On the origin of mixing costs: Exploring information processing in pure and mixed blocks of trials

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Abstract

In a reaction task responding has often proved faster when the levels of the independent variable are presented isolated from each other, in pure blocks than when they are presented randomly intermixed, in mixed blocks. This difference in response time is denoted here as mixing costs. This paper presents a theoretical review of mixing costs with special emphasis on their origin. In Section 1, two views on the origin of mixing costs are delineated, which are subsequently elaborated in Sections 2 and 3. The strategic view asserts that subjects are less well prepared in mixed blocks than in pure blocks, due to greater uncertainty about the level of the independent variable to be presented on the forthcoming trial. The stimulus-driven view attributes mixing costs to more pronounced trial-to-trial adaptation of processing in mixed blocks than in pure blocks, due to greater inertial variability. Section 4 reviews mixing costs deriving from various areas of human performance, and concludes that the dominant strategic view in the literature is not warranted, and that stimulus-driven factors have been underestimated.

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1. Introduction

When planning the design for a reaction experiment, the cognitive psychologist is usually faced with the problem whether to present the independent variable(s) in pure blocks or in mixed blocks of trials. In pure blocks only one level of a variable is

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presented across trials, and so the experiment contains as many pure blocks as the variable has levels, or a multiple of it. In mixed blocks all levels of the variable are presented across trials, usually, though not necessarily, in a random order. Various methodological considerations may make an experimenter decide in favor of either one of these designs. For instance, if an experiment contains many conditions, preference is usually given to present most of the variables in mixed blocks, so as not to put too great a strain on counterbalancing procedures (cf. Sperling and Dosher, 1986).

The present paper takes another perspective on pure and mixed blocks than tracing methodological considerations for using either one of these presentations. Instead, interest is taken in how a composite blocked-mixed design, comprising both a pure and a mixed presentation of the levels of the independent variable, can be used for exploring aspects of perceptual and cognitive processing. The basis for this idea is that the results deriving from either block type have often been found to differ in two respects. First, the levels of a variable are usually responded to slower when presented in mixed blocks than when presented in pure blocks; a difference denoted as mixing costs. Second, mixing costs are often found to be asymmetric in that the effect of a variable is smaller in mixed blocks than in pure blocks. Apparently then, there is more to pure and mixed blocks than a mere choice element for the experimental design: The type of block affects the mental state of the subject, and accordingly his or her responding behavior.

1.1. Block type and mental state

To better appreciate how block type might affect the mental state of the subject, consider a four choice reaction experiment in which a visual stimulus appears at one of four horizontally aligned locations in the visual field and the response concerns the pressing of one of four horizontally aligned response keys. There are two conditions of stimulus-response (S-R) compatibility. In the compatible condition, the S-R mapping is spatially congruent in that the the stimulus locations from left to right are mapped onto the response keys from left to right. In the incompatible condition, the S-R mapping is spatially opposite in that the stimulus locations from left to right are mapped onto the response keys from right to left. The S-R relations are presented in the blocked-mixed design, consisting of two pure and two mixed blocks. In the pure blocks, the compatible and incompatible S-R relations are separately presented. In one of the mixed blocks, the left and right most stimuli require compatible responses and the central stimuli incompatible responses, whereas this is reversed in the other mixed block. Using this experimental design, mixing costs have been reported that are large for compatible relations, and small or absent for incompatible relations (e.g., Duncan, 1977a,b,1978; Stoffels, submitted).

