (1902), Spearman (1927), Mowrer and Jones (1943), Hull (1951), Bills (1964), and others. The inhibition to continue processing, or the tendency to become distracted, $\lambda(t)$, increases linearly during processing with a rate μ_1 and decreases linearly during distraction with a rate μ_2. We want to emphasize that in this paper, "inhibition" is a mathematical function (Eq. (1)), describing the probability that the subject will stop processing. Although the label "inhibition" has been and still is being, used in more than one sense by many authors, no connotation should be given to it in the present context.

Assumption (c2) is not very essential. The original Inhibition model of Van der Ven and Smit (1984) assumed that δ, which reflects the subject's tendency to resume the processing, increases during distraction and decreases during processing, which is the mirror image of assumption (c1). But this model was mathematically too complex and computer simulations showed it to yield the same type of RT series as the present version (Van der Ven & Smit, 1984).

How does the Inhibition model fit the general findings of RT fluctuation and deterioration? The model was originally developed to account for the presence of intra-individual RT variance on equivalent task units. The model attributes this RT variance to distractions, although we will see that the size of the RT variance does depend on the processing time A (which can be intuitively understood from the overload hypothesis). More interestingly, however, the Inhibition model predicts another empirical finding, that is, the occurrence of a monotonely increasing trend in the RT mean and variance. This prediction can be intuitively understood as follows: If the initial inhibition $\lambda(0)$ is low, distraction hardly occurs at the beginning of the task. Due to an increasing inhibition, distraction and consequently also the RT level and fluctuation will show an increasing trend. However, during distractions the inhibition decreases, and there will be a point where processing and distraction are in balance. The result is that the RT trend gradually flattens out, and that the RT series reaches a stationary level (Fig. 3).

From the model assumptions (a), (b), and (c), the following formal

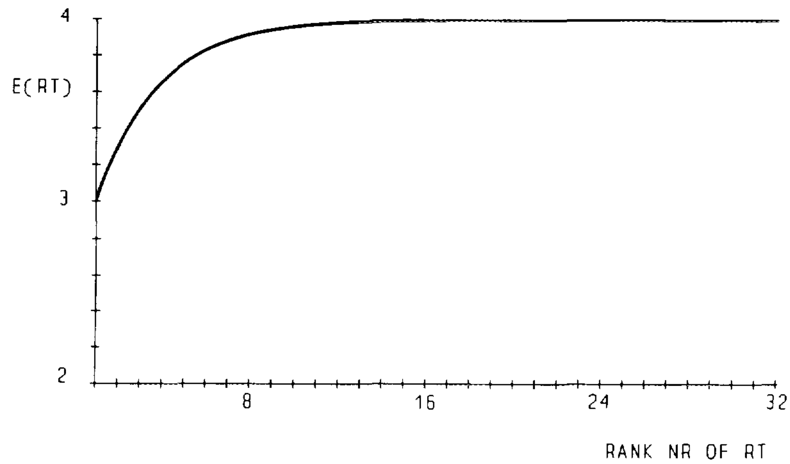

FIG. 3. The RT trend as predicted by the Inhibition model in case of a low initial inhibition ($\alpha = 3$, $\beta = 1$, $\theta = .7$): Expected RT (*Y* axis) as function of task unit nr. (*X* axis).

equation for the trend in mean RT can be derived mathematically (see Van Breukelen et al., 1987):

$$E(T_k) = \alpha - \beta\,\theta^{k-1}, \tag{2}$$

where k is the task unit nr. (e.g. the line number of the Bourdon test) and α, β, θ are not additional model parameters, but are specific mathematical functions of all five model parameters A, $\lambda(0)$, μ_1, μ_2, and δ and used for notational convenience:

$$\alpha = A^*(1 + \mu_1/\mu_2), \tag{3}$$

α represents the RT mean under stationarity, $E(T_{stat})$, and β and θ are trend parameters, and $\beta > 0$ (generally), and $0 < \theta < 1$ (always). For their precise relation to the model parameters, see the Appendix.

How these parameters can be estimated from observed RT series will be explained in the next section. Equation (2) may be understood as follows: α is the stationary RT mean that is reached after a fair number of items, for instance at $k = 10$. As Eq. (3) shows, this RT mean depends on the processing time, A, as well as on the rates of inhibition increase, μ_1, and decrease, μ_2; θ lies between 0 and 1 and determines how fast stationarity is reached. If θ is near 0, the term θ^{k-1} rapidly approaches 0 as the task unit (e.g. Bourdon line) number k increases and so stationarity is attained after a few RTs. If θ is near 1, the trend becomes almost linear and stationarity is postponed (the model excludes the values 0 and 1, see Appendix). For example, $\theta = .10$ yields 1, .10, .01, .001, .0001, but $\theta = .90$ yields 1, .90, .81, .73, .66, for the term θ^{k-1} of the first five RTs; β indicates the slope of the trend. If the initial inhibition, $\lambda(0)$, is low, then

$\beta > 0$, and an increasing RT trend results, since $\beta\theta^{k-1}$ goes from β (for $k = 1$) to 0 (large k). β also equals the total amount of RT trend due to distraction, that is, the difference between the stationary RT mean, α, and the expected RT on the first task unit, $\alpha - \beta$.

The Inhibition model predicts the same type of trend for the RT variance (the RT fluctuation between successive task units) as for the RT mean. The size of the stationary RT variance reached for large k depends on all model parameters except $\lambda(0)$. So it also depends on the processing time A (see the Appendix for equations; see Van der Ven *et al.*, 1989, or Van Breukelen *et al.*, 1987, for all proofs).

The next section discusses how the model can be applied to empirical studies and how meaningful measures of speed and concentration can be derived from it.

APPLICATION OF THE INHIBITION MODEL: GENERAL METHOD

Trend Analysis and Diagnostic RT Measures

The Inhibition model can be applied to individual RT series on tests such as the Bourdon, by trend analysis using Eq. (2) with the method of least squares, analogously to linear regression analysis: α, β, and θ are estimated from the data such that the resulting trend function fits the RT series as well as possible; that is, the sum of squared residuals (deviations between RTs predicted by (2) and actual RTs) is minimized. We next substitute the *MS*(residual) of trend analysis for the stationary RT variance, and the minimum RT for the processing time A, in the equations given in the Appendix. From these equations we can then calculate the distraction parameters $\lambda(0)$, δ, μ_1, μ_2 for each individual RT series and use them as test scores. This is of course only meaningful if the model is valid. An example of these calculations, based upon one of our experiments, is given in the Appendix.

However, in the sequel we will only use trend analysis and somewhat more global measures than the model parameters. The reasons for this are twofold: First, there are some statistical problems with the parameter estimation in case of short RT series and in case of interrupted-working conditions (which occur in some experiments). Second, there are several versions of the inhibition model (Van der Ven & Smit, 1984; Van der Ven et al., 1989; Van Breukelen et al., 1987; Van Breukelen, 1989a). All incorporate the same distraction and overload hypothesis and predict the same type of RT trend, but they differ in mathematical details. Only the properties and measures that are shared by all versions are of interest to us, since experimental and diagnostic conclusions should not depend on the particular mathematical version. To distinguish these global measures from the version-specific parameters, they will be presented by capital letters instead of greek symbols.

