Covert signs of expectancy in serial reaction time tasks revealed by event-related potentials

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Choice reaction time is strongly determined by the sequence of preceding stimuli. With long response-stimulus intervals (RSIs), a cost-benefit pattern is observed, which has been related to expectancy, whereas with short RSIs a benefit-only pattern emerges, possibly because of automatic facilitation. In the present study, event-related potentials were recorded while subjects performed serial choice responses to visual and auditory stimuli at long and short RSIs. As expected, reaction times displayed *cost-benefit* and *benefit-only* patterns at long and short RSIs, respectively. In contrast, sequential effects in event-related potential amplitudes displayed a cost-benefit pattern, unaffected by the RSI. The results demonstrate that an expectancy-like mechanism is always active in serial tasks but appears to influence performance only when the RSI is long.

In the present study, we investigate the relation between sequential patterns in reaction times (RTs) and event-related potentials (ERPs) in serial two-choice RT experiments. A substantial number of studies have shown that the pattern of sequential effects in RTs changes significantly when the time between the response and the arrival of the next stimulus (response-to-stimulus interval, RSI) is manipulated. With long RSIs, a cost-benefit pattern is observed, suggesting an underlying expectancy-like mechanism, named subjective expectancy (Kirby, 1980). With short RSIs, a benefit-only pattern is observed, suggesting an automatic-like process, named automatic facilitation. Some of the studies with long RSIs have included ERP measurements and have shown that the amplitude of the P300 component displays a cost-benefit pattern that is similar to that for the RTs. The similarity of the cost-benefit patterns strongly indicates that both are elicited by one and the same underlying expectancy mechanism. In the present study, we want to find out whether the parallel between P300 amplitude and RT can be extended to short RSIs and, in general, to contribute to a better understanding of the relative role of expectancy and automatic facilitation mechanisms in sequential effects by recording ERPs.

Many earlier studies have shown that when stimuli from two or more discrete classes are presented in random order, choice RT is strongly determined by the sequence of preceding stimuli (see, e.g., Bertelson, 1963; Kirby, 1976).

The differences in RT are not only visible in the first-order (FO) effect—that is, the influence of the immediately preceding event—but also in higher order (HO) effects, caused by events earlier in the sequence (Kirby, 1976; Soetens, Boer, & Hueting, 1985). In principle, sequential effects might arise from the sequence of subsequent stimuli, responses, or stimulus-response assignments (Soetens, 1998). Because the present paper is not concerned with the specific locus of the sequential effects within the information processing chain, we prefer neutral terms such as *trial sequence* or *S-R cycle* to the more common *stimulus sequence*.

The sequential pattern of RT changes under various conditions of RSI, compatibility, and type of stimuli used. For example, completely different FO and HO patterns of RTs are observed between conditions with short and long RSIs. These different patterns have been ascribed to two different mechanisms—namely, automatic facilitation for short RSIs and subjective expectancy for long RSIs (see, e.g., Soetens, 1998; Soetens et al., 1985).

With long RSIs—for example, 500 msec or more in a spatially compatible two-choice task—HO sequential effects show a cost-benefit pattern that is typical for expectancy (Audley, 1973). This means that sequences eliciting short RTs when they are followed by a trial repetition (R), proportionally elicit long RTs when followed by a trial alternation (A), and vice versa. For example, when runs of repetitions (RRR) or alternations (AAA) are continued (RRRR, AAAA), RT decreases with the length of the run, whereas RT increases if the same runs are interrupted (RRRA, AAAR). In the first case, RT is assumed to be fast because the actual event matches the expectancy of the subjects, whereas, in the second case, RT is long because expectancy is disconfirmed.

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In contrast to long RSIs, no cost–benefit pattern emerges in two-choice tasks when RSIs are short—for example, 100 msec or less. On the contrary, some sequences then only have benefits and are always followed by short RTs (e.g., RRRR, RRR*A*), whereas other sequences are followed by long RTs (e.g., AAAA, AAA*R*). This is called a benefit-only pattern and has been associated with the concept of automatic facilitation (Kirby, 1976; Soetens, Deboeck, & Hueting, 1984; Vervaeck & Boer, 1980). Automatic facilitation explains the benefit-only pattern as being a consequence of residual memory traces left by previous stimulus–response cycles, decaying over time (Bertelson, 1961; Hyman, 1953). Kirby (1980) suggests that, with short RSIs, these traces have not faded out by the arrival of the next stimulus, so that HO effects can ensue. However, the results of many studies show that the passage of time might not be the only determining factor, but also the number of intervening stimuli (Pashler & Baylis, 1991; Soetens, 1990, p. 62). Thus, it is possible that any remaining traces of previous stimulus–response cycles in the RT pattern are hidden by the upcoming influence of subjective expectancy with increasing RSIs.

