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Automatic Aftereffects in Two-Choice Reaction Time: A Mathematical Representation of Some Concepts

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A mathematical model is developed to describe sequential effects in two-choice reaction time experiments with a short response–stimulus interval. Evidence is briefly discussed that in conditions with short response–stimulus intervals, automatic aftereffects dominate sequential effects, and the influence of subjective expectancy can be neglected. In these conditions the model premises three components of automatic aftereffects—facilitation, inhibition, and noise, with a common decay factor. Influence of response–stimulus interval and practice on sequential effects are examined and related to parameter changes in the proposed *single-decay model.* The decrease of automatic aftereffects with increasing response–stimulus interval is primarily ascribed to an increasing decay factor. The parameter representation of the model also clarifies the issue of the disappearance of automatic aftereffects with practice. It shows a gradual fading of inhibition in the initial stages of practice, together with a slower decrease of the facilitation effect. The single-decay model provides a satisfactory explanation for the processes involved in compatible two-choice reaction time with short response–stimulus interval.

During the presentation of a series of random binary stimuli, subjects react as if certain sequences are more likely to occur than others. Remington (1969) demonstrated that a reaction time (RT) in a two-choice task depends upon the specific sequence of the preceding stimuli. Influences caused by events dating one trial back are called first-order effects, whereas influences caused by earlier trials are called higher order effects. Several efforts have been made to develop theories relevant to sequential effects. In general, two main categories of theories can be distinguished: theories based on strategies and expectancies on the one hand and theories based on automatic aftereffects on the other. The aim of the present article is to develop a mathematical model for only one category, namely, automatic aftereffects.

There is disagreement in the literature concerning the nature of automatic aftereffects. Some authors argue that it is a form of expectancy, whereas others claim that automatic effects are different and independent concepts. Recent data obtained in our laboratory seem to support the notion of separate concepts. The methods and conditions separating automatic aftereffects from expectancy are studied in a separate report (Soetens, Boer, & Hueting, 1984). In the present article we assume that both concepts are different. Some of the differentiating aspects will be briefly discussed.

Subjective expectancy is an explanatory concept with respect to subjects' expectancies concerning a specific stimulus and their preparation for this event (Bertelson, 1961, 1963; Kirby, 1976; Laming, 1968). Typical for expectancy is its two-sided effect: It has a cost and a benefit. If an expectancy is confirmed, a short RT follows; if it is not, RT is prolonged. The effect is easy to detect in a two-choice task, where high expectancy of one stimulus implies low expectancy of the alternative. Expectancy can explain a first-order alternation effect, that is, faster reactions to a different stimulus when compared to reactions to a repeated stimulus. The effect is described as the subjects' tendency to expect more alternations than repetitions, in a way analogous to the gambler's fallacy phenomenon (Jarvik, 1951). Expectancy can also explain some higher order

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sequential effects. Higher order expectancy effects can be described as the subjects' preference for a continuation of an unbroken run of identical events, that is, alternations or repetitions (Kirby, 1976, 1980). For example, after a series of alternations, another alternation is expected. The longer the preceding alternation run, the stronger the expectancy. When the expectancy is confirmed, a short RT ensues, but when it is disconfirmed, RT is long. The same reasoning applies to repetition runs.

Expectancy effects are mostly reported in experiments with a relatively long response–stimulus interval (RSI; Hale, 1967; Kirby, 1972; Williams, 1966). Vervaeck and Boer (1980) suggested that the process of building up an expectancy needs a critical minimum time. This time can be estimated by reviewing the literature on first-order sequential effects. First-order alternation effects are usually found with RSIs of more than ½ s. Kirby (1980) remarks, however, that there could be serious confounding of RSI influences with compatibility. Results of pilot studies in our laboratory suggest that the critical minimum RSI for expectancy in a spatially compatible two-choice task is about 100 ms. Kirby (1976), however, reported subjective expectancy in experiments with RSIs of 1–50 ms, but his actual RSI was longer because his subjects had a "time-on-key" period between the reaction and the onset of RSI. The RT counter stopped when the telegraph key was pushed down, but RSI started at the moment that the key was released. Thus, subjects could delay the onset of RSI by keeping the key down. The time on key can be estimated by consulting Welford (1977), who reports an average of 150–200 ms, using a similar, if not the same, apparatus. The actual RSI of Kirby would then probably exceed 200 ms, which explains the finding of an expectancy effect. The same confusing methodology was also used by other researchers (e.g., Bertelson & Renkin, 1966), and sometimes the actual RSI was additionally prolonged with the warming-up time of the presented stimuli when incandescent lamps were used (Keele & Boies, 1973). Apart from methodological differences, the influence of RSI has often been compounded with the influence of other variables, such as stimulus–response compatibility, practice, and number of alternatives. For a detailed analysis concerning the interactions of some of these variables we refer to Soetens et al. (1984).

The second category, *automatic aftereffects,* is usually associated with short RSI experiments. Automatic aftereffects are assumed to be short-lived automatic consequences of processing a stimulus. In contrast with subjective expectancy, automatic aftereffects seem to work only in one direction, namely, a gain in processing speed. Several researchers found that in short RSI conditions, RT to a repeated stimulus was faster than RT to a different stimulus (Bertelson, 1961, 1963; Hyman, 1953). This effect was called the *repetition effect* and was originally observed as a first-order effect. The effect, later renamed *automatic facilitation,* has been replicated repeatedly (e.g., Hale, 1967; Kirby, 1976). The repetition effect also appeared in experiments with relatively long RSIs (Bertelson, 1963; Bertelson & Renkin, 1966; Entus & Bindra, 1970), but this was probably due to the interaction of stimulus–response compatibility. The effect also increases when the number of alternatives is incremented (Hoyle & Gholson, 1968; Hyman, 1953; Remington, 1969, 1971). Automatic facilitation is said to decay over time but has not necessarily disappeared with the arrival of the next stimulus. Therefore, an accumulation can take place, thus creating higher order facilitation effects (Kirby, 1976; Remington, 1969). The effects of earlier trials are progressively less influential, suggesting that they decay over time. The fact that facilitation occurs only with short RSIs is also an indication that it dissipates with time. Moreover, several authors found decreasing repetition effects with increasing RSIs (Bertelson, 1961; Bertelson & Renkin, 1966; Smith, 1968; Umilta, C. Snyder, & M. Snyder, 1972), supporting the notion of a decaying repetition effect.

According to Laming (1968), facilitation is a general phenomenon, not limited to a specific stimulus. His results suggest that at short RSIs, after a sequence of repetitions, there is always a facilitation effect, no matter whether the stimulus to come is a repetition or an alternation. Suppose, for example, that P and Q are the two possible alternatives in a two-choice task. Let us consider as a typical example a multiple repetition sequence $PPPP$. Laming observed that RT is short when the repetition sequence is continued, but more important, when an alternation occurs, RT is also shorter than after any other alternation sequence. In other words, RT_{PPPPQ}[1] is shorter than any other $RT_{\ldots\text{PQ}}$. This one-sided effect is clearly anti-expectancy.