The following global RT measures can be derived from the model:

—the minimum RT, which roughly equals the processing time *A;*
—the difference between the (stationary) mean RT and the minimum RT, which estimates the mean distraction time per item, denoted as *D;*
—the ratio *A/D*, which indicates the proportions of processing and distraction time.

This ratio *A/D* is our measure of concentration and it will therefore be denoted as *C*. *A* and *D* are simply Obersteiner's (1879) measures. *C* can be derived from Eq. (3): in the stationary state, *D* equals $(\alpha - A) = A(\mu_1/\mu_2)$, which obviously depends on *A*. This is corrected by taking the ratio of *A* and *D*, which equals (μ_2/μ_1), and represents the amount of processing time per unit distraction time. This correction can be easily understood with the following example: Suppose two patients each have on the average a distraction of 1 sec after 3 sec of processing, so they concentrate equally well. Now suppose patient I has a processing time *A* of 12 sec., but patient II is slower and has $A = 18$. Then their total distraction time $D = 4$ and 6 respectively, but their concentration $C = 12/4$ and 18/6, which are both 3.

In summary, a subject's RT performance can be described in terms of speed (slowness) of processing *A* and concentration *C*. The RT mean (3) is a mixture of speed and concentration, and so a subject can be slow either due to a low processing speed or to an impaired concentration. The RT mean does not distinguish between these two. The RT variance reflects distraction, but its size depends on *A* (see the appendix). So the RT variance is also a mixture of speed and concentration.

The measures *C* and *A* were applied to several sets of experimental data, which are summarized in the remaining sections. RT series were analyzed for trend using Eq. (2), and the effects of several task factors on *A* and *C* were studied to test the validity of the model and of these measures. For example, it is generally assumed that lack of rest and the presence of distracting stimuli affect concentration. Usually, this is tested by looking at the mean RT. We look at *C* instead. However, before discussing these data we must first explain the general testing procedure by which they were obtained.

Testing Procedure

In experimental as well as diagnostic applications of the Inhibition model, it is essential to use a pure concentration test; that is, sources of major processing time variability between successive task units must be eliminated, such that RT fluctuations reflect distraction only, and that *A* and *C* are meaningful measures that can be estimated by using the minimum RT and the mean RT.

First of all, this means that the task units of the test must be equivalent (see Huiskamp & De Mare, 1947). The Bourdon test lines meet this condition reasonably well. In other tests, items may have to be grouped to get equivalent units and RTs must then be recorded per unit, not per item.

Second, we must eliminate major practice effects by giving sufficient practice, followed by some rest, before the actual test administration. As Oehrn and Kraepelin already recognized, the study of inhibition and the measurement of concentration should not be confounded by practice effects. A decreasing trend in the processing time due to practice effects would mask the increasing trend in distraction time due to inhibition, and all types of trend could then occur at the observable level of response times. Moreover, practice effects invalidate the estimation of A by the minimum RT and consequently the estimation of D and C.

Finally, the occurrence of serious speed–accuracy trade-off effects within a test administration must be checked. The minimum RT is used to estimate the processing time A, but if this minimum RT was obtained on a task unit in which many more errors occurred than in the other units, this suggests an incomplete processing of the task unit (see also Donders, 1868, p. 428). The minimum RT then underestimates the processing time and must be replaced by the minimum of all other RTs.

The next section gives a survey of experimental studies of the Inhibition model. These have been subdivided according to the experimental factor involved:

1. The first experiments make use of frequent and short resting periods to test the distraction and overload hypothesis, and the Inhibition model's prediction of trend;
2. Next, some experiments test whether subjects can voluntarily control their distraction (which is hardly to be expected according to the Inhibition theory);
3. Next, some studies of the effects of task mixing are summarized. These tested whether task mixing, like rest, can reduce overload and thereby distraction;
4. Finally, two practical applications of the model are discussed.

EFFECTS OF SHORT RESTING PERIODS

Several older studies of massed versus spaced practice on motor tracking and mental tasks requiring sustained attention, showed that performance can be improved by allowing subjects to rest (see Eysenck & Frith, 1977, for a survey). Studies of "mental blocks" showed that these blocks can be reduced or even prevented by giving a short rest after every 2 min (Bills, 1935; Foley & Humpries, 1962; Sanders & Hoogenboom, 1970). These effects are generally attributed to the accumulation of mental fatigue or "inhibition" during sustained work, and its dissipation during rest. This interpretation is perfectly in line with the distraction and overload hypotheses and with the Inhibition model: if distractions are necessary resting periods that serve to reduce the inhibition that accumulates during processing, then these distractions may be prevented or reduced by giving short resting periods, which serve as controlled distractions.

However, no formal model like the Inhibition model was fitted in these older studies. Instead, "Inhibition" served as a loosely defined concept to "explain" the effect of rest. Furthermore, resting periods were given after hours (studies of massed versus spaced work) or minutes (studies of blocks) of working. The present hypotheses concern distractions of which the frequency and duration are expressed in seconds and msecs., not minutes or hours. The Bourdon–Vos test, for instance, takes about 8 min to administer, and RT fluctuations and trend are present from the start. So resting periods after 2 min, as given in some of these older studies, would at best eliminate the most extreme distractions, apparent as outliers or "blocks." The experiments summarized below served to fill this gap between older studies and the Inhibition model, by giving very short resting periods very frequently and by studying the effects on RT trend and on RT measures derived from the model, in particular, C. To illustrate the general methodology of these experiments, we will discuss one of these in greater detail.

Effects of Short Resting Periods on Children with Learning Problems

An experiment was run with as task the pencil-and-paper Bourdon–Vos test, and as subjects all 18 children of a class of a dutch school for children with learning problems. This class consisted of 16 boys and 2 girls, aged between 9:6 and 11:6. Their learning problems concerned attention, language, and arithmetic. None of them had a sensory or motor handicap. Each child was tested twice, with a test–retest interval of 1 week, on Wednesday morning in a separate room at school. Each test was preceded by the instruction to work fast but without making errors, followed by five practice lines with feedback on errors, and a short rest of about 1 min.

Each child was tested once under the standard ("no-rest") conditions, where the entire Bourdon–Vos test of 33 lines of 24 dot patterns each had to be completed without any pause. The other test was under a "rest" condition in which each test line was given on a separate sheet and the child was allowed to rest between lines as long as he or she wanted, with a minimum of 5 sec. The order of both test conditions was counterbalanced between children.