Automatic facilitation differs from typical repetition priming effects in that it is not *event* specific. That is, some sequences seem to create a state of the organism that is beneficial for the *processing* of any stimulus that will come next, whereas other sequences create a detrimental state. Laming (1968) described the effect as being noise in the process of identifying the stimulus, which increases when many stimulus alternations have occurred, whereas it decreases with many preceding repetitions.

Also, stimulus–response compatibility and the type of stimuli used influence the specific RSI at which a benefit-only pattern changes into a cost–benefit pattern. For example, repetition effects or benefit-only patterns at long RSIs have been found with symbolic stimuli or when more than two response alternatives are used (see, e.g., Bertelson & Renkin, 1966; Campbell & Proctor, 1993; Kirby, 1980; Pashler & Baylis, 1991). Although the switch to a cost–benefit pattern in spatially compatible two-choice situations has been observed at RSIs of 100 msec, much longer RSIs are necessary for the change in pattern in less compatible conditions (Soetens et al., 1985).

The cost–benefit (expectancy) and benefit-only (automatic facilitation) terminology suggests that reference should be made to the theory of controlled and automatic processing (Posner & Snyder, 1975; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). However, the term *expectancy* in the present context is mainly used to describe a phenomenon that elicits a cost–benefit pattern in RTs or ERPs and does not necessarily refer to voluntary, conscious, or controlled processes. Whether or not these attributes hold for the sequence-dependent “expectancies” is an empirical question. We come back to this issue in the general discussion.

Although, in some conditions, HO sequential effects are dominated by automatic facilitation and in others by

expectancy, the relationship between both processes remains to be determined. That expectancies may be present even at short RSIs, where a benefit-only pattern is normally dominant, is suggested by the findings of Soetens et al. (1985; Soetens et al., 1984). After long alternation sequences, RTs were unusually short when they were continued (AAAA), and RTs were unusually long when they were discontinued (AAA*R*). That is, such sequences formed an exceptional cost–benefit pattern with short RSIs in an otherwise dominating benefit-only pattern of automatic facilitation. It seems as if, after a highly conspicuous series of stimuli, expectancy suddenly breaks through. Soetens et al. (1985) argued that a differentiation should be made between expectancy, on the one hand, and observable effects of these expectancies on behavior as a consequence of preparation, on the other hand. Expectancies may be present in all conditions, but with short RSIs, they may not influence behavior because not enough time is available to prepare responses on the basis of these expectancies.

One way to approach the question of whether there are covert expectancy processes when in overt behavior a benefit-only is observed is the use of event-related brain potentials. ERPs consist of various components that can be related to the ongoing activity of different aspects of information processing and can be an indication of covert processes. In relation to the present questions, it is possible that RTs and ERPs follow different patterns in short-RSI conditions.

Patterns of ERPs in serial choice RTs have not yet been studied with short-RSI conditions, but a lot of research has been done with long RSIs. In ERP studies with relatively long and constant interstimulus intervals (ISIs), sequential effects similar to those with RTs at long RSIs have been observed also in the amplitude of the P300 component when large amplitudes are considered to reflect more costly processing than do small ones. For example, Squires, Wickens, Squires, and Donchin (1976) found that sequential effects in P300 amplitude followed a cost–benefit pattern, indicative of an expectancy mechanism. Many subsequent researchers have replicated the similarity of sequential effects of P300 amplitude and response latencies in choice RT tasks (Duncan-Johnson, Roth, & Kopell, 1984; Ford, Duncan-Johnson, Pfefferbaum, & Kopell, 1982; Sommer, Matt, & Leuthold, 1990a). This is considered to be strong evidence that the pattern of changes in P300 amplitude and RTs is elicited by one and the same expectancy mechanism.

However, recent research has shown that sequence-dependent RT and ERP patterns for the same data set may be dissociated. For relatively long ISIs of 1.3 sec, Sommer et al. (1990a) showed an FO alternation effect—that is, RTs were faster to a different stimulus than to the same stimulus. P300 amplitude, on the other hand, displayed an FO repetition effect—that is, the amplitude was smaller for repeated than for unrepeated stimuli. The FO effects in P300 amplitude and in RT become more similar with

practice (Sommer, Matt, & Leuthold, 1990b) and with further increasing ISIs (Leuthold & Sommer, 1993).