So, in pure and mixed blocks subjects respond to exactly the same events, but still their responding behavior is obviously not the same. To provide a starting point for a possible explanation of this phenomenon, it is useful to reflect on what could be different in the mental state of the subject when conducting the same tasks in pure and mixed blocks. An immediately apparent difference is that whereas in pure blocks subjects know for sure the nature of the S-R relation that will be presented on each trial, they are ignorant about this in mixed blocks. In other words, subjects have greater
uncertainty in mixed blocks than in pure blocks about the nature of the forthcoming S-R relation. Many accounts of mixing costs have implicitly or explicitly taken the concept of uncertainty as the starting point for theorizing. Hereby it has been often overlooked, however, that uncertainty is not the only feature that makes pure and mixed blocks psychologically distinct. Another difference is that transient variations in mental state due to intertrial variability are, on the average, stronger in mixed blocks than in pure blocks. To see this point, suppose that in the above experiment, separate response selection processes are needed to arrive at the correct response for the compatible and incompatible S-R relations. It has been proposed, for instance, that compatible relations are laid on a direct associative basis, while incompatible relations need search (e.g., Van Duren and Sanders, 1988; Komblum et al., 1990; De Jong et al., 1994). With respect to these processes, no trial-to-trial adaptations are necessary in pure blocks, but in mixed blocks, where compatible and incompatible S-R relations are randomly presented across trials, adaptations of these processes are necessary on about half of the trials. This view renders account of possible transient shifts of mental state as a consequence of intertrial variability, whereas uncertainty takes the perspective of an invariant mental state during a block of trials.

At this point it is emphasized that neither uncertainty nor intertrial variability of mental states are in themselves explanatory constructs for the occurrence of (asymmetric) mixing costs, but merely provide possible psychological bases on which accounts of mixing costs may be developed. However, since these psychological bases are very different, so is the theorizing deriving from them. In general it can be stated that models deriving from the uncertainty perspective rely on strategic principles, as they emphasize that block type determines to what degree a subject can prepare for forthcoming events. By contrast, models deriving from the perspective of intertrial variability emphasize stimulus-driven aspects of processing in that perceptual and cognitive actions are thought to leave behind traces of activation, which either aid or impede subsequent actions. The details of these views will be elaborated in Section 2 and Section 3.

1.2. Overview

Although the perspectives provided by uncertainty and intertrial variability are not mutually exclusive, there has hardly been any research that gives full credit to both. The intertrial variability perspective has usually occurred in research that missed out a pure condition and scrutinized dynamic transitions among trials of mixed blocks. This perspective has rarely been encountered in research using the blocked-mixed design, in which the variation of uncertainty among blocks has taken all attention. It is the aim of this paper to provide a more balanced view on mixing costs, in which characteristics of either main perspective are taken into account. This will be attempted in the next four sections. Section 2 presents the theoretical developments deriving from the perspective of uncertainty. Section 3 highlights the perspective of intertrial variability and examines its contribution to research into mixing costs. In Section 4 two different methods are proposed to distinguish between the perspectives of uncertainty and intertrial variability. This is followed by a concise review of studies that used either of the two methods, whereby the results are evaluated in the light of either main perspective. Finally, Section 5 presents the main conclusions of this paper.
2. Uncertainty and preparatory state

The view discussed in this section attributes mixing costs to a suboptimal preparatory state in mixed blocks relative to pure blocks. The logic is simple. In mixed blocks subjects experience greater uncertainty about the category of a forthcoming event than in pure blocks, which might lead them either to abandon category specific preparation or to prepare for the ‘worst possible case’, in either case resulting in costs on reaction time. This section will start with a reflection on the concept of uncertainty that is assumed to underly the preparation view. Then, some models are discussed that are often encountered in the context of uncertainty.

2.1. Uncertainty

Uncertainty can be defined as the degree to which the occurrence of events or of categories of events are unpredictable to the subject. This concept came into vogue under the influence of information theory, which assumed that the human processing system is essentially engaged in reducing uncertainty, or, stated differently, in processing information (Shannon and Weaver, 1949). In the context of a choice reaction task, this implies that an increment in the number of alternative stimuli causes each stimulus, when presented, to reduce more uncertainty and hence to convey more information. This insight led to the formulation of the Hick-Hyman law, stating that reaction time (RT) is a linear function of the information conveyed by the stimulus (Hick, 1952; Hyman, 1953).