This experiment was a direct test of the distraction and overload hypotheses as well as of the Inhibition model. The short resting periods were expected to function as controlled distractions, during which inhibition could decrease to about its initial level. The presentation of test lines on separate sheets in the rest condition was assumed to reduce noise from surrounding lines and thereby further reduce the inhibition (Kahneman, Treisman, & Burkell, 1983). These hypotheses lead us to the following prediction: In the no-rest condition an increasing trend in RT mean and variance across successive test lines was predicted (see Eq. (2)). In the rest condition however, the inhibition was expected to stay low due to the resting periods and so no (or much less) trend in RT mean and RT variance across lines was predicted for the rest condition. Consequently, RT mean, RT variance, and mean distraction time D were expected to be lower and concentration C to be higher in the "rest" condition than in the no-rest condition.

All individual RT series were analyzed for RT trend according to Eq. (2), by splitting the SS(total) into a SS(trend) and SS(residual) and testing the first against the latter with an F-test. In the no-rest condition 17 of the 18 RT series showed an increasing RT trend, of which 10 were significant ($p < .05$). In the rest condition only 5 series had an increasing trend, none of them significant.

Figure 4 shows the RT series obtained by averaging across all 18 children, for no-rest and for rest. The trend function explained 77% of the SS(total) of the average no-rest RT series ($p < .001$), and only 12% of the SS(total) of the average rest series ($p > .05$). This fits the prediction very well: an increasing trend in the "no-rest" series, and no trend in the rest series.

The Inhibition model predicts the same type of trend in the RT variance (see appendix). This prediction was also confirmed, through analysis of

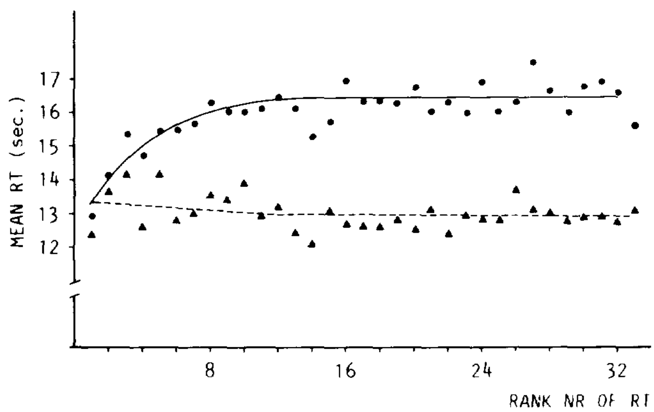

FIG. 4. Average RT series and fitted trend function in the "no-rest" (circles) and "rest" (triangles) condition.

the individual residual RT series, which are obtained by subtracting the fitted trend functions from the actual RT series. On the average, the residual variance increased from 3.2 in the first quarter of the series to about 5.0 in the other quarters, in the no-rest condition, and stayed at an average level of 2.1 in the rest condition.

The size of the rest versus no-rest effect was also evaluated by ANOVA of *A*, *D*, *C* and the *MS*(residual) after trend elimination. The latter is a better measure of short-term RT fluctuation than the raw variance ($s^2 = MS$(total)), which partly reflects the trend in mean RT. The results are summarized in Table 1. As predicted, *D* and the residual variance were lower, and *C* was higher, under rest than under no-rest. The small but significant effect on *A* may be due to rounding errors (RTs were measured in sec with a stopwatch), or to the fact that the minimum RT overestimates the true *A* if substantial distraction is present (which is the case in the no-rest condition, but not in the rest condition).

Since all distraction measures should perhaps be based upon the stationary part of the RT series only, a reanalysis was done with all measures except *A* based upon RTs 9 to 32. As might be expected from Fig. 4, this yielded somewhat larger effects of rest versus no-rest and the same conclusions as the first analysis.

As a check on speed–accuracy trade-off effects within and between tests, the number of omissions (uncrossed patterns of four dots) was analyzed (crossed non-fours hardly occur). No trade-off effects were found. In fact, accuracy was even higher under rest than under no-rest (overall total: 32 versus 126 omissions; $p < .001$ with the sign test). While our model is restricted to response time and makes no assertions on accuracy, a tentative interpretation is that distractions can lead to an incorrect transfer of outcomes from one processing stage to the other, such as from stimulus identification to response selection.

TABLE 1
Effects of Very Short Resting Periods

	Condition		
Dependent variable	No rest	Rest	F^*
Mean RT	16.0	13.0	103.27
Minimum RT (A)	12.0	10.9	20.63
Mean distraction (D)	4.0	2.1	70.65
Raw variance	4.9	2.3	57.87
Residual variance	4.1	2.1	35.24
Concentration (C)	3.2	5.7	54.55

Note. Effects of rest on RT performance on the Bourdon–Vos cancellation test by children with learning problems. Averages of RT measures and F test ($df = 1, 16$).
* $p < .001$ for all variables.

In summary, "rest" resulted in less distraction (D) and a better concentration (C).

Summary of Further Experiments with Short Resting Periods

Several other experiments with short resting periods have been run, of which a short summary will be given.

In the study described above, the effects of rest and of reducing external distractors (surrounding test lines) were confounded. A small-scale replication study by Souren (1989), in which both factors were separated, demonstrated that the resting periods and the presentation of test lines on separate sheets both contributed about 50% to the effects in table 1.

An earlier experiment, using a computerized Bourdon test and a computerized digit addition task (called the Pauli test, following Arnold, 1975) and student volunteers as subjects, yielded essentially the same results as the experiment above (Van Breukelen et al., 1987). The RT series were almost rescaled copies of Fig. 4.

An experiment by Vloet (1990) with a computerized Pauli test and student volunteers, compared no-rest performance with three rest versions: resting periods after each successive 3, 6, or 9 additions, with a duration inversely related to the frequency, such that the total resting time was the same for all three versions. RTs were analysed per set of 6 successive responses. Again, an increasing RT trend was found under no-rest, and concentration C was much higher for all rest conditions than for no-rest. Two new findings were that (a) in all rest conditions, there was an increasing RT trend across the (3, 6, or 9) responses between two resting periods, and (b) concentration was slightly higher in the conditions in which a rest period was given after 3 or 6 additions than after 9 additions. These findings are easily understood from the inhibition model assumption (c1): in the rest conditions, the (3, 6, or 9) stimuli between two successive resting periods constitute a very short no-rest series and will therefore show some trend, analogously to the no-rest trend, but at the micro-level (finding (a)). As the frequency of resting periods increases, there is less opportunity for the inhibition to increase, and so rest-3 and rest-6 will be more effective than rest-9 (finding (b)). These findings also imply that even very frequent resting periods do not eliminate distraction completely.

EFFECTS OF MOTIVATION

Van der Ven (1974) reported that children could be stimulated to increase their speed without loss of accuracy. This lead to the hypothesis that subjects can control their distraction, since a reduction of the processing time leads to a lower accuracy. This control hypothesis appears to be at variance with the overload hypothesis and its formalization, the inhibition model, unless we assume that inhibition can be controlled (see Eq. (3)). We therefore expected that motivation would not reduce distraction. The finding of Van der Ven (1974) could have been an artifact of practice, since all children had first been tested without motivation and without prior practice, and next under a more stimulating condition. Some new, counterbalanced, experiments were therefore run to test the control hypothesis properly. Again, one of these will be explained in greater detail to illustrate the general method and result.