Important for the present purposes is that the HO sequential effects in P300 amplitude cannot be ascribed to a strictly controllable process (cf. Sommer, Leuthold, & Matt, 1998). Matt, Leuthold, and Sommer (1992) manipulated voluntary expectancies of their subjects toward a preference for stimulus alternations or repetitions, whereas in fact they were equiprobable. Although there were clear alterations of sequential effects in RTs, changes for P300 amplitude were few and small. Also, Sommer et al. (1990a) showed that conscious expectancies for a given stimulus, as measured with subjective ratings, are hardly affected by the trial sequence at all. Finally, HO sequential effects in P300 amplitude are unaffected by even large amounts of practice (Sommer et al., 1990b). On the basis of their results, Sommer et al. (1998) suggested that sequential effects in P300 are generated by a low-level and largely uncontrollable variant of expectancy.

If the expectancy mechanism is uncontrollable, it might also remain active at short RSIs. It is conceivable, then, that P300 amplitude still shows a cost-benefit pattern even when RTs show a relatively pure benefit-only pattern. If, on the other hand, there is no time to develop expectancies in short-RSI conditions (Vervaeck & Boer, 1980), the cost-benefit pattern in P300 amplitude should not be present. In this paper, we investigate this hypothesis in two experiments using two-choice stimulus location to response location tasks, in the auditory and visual modality, respectively.

EXPERIMENT 1

Method

Subjects. We tested a total of 10 right-handed subjects (6 males), who were from 22 to 35 years of age. They had no prior experience in the particular task of this study.

Apparatus and Stimuli. Stimuli consisted of single 40-msec bursts of 66-dB(A) white noise, presented at random and equiprobably to either ear via headphones. RSI, defined as the interval between response onset and onset of the next stimulus, was either 40 or 500 msec. Coulbourn modules controlled stimulus presentation. Stimuli and responses were coded as voltage pulses for a trigger signal. Responses were performed on two telegraph keys, mounted 20 cm apart on a horizontal panel, orthogonal to the midsagittal plane. The keys were operated with the index fingers.

Procedure. The subjects were comfortably seated in a dimly lit, sound attenuated, and electrically shielded room, using a fixed chin rest. They responded compatibly to right- and left-ear stimuli, respectively, with right and left keypresses, which were to be both fast and accurate.

The subjects were advised to fixate a dot in front while responding. The 40- and 500-msec RSI conditions lasted about 20 and 40 min, interrupted by short breaks after every 50 and 100 sec, respectively. Each subject participated first in the 40- and then in the 500-msec RSI condition. The order of the RSI conditions was not balanced, because HO sequence effects in RTs are much less affected by practice at long RSIs than by practice at short RSIs (Soetens et al., 1985; Soetens et al., 1984). Similarly, at long RSIs, HO sequence effects in P300 amplitude are practice insensitive (Sommer et al., 1990b).

Electrophysiological recordings. The electroencephalogram (EEG) was recorded with a linked mastoid reference from Fz, Cz, and Pz (TC = 10 sec, HFF = 40 Hz). In addition, the vertical electro-oculogram (vEOG) was recorded from electrodes above and below the right eye. These electrophysiological signals were digitized along with the trigger signal at 100 Hz for continuous time segments of 18.5 sec. Data storage between segments required less than 1.5 sec. Off line, the trigger signals were decoded, and the data were separated into individual trials with 400-msec prestimulus and 690-msec post-stimulus epochs.

Data analyses. Each trial was coded according to 16 fourth-order sequences of trial repetitions and alternations (from RRRR over AAAR and RRRA to AAAA). Analyses of RTs, error rates, and ERPs were based on these sequences. The same set of trials was considered for both RTs and ERPs. In these trials, both the present and the immediately preceding response had to be correct, and the respective ERPs had to be artifact free. A response was considered correct if the proper key had been pressed no earlier than 150 msec following stimulus onset. For the error rates, only present trials were considered, and any artifacts in ERPs from eye movements, blinks, or amplifier saturation were disregarded. The number of artifacts did not vary as a function of experimental condition. Note that errors and artifacts did not affect the classification of the trial sequence.