The notion that information constitutes the basic unit of human ‘information’ processing turned out to be wrong, or at least liable to serious limitations. Several variables, like stimulus discriminability, S-R compatibility, practice and intertrial repetition have been found to affect RT without changing the information value of the stimulus alternatives (e.g., Shallice and Vickers, 1964; Fitts and Seeger, 1953; Mowbray and Rhoades, 1959; Bertelson, 1961). For the present argument it is of interest that the phenomenon of mixing costs also provides a specific violation of the Hick-Hyman law. Mixing costs are generally not abolished, perhaps even not diminished, when the number of alternatives is held constant across pure and mixed blocks (e.g., Forrin, 1975; Los, submitted a). For instance, Forrin (1975) observed clear mixing costs when he presented letters and digits in the blocked-mixed design for speeded naming, although he kept the number of task relevant alternatives constant across pure and mixed blocks, by composing each mixed block of half of the number of digits and letters used in pure blocks. In further disagreement with the Hick-Hyman law, Forrin also confirmed a well known counterpart of mixing costs, namely that increasing the number of alternatives within a well learned category (i.e., digits or letters) does not affect RT (see also Leonard, 1959; Mowbray, 1960; Morin and Forrin, 1962). These and many other demonstrations stimulated theorizing to go beyond the quantitative concept of information and to focus instead on hypothetical structures and processes of the mind.

The rejection of information theory spelled the end of information as the basic unit of human processing. It is remarkable in this respect that the concept of uncertainty did not accompany the concept of information in its disappearance from the scene. Uncertainty
resisted the storm against information theory and even branched off into several subtypes, like ‘time uncertainty’ (e.g., Klemmer, 1957; Niemi and Näätänen, 1981), related to unpredictability of the timing of events, and ‘event uncertainty’ or ‘stimulus uncertainty’ (e.g., Grice, 1968; Sperling and Dosher, 1986; Van Duren and Sanders, 1988), related to unpredictability of the contents of events. However, unlike the role of information within information theory, uncertainty was not taken any longer as a mere input for a processor whose purpose is to reduce ‘uncertainty’, but provided instead the starting point for theorizing about underlying mechanisms. This led to proposals of a wide range of mental structures, like pathways, thresholds and special analyzers. Yet, however different these structures, they were governed by a common principle: the possibility to prepare the proposed mental structure to deal more effectively with anticipated events. Subjects may preset a threshold, pathway or process, and more effectively so as they have less uncertainty about the nature of forthcoming events. Thus, uncertainty became intimately related to the state of preparedness of the subject for forthcoming events. The models to be discussed next may serve as examples along this line of thinking.

2.2. Dealing with uncertainty – Some preparation models

The models that are discussed in this section attribute mixing costs to suboptimal preparedness for forthcoming events in mixed blocks relative to pure blocks as a consequence of greater uncertainty about forthcoming events. Thus, in this context the variable ‘block type’ is conceived of as synonymous to the variable ‘uncertainty’ with the levels ‘low uncertainty’, as occurs in pure blocks, and ‘high uncertainty’, as occurs in mixed blocks. A main division among the models to be discussed concerns the means by which preparation is realized. In criterion-based models, preparation is nonspecific and concerns the adaptation of a processing criterion optimal for the situation at issue. In structural models, the preparation is directed towards specific processes or pathways that are believed to be involved. Critical comments to the models concerning their reliance on preparatory principles will not be presented here, but are deferred until Section 4. Here, main properties of the models and some general criticisms will be dealt with.

2.2.1. Criterion-based models

Criterion-based accounts of mixing costs are important, because they relate to general information processing models like cascade models (McClelland, 1979), random walk and diffusion models (e.g., Ratcliff, 1978). These models could be characterized by two components, a growth of stimulus related activation in time, and a criterion determining at which level of accumulated activation the subject releases his or her response. The growth of activation is typically thought to proceed in a stimulus-driven way, whereas the criterion is assumed to be under strategic control of the subject. Some models that have been suggested as explanations for mixing costs will now be described in greater detail.