Effects of Motivation on Children with Learning Problems

Subjects were another class of 14 boys and 4 girls with learning problems, from the same school and of the same age as in the experiment with resting periods. The procedure was also the same, except that (a) in the standard condition speed and accuracy were not mentioned in the instruction, and (b) the rest condition was replaced by an "incentive" condition where the instruction emphasized concentration to increase speed (decrease the mean RT) without loss of accuracy, and a competition was suggested with a class from another school. The test form was the same standard form with all 33 lines on a single sheet, for both conditions.

According to the control hypothesis subjects are able to keep their inhibition low, and so their RT series under "incentive" should look like that of the rest condition in Fig. 4. Their distraction D should be lower and their concentration C higher, under "incentive" than under "no-incentive." In contrast, the overload hypothesis and the Inhibition model suggest that such control may be impossible, and so the incentive should either have no effect or have a trade-off effect, that is, a decrease of the processing time A at the expense of accuracy. The RT series under incentive should then look like under no-rest (Fig. 4) and no-incentive and either coincide with the "no-incentive" series (if the incentive is ineffective) or lie below and parallel to it (if a trade-off effect occurs). The processing time A, and due to its dependence on A also the distraction time D, might then be lower but the concentration C not higher for incentive than for no-incentive.

Figure 5 shows the average RT series obtained in this experiment. The trend is increasing in both conditions, with 32% (no-incentive) and 69% (incentive) of the variance explained by the trend function, and the incentive curve lying just below the no-incentive curve. In the no-incentive condition 15 of the 18 individual series were increasing, of those, three significantly ($p < .05$). In the incentive condition all 18 individual series were increasing, of those, six significantly. In both conditions the residual RT variance after trend elimination showed a clear increasing trend.

These results are in line with the Inhibition model and contradict the

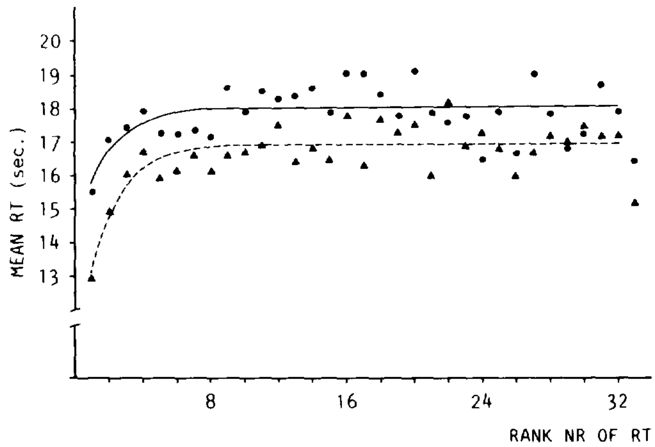

FIG. 5. Average RT series and fitted trend function in the "no-incentive" (circles) and "incentive" (triangles) condition.

control hypothesis. Further analyses of the RT measures supported this conclusion (Table 2): None of the RT variables was affected significantly or substantially by the incentive. The total number of omissions was 112 for no-incentive and 119 for incentive ($p > .70$ with the paired sign test). So if the incentive had an effect at all, it was a very small trade-off effect as much as a concentration effect.

The results of this experiment agree with those of an earlier study with a computerized Bourdon and Pauli task and students as subjects (Van Breukelen et al., 1987). In that study, the incentive consisted of a financial reward for improvement of speed without loss of accuracy. The resulting RT series looked very much like those in Fig. 5, and accuracy was lower in the incentive condition than in the no-incentive condition.

TABLE 2
Effects of Motivation

	Condition		
Dependent variable	No incen.	Incen.	F*
Mean RT	17.8	16.6	4.20
Minimum RT (A)	13.3	12.5	3.42
Mean distraction (D)	4.5	4.1	1.24
Raw variance	8.3	6.8	0.99
Residual variance	8.2	6.1	2.25
Concentration (C)	3.3	3.7	0.63

Note. Effects of motivation on RT performance on the Bourdon–Vos test by children with learning problems. Averages of RT measures and F test ($df = 1, 16$).
* $p > .05$ for all variables.

These results do not imply that distraction is always beyond voluntary control. But they do suggest that under standard testing conditions all controllable distraction is already minimized by the subject without any additional incentive. What is left then, is the type of very short distractions as assumed by the Inhibition model.

EFFECTS OF TASK MIXING

A deterioration of performance during prolonged work, as predicted by the Inhibition model, has been reported in many ergonomic studies of tasks lasting for hours (Taylor, 1966; Mackie, 1977; O'Hanlon, 1981; Hockey, 1983). This performance decrement is sometimes attributed to "boredom" rather than overload, that is, to the monotony of the task, and Mackworth (1969) considered it as an instance of neural habituation to prolonged stimulation. Task variation might then be expected to prevent or reduce this deterioration and, indeed, such an effect was reported by Robinson and Bills (1926). On the other hand, task variation makes work not only more interesting but also more demanding since the subject repeatedly has to "reset" his mind for another task, as one may recognize from daily life.

The two above-mentioned effects of task variation, prevention of boredom but also an increase of "work load," would seem to counteract each other at the measured level of RTs. However, they may be distinguished in terms of the measures derived from the Inhibition model. If task variation prevents "boredom" or "habituation," this might be expected to reduce inhibition and increase concentration C. The extra load of having to reset continually, on the other hand, might be considered as just an additional task component, resulting in a slight increase of the processing time A. This is, of course, only a tentative prediction. It is conceivable that for brain-damaged subjects, frequent task variation is itself distracting and leads to a lower C. Since the experiments summarized below were mainly run with healthy subjects, replications with neuropsychological patients will be necessary.

Homogeneous versus Mixed Tasks

A small-scale study of task mixing effects was run by Souren (1989), who retested six of the learning disabled children of the previous experiments twice in a counterbalanced experiment. Each child was tested once with the standard Bourdon test (Fig. 1) and once with a modified test form where all even lines had been replaced with six digit additions (see Fig. 6), since a preliminary test indicated that the children needed about the same time for six of these additions as for a single Bourdon line, that is, about 15 sec. The results of this mixture of the Bourdon and the Pauli test were as predicted: the RT series of the "mixed" condition showed

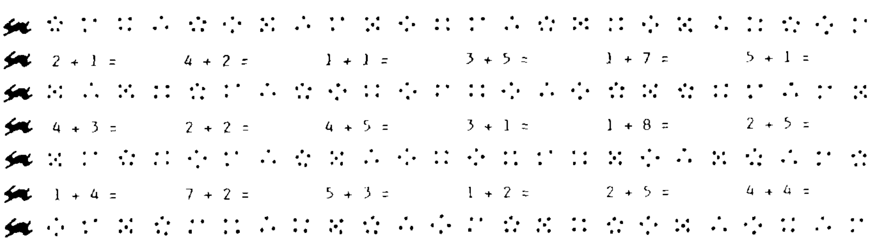

FIG. 6. Sample of the mixed task form used by Souren (1989). The "hares" were added to the original Bourdon–Vos test in all pencil-and-paper experiments. These had to be crossed by the child before starting to process the line. In this way the transition from one line to the next could be determined reliably.

less increasing trend than the standard series, and C was much higher (4.0 versus 2.4) and A slightly higher (11.8 versus 11.3) under "mixed" than under standard testing conditions. The mean RT was about 15.3 sec in the mixed condition against 16.4 sec in the homogeneous condition. The sample size of six children was too small to draw any definitive conclusion from this study, however.