Vervaeck and Boer (1980) discovered that Laming's general facilitation effect changed into a stimulus-specific effect after extensive training. They concluded that this development can not be explained by facilitation alone. Therefore, an alternative model was suggested, drawing a clear line between facilitation as a stimulus-specific effect on the one hand and a second concept, namely *inhibition,* on the other hand. The model assumes two channels or pathways, one for each of the two stimuli, going from stimulus intake to response execution, and the influence of automatic aftereffects, facilitation and inhibition, is located somewhere along these pathways. Each channel is assumed to have a neutral state, which can be changed from extreme excitation to extreme inhibition. When a particular stimulus is presented, its corresponding "home" channel will be used, causing the excitation of that channel. The critical assumption of the model of Vervaeck and Boer concerns the influence of stimulus processing on the "alternative" channel. It is proposed that an alternation to the home channel inhibits the alternative channel, whereas repetitions on the home channel do not modify the state of the alternative channel. As an analogy of the model, consider the electrical induction phenomenon. Alternations can be compared with abrupt changes in electrical potential, which cause induction in nearby channels. In the model, inhibition is comparable to induction and inhibits the processing on the alternative channel. Repetitions on the home channel can be compared to small changes in potential, thus not affecting the state of the alternative channel. It is further assumed that inhibition, similar to facilitation, decays over time. In this way, repetitions on the home channel allow the dissipation of inhibition on the alternative channel. Vervaeck and Boer argued that the inhibition effect could, in fact, explain the same phenomenon as the general facilitation effect proposed by Laming (1968). Indeed, the dissipation of inhibition on the alternative channel seems to work as a facilitation. It should be noted that the inhibition effect is stimulus specific, because an alternation from the alternative channel to the home channel induces no inhibition on the home channel.

A third concept associated with sequential effects in short RSI experiments is suggested by Laming (1968). He proposes the existence of an internal standard to identify the incoming signals. When a series of repetitions is presented, the standard becomes sharp and enables the subject to detect either signal with relative ease. When the signals are alternated, the image becomes blurred and the identification of either signal is more difficult. This blurring of the standard can be described as noise in the process of identifying the stimulus. Laming used this noise to explain the slowing down of RTs to either stimulus after sequences with many alternations.

All three concepts mentioned earlier have proven useful in explaining part of the data obtained in two-choice RT-tasks with short RSI, but their mutual relationship is not well defined. For example, does an inhibition overrule a preceding facilitation, vice versa, or are they approximately equal in strength? What is the speed of decay of such effects as facilitation, inhibition, and noise? Are these concepts redundant, and if so, to what extent? It might be rewarding, therefore, to establish relationships between the components of automatic aftereffects by means of a mathematical model.

In the model that we propose no parameter for subjective expectancy is incorporated. Therefore, the model applies only to sequential data caused by automatic aftereffects. In a separate report Soetens et al. (1984) found that in short RSI conditions (RSI < 100 ms) the influence of subjective expectancy is negligible. Briefly, the argumentation is as follows: A repetition–alternation function is derived, representing the effects of each particular sequence of preceding stimuli on the RT to the next event that is either a repetition or an alternation. Figure 1, Panel a shows an example of a repetition–alternation scattergram, based on Kirby (1972). For each preceding sequence of stimuli, RT to a repetition is set

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[1] The presentation order of stimuli is given by the left to right reading order. The right-most letter denotes the current stimulus.

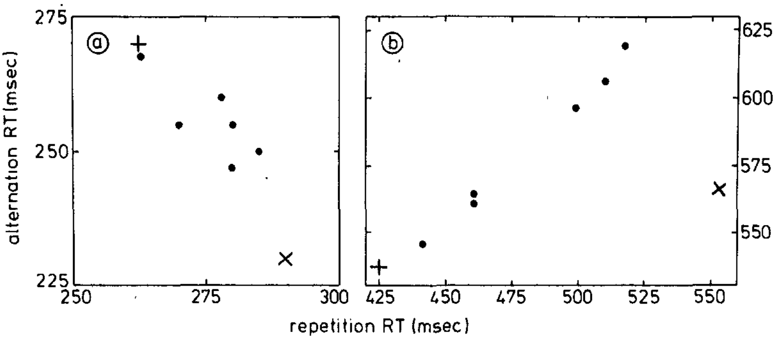

Figure 1. Repetition–alternation scattergram based on data of Kirby (1972), representing an expectancy condition in the left panel, and data of Vervaeck and Boer (1980), representing automatic aftereffects in the right panel. (The crosses stand for reaction times [RTs] after a sequence of three alternations; the plus signs stand for RTs after a sequence of three repetitions. [From Soetens, Boer, & Hueting, 1984])

out along the abscissa, and RT to an alternation is set out along the ordinate. Kirby assumed that expectancy was dominant in these data. The cross in Figure 1, Panel a represents RTs after three alternations. Subjects expect a continuation of this run. Hence, RT to a subsequent alternation is relatively short, whereas RT to an unexpected repetition is long. The plus sign in Figure 1, Panel a represents RTs after a run of three repetitions. A continuation of this run is expected. Hence, RT to a repetition is short. The repetition–alternation function for expectancy data thus describes the negative trading relation between expecting a particular event and not expecting the alternative event (cf. Kinchla, 1980). Audley (1973) predicted this time exchange relation with a slope of −45° on the assumption that there is a linear relationship between expectancy and two-choice RT.

Positive slopes are predicted for the repetition–alternation function of automatic aftereffects data. In contrast to expectancy, automatic aftereffects are one-sided, so that some sequences create a benefit for either of the subsequent events. Figure 1, Panel b shows a repetition–alternation scattergram based on data of Vervaeck and Boer (1980). Vervaeck and Boer assumed that automatic aftereffects were dominant here. The plus sign represents RTs after three previous repetitions. It is apparent that RT is short whether the next event happens to be a repetition or an alternation. The other points form a positive slope in the repetition–alternation function, except for the point marked by the cross. This represents RTs after three previous alternations. Soetens et al. (1984) showed that this point is an exception, indicating the breakthrough of expectancy. We therefore decided to omit this point in the analysis of the present experiments in order to avoid traces of expectancy. Without the discrepant point, correlation in Figure 1, Panel b is .99, and the slope of the best-fitting straight line is 34°. The general prediction of automatic aftereffects is a positively sloped repetition–alternation function that contrasts substantially with the negatively sloped repetition–alternation function predicted for an expectancy condition.

In the following experiments, the repetition–alternation function is tested for a positive slope and a high correlation as a check on the dominance of automatic aftereffects.

A General Model

The information flow from the perception of stimulus P to its corresponding response is called the *P channel* and, for stimulus Q, the the *Q channel*. In the case of two similar stimuli it is assumed that both channels have similar characteristics and, consequently, it can be assumed that the time needed for information to flow through each channel is equal. This is called the neutral time T_0. The absolute value of T_0 depends upon the complexity of the stimulus–response relation and can vary from subject to subject. More permanent changes within one subject, such as learning effects, can also influence this neutral time. The value of T_0 is estimated as a function of the overall mean RT.

If, in this neutral state, a *P* stimulus is presented, then, in case of a correct response, the *P* channel is triggered. The result is a facilitation for a following *P* stimulus if RSI is not too long. This can be represented as a decrease in processing time for a following *P* stimulus with a factor f, with $0 \leqslant f \leqslant 1$. So

$$T^{P}_{P} = T_0 - fT_0, \qquad (1)$$

where T^{P}_{P} is the time needed for processing a *P* stimulus after the arrival of a *P* stimulus, the subscript relating to the preceding stimulus, the superscript to the appropriate channel.

On the *Q* channel on the contrary, this *P* stimulus can give rise to an inhibition effect, which, according to this concept, results in an increase of processing time for a subsequent *Q* stimulus with a factor say i, with $i \geqslant 0$. Inhibition effects on the *Q* channel appear only when switching from the *Q* to the *P* channel. This happens only in 50% of all *P* stimuli. This means that the actual increase of processing time is $i/2$. Processing time on the *Q* channel is as follows:

$$T^{Q}_{P} = T_0 + iT_0/2, \qquad (2)$$

where T^{Q}_{P} is the processing time needed on the *Q* channel after the arrival of a *P* stimulus, the subscript relating to the preceding stimulus and the superscript to the appropriate channel.