Results and Discussion

Performance. To check the influence of RSI on HO effects, we used the slopes of the repetition and alternation functions, as described by Soetens et al. (1985). Therefore, RTs are depicted in Figure 1 as a function of HO sequences for both RSI conditions. The left part of the curve, representing all sequences ending with an FO repetition, is called the repetition curve. The right part is

Figure 1. Experiment 1: Sequential effects in reaction times and error rates.

called the alternation curve, as it contains all sequences ending with an FO alternation. The critical parameter is the slope of the alternation function. A positive slope, parallel to the repetition curve, is a benefit-only pattern, typical for automatic facilitation, whereas a negative slope, opposite to the slope of the repetition curve, is a cost-benefit pattern, typical for subjective expectancy. In the following analyses, differences in the slopes are assessed by comparing the linear components of the regressions lines for FO repetition and alternation sequences.

An analysis of variance (ANOVA) was performed on RT with repeated measures on factors RSI (RSI 40 vs. RSI 500), FO sequence (repetitions vs. alternations), and HO sequences (RRR to AAA).

Responses were faster in the RSI 500 than in the RSI 40 condition [$M = 301$ vs. 428 msec, $F(1,9) = 23.5$, $p < .001$]. There was no FO effect, either in the overall data or in any of the RSI conditions. However, there was a strong RSI $\times$ FO $\times$ HO interaction [$F(1,9) = 28.1$, $p < .001$]. For the RSI 40 condition, the slopes of both the repetition and the alternation branches are positive, but more so for the alternation branch [$F(1,9) = 9.0$, $p < .05$]. In contrast, the linear trends across the repetition and alternation branches in the RSI 500 condition differed in direction [$F(1,9) = 46.5$, $p < .001$]. A different way of looking at the RSI $\times$ FO $\times$ HO interaction is by comparing trends across RSI conditions, separately for repetition and alternation branches. The slopes of the repetition curves are positive for both RSIs, yielding a main effect for the linear trend across the HO sequences [$F(1,9) = 71.9$, $p < .001$]. The slight difference in the positive slopes was reflected by a tendency for an RSI $\times$ HO interaction ($p = .07$). The linear trends across the alternation branches of the RSI conditions differed in direction [$F(1,9) = 31.6$, $p < .001$]. The positive RSI 40 slope was steeper than the negative RSI 500 slope, yielding a small main effect of the HO sequence [$F(1,9) = 8.8$, $p < .05$].

More errors were made for long RSIs than for short RSIs [$M = 10.8\%$ vs. 5.8% ; $F(1,9) = 9.3$, $p < .05$]. In line with predictions, more errors were made for sequences ending with an alternation than for those ending with repetitions [$M = 10.9\%$ vs. 5.7% ; $F(1,9) = 15.5$, $p < .01$], and this was so for short- as well as for long-RSI conditions. Sequential effects in error rates involving HO sequences are similar to the pattern in mean RTs, as can be seen in Figure 1. All error curves are parallel to RT curves. This similarity in pattern between RTs and error rates excludes an explanation of the sequential effects in terms of a speed-accuracy tradeoff.

In particular, the opposite slopes of the alternation curve were replicated in the error data. As was the case for RTs, there was an RSI $\times$ FO $\times$ HO interaction [$F(1,9) = 11.1$, $p < .01$], again stressing the different patterns for both RSI conditions. This latter interaction was evidently caused by a difference in the HO slope across the alternation branch between the RSI conditions [$F(1,9) = 19.3$, $p < .01$], which was not present for the repetition branch ($F = 1.1$).

On the whole, the two conditions of this study show two different sequential RT patterns. They reproduce RT patterns, similar to those described in earlier studies (Kirby, 1976; Soetens et al., 1985), that have been related to different mechanisms, named automatic facilitation and subjective expectancy. The present study extends these findings from visual to auditory stimuli. The repeated measures design and fixed ordering for the RSI conditions may have led to an increased error rate in the RSI 500 condition, as compared with the findings of Soetens et al. (1985), but do not seem to have interfered with the HO sequential patterns.