Jansen and Roskam (1989) ran two similar experiments with students as subjects. As tasks, computer versions of the Bourdon, the Pauli, and Posner's (1978) letter-matching task were used. Again, task mixing reduced the amount of increasing RT trend and tended to increase C, indicating that subjects were less distracted in the mixed condition. In terms of RT mean and processing time A, the results were less consistent. This was probably due to the fact that conditions were not counterbalanced in one experiment, and that tasks were mixed in a quasi-random order, that is, every "line" of 12 stimuli consisted of 6 stimuli of each task, and these 12 stimuli were randomized. As a result, task alternation was almost unpredictable and occurred on the average after every two stimuli. If resetting one's mind to a new task takes some processing time, the overall effect of this type of task mixing on the mean RT may be either positive, negative or zero, depending on the sizes of the concentration and processing time effects.

This interpretation was supported by a recent experiment by Ickenroth and Roskam (in preparation), in which homogeneous task performance was compared with a random mix as well as a fixed mix of the Bourdon and the Pauli task. The fixed mix consisted of an alternation after every sixth response. Compared with the homogeneous condition, the random mix yielded less RT trend and a better concentration, but also a higher processing time and thereby a higher mean RT. The fixed mix yielded less RT trend and a better concentration, while leaving the processing time almost unaffected. The net result was a lower RT mean than in the homogeneous condition. In this experiment as well as in the pilot study of Souren (1989), the fixed-mix effect on RT trend was about one-third the size of the "rest" effect in our experiment with children (see Fig. 4 and Table 1).

Are Neural Processors and Inhibition Task-Specific?

The previous experiments showed similar effects of resting periods and task mixing (less or no increasing RT trend, a higher concentration), although the effects of rest were larger. One could argue that task mixing and rest come down to the same at a more fundamental level. One possible interpretation is that resting periods amount to task mixing, since during rest the subject is free to look at, or think of, other things. The other interpretation is that, on the contrary, task mixing amounts to rest, but then at the level of neural processors. If the two tasks appeal to different neural processors, such as a perceptual (Bourdon) and a numerical (Pauli) one, task mixing implies that one processor is allowed to rest while the other is working, and vice versa. Only peripheral (sensory and motor) systems have to work continuously. So if each processor has its own inhibition level, an alternation of tasks appealing to different processors leads to a simultaneous increase of the inhibition of the active processor and decrease of the inhibition of the inactive processor. The net result is test performance similar to that observed under "rest" conditions as far as central (as opposed to peripheral) processors are concerned. The fact that task mixing is less effective than rest seems to support this *processor-specific inhibition hypothesis*. It was therefore tested in two further experiments (Jansen & Roskam, 1989; Jansen, 1990), based upon the following reasoning: if the task mixing effect is due to an alternation between neural processors, each with its specific inhibition, the effect should depend on the type of task mixing: a mix of two perceptual or of two verbal tasks (same processors) should be ineffective or less effective than a mix of a perceptual and a verbal task (different processors). The results of these experiments (Jansen & Roskam, 1989; Jansen, 1990) were inconclusive, since the prediction was contradicted by one experiment, but confirmed by the other. However, in these two experiments random mixes (unpredictable task alternations) were used.

The recent fixed-mix experiment by Ickenroth and Roskam (in preparation), already mentioned in the previous section, allowed a new test of the hypothesis of processor-specific inhibition. It was tested against the *single inhibition hypothesis*, which assumes that there is only one single inhibition level, of which the rates of increase (μ_1) and decrease (μ_2) may depend on the activated processor. According to the processor-specific inhibition hypothesis, task mixing will reduce RT trend on both tasks if they appeal to different processors (which was assumed to be the case in this experiment, since the tasks were the Bourdon cancellation test and the Pauli digit addition test, respectively). In contrast, it can be shown mathematically that according to the single inhibition hypothesis, task mixing may reduce trend on one task while increasing trend on the other task. Overall, that is, averaged across tasks, mixing may or may not reduce RT trend compared with homogeneous work, depending on the specific parameter values.

The results of this experiment can be summarized as follows: For the Pauli task, the RT curves of homogeneous and fixed-mix looked somewhat like Fig. 4, that is, both started at the same RT level, but the increasing trend in the fixed-mix series was only half the size of that in the homogeneous series. For the Bourdon task the RT curves looked like Fig. 5, that is, both curves showed an increasing trend and were roughly parallel, with the fixed-mixed series lying slightly above the homogeneous series. Stated differently, task mixing reduced distraction on the Pauli task, while slightly increasing the processing time on the Bourdon task. Averaged across the two tasks, the fixed-mix condition showed the modest beneficial effect already reported in the previous section. These results are halfway between both hypotheses and therefore inconclusive, the more so as it is not entirely clear whether the Bourdon is really a perceptual task or perhaps a numerical one after all.

SOME PRACTICAL RESULTS

For proper diagnostic use of both tasks and concentration measures, more is needed than the experimental studies discussed so far. First of all, it is important that the measures C and A can be reliably measured. Second, they should be helpful in discriminating between different types of patients (compare Obersteiner, 1879). Although such studies have yet to be done, a few results can be reported.

Of all 36 children in our experiments, 18 also volunteered in the study of Souren (1989) 2 months later. Based on the results of the standard test conditions the following tentative retest reliabilities were obtained for the Bourdon–Vos test: .85 for the processing time A and .70 for concentration C and distraction time D. The number of omissions (uncrossed fours) had a reliability of only .46, which is in line with Kamphuis (1962) and Vos (1988) and suggests that unlike RT measures, accuracy is an unreliable diagnostic in Bourdon-like tasks.

A nice practical application of our measures was reported by Bruggeman, Eling, and Jansen (1990). They administered a computerized Bourdon test as well as the pencil-and-paper version to a group of 11 patients who were classified by psychologists as having concentration problems due to brain damage and a group of 10 patients without concentration problems. Although the study originally aimed at a comparison between the two test versions, additional analyses were done using the RT measures derived from the Inhibition model, with the following result: In the case of the computerized test, which had been preceded by a practice series, the concentration measure C turned out to discriminate significantly and better than any other test score between these two groups of patients. Furthermore, there was no group difference with respect to the processing time A, indicating that the group differences are due to distraction rather than "cognitive slowing." In the case of the pencil-and-paper test, which had been administered without extensive prior practice series, this result was not found. This suggests that if the test is administered properly, with a prior practice series and exact recordings of RTs, the test scores derived from the Inhibition model may be very useful for diagnostic purposes.