2.2.1.1. Variable-criterion models. A first example concerns the variable-criterion model developed by Grice and colleagues (Grice, 1968; Grice et al., 1977, 1982). The initial concern of this model was to account for asymmetric mixing costs that are observed
when loud and soft auditory signals, requiring the same simple response, are presented in the blocked-mixed design. Specifically, mixing costs have been found for either intensity level, but larger ones for the soft tones (e.g., Wundt, 1874; Grice and Hunter, 1964; Sanders, 1977). Grice's (1968) account of this result is shown in Fig. 1A. He assumed that the energy conveyed by a stimulus (represented as evidence in Fig. 1A) accumulates over time, yielding a monotonously growing input function. The response to the stimulus is evoked when the accumulated energy exceeds an independently set response criterion. The rate of the input function is assumed to be relatively stable, and merely dependent on energetic aspects of the stimulus, like its intensity. By contrast, the criterion is assumed to fluctuate according to the properties of the normal distribution, and thus accounts for random variation in RT. In addition, the criterion is believed to be sensitive to a multitude of motivational and strategic factors (see Nissen, 1977, for a review). For instance, Grice (1968) suggested that subjects receiving only soft signals might well be satisfied with a lower level of accumulated activation, and thus adopt a lower criterion than subjects receiving only loud signals.

Fig. 1A illustrates how this model accounts for the interaction between block type and auditory signal intensity. In accord with their physical characteristics loud signals are associated with a steeper input function than soft signals. Block type modulates the ensuing effect of intensity on RT by affecting the level at which the criterion is set. When loud and soft signals are presented in pure blocks, the effect of intensity on RT is small, because the time advantage of loud stimuli due to faster activation accrual is at least partially offset by the need to reach a higher response criterion. By contrast, when intensities are presented in mixed blocks, the effect of intensity is much larger, because the response is released upon exceeding a common criterion. To obtain a quantitative fit between the model's prediction and the data, Grice (1968) was forced to assume that the criterion used in mixed blocks was well above that used for either intensity level in pure blocks (see Fig. 1). Interestingly, he conjectured that this elevation of the criterion reflects a greater stimulus uncertainty experienced by the subjects when confronted with a mixed presentation of stimuli (p. 364).

Recently, Strayer and Kramer (1994a,b) proposed similar ideas to those of Grice's in their study of a blocked-mixed presentation of two classes of probe types in the Sternberg (1966) memory-search paradigm. At the beginning of each block they presented subjects with a memory set that varied from two to six target words. On each trial a single probe word was presented, of which the subject had to indicate whether it was a target or a nontarget. The crucial variable was probe type, indicating whether it was a target or a nontarget. The crucial variable was probe type, indicating whether the

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1 Actually, Wundt (1874) and Grice and Hunter (1964) used a between-subjects design, implying that pure blocks of loud tones, pure blocks of soft tones and mixed blocks of loud and soft tones were administered to three separate groups. However, this blocked-mixed design as a between-subjects design does not principally differ from the blocked-mixed design as a within-subjects design, and patterns of mixing costs resulting from these designs have proved qualitatively similar. Thus, the asymmetric mixing costs observed by Wundt (1874) and Grice and Hunter (1964) have been replicated in a within-subjects design (e.g., Sanders, 1977). Furthermore, note that the asymmetry of mixing costs reported in these studies is opposite to the general pattern of mixing costs described in the introduction in that mixing costs are larger for the variable responded to more slowly in pure blocks, namely, soft tones.
Fig. 1. Three views on mixing costs. A: Grice's (1968) variable-criterion model, accounting for the overadditive interaction between block type and tone intensity. B: Strayer and Kramer's (1994a, 1994b) interpretation of mixing costs for consistently mapped (CM) and variedly mapped (VM) memory targets in Sternberg's (1966) memory-search paradigm, using Ratcliff's (1978) memory retrieval theory. C: Sanders's (1977) serial stage interpretation of mixing costs for luminous intensity. In A and B, block type determines how the response criterion is set, generally leading to an interaction with the variable at issue. In C, luminance and block type affect the reaction process selectively (i.e., at stage 1 and 4, respectively), leading to additive effects. (P = pure-block criterion; M = mixed-block criterion; S = stage; ** = effect of a variable in pure blocks; * = effect of a variable in mixed blocks.)

probe was from a consistently mapped (CM) or from a variedly mapped (VM) target/nontarget set. Specifically, the total set of probes was divided in two subsets, one CM and one VM subset. The CM subset was further divided in two sections, one from which exclusively targets were selected, another from which exclusively nontargets were selected. The VM subset was not further divided, so that targets in one block could serve as nontargets in another block and vice versa. As the division of the CM subset applied throughout all sessions of an experiment, CM probes were gradually detected automatically as targets or nontargets in the course of extensive training sessions, whereas VM probes always needed controlled search (cf. Schneider and Shiffrin, 1977; Shiffrin and Schneider, 1977). Strayer and Kramer's (1994a, 1994b) major objective was to study contextual influences in the development of automaticity. For this purpose they presented the variable probe type in the blocked-mixed design. In pure blocks all memory targets and all probes were either from the CM or from the VM subset; in mixed blocks memory targets and probes were drawn from both subsets.