P300 amplitude. For the RSI 40 condition, there was considerable overlap of the ERPs between successive trials. This is shown in the left panel of Figure 2 for the ERPs at each electrode of 1 subject and for some selected trial sequences. The overlap can be seen most clearly in the prestimulus time segments for which there is systematic ERP activity. For example, in the RRAR sequence, we see a clear positive peak around 200 msec prior to stimulus onset, followed by a smaller negative peak. This overlap most likely extends also into the poststimulus segment. Such overlap between subsequent ERPs not only distorts the measurement of the component in question, but also makes it virtually impossible to find a suitable baseline. Overlap from ERPs to subsequent stimuli, on the other hand, should generally be less problematic, because, with RTs of more than 400 msec, the next P300 should come late enough not to distort the present P300. We therefore applied the procedure for the correction of overlap between adjacent ERPs (ADJAR), developed by Woldorff (1993), to the ERPs of the RSI 40 condition before making any amplitude measurements.¹

In its advanced version (Level 2), ADJAR yields separate estimates of the contributions of the ERPs elicited by the preceding and the subsequent stimuli to any given ERP. In an iterative procedure, these estimates are optimized, and, finally, both are subtracted from the original ERP. We ran this procedure with 10 iterations where all estimates had approached asymptote. The right panel of Figure 2 demonstrates the resulting waveform. After ADJAR, the prestimulus epochs showed considerably less activity, and the final part of the recording epochs showed a better return to baseline than before correction. Figure 3, left panel, shows the grand average of the ADJAR-corrected ERPs from the RSI 40 condition. Note that, even after ADJAR, there was some systematic activity starting about 100 msec preceding the stimulus. Clearly, this must be response-related activity to the previous stimulus, which is time-locked to the stimulus eliciting the present ERP by our use of constant RSIs. Because ADJAR cannot remove this stimulus-locked ERP activity, we used a baseline from 400 to 200 msec preceding the stimulus for the measurement of all ERP amplitudes.

Figure 3 clearly demonstrates cost-benefit patterns when the ERPs for continued and interrupted runs of both repetitions and alternations are compared. Large amplitudes are recorded after unexpected sequences—

Figure 2. Experiment 1: Demonstration of the effect of overlap correction for the event-related potentials (ERPs) of 1 subject from the RSI 40 condition. The figure displays ERPs of the most extreme and also of two intermediate sequences (RRAR and RRAA) in its original (left column) and corrected versions (right column). Note the smoothing of the prestimulus baselines, particularly for the RRAR and RRAA sequences.

that is, interruptions of runs—whereas small amplitudes are recorded after expected sequences—that is, continuations of runs. This pattern holds not only for the RSI 500 condition, where it was expected, but also for the RSI 40 condition.

P300 amplitude was quantified as average amplitude in an interval between 280 and 370 msec—centered around the average peak latency—relative to the baseline just described. Figure 4 displays the sequential effects in this measure for both RSIs. The figures confirm the cost-benefit pattern for the HO sequences. The slopes of the repetition curves are positive, and the slopes of the alternation curves are negative. This pattern is in agreement with the pattern of RTs for the RSI 500 condition but is opposite to the RT pattern in the RSI 40 condition. Also, the commonly observed FO repetition effect for both

RSI conditions is visible as the difference between the general levels of the repetition and alternation curves.

The same ANOVAs as those used for the RT data were applied to P300 amplitude, with the additional inclusion of repeated measures on electrode site (Fz, Cz, Pz). In some cases, the question of differential scalp distributions across experimental conditions arises. Here an ambiguity may emerge when there are overall amplitude differences between conditions (McCarthy & Wood, 1985). When amplitude changes occur because of variations in the activity of an invariant underlying intracranial generator structure, the effects at different electrodes will be multiplicative—for example, increasing or decreasing the amplitude by a certain percentage at each electrode. In this case, because of its additive model, the ANOVA will yield an interaction between the condition in question

Figure 3. Experiment 1: Grand average event-related potentials (ERPs) with midline electrodes superimposed, and the vertical electrooculogram for the most extreme trial sequences. The left and right sides display ERPs from the 40- and 500-msec response-to-stimulus interval condition, respectively.

and the electrode site. In order to disambiguate such effects, we repeated the ANOVA after scaling the ERPs to the same overall amplitude across electrode sites within each condition. Scaling was performed with the average vector length across electrodes in the grand average for each condition.

The FO effect was highly significant [$F(1,9) = 24.4$, $p < .001$], with repetitions yielding smaller amplitudes than alternations ($M = 1.2$ vs. $2.8 \mu\text{V}$). RSI did not alter this FO effect ($F < 1$). Again, the cost-benefit pattern was reflected by a strong FO $\times$ HO interaction [$F(1,9) = 73.0$, $p < .001$], but now it was unmodulated by RSI ($F < 1$). The FO $\times$ HO interaction was present also when the RSI 40 was tested alone [$F(1,9) = 25.0$, $p < .001$]. Note that there were no influences of RSI on sequential effects even in the interaction with the electrode. This held true also after scaling the amplitudes.