SUMMARY, PRACTICAL IMPLICATIONS, AND LIMITATIONS

We first summarize the empirical support for the model and the hypotheses that can be derived from the experiments reviewed in this paper, discuss some practical implications for speed and concentration testing, and finally discuss some limitations of the present results and the question of what needs to be done yet.

Our survey of experiments supports the following conclusions:

(1) Response time series on some typical concentration tests show a particular type of increasing trend. This trend can be explained by the Inhibition model;

(2) The distraction and the overload hypothesis are supported;

(3) The measure of concentration derived from the model appears to be reliable and valid, given certain precautions concerning the test administration, that is, prior practice and equivalent task units.

The Inhibition model correctly predicts trend in response time under standard (no-rest) testing conditions. It also explains the effects of rest and task mixing on the RT series, as well as the inefficacy of motivation.

The formally derived measure of concentration, C, appears to discriminate between task factors that are effective in increasing concentration (rest, task mixing, separation of stimuli) and factors that are not (motivation). It also appears to discriminate between patients classified as having concentration problems and patients without such problems. In some experiments, however, the results were less clearcut with respect to A and C than with respect to RT trend, possibly due to processing time variability which invalidates the present estimation of A and C, while leaving the type of RT trend unaltered (Van Breukelen, 1989a).

The present theory and data have some practical implications for the measurement of speed and concentration through RT recordings. With respect to the *testing procedure*, it is important that the test consists of equivalent task units (such as test lines of the same composition instead of individual stimuli), and that the actual administration is preceded by a practice series. Both requirements are necessary to prevent processing time variability and thereby to allow RT variance to be attributed to fluctuation in concentration. Only then can C and A be validly used.

With respect to the *scoring procedure*, care must be taken that the RT series are analyzed for trend, and that summary RT measures are based on an explicit and validated RT model, such as the inhibition model, instead of on intuition or tradition only. The presence of RT trend and RT variance, as well as the positive skew of empirical RT distributions (Luce, 1986), should be a warning against the uncritical use of RT means as the most important, or even the only, summary measure of RTs. A global and simple trend analysis can be done by comparing the averages across successive groups of, say, 10 RTs. A decreasing trend suggests that the practice series may not have been long enough to prevent trend in the processing time during the actual testing. This in turn implies that all summary measures, RT mean, and variance, as well as A and C, are confounded. In contrast, increasing trend indicates distractions due to accumulating inhibition and does not invalidate our summary measures A, D, and C, although the latter two should perhaps be based on the stationary part of the series only. With respect to the choice of a summary measure, the present model suggests that the commonly used RT mean is a mixture of processing speed (A^{-1}) and concentration (C) and may not be easily interpretable. The same holds for the RT variance (see Appendix). In this respect, A and C are better summary measures, at least given the precautions of equivalent task units and prior practice. It is an ironical fact that A and D ($= A/C$) were already distinguished more than a century ago by Donders and Obersteiner.

The present approach has its own limitations, of course. An obvious one is the fact that it does not deal with task decomposition into processing stages, such as by Donders (1868) and more recently Sternberg (1969). In fact, it is complementary to their popular "stage" approach by suggesting alternatives to the RT mean as dependent variable. For instance, a reasonable guess might be that task factors like stimulus discriminability and response modality, and subject factors like sensory handicaps will affect A rather than C, whereas the presence of distracting stimuli and the subject's mental state (headache, concussion) may be expected to affect C.

Another limitation concerns the subject population. Although some of our studies were based on subjects reported to have concentration problems, applications to people with different types and degrees of brain damage are still needed. It appears to be difficult to demonstrate specific attentional disurbances in certain patient populations (Brouwer, 1985; Van der Meere, 1988), but a recent study suggests that Sternberg's additive factor method may be useful in locating disturbances in specific processing stages by looking at interactions between task and subject factors (Shum, McFarland, Bain, and Humphreys, 1990). It will be interesting to see if the use of our RT measures in such studies sheds new light on the nature (speed A^{-1} versus concentration C) and locus ("stage") of attentional deficits in patient populations. We must observe, however, that the additive factor method is disputed (see Luce, 1986).

In a similar way, model-based RT measures may yield new insights into the effects of ageing on RT performance. Welford (1988) gives an interesting review of age effects on the parameters of Hick's well-known law. This law states that in choice RT tasks, mean RT increases as a linear function of the logarithm of the number of stimulus alternatives. It appears that ageing affects the intercept as well as the slope of this linear relation, but that the slope effect almost vanishes as a result of practice. It would be interesting to reanalyze such data in terms of our measures A and C. For instance, if C is constant across varying numbers of stimulus alternatives, Hick's law holds for A as well as for the mean RT ($= A^*(1 + C^{-1})$). His slope and intercept parameters can then both be decomposed into a processing and a distraction component. How will age effects be in terms of such measures?

Another important but unresolved question is that of the neurological foundation for the rest and mixed task effects. How can the inhibition model be interpreted in terms of neurological processes? It is tempting of course to speculate about the way parameters of our inhibition model might be related to neurophysiological processes or to the functioning of certain neuro-anatomical structures. However, the inhibition model is a purely formal model, which seems to be capable of describing variation in concentration during task performance. It is not based on assumptions about the relevance of particular neurophysiological processes or anatomical structures, nor have we attempted to correlate results to neurophysiological measures. The assumption that during task performance the system might stop at a particular moment in time with the processing of a particular task and that the chance of stopping increases with time may suggest that the refractory period of nerve cells is a mechanism that might be involved. However, from the inhibition theory one cannot simply deduce that increase of inhibition is based on the functioning of individual cells or of groups of cells. For the moment we prefer not to speculate too much about the relation between the parameters of our model and the human brain.

Related is the question whether the mixed task effect is really a rest effect in disguise; that is, a result of an alternation between different neural processors. The assumption that different tasks involve to a certain extent different psychological processes, localised at different sites of the brain is currently generally accepted, not in the least due to many neuropsychological studies describing all kinds of dissociations (see for a description and discussion Shallice, 1988). Not only lesion studies but also dual task studies have been interpreted as demonstrating dissociations of particular processes (Kinsborne and Hicks, 1978). The general line of reasoning in this type of studies is that certain task combinations produce larger decrements in performance and other combinations little or no decrement, and therefore it is often concluded that in the latter situation the two tasks can be performed more or less independently of each other and that they involve processes that are represented in different areas of the brain.

These questions about the neurological foundations of the Inhibition model and the effects of rest and task mixing, as well as the question of the components or "stages" in the processing part, all deserve a serious answer. First, however, new experiments must show to what extent our approach can be generalized to several classes of neuropsychological patients and whether it leads to new insights with respect to the nature of RT performance deficits as well as to improved diagnostics.