Both effects, facilitation and inhibition, decay over time. The decay factors are named d_f and d_i, respectively. Both have a positive relation with time (d_f, $d_i \geqslant 1$). The moment the next stimulus is about to arrive, the needed processing times of Equations 1 and 2 have changed to

$$T^{P}_{P} = T_0 - fT_0/d_f \qquad (3)$$

$$T^{Q}_{P} = T_0 + iT_0/2d_i. \qquad (4)$$

Following the same reasoning, the situation on the *P* channel after a second *P* stimulus will be

$$T^{P}_{PP} = T_0 - fT_0/d_f - fT^{P}_{P}, \qquad (5)$$

where T^{P}_{PP} is the needed processing time on the *P* channel (superscript) after the stimulus sequence *PP* (subscripts). Note that the facilitation caused by the last *P* stimulus exerts its influence on the momentary processing time before this stimulus had arrived, this being T^{P}_{P}. After decay, processing time will be the following:

$$T^{P}_{PP} = T_0 - fT_0/d_f^2 - fT^{P}_{P}/d_f. \qquad (6)$$

According to the two-channel theory, the arrival of this second *P* stimulus does not induce an inhibition effect on the *Q* channel. So, apart from decay, no changes occur on the *Q* channel.

If, on the contrary, the second stimulus were to be *Q*, an alternation, then an increase of the general noise level is predicted. Again this noise effect will decay over time. Because the noise influence is not channel specific, it will be found in both channels. Besides this noise effect, there will be an inhibition in the *P* channel. Processing time in this channel after the sequence *PQ* and after decay can be derived from Equation 3:

$$T^{P}_{PQ} = T_0 - fT_0/d_f^2 + (i/d_i + n/d_n)T^{P}_{P}, \qquad (7)$$

where i is the inhibition parameter with its decay d_i, and n represents the influence on the noise level with its decay d_n ($n \geqslant 0$ and $d_n \geqslant 1$). Note again that inhibition and noise exert their influence on the momentary necessary processing time T^{P}_{P}. The influence on noise level, caused by the alternation *PQ*, can also be found in the *Q* channel, where, moreover, a facilitation occurs. Integrating this influence in Equation 4, processing time on the *Q* channel after sequence *PQ* and after decay can be expressed as follows:

$$T^{Q}_{PQ} = T_0 + iT_0/2d_i^2 + (n/d_n - f/d_f)T^{Q}_{P}, \qquad (8)$$

with noise (n) and facilitation (f) exerting their influence on the momentary necessary processing time on the *Q* channel, T^{Q}_{P}.

If this reasoning is continued and the model limited to sequences of four stimuli, 16 formulas are obtained, representing 16 states of a channel, each corresponding to a specific sequence of events.

Model Predictions

The general model predicts sequence effects depending on the values of the parameters. These parameters can be influenced by factors such as practice, RSI, and other task variables. Some restrictions can be set for the parameters apart from those already mentioned in developing the model. In short RSI experiments it can be expected that a first-order facilitation effect will occur. This means $f > n$, because otherwise the noise effect caused by an alternation overrules the first-order facilitation effect. To have a better idea how the model predicts the differences in RT as a function of the sequence, arbitrary values can be given to the parameters and the predictions compared with data from a short RSI experiment. For f and i a value of 0.5 was chosen and for noise $n = 0.2$. All decay factors were given the value 3.

Figure 2 shows how RTs are predicted as percentages of the neutral processing time T_0. Sequences on the horizontal axis are in the order of increasing RT prediction. The curve is divided into two parts according to the first-order effect. The first part, with first-order repetitions, is termed the *repetition curve,* whereas the second part, with first-order alternations, the *alternation curve.* Throughout the article the same order of sequences is maintained in all figures. In this way, it is easy to compare the evolution of the data with the predictions in Figure 2. Decreasing parameter i (inhibition) from 0.5 to 0.2 and plotting the predicted values (see Figure 2) cause a change in the slope of the alternation curve, whereas the repetition curve is practically unaffected. Decreasing parameter f (facilitation) from .5 to .25 results in a shift in the repetition curve with respect to the alternation curve. Increasing the d parameter flattens both repetition and alternation curve, bringing them closer to the 100% level. For clarity, the latter is not shown in Figure 2. The predictions are compared with the data of Vervaeck and Boer (1980), who used an RSI of approximately 55 ms. A comparison of the observed RTs with the model predictions shows that the model foretells fairly well which sequences cause shorter RTs and which cause the longer RTs.

Experiment 1

To make predictions, arbitrary values were set for the model parameters in the prior sec-

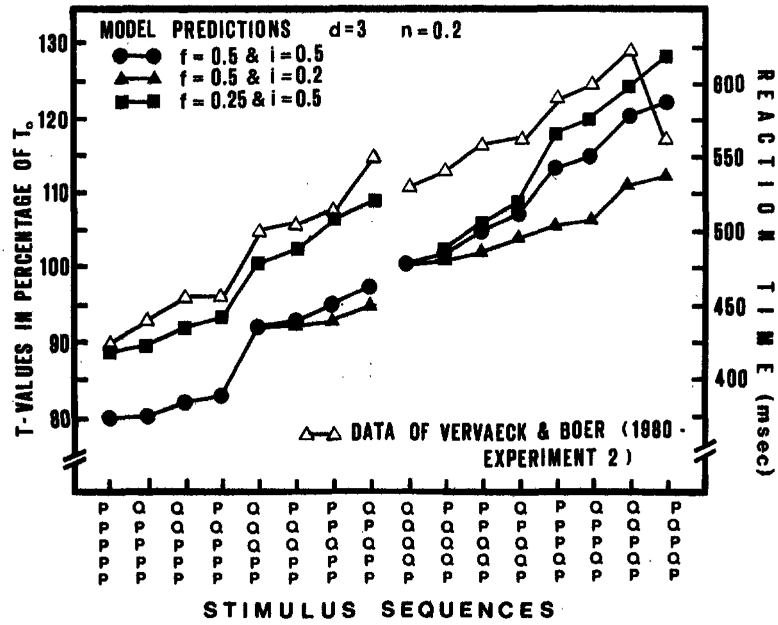

Figure 2. Predicted reaction time of the general model, as a function of stimulus sequences, with two values for facilitation (f) and inhibition (i). (P is the current stimulus and Q the alternative. Read the strings in chronological order from top to bottom. The lowest letter denotes the current P stimulus. Predictions are expressed in percentages of the neutral processing time and compared with data of Experiment 2 of Vervaeck and Boer—"Sequential effects in two-choice reaction time: Subjective expectancy and automatic aftereffect at short response-stimulus intervals" by K. R. Vervaeck and L. C. Boer, 1980, *Acta Psychologica, 44,* 175–190. Adapted by permission of the authors.)

tion. The optimum values for these parameters can be calculated by comparing model predictions with medians of a large data set and changing the parameter values by means of a grid search. The data set in this experiment contains approximately 1,100 RTs per stimulus sequence.

The general model, as proposed, contains too many parameters. Some of the treated concepts could be redundant. In Experiment 1 an attempt is made to eliminate redundant concepts by comparing the experimental data with approximations obtained from three simplified forms of the general model.