In contrast to the lack of modulations of sequential effects, RSI did affect P300 amplitude in general [$F(1,9) = 15.5$, $p < .01$] and in interaction with electrode [$F(2,18) = 10.6$, $p < .01$]. An ANOVA on scaled amplitudes confirmed that reducing RSI from 500 to 40 msec changed the common centroparietal distribution of P300 [$M(\text{Fz to Pz}) = 1.7, 4.3, 3.4 \mu\text{V}$] to a frontocentral topography [$M(\text{Fz to Pz}) = 1.2, 1.1, 0.3 \mu\text{V}$; $F(2,18) = 6.0$, $p < .05$]. In addition, in unscaled data, there were interactions of electrode with FO [$F(2,18) = 15.3$, $p < .01$] and with both FO and HO [$F(14,126) = 2.7$, $p < .05$]. These interactions are probably due to the fact that amplitude changes at different electrodes are multiplicative rather than additive, because they disappeared after scaling for amplitude ($p \geq .1$).

The sequential effects in P300 amplitude for the RSI 500 condition were mainly a replication of earlier results (Leuthold & Sommer, 1993; Sommer et al., 1990a) for long

Figure 4. Experiment 1: Sequential effects in P300 amplitude at the midline electrodes. The left panel shows the RSI 40 condition after overlap correction, and the right panel shows the RSI 500 condition.

and constant ISIs, with HO effects in ERPs and RTs showing similar cost-benefit patterns. The present study, which defined the relevant stimulus in terms of the stimulated ear, extends earlier findings in which tone frequency was used to define the relevant stimulus.

The situation is different, however, in the RSI 40 condition. Whereas the alternation curve in RTs showed a highly significant change from a positive slope for RSI 40 to a negative slope for RSI 500, it remained negative across RSIs for P300 amplitude. This result is not an artifact of the overlap correction. First, the cost-benefit pattern also is visible for the extreme sequences in the uncorrected waveforms (cf. Figure 2). For these sequences, overlap by ERPs to preceding stimuli is a minor problem, because it concerns stimuli which elicit only small P300s. For example, an RRRA trial is preceded by equal parts by ARRR and RRRR stimuli, both of which elicit small ERPs. Second, even the uncorrected ERPs yielded similar results when analyzed in a way analogous to the corrected versions.

The dissociation between HO sequential effects in RTs and ERPs at short RSIs indicates that expectancies are present in these conditions but have no direct effect on behavior. Possibly these expectancies need a minimum time to develop into a preparatory state that can influence the RT process.

Whereas the general picture presented by the data of Experiment 1 conforms with previous results, there were no FO effects in the RTs. With visual stimuli, mostly an

FO repetition effect was found for short RSIs, and an FO alternation effect for long RSIs (see Kirby, 1980). Inasmuch as auditory localization tasks have not been used in previous studies of sequential effects, the specifics of this task may be responsible for our findings. To assess this hypothesis and to test the generalizability of our findings across modalities, we decided to repeat the experiment with a visual localization task.

EXPERIMENT 2

Method

Apart from the subjects and modality of stimulation, the method and instructions followed those of Experiment 1. Experiment 2 was performed with a new sample of 10 unpracticed right-handed subjects (3 males, 20 to 36 years of age). Stimulation was provided by three light-emitting diodes (LED) of 3-mm diameter, aligned horizontally at distances of 6 mm between their centers. Viewing distance was 1 m. The middle LED was red and lit continuously, providing a fixation point and spatial reference. The outer LEDs were green and served as response signals when lit.

Results and Discussion

Performance. Unless stated otherwise, data analysis was conducted as in Experiment 1. Figure 5 depicts RTs and error rates for the two RSI conditions and the 16 trial sequences.

As in Experiment 1, responses were faster in the RSI 500 than in the RSI 40 condition [$M = 313$ vs. 368 msec; $F(1,9) = 20.9, p < .01$]. In contrast to Experiment 1, there

Figure 6. Experiment 2: Grand average event-related potentials (ERPs) with midline electrodes superimposed, and the vertical electrooculogram for the most extreme trial sequences. The left and right sides display ERPs from the 40- and 500-msec response-to-stimulus interval condition, respectively.

disappeared ($p = .1$) and the interaction with FO and HO was greatly diminished [$F(1,9) = 6.43, p < .05$].