APPENDIX

The following equations give the details of the trend predicted by the Inhibition model. Proofs can be found in Van der Ven et al. (1989) and Van Breukelen et al. (1987).

$$E(T_k) = E(T_{stat}) - \beta\theta^{k-1} \quad (A.1)$$

$$\sigma^2(T_k) = \sigma^2_{stat} - (2/\delta)\beta\theta^{k-1}, \quad (A.2)$$

with

k = task unit nr. (e.g., line number in the Bourdon test)

$$E(T_{stat}) = A(1 + \mu_1/\mu_2) \quad (A.3)$$

$$\sigma^2_{stat} = 2(1 - \theta)(\mu_1/\mu_2) \quad (A.4)$$

$$\theta = \exp(-A\mu_2/\delta) \quad (A.5)$$

$$\beta = (1 - \theta)[E(\lambda_{stat}) - \lambda_0]/\mu_2 \quad (A.6)$$

$$E(\lambda_{stat}) = \delta(\mu_1/\mu_2). \quad (A.7)$$

Equation (A.7) gives the stationary average inhibition level that is reached after a fair number of items. If $\lambda_0 < E(\lambda_{stat})$, then $\beta > 0$ and the RT trend is increasing.

Estimation of the Model Parameters

With regression analysis the trend parameters $E(T_{stat})$ ($= \alpha$ in the main text), β and θ are estimated. A is estimated by the minimum RT, and

σ^2_{stat} by the *MS*(residual) of trend analysis. The Inhibition parameters μ_1, μ_2, δ, and λ_0 are then calculated as follows:

$$\mu_2 = \frac{2(\alpha - A)(1 - \theta)}{A \times MS(\text{residual})}$$

$$\mu_1 = \mu_2 \times \frac{(\alpha - A)}{A}$$

$$\delta = \frac{-A\mu_2}{\ln(\theta)}$$

$$\lambda_0 = \left(\frac{-\mu_2\beta}{1 - \theta}\right) + \left(\frac{\delta\mu_1}{\mu_2}\right)$$

Example: The upper-RT series in Fig. 4 yielded as estimates: $\alpha = 16.5$; $\beta = 3.2$; $\theta = 0.76$; $A = 12.9$; *MS*(residual) = 0.20. Inserting these values in the equations above yields $\mu_2 = 0.67$; $\mu_1 = 0.19$; $\delta \approx 31.5$; $\lambda_0 \approx 0$. This last result, $\lambda_0 \approx 0$, is mainly due to the fact that the first RT was also the minimum RT (which is frequently the case), which in turn is the (biased) estimator of A.

Observe that since this example is based upon an average RT curve (averaged across 18 different children), no interpretation must be given to the parameter estimates. In particular, *MS*(residual) will generally be smaller as the average is based upon a larger number of individuals.

REFERENCES

Abelson, A. 1911. The measurement of mental ability of 'backward' children. *British Journal of Psychology*, **4**, 268–314.

Arnold, W. 1975. *Der pauli-test*. Berlin: Springer.

Bertelson, P. & Joffe, R. 1963. Blockings in prolonged serial responding. *Ergonomics*, **6**, 109–116.

Bills, A. G. 1931. Blocking: a new principle of mental fatigue. *American Journal of Psychology*, **43**, 230–275.

Bills, A. G. 1935a. Some causal factors in mental blocking. *Journal of Experimental Psychology*, **18**, 172–185.

Bills, A. G. 1935b. Fatigue, oscillations and blocks. *Journal of Experimental Psychology*, **18**, 562–573.

Bills, A. G. 1964. A study of blocking and other response variables in psychotic, brain-damaged and personality-disturbed patients. *Behaviour Research and Therapy*, **2**, 99–106.

Bourdon, B. 1895. Observations comparatives sur reconnaissance, la discrimination et l'association. *Revue Philosophique*, **40**, 153–185.

Brickenkamp, R. 1962. *Test d2 (Aufmerksamkeitsbelastungs-test)*. Göttingen (Germany): Hogrefe.

Broadbent, D. E. 1958. *Perception and communication*. London: Pergamon Press.

Brouwer, W. H. 1985. *Limitations of attention after closed head injury*. Doctoral dissertation, University of Groningen, The Netherlands.

Bruggeman, C., Eling, P., & Jansen, R. 1990. Een nieuwe maat voor de diagnostiek van aandachtsstoornissen [A new measure for the diagnosing of attentional disorders]. *Nederlands Tijdschrift voor de Psychologie [Dutch Journal of Psychology]*, **45**, 206–213.

Cornelius, S. W., Willis, S. L., Nesselroade, J. R., & Baltes, P. B. 1983. Convergence between attention variables and factors of psychometric intelligence in older adults. *Intelligence*, **7**, 253–269.

Donders, F. C. 1868. Over de snelheid van psychische processen [On the speed of mental processes]. In W. G. Koster (Ed.) (W. G. Koster, Trans.), *Attention and performance*, (Vol. 2, pp. 412–431). Amsterdam: North-Holland.

Dumas, G. 1934. *Nouveau traité de psychologie* [New essay on psychology], Vol. 4. Paris: Alcan.

Dürr, E. 1914. *Die Lehre von der Aufmerksamkeit* [The theory of attention]. Leipzig (Germany): Quelle & Meyer Verlag.

Eling, P. & Renier, W. 1981. MBD: What's in a name? *Tijdschrift voor Orthopedagogie en Kinderpsychiatrie [Dutch Journal of Orthopedagogy and Child Psychiatry]*, **6**, 85–94.

Eysenck, H. J. & Frith, C. D. 1977. *Reminiscence, motivation and personality: a case study in experimental psychology*. New York: Plenum Press.

Ferrier, D. 1876. *The functions of the brain*. London: Smith, Elder.

Foley, P. J. & Humphries, M. 1962. Blocking in serial simple reaction tasks. *Canadian Journal of Psychology*, **16**(2), 128–137.

Henning, H. 1925. *Die aufmerksamkeit* [Attention]. Berlin: Urban & Schwarzenberg.

Hockey, G. R. J. 1982. *Stress and fatigue in human performance*. New York: Wiley.

Huiskamp, J., & De Mare, H. 1947. Eenige opmerkingen over de Wiersma–Bourdon Test [Some observations on the Wiersma–Bourdon test]. *Nederlands Tijdschrift voor de Psychologie, [Dutch Journal of Psychology]*, **2**, 75–78.

Hutt, H. 1910. Rechenversuche bei Manisch-Depressiven. *Psychologische Arbeiten*, **5**, 338–370.

James, W. 1890. *The Principles of Psychology*. New York: Holt.

Jansen, R. W. T. L. & Roskam, E. E. Ch. I. 1989. Mental processing and distraction. In E. E. Ch. I. Roskam (Ed.), *Mathematical psychology in progress* (pp. 133–156). New York: Springer.