In a first submodel, it is assumed that decay is independent of whatever effect caused it. Expressed in parameters, this means $d_f = d_i = d_n$. This is termed the *single-decay model.* The facilitative influence of repetitions has been ascertained so many times that the facilitation parameter is considered to be indispensable in all models. The concepts of noise and inhibition are more open to question. For this reason, two other submodels are analysed, each leaving out one of these concepts. The second submodel eliminates the noise factor. This model can be compared to the two-channel representation as proposed by Vervaeck and Boer (1980). Translated in parameters of the general model, this means $n = 0$ and $d_n = 1$, leaving the possibility of different decay factors for facilitation and inhibition. This model is referred to as the *model without noise.* In a third submodel, inhibition is eliminated, meaning $i = 0$ and $d_i = 1$, and a possibility for different decay factors for facilitation and noise. This is called the *model without inhibition.*

To obtain comparable values between model predictions and median RTs, a value for T_0 has to be chosen. A reasonable approximation is to keep T_0 constant for every experimental condition, with a value of $T_0 = M_{RT}/M_T$, where M_T is the mean of all computed T values and M_{RT} the mean of the median RTs per sequence.

In the present experiment, the influence of subjective expectancy was kept to a minimum by applying very short RSIs. To reduce the remaining traces of expectancy, we tested the models without RTs after three alternations. Moreover, before applying the model to the observed data, we calculated the slope and correlation of the repetition–alternation function.

Method

Subjects. Twenty subjects volunteered for the experiment. They were all unfamiliar with RT tasks.

Apparatus. Stimuli were presented by means of two 7-segment light emitting diodes (LED), displaying the character 0. Each LED measured 15 mm × 16 mm and their centers were set 45 mm apart on a black vertical panel. The panel was placed 2.6 m from the subject, resulting in a between-stimulus visual angle of 1°. A white vertical line separated the two displays. Before the start of each 100-trial-block of stimuli, a third LED, placed 45 mm to the left of the left stimulus and displaying the character 8, was used as a warning signal. The room was semidarkened to make the stimuli clearly visible. Two push buttons connected to microswitches, which were to be manipulated by the subject's forefingers, were placed on a horizontal response panel in front of the subject. The left hand operated the left key in response to the left LED, and the right hand operated the right key in response to the right LED. The experiment was controlled by an HP2100A minicomputer.

Procedure. RT was recorded as the time between stimulus onset and the moment that either of the response keys was switched down. This switching terminated stimulus exposure and started RSI, which lasted 20 ms. Thus, "time on key" overlapped RSI.

Complete randomization of all stimulus sequences was accomplished by basing the chance of exposure of a particular stimulus on the value of the RT to the previous stimulus. When this RT, in ms, was an even number, the left stimulus was presented on the subsequent trial. When RT was odd, the right stimulus was presented on the subsequent trial. With this procedure, after eliminating errors and error sequences, each stimulus sequence occurred on average 55 times per 1,000 stimuli, with a standard deviation of 3.08. No error correction was possible.

Each subject participated in one 15-min session. During all trial blocks, stimuli succeeded at a pace depending on the subject's RTs. After two 50-trial practice blocks, during which the subject was instructed to keep the error rate less than or equal to 4% he or she ran through 10 experimental blocks, each consisting of 100 trials. Between blocks there was a 30-s rest period, during which the subject was informed of the error rate in the immediately preceding block.

Results and Discussion

Errors amounted to 1.88% and were positively correlated with median RT across sequences. Thus an explanation of sequential effects in terms of speed/accuracy trade-off is ruled out. Median RTs were calculated per sequence per subject and averaged over subjects. Figure 3 shows median RTs and error percentages as a function of stimulus sequences.

The analysis of the repetition–alternation function revealed a high correlation (.95 with RTs after three alternations excluded), indicating considerable linearity in the scattergram. The slope of the best-fitting straight line was 43°. This slope clearly indicates a domination of automatic aftereffects.

In general the trend of the data in Figure 3 corresponds with the predictions of Figure 2 and with the data of Vervaeck and Boer (1980). An ANOVA with first-order and higher order effects as within-subjects factors revealed significant main effects, $F(1, 19) = 8.52$, $p < 0.01$, for first-order effects, and $F(7, 133) = 10.97$, $p < 0.001$, for higher order effects.

The minimum standard error of estimate was computed between the median RTs for each of the 16 sequences of four consecutive

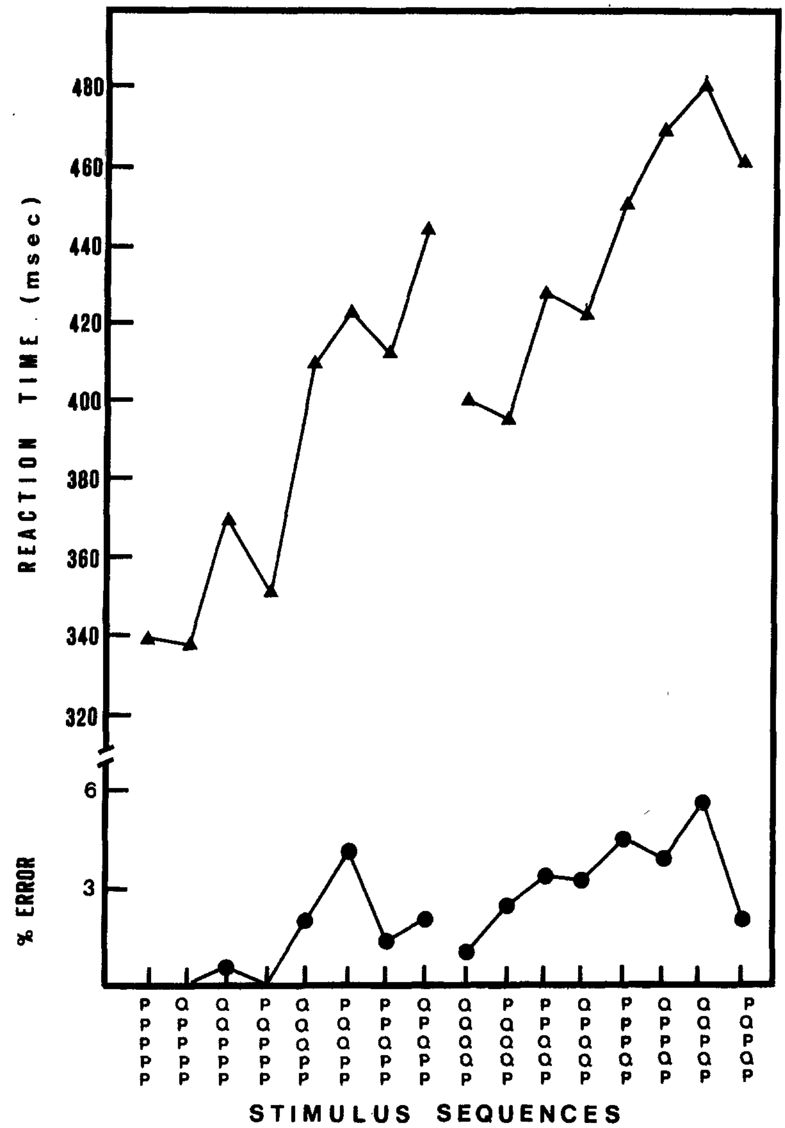

Figure 3. Results of Experiment 1: median correct reaction time and error percentage as a function of preceding stimulus sequences. (The order of sequences on the horizontal axis is the same as in Figure 1. Each point on the reaction time [RT] curve represents approximately 1,100 RTs.)