Sequential effects in P300 amplitude are in total agreement with Experiment 1, which is of particular interest in regard to the RSI 40 condition, where they have not been observed previously. Therefore, these findings have to be considered to be reliable.

GENERAL DISCUSSION

In serial two-choice RT experiments, two mechanisms appear to be responsible for the occurrence of sequential effects. Automatic facilitation has been found to dominate in conditions with short RSIs, whereas subjective expectancy dominates in conditions with long RSIs. The primary aim of the present contribution was to assess the relationship between these two mechanisms. By recording ERPs, we found support for the conjecture that, under both short- and long-RSI conditions, there is a buildup of

expectancies that influences performance, however, only at long RSIs.

In contrast to the similarity of sequential effects between RTs and ERPs in conditions with long RSIs (Sommer et al., 1990a; Squires et al., 1976), different sequential effects were found with short RSIs. With short RSIs, RTs showed the typical benefit-only pattern of automatic facilitation, but P300 amplitude displayed the same cost-benefit-like pattern of subjective expectancy as in long-RSI conditions.

The observation of RSI-independent HO sequential effects in P300 amplitude lends support to the suggestion of Soetens et al. (1985; Soetens et al., 1984). They argued that expectancies may be present in all conditions, but at short RSIs they may not influence behavior. Therefore, a differentiation should be made between expectancy, on the one hand, and observable effects of these expectancies on behavior, on the other hand. This suggestion was based on exceptional RT effects on some

Figure 7. Experiment 2: Sequential effects in P300 amplitude. The left panel shows the RSI 40-msec condition after overlap correction, and the right panel shows the RSI 500-msec condition.

stimulus sequences. The present results for ERP amplitudes show expectancy- typical cost-benefit patterns across the whole range of trial sequences, even at short RSIs, whereas at the behavioral level there was benefit-only, even without any sign of a breakthrough of expectancy. Therefore, we must conclude that expectancy is present at all RSIs but that, at short RSIs, automatic facilitation dominates RTs.

This interpretation is in accord with the idea that the expectancies in ERP amplitudes at long RSIs show some properties that are more of an automatic-like, rather than a controlled, nature and, as such, must be differentiated from expectancies related to higher cognitive processes (Johnson, 1988; Sommer et al., 1998). For instance, it has been shown that the P300 cost-benefit pattern is unconscious (Sommer et al., 1990a) and not influenced by probability manipulations (Matt et al., 1992). Finally, in the present data, the cost-benefit pattern observed in ERPs during long RSIs remains stable under a short-RSI condition, where this pattern is abolished for RTs. Although somewhat speculative, we consider it plausible that the critical factor for the switch from the cost-benefit to the benefit-only pattern in RTs relates to the availability of time. Because controlled processes are considered to be slow and time consuming (Shiffrin & Schneider, 1977), one should expect a change in sequential effects if they are the product of a controlled process. The insensitivity of sequential effects in P300 amplitude

toward time availability supports the idea that the process generating the cost-benefit pattern in P300 is not a controlled process in the strict sense. Therefore, the present findings from the RSI 40 condition add a further piece of evidence for the idea that the mechanism underlying the generation of sequential effects in P300 amplitude may be of a mixed nature. The properties of the subjective expectancy process clearly cuts across the classical distinction between automatic and controlled processing. This is no exceptional finding, since several automatic-like cost-benefit patterns have also been observed in priming studies (e.g., Neumann, 1990; Neumann & Klotz, 1994).

In order to integrate our electrophysiological and behavioral findings, we assume that the sequential effects observed in P300 amplitude reflect a process that is responsible, in some sense, for sequential effects in RTs at long RSIs. We may, then, suggest the following mechanism. Expectancy, which is evoked in perceptual processes, feeds into the information-processing system at later, possibly response-related stages. This feed-forward system seems to need a minimum time, which is available in the RSI 500 condition but not in the RSI 40 condition. In the latter, the same expectancy patterns are present as those reflected in the P300 amplitude, but there is not enough time to influence the later stages. Support for such a minimum preparation time, based on expectancy, is found in discrete choice RT studies with variable fore-

periods between an informative precue and the imperative stimulus. Sanders (1972), for example, found that at least 150–200 msec were needed for the precue to have an effect on the RT. It is notable that this kind of mechanism can also explain why automatic facilitation survives over longer intervals when the RSI is short (HO effects over three to four stimuli), as compared with long RSIs. In the former, the sequential information that is supposed to influence response-related processes has to be updated with each intervening stimulus, so that its interaction with the RT process is prevented.