Jansen, R. W. T. L. 1990. *Mental speed and concentration*. Doctoral dissertation, University of Nijmegen, the Netherlands.

Jensen, A. R. 1982. Reaction time and psychometric g. In H. J. Eysenck (Ed.), *A model for intelligence* (pp. 93–132). Berlin: Springer-Verlag.

Kahneman, D., Treisman, A., & Burkell, J. 1983. The cost of visual filtering. *Journal of Experimental Psychology: Human Perception and Performance*, **9**(4), 510–522.

Kamphuis, G. H. 1962. Een bijdrage tot de geschiedenis van de Bourdon test [A contribution to the history of the Bourdon test]. *Nederlands Tijdschrift voor de Psychologie [Dutch Journal of Psychology]*, **17**, 247–268.

Kaufman, A. S. 1975. Factor analysis of the WISC-R at eleven age levels between 6.5 and 16.5 years. *Journal of Consulting and Clinical Psychology*, **43**, 135–147.

Kinsbourne, M. & Hicks, R. E. 1978. Functional cerebral space: a model for overflow transfer and interference effects in human performance. In J. Requin (Ed.), *Attention and performance VII* (pp 81–97). Hillsdale (NJ): Erlbaum.

Kraepelin, E. 1902. *Die arbeitskurve* [The working curve]. Leipzig: Wilhelm Englemann.

Kraepelin, E. 1913. *Psychiatrie* (Vol. 3). Leipzig: Barth.

Luce, R. D. 1986. *Response times: their role in inferring elementary mental organization*. New York: Oxford University Press.

Luria, A. R. 1973. *The working brain*. London: Allen Lane, Penguin Press.

Mackie, R. R. 1977. *Vigilance: theory, operational performance, and physiological correlates*. New York: Plenum press.

MacMillan, M. 1992. Inhibition and the control of behavior. *Brain and Cognition*, **19**, 72–104.
Mackworth, J. F. 1969. *Vigilance and habituation: A neuropsychological approach*. Harmondsworth, UK: Penguin.
Mowrer, O. H., & Jones, H. G. 1943. Extinction and behavior variability as functions of effortfulness of task. *Journal of Experimental Psychology*, **33**, 369–386.
Nayrac, J. P. 1914. *Physiologie et psychologie de l'attention* [Physiology and psychology of attention]. Paris: Alcan.
Obersteiner, H. 1879. Experimental researches on attention. *Brain*, **1**, 439–453.
Oehrn, A. 1895. Experimentelle Studien zur Individual-psychologie (Experimental studies on individual differences). *Psychologische Arbeiten*, **1**, 92–151.
O'Hanlon, J. F. 1981. Boredom: Practical consequences and a theory. *Acta Psychologica*, **49**, 53–82.
Peak, H., & Boring, E. G. 1926. The factor of speed in intelligence. *Journal of Experimental Psychology*, **9**, 71–94.
Posner, M. I. 1978. *Chronometric explorations of the mind*. Hillsdale, NJ: Erlbaum.
Ribot, Th. 1902. *Psychologie de l'attention* [The psychology of attention] (6th ed.). Paris: Alcan.
Robinson, E. S. & Bills, A. G. 1926. Two factors in the work decrement. *Journal of Experimental Psychology*, **9**, 415–443.
Sanders, A. F., & Hoogenboom, W. 1970. On the effects of continuous active work on performance. *Acta Psychologica*, **33**, 414–431.
Shallice, T. 1988. *From neuropsychology to mental structure*. Cambridge: Cambridge press.
Shum, D. H. K., McFarland, K., Bain, J. D., & Humphreys, M. S. 1990. Effects of closed-head injury on attentional processes: an information-processing stage analysis. *Journal of Clinical and Experimental Neuropsychology*, **12**, 247–264.
Souren, D. A. P. B. 1989. *Volgehouden selectieve aandacht bij kinderen met leermoeilijkheden* [Sustained selective attention of children with learning disorders]. Master thesis, University of Nijmegen, the Netherlands.
Spearman, C. E. 1927. *The abilities of man*. London: McMillan.
Sternberg, S. 1969. The discovery of processing stages: Extensions of Donders' method. *Acta Psychologica*, **51**, 41–59.
Taylor, M. M. 1966. The effects of the square root of time on continuing perceptual tasks. *Perception and Psychophysics*, **1**, 113–119.
Tipper, S. P. 1985. The negative priming effect: inhibitory priming by ignored objects. *Quarterly Journal of Experimental Psychology*, **37a**, 571–590.
Van Breukelen, G. J. P., Jansen, R. W. T. L., Roskam, E. E. Ch. I., Van der Ven, A. H. G. S., & Smit, J. C. 1987. Concentration, speed and precision in simple mental tasks. In E. E. Ch. I. Roskam & R. Suck (Eds.), *Progress in Mathematical Psychology* (Vol. 1, pp. 175–193). Amsterdam: Elsevier.
Van Breukelen, G. J. P. 1989a. Some modified Inhibition models for response time series. In E. E. Ch. I. Roskam (Ed.), *Mathematical psychology in progress* (pp. 115–132). New York: Springer.
Van Breukelen, G. J. P. 1989b. *Concentration, speed and precision in mental tests*. Doctoral dissertation. University of Nijmegen, the Netherlands.
Van der Meere, J. J. 1988. *Attentional deficit disorder with hyperreactivity: A misconception*. Doctoral dissertation, University of Groningen the Netherlands.
Van der Ven, A. H. G. S. 1974. The correlation between speed and precision in time limit tests. *Nederlands Tijdschrift voor de Psychologie [Dutch Journal of Psychology]*, **29**, 447–456.
Van der Ven, A. H. G. S., & Smit, J. C. 1984. *Serial reaction times in concentration tests and Hull's concept of reactive inhibition*. (Report No. 84 MA 05). The Netherlands: University of Nijmegen, Department of Psychology.

Van der Ven, A. H. G. S., Smit, J. C. & Jansen, R. W. T. L. 1989. Inhibition in prolonged work tasks. *Applied Psychological Measurement*, **13**, 177–191.

Vloet, A. 1990. *Een vergelijking van het inhibitie—en het IMAX model* [A comparison between the inhibition—and the IMAX model]. Master thesis, University of Nijmegen, the Netherlands.

Vos, P. G. 1988. *De Bourdon-Vos test*. Lisse, The Netherlands: Swets & Zeitlinger.

Voss, G. 1899. Ueber die schwankungen der geistigen arbeitsleistung [On the variance of mental performance]. *Psychologische Arbeiten*, **2**, 399–449.

Welford, A. T. 1988. Reaction time, speed of performance, and age. In J. A. Joseph (Ed.), *Central determinants of age related declines in motor function*. New York: New York Academy of Sciences.

Wiersma, E. D. 1910. Die psychologie der epilepsie [The psychology of epilepsy]. *Folio Neuro-biologica*, **6**, 417–476.