Table 1
Goodness of Fit for Different Models to the Data of Experiment 1

Model	S_e	% var
Single decay	9.29 (11.37)	.953 (.929)
Without noise	15.55 (17.88)	.869 (.826)
Without inhibition	9.89 (11.47)	.947 (.927)

Note. Numbers in parentheses give the results of the models when the point with three alternations is included (RT_{QPQPP}, RT_{PQPQP}); S_e = standard error of estimate in milliseconds; % var = percentage of variance accounted for.

stimuli and its corresponding value in one of the models by using the following formula:

$$S_e = \sqrt{\frac{\sum_{n=1}^{N} (RT_n - T'_n)^2}{N}} \text{ with } T'_n = T_n \cdot T_0 = T_n \cdot M_{\mathrm{RT}}/M_{\mathrm{T}}, \quad (9)$$

where M_{T} is the mean of all computed T values and M_{RT} the mean of the median RTs per sequence. T_0 is the estimated neutral processing time. N is the number of sequences used in the analysis (14 without the sequences after three alternations and 16 with all sequences). RT_n is the median RT per sequence, and T_n is the calculated T value per sequence. By means of a computer program, a grid search was performed on all parameters of the model. For every combination of parameter values, T values and standard error were calculated. After the grid search, a minimum standard error indicated the best model approximation. Table 1 shows the computed minimum standard errors and percentage of variance accounted for by the respective models.

Table 1 indicates that a model without noise is the least appropriate to explain automatic aftereffects in the present data. Although all models explain more than 85% of the variance, there still is a sizeable difference between the model without noise and both other models. Apparently, inhibition and facilitation alone are not sufficient to explain all sequential effects with short RSI.

Single decay seems to be the most promising model, although the difference between it and the model without inhibition is small. In the latter, however, facilitation is equal to one. Note that in the development of the model, $f = 1$ has been defined as the maximum tolerated value for the facilitation parameter. Probably, the best approximations of the model without inhibition will predict f values greater than one. This implies that the model predicts the possibility for negative RTs. This also raises doubts about the value of the model without inhibition. Other parameter values are $n = .55$, $d_n = 3.5$, and $d_f = 6.5$. The single-decay model generated the following optimum parameter values: facilitation $f = .45$, inhibition $i = .50$, noise $n = .20$, with a common decay $d = 3.0$. A further evaluation of both remaining models is made in Experiment 2.

Experiment 2

In this experiment RSI was systematically manipulated. It is predicted that the strength of the decay parameter increases as RSI is prolonged. Automatic aftereffects are assumed to be short-lived automatic consequences of the processing of a stimulus. This implies their decay over time. An indication of the presence of decay is the fact that automatic effects seem to appear only in experiments with relatively short RSI. Moreover, the aftereffects of earlier trials are progressively less influential. Experimental support for the notion of decay has been found by several researchers who observed decreasing repetition effects with an increasing RSI (Bertelson, 1961; Bertelson & Renkin, 1966; Hale, 1967; Smith, 1968; Umilta et al., 1972). There are, however, other researchers who found little or no effect of a changing RSI on the repetition effect (Keele, 1969; Keele & Boies, 1973; Schvaneveldt & Chase, 1969). These seemingly conflicting results can be ascribed to other variables such as stimulus–response compatibility, practice, and number of alternatives, whose influences are often compounded with RSI influences. The interaction of some of these variables is studied by Soetens et al. (1984).

Both remaining models were tested under each RSI condition. In the single-decay model it is expected that the common decay factor will rise with an increasing interval, leaving the other parameters unchanged. In the model without inhibition, both decay factors, d_f and d_n, are expected to increase. An increase of decay will make first-order effects more important in relation to higher order effects. In general, an increase of decay means a decrease of all automatic aftereffects.

RSI manipulation was limited to a maximum of 100 ms in order to minimize expectancy. The risk that expectancy will surface increases as RSI is increased. Therefore, the data were tested for traces of expectancy by means of the repetition–alternation function before applying the models.

Method

Unless otherwise mentioned, the experiment was identical to Experiment 1. RSIs were 20, 30, 50, 70, and 100 ms. In each RSI condition 10 subjects participated—a total of 50 subjects.

Results and Discussion

Errors amounted to 2.09% and were positively correlated with median RT across sequences. Figure 4 represents median RTs for five different RSIs and overall error percentages as a function of stimulus sequences.

The repetition–alternation function displayed positive slopes between 30° and 40° and a correlation between .80 and .98 for the 20–70-ms RSI conditions. Thus, it can be assumed that in these conditions the influence of expectancy is of minor importance. In the 100-ms RSI condition, however, the slope is 26° and the correlation drops to .48. This was interpreted as a growing influence of expectancy.

The increasing influence of expectancy is also visible in Figure 4, where the three rightmost points of the repetition and the alternation curve in the 100-ms condition deviate from the monotonically increasing course observed in the other conditions. The gradual disappearance of the first-order repetition effect, which has been found in other studies (e.g., Bertelson & Renkin, 1966), is not very clear from Figure 4. Only after RSI = 50 ms does first-order repetition gradually diminish. If RSI is continually prolonged, the alternation curve will probably drop beneath the level of the repetition curve. This represents a change from a first-order repetition effect to a first-order alternation effect, which has often been ascertained in two-choice RT experiments with longer RSIs (Entus & Bindra, 1970; Hale, 1967; Williams, 1966). An experiment demonstrating this change in first-order effect was carried out by Soetens et al. (1984).

An ANOVA was carried out on the data of Experiment 2 with RSI as between-subjects factor and first-order and higher order effects as within-subjects factors. All main effects were significant. There was no interaction between first-order effect and RSI, $F(4, 45) = 1.02$. The first-order repetition effect remains in all RSI conditions. On the other hand, interaction between RSI and higher order effects was significant, $F(28, 315) = 1.82$, $p < 0.01$. This supports the notion of decaying higher order effects with increasing RSI, which is also visible in Figure 4. The 20-ms RSI condition displays the steepest slope, whereas in the 100-ms RSI condition, the slope has virtually disappeared in the alternation curve.

Table 2 shows that in all RSI conditions, both models account for more than 80% of the variance. As it turns out, there is no clear explanation for the results of the model without inhibition. Facilitation maintains a value of 1.0. The noise parameter is about 0.30 except for RSI = 20 ms, where noise is 0.60. Noise decay varies around 3.0, and decay of facilitation is very unstable. Moreover, several comparable minima were generated by the computer program, with diverging parameter values, indicating an instability in the model. This, together with the prediction of negative RTs after facilitation ($f > 1.0$), also disqualifies the model without inhibition.

An explanation in terms of the single-decay model appears more likely. Standard error of estimate is smaller in all conditions, except for RSI = 100 ms. The computer program generated only one clear minimum standard error of estimate in all conditions. Parameter values are rather stable over different RSI conditions. Facilitation fluctuates around .50, inhibition around 0.50, and noise around 0.20. Diverging values of noise and inhibition in the 100-ms RSI condition can be explained as the increasing influence of expectancy. This was already apparent from the correlation of the repetition–alternation function, which dropped to .48 in the 100-ms RSI condition. Table 2 further shows that the single-decay model predicts an increasing decay with increasing RSI. Although the change in decay factor is not spectacular, there is a positive relation with RSI. According to the model predictions, an increasing *d* parameter is reflected by a flattening of both repetition and alternation curves and a diminishing first-order effect. The former is visible in Figure 4, especially if the data that can be ascribed to expectancy are not considered. The latter manifests itself only in the longer RSI conditions.