The absence of a benefit-only pattern in ERP results reveals some aspects of the interaction between both mechanisms. Pashler and Baylis (1991) claimed that the repetition effect is situated in the response selection stage, on the basis of their specific empirical data. Several other researchers have found evidence that automatic facilitation may be present in all processing stages (Rabbitt & Vyas, 1973; Soetens et al., 1984), including the early perceptual stages (Maljkovic & Nakayama, 1994, 1996). Because the low-level expectancy mechanisms also seem to be active in these early stages, as shown by the present ERP data, it can be assumed that both mechanisms are working in parallel, probably following different pathways. Following Sanders' (1977, 1980) idea of dividing information-processing mechanisms in those mechanisms related to the structural or functional pathways, we can associate automatic facilitation to the structural pathway, whereas expectancy mechanisms can be related to the functional pathway. Automatic facilitation effects can be regarded as working directly on the lowest level connection between stimulus- and response-related nodes, more or less working according to the principle of connectionist networks, facilitating or inhibiting pathways under the influence of frequent use. Subjective expectancy effects, on the other hand, follow a different pathway, independent of the low-level connection between stimulus and response, making use of somewhat higher cognitive nodes, related to sequential structure. In agreement with the general assumption that the use of higher cognitive nodes (deeper processing) takes more time, it explains why this mechanism can only interfere in the low-level stream of information when enough time is available.

The suggestion that sequential effects in P300 amplitude are not caused by a controlled process may seem at odds with other findings that indicate that P300 amplitude reflects a controlled resource-consuming process. For example, P300 amplitude declines with perceptual load on secondary tasks (see, e.g., Sirevaag, Kramer, Coles, & Donchin, 1989) and with practice (Rösler & Manzey, 1986). However, this contradiction may be resolved by considering the sequence-independent changes in P300 with the RSI. There was a decrease in amplitude when the RSI was decreased from 500 to 40 msec, particularly at Pz and Cz, leading to a change in scalp topography. However, this change in topography with the RSI did not interact with the FO or HO sequence, even when

overall amplitude differences were controlled for by scaling. Therefore, the change appears to concern some aspect of P300 that is unrelated to the sequential effects. In other words, reducing the RSI removes a part of P300 that is present at long RSIs but that is unrelated to the trial sequence. What is left, then, at short RSIs may be a less concealed view of the sequence-dependent P300. This residual P300 has ascalp topography that is quite unlike the centroparietal P3b.

The results of the ANOVA on scaled P300 amplitudes also speak against a possible alternative interpretation of our findings: One might conceive that, at long RSIs, both a more frontal P300 and a separate parietal P300 component are influenced by the trial sequence in a similar vein. At short RSIs, the parietal P300 is diminished or eliminated, leaving mainly the frontal P300. In this case, one would expect not only a global reduction of P300 amplitude and a global change of scalp distribution, but also a change in scalp distribution as a function of the trial sequence. In other words, there should be an interaction of the trial sequence and electrode site with the RSI. However, nowhere in our data did such an interaction appear. The only interaction of electrode site and trial sequence that survived scaling for amplitude was observed in Experiment 2, where, independent of RSI, the FO and HO sequence interacted with electrode site. However, this interaction merely indicates that the generator structure of the P300 may differ between certain trial sequences and does not bear on the question of whether the RSI affects the generator configuration. Therefore, our data are rather more consistent with the idea that, both at long and at short RSIs, we are dealing with the same sequence-sensitive aspect of P300 and that the main difference between the two conditions lies in the contribution of a sequence-independent subcomponent of P300.

The sequence-sensitive component resembles the more frontal variants of P300, such as the P3a, elicited by very rare unattended stimuli (Ford, Roth, & Kopell, 1976), or the novelty-P3 to singular events in the experimental context (Courchesne, Hillyard, & Galambos, 1975). Common to these frontal variants of P300 is their involuntary elicitation. This converges with our suggestion that the frontal and sequence-dependent aspect of P300 is probably the product of a low-level (automatic) expectancy mechanism.

In conclusion, our ERP results suggest that the mechanism that is responsible for the expectancy effects in RTs at long RSIs is active also at short RSIs. Because we interpret the sequential effects in ERPs as being the product of an uncontrollable mechanism, it seems that this mechanism influences overt responses only when RSIs are of sufficient length.

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NOTE

1. We did not apply ADJAR to the RSI 500 condition because there was very little overlap of ERPs in this condition, rendering this correction procedure meaningless.

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