The *d* parameters in the general model were originally proposed as time-dependent parameters. A closer look at the data in the present experiment, however, shows that the number of intervening stimulus–response cycles also affects *d*. To explain this influence, consider first the data of the 100-ms RSI condition. Figure 4 and the analysis with the repetition–

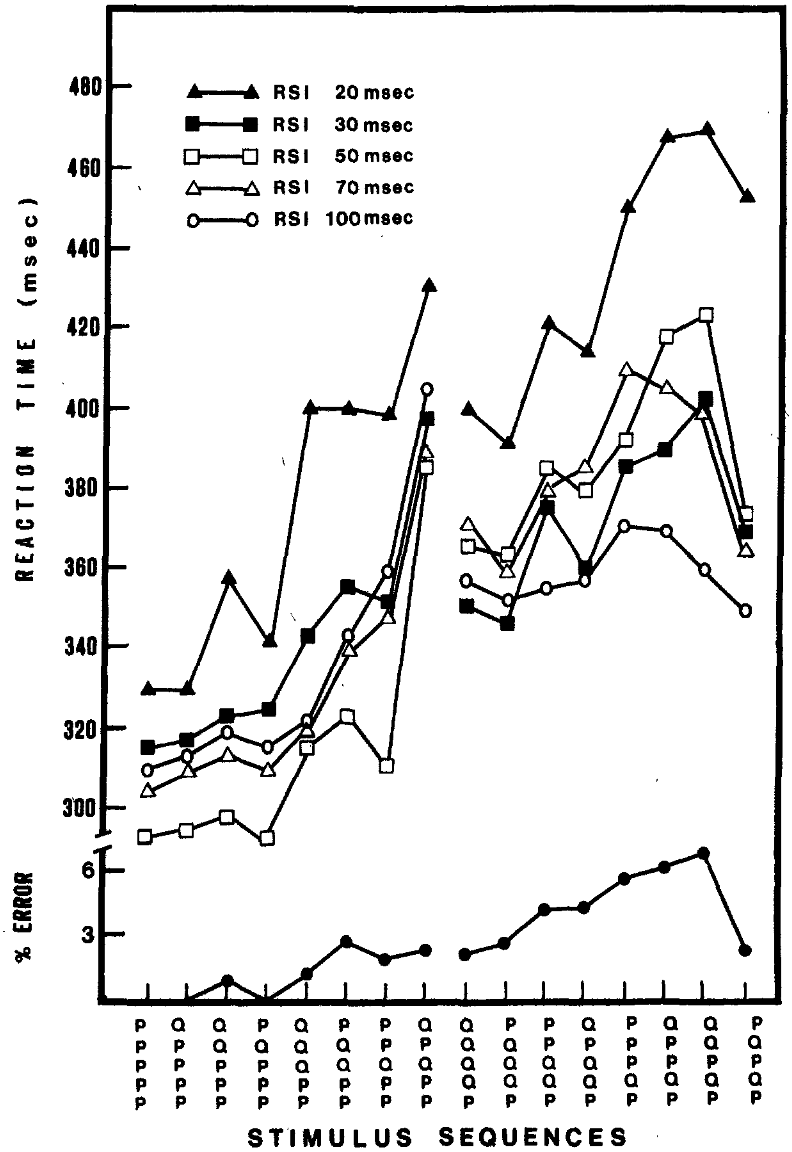

Figure 4. Results of Experiment 2: median correct reaction time (RT) and overall error percentage as a function of preceding stimulus sequences with response–stimulus interval as parameter. (Each point on the RT curves represents approximately 550 RTs.)

Table 2
Goodness of Fit and Parameter Values for Different Response–Stimulus Interval (RSI) Conditions of Experiment 2

RSI	S_e	% var	f	i	n	d	d_f	d_n
Single-decay model								
20	8.43	.96	.46	0.60	0.20	3.20		
30	7.10	.95	.34	0.45	0.20	3.50		
50	7.01	.98	.60	0.60	0.15	3.50		
70	7.28	.90	.50	0.50	0.15	4.00		
100	8.10	.86	.50	0.10	0.30	5.50		
Model without inhibition								
20	9.89	.95	1.00		0.60		6.80	3.60
30	8.09	.93	1.00		0.35		8.00	3.00
50	13.28	.92	1.00		0.30		4.00	2.50
70	9.69	.82	1.00		0.30		5.50	3.00
100	7.92	.87	1.00		0.20		9.50	3.00

Note. S_e = standard error of estimate in milliseconds; % var = percentage of variance accounted for; f = facilitation; i = inhibition; n = noise; d = decay; d_f = decay of facilitation; d_n = decay of noise.

alternation function indicate that higher order automatic effects have almost disappeared after 100 ms. On the other hand, the experiment shows that third- and fourth-order automatic aftereffects exist in the short RSI conditions, indicating that their influence extends over a period of four interstimulus intervals, together lasting over more than 1 s. It is clear that the intervening stimulus–response cycles prolong the existence of automatic effects. This apparent contradiction can be explained by assuming that monitoring, or the stimulus–response cycle itself, protects existing aftereffects or at least hampers their decay. With this assumption, the decay factor of the single decay model is not only related to time but also to event rate.

It can be concluded that the single-decay model gives the best approximations to the present data. The proposed common decay factor has a tendency to increase with increasing RSI. The decay factor seems to depend on event rate as well as on time.

Experiment 3

The aim of this experiment is to examine the influence of practice on automatic aftereffects, particularly on the parameters of the single-decay model. Many researchers have investigated the influence of practice on choice RT (e.g., Hale, 1968, 1969; Teichner & Krebs, 1974). Uniformly, it has been established that RT decreases with practice. However, reduction rate is not always the same and seems to depend on other variables such as RSI and stimulus–response compatibility. The reduction phenomenon has been explained by some authors as a change of strategy (Fletcher & Rabbitt, 1978), whereas others attribute it to shortcuts becoming "built into" the central mechanism on frequently used channels (Kirby, 1980, p. 103; Welford, 1968). Again, it is important to make a distinction between practice effects occurring in conditions with dominating expectancy influences and practice effects in conditions with dominating automatic effects.

The influence of practice on sequential effects has been studied in other reports (Kirby, 1976; Soetens et al., 1984; Vervaeck & Boer, 1980). These studies show that sequential effects fade out with practice. Theoretically, it is often assumed that a change of strategy takes place so that subjects cease to favor one stimulus above the other as a consequence of the previous stimulus sequence. However, this explanation applies only to practice influence on sequential effects in expectancy conditions, not in automatic aftereffects conditions prevailing at short RSIs. Yet in an experiment with short RSI, Vervaeck and Boer (1980) found a disappearing slope of the alternation curve. This was explained as a change from a general repetition effect to a stimulus-specific one, which in the present model corresponds with the disappearance of inhibition. If we look at the predictions in Figure 2, this can indeed be expected. Decreasing the inhibition parameter *i* results in a disappearing slope in the alternation curve. In Vervaeck's article it was mentioned that 1 subject was trained to an even higher practice level (30,000 trials), resulting in a disappearance of all higher order sequential effects, including facilitation. As predicted by the general model, the decline of facilitation (*f*) results in a shift of the repetition curve in relation to the alternation curve. In short, it can be expected that both effects, inhibition and facilitation, will diminish with practice, inhibition disappearing somewhat faster than facilitation.

Method

Unless otherwise mentioned, Experiment 3 was identical to Experiment 1. RSI was 50 ms. Six subjects participated in seven individual testing sessions. A session consisted of 10 experimental blocks of 100 trials. Each session was preceded by a 50-trial warming-up block. The frequency of testing was about one session every 7 days.

Results and Discussion

Error rate amounted to 3% approximately and was correlated with median RT across sequences as in the other experiments. Maximum differences of mean error rate between different sessions was 1.3%. In Figure 5 median RTs and error percentages are plotted as a function of stimulus sequences for seven practice sessions. For clarity, Sessions 4–5 and 6–7 are combined and only the overall error curve is drawn. Error curves parallel median RT for all sessions.

The repetition–alternation function again displayed positive slopes going from 55° for unpracticed subjects to 30° for experienced subjects, with correlations of at least .85. It can be safely assumed that the data are determined only by automatic aftereffects.

An ANOVA with three within-subjects factors—practice (7 levels), first-order effects (2 levels), and higher order effects (8 levels)—yields a highly significant practice effect, $F(6, 30) = 16.52$, $p < 0.001$. The decrease of RT with practice is evident. Overall median RT changes gradually from 355 ms for unpracticed subjects to 281 ms for highly practiced subjects. In the single-decay model this is projected as a decreasing neutral processing time ($T_0 = M_{RT}/M_T$). This points to more permanent changes in the frequently used stimulus–response channels. The ANOVA further reveals a minimally significant first-order effect, $F(1, 5) = 9.06$, $p < 0.05$. The first-order repetition effect demonstrated in the 50-ms RSI condition of Experiment 2 is tempered by practice. This is supported by an interaction between practice and first-order effect, $F(6, 30) = 3.60$, $p < 0.01$. First-order effects are significant for unpracticed subjects, $F(1, 5) = 16.52$, $p < 0.01$, but not for practiced subjects, $F(1, 5) = 5.37$. The disappearing first-order effect is also visible in Figure 5, where the level of the repetition curve shifts in the direction of the level of the alternation curve. In the final practice session the difference between both levels is minimal. In the model prediction of Figure 2 it has been shown that such a shift corresponds to a decreasing facilitation.

Remarkable is the change of the slope of the alternation curve with practice. This development is different from the change of the slope of the repetition curve. An interaction between practice, first-order effects, and higher order effects in the ANOVA supports this differentiating effect, $F(42, 210) = 2.14$, $p < 0.001$. The slope of the regression line for the alternation curve gradually diminishes to a practically horizontal course in the final session. Coefficients of regression are shown in Table 3. In Figure 2 the model predictions indicated that such a change of the slope of the alternation curve can be associated with a diminution of the inhibition parameter in the single-decay model.

Table 3 shows that the model accounts for 98% of the variance on all practice levels. Note that the model scales all RTs relative to T_0, so that no parameter changes can be attributed to the decrease of sequential effects proportionally to the overall baseline RT. All parameters evolve as expected. Facilitation and inhibition decrease with every session. Inhibition even disappears completely for highly practiced subjects, as could be predicted from the evolution of the slope of the alternation curve. The evolution of the facilitation parameter in Table 3 suggests the disappearance of facilitation after extensive practice. Decay and noise remain constant over all practice levels and are approximately at the same level as in the 50-ms RSI condition of Experiment 2. The very low standard errors of estimate for all practice levels are striking. The single-decay model approximates the experimental data within a range of a few milliseconds.

General Discussion

In the present study a mathematical model had been proposed, describing the supposed components of automatic aftereffects in serial two-choice RT experiments. It is assumed that sequential effects are caused by two independent processes, namely, automatic aftereffects

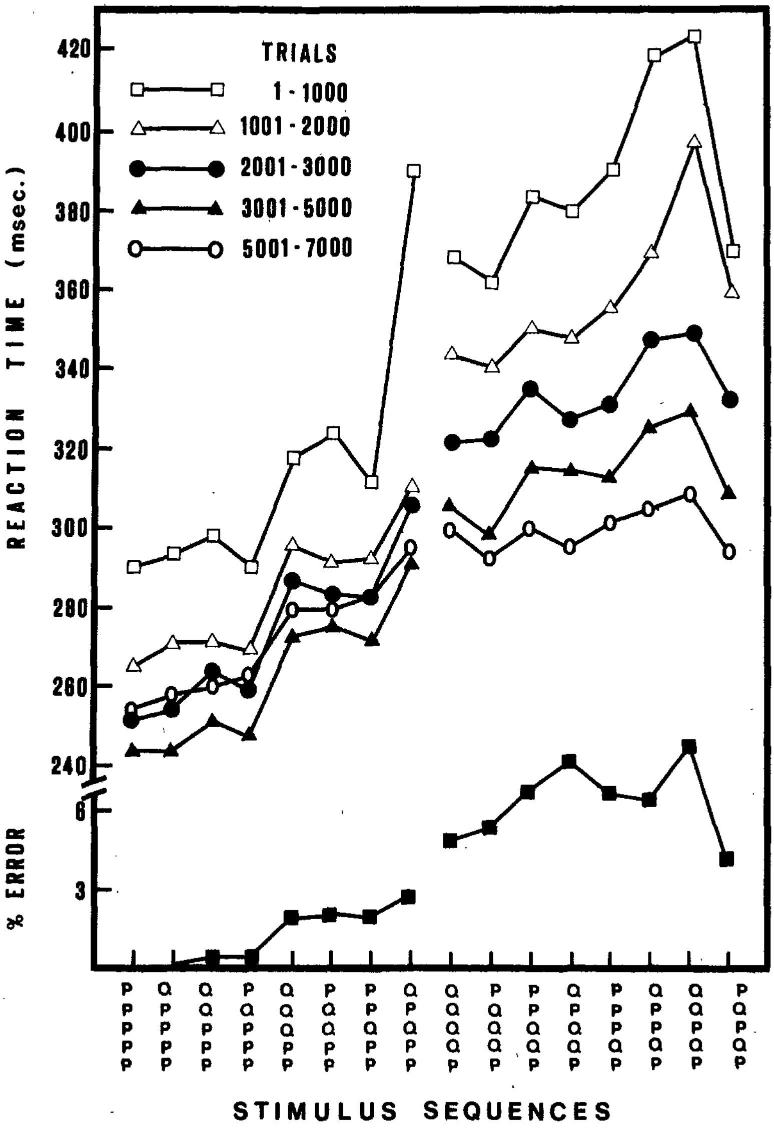

Figure 5. Results of Experiment 3: median correct reaction time (RT) and overall error percentage as a function of preceding stimulus sequences with level of practice as parameter. (Each point on the RT curves represents approximately 550 RTs.)

Table 3
Goodness of Fit and Parameter Values of the Single Decay Model for Different Practice Levels

Practice level	S_e	% var	d	f	i	n	Slope[a]
1	6.15	.99	3.50	.60	0.60	0.15	34.0
2	6.23	.99	3.10	.61	0.40	0.20	29.0
3	4.20	.99	3.00	.52	0.30	0.15	16.3
4	3.48	.99	3.00	.52	0.30	0.15	16.0
5	4.37	.98	3.15	.47	0.20	0.20	15.6
6	2.82	.98	3.45	.37	0.15	0.15	11.7
7	2.22	.98	3.50	.36	0.00	0.20	4.3

Note. S_e = standard error of estimate in ms; % var = percentage of variance accounted for; d = decay; f = facilitation; i = inhibition; n = noise.
[a] slope = slope of the alternation curve, expressed as increase of median reaction time in milliseconds per sequence.

and subjective expectancy. Automatic aftereffects are usually associated with short RSI experiments, whereas subjective expectancy is associated with long RSI experiments. Soetens et al. (1984) showed how both concepts can be separated. The proposed mathematical model is specifically intended to describe automatic aftereffects. Before applying the model, we checked the data on the influence of expectancy.

The proposed single-decay model was apt to explain sequential effects in a two-choice RT task with short RSI. The model suggested the existence of three different components of automatic aftereffects, namely, facilitation, inhibition, and noise. Attempts to explain the results of the present experiments without one of these components failed. This was demonstrated in Experiment 1, where we attempted to rule out noise or inhibition.

In Experiment 2 we studied the relation between automatic aftereffects and RSI. The prediction that automatic aftereffects would diminish with increasing RSI, due to an increasing decay, was supported by the data. The results are in agreement with earlier studies (Bertelson, 1961; Bertelson & Renkin, 1966), where a decreasing repetition effect was found with increasing RSI. An exception is the results of Schvaneveldt and Chase (1969), who did not find any indications for decaying sequential effects in a two-choice task where subjects had to press lighted buttons. It might well be that, because of the extreme compatibility of the task, expectancy is already dominating in there shortest RSI condition (100 ms). Their sequential data indeed showed expectancy patterns. However, there is no obvious explanation for the absence of decay in their incompatible arrangement. It is not clear whether this can be attributed to a transfer of training effect (the subjects participated in several conditions), to the value of RSI (it is unclear whether RSI include time on key), or to the role of eye movements as a consequence of eccentric stimulus presentation.

In the results of Experiment 2 the effect of decaying automatic aftereffects is visualized in Figure 4 as a flattening of both repetition and alternation curve with increasing RSI. The change of the first-order repetition effect with increasing RSI is not so clear, except for a gradually diminishing effect from RSI = 50 ms on. This trend was confirmed by Soetens et al. (1984), who employed an RSI of 250 ms with a completely identical experimental method. They observed a complete disappearance of the first-order repetition effect. Some researchers (Entus & Bindra, 1970; Hale, 1967; Kirby, 1976) even found that an originally first-order repetition effect changed into a first-order alternation effect with rising RSI, indicating the increasing influence of expectancy on the first-order effect. This seems to happen only when RSI becomes sufficiently long. Welford (1977) suggests that an individual needs time to build up expectancies. The increasing influence of subjective expectancy when RSI is prolonged can also be found in the higher order sequential effects of Experiment 2, even with the short RSIs used there.

Changes in the parameters of the single-decay model due to RSI manipulation give the opportunity to be more explicit about the changes in automatic aftereffects with increasing RSI. The model shows that all but one of the parameters have a constant value with a changing RSI. Only the decay parameter is responsible for the decrease in repetition effects. The original strength of facilitation, inhibition, and noise evoked by previous stimulus processing is independent of the subsequent interval. Although the decay parameter increases monotonically as RSI increases, this does not necessarily imply that the rate of decay is independent of the interval. The data in Experiment 2 showed that, whereas automatic aftereffects seem to disappear at a rapid rate without intervening events in the 100-ms RSI condition, they seem to persist much longer with intervening events in the short RSI conditions. The intervening stimulus–response cycles hamper the decay of automatic aftereffects. The rate of decay is thus slowed down in the short RSI conditions. It can be concluded that the proposed *d* parameter is not only a function of time but also of the number of intervening events.

Experiment 3 demonstrated the dissipation of automatic aftereffects with practice. The gradual rotation of the alternation curve in Figure 5 is an indication of a dissipating inhibition effect, as is demonstrated with the manipulation of the inhibition parameter in Figure 2. The decreasing inhibition with practice is also supported by the predictions of the single-decay model. The calculated inhibition parameter gradually diminishes to a value of zero. Also the slower decrease in facilitation, which Vervaeck and Boer (1980) detected after extensive training of one subject, is demonstrated adequately in the same analysis with the single-decay model. The decay parameter remained constant over all training levels.

The decrease of automatic aftereffects with practice can be related to a decreasing monitoring time as proposed by Welford (1968). Monitoring, as defined by Welford, is a process during which subjects check for errors after responses are executed. Subjects already familiar with a particular task need not check for correct responses, or at least checking becomes superficial (Annett, 1966). Experienced subjects, then, do not need monitoring. Checking for correct responses can happen only if the preceding stimulus–response cycle has left some residual neural activity. Automatic aftereffects can be regarded as such residuals. Kirby (1980, pp. 146–147) observed that it is not too farfetched to assume that monitoring is the primary function of automatic aftereffects, and not the facilitation of some subsequent stimulus–response cycle. Now, if monitoring becomes superfluous with practice, automatic aftereffects such as facilitation and inhibition lose their function and gradually disappear.

The overall reduction of RT with practice has been explained in two ways. The first theory proclaims a change of strategy. For example, Fletcher and Rabbitt (1978) found evidence suggesting that with increasing practice, subjects tended to respond in terms of change or constancy between successive displays. This is very unlikely to happen in short RSI experiments because processing rate is much too high to give subjects the opportunity to develop strategies or expectancies. An alternative theory suggests a change in stimulus–response mapping. In other words, changes occur in the frequently used channels, and shortcuts become built into the central mechanism. This idea is better suited to a high-speed processing experiment and also fits into the ideas of the present model. The disappearance of some processing fraction during the stimulus–response cycle is not impossible. Possibly something similar happens to monitoring, although this stage of processing is situated during RSI.

Some conclusions can also be drawn about the locus of automatic aftereffects in the processing system. If it is assumed that a part of the RT process cannot be influenced by the components of automatic aftereffects, this should result in an invariable fraction of RT. The analysis of the data with the single-decay model was repeated with different values for an invariable RT fraction. All results were negative, that is, standard errors increased with an increasing invariable RT fraction, whereas the percentage of variance, accounted for by the model, decreased. This means that the single-decay model predicts automatic aftereffects on all processes of the stimulus–response cycle. This is in accordance with the information-reduction paradigm developed by Bertelson (1965). The results of his experiments imply that part of the repetition effect is due to the repetition of the signal, but the main influence is due to the repetition of the response. The complexity of the results in other studies strongly suggests that more complex central mechanisms are involved. Rabbitt (1968), for example, found that an initially strong stimulus effect changed into a strong response effect. Rabbitt and Vyas (1973) provided evidence of repetition effects on five out of six processing stages: perceptual identification, signal coding, signal–response mapping, response selection, and response programming. On the whole, the literature on the locus of sequential effects is highly controversial. Moreover, some researchers found that the impact of the effects on the different processing stages changed with RSI (Eichelman, 1970) and stimulus–response mapping (Peeke & Stone, 1972). To confirm the predictions of the present model with respect to the location of automatic aftereffects, further research is necessary.

The single-decay model is specifically designed to explain sequential data arising from automatic aftereffects in two-choice tasks. Generalization of the results to multiple-choice experiments is difficult. It is known that incrementing the number of alternatives gives rise to stronger repetition effects (Hale, 1969; Hoyle & Gholson, 1968; Hyman, 1953; Remington, 1969, 1971) that extend over longer RSIs. This might be an indication for stronger automatic aftereffects, but still the RSI seems to be sufficiently long for building up expectancy. Expectancy in a two-choice task has a two-sided effect that distinguishes it from automatic effects, but expectancy in multiple-choice tasks is more complex, as can be derived from results in guessing experiments (Schvaneveldt & Chase, 1969). Identifying unique data patterns for automatic aftereffects, as opposed to expectancy effects, might well turn out to be extremely difficult in multiple-choice experiments. There is definitely a need to resolve the complex issues inherent in multiple-choice experiments. For example, why is it that some researchers did find decreasing repetition effects with increasing RSI (Smith, 1968; Umilta et al., 1972), suggesting a decay, whereas others did not find any indications for decay (Keele, 1969; Keele & Boies, 1973; Schvaneveldt & Chase, 1969)?

The merit of the single-decay model is that it offers a quantitative approach to the analysis of automatic aftereffects. Many studies on sequential effects have often been limited to the observation of one isolated component and did not show its relationship to the other components involved. The mathematical model shows the mutual relationship between the components of automatic aftereffects and how they change with experimental manipulation. The single-decay model provides a satisfactory explanation for the processes involved in compatible two-choice RT tasks with short RSI. In future applications, the model can help to identify the presence of automatic aftereffects in other RT research.

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