The main results of the posttraining phase were as follows. In pure CM blocks, an almost flat search function was found, that is, RT hardly varied as a function of memory-set size, which is indicative for automatic detection. By contrast, in pure VM blocks a considerable slope of the search function was found, which is indicative for controlled search. In mixed blocks, the search functions for CM an VM probes were much less different from each other and laid in-between the pure block CM and VM functions. Accuracy data generally followed the predictions of the speed-accuracy trade-off. That is, responding was more accurate in the CM-mixed than in the CM-blocked condition, but less accurate in the VM-mixed than in the VM-blocked condition. Stated in terms of mixing costs, this pattern of results can be summarized as follows. With respect to RT, mixing costs were found for the CM probes, whereas mixing
benefits were found for the VM probes. With respect to accuracy, the reverse pattern was observed, that is, mixing benefits were found for CM probes, whereas mixing costs were found for VM probes.

Strayer and Kramer (1994a,b) fitted this pattern of data to Ratcliff's (1978) theory of memory retrieval (see Fig. 1B). This retrieval theory shares the property of a variable criterion with Grice's (1968) model, but it identifies a different source for random variation in RT, namely the memory-comparison process. This process comprises parallel comparisons of the probe to each memory target. Each individual comparison of the probe to a target is hereby described as a capricious growth of evidence in time, called a diffusion process, which drifts toward an upper or lower criterion. The drift rate of each diffusion process depends on the relatedness between the probe and the memory target. As the relatedness increases from low to high, the drift rate of the diffusion process increases from negative to positive. The diffusion process starts off at a value on the evidence axis in-between the upper and lower criterion. A positive response (i.e., target present) follows a self-terminating comparison process, as it is emitted when any one of the diffusion processes reaches the upper criterion. A negative response follows an exhaustive comparison process, as it is emitted when all diffusion processes reach the lower criterion. Strayer and Kramer (1994a,b) obtained an excellent general fit of their data to the retrieval theory. Furthermore, they found that the drift rate of the comparison process decreased and the level of the criterion increased in accordance with memory load. Importantly, block type affected mainly the criterion, which increased from the pure CM condition to mixed conditions and from mixed conditions to the pure VM condition, but left the drift rate parameter generally unaffected. Only at higher memory loads was the drift rate in the pure CM condition higher than in the other conditions. Thus, in line with Grice's work, Strayer and Kramer (1994a) identified the level of uncertainty as a main determinant of criterion positioning (though not the only determinant as will be discussed in Section 4.1).

It is clearly a strong point of the variable criterion models discussed here that they can be brought into quantitative agreement with the data. Yet, this does not necessarily imply that the qualitative interpretation of the data becomes a trivial exercise. Two examples relating to the concept of uncertainty may illustrate this point. First, as described before, Grice (1968) found the criterion in his mixed condition (of loud and soft tones) to be elevated relative to his pure conditions, and attributed this difference to stimulus uncertainty. However, when fitting the model to eyelid conditioning data, resulting from a similar design (Grice and Hunter, 1964), Grice (1968) found the criterion estimated for mixed conditions to lie in-between the criteria estimated for the blocked conditions. Consequently, Grice conjectured that stimulus uncertainty does not manifest itself in the eyelid conditioning data. However, precisely the in-between position of the criterion in mixed blocks was interpreted by Strayer and Kramer (1994a,b) as a manifestation of uncertainty about the forthcoming class of the probe type. Thus, there seems to be no general consensus as to how uncertainty becomes manifest in the relative positioning of the criteria.

Moreover, it might even be possible to completely deny any role to uncertainty in Strayer and Kramer's (1994a, 1994b) studies without disputing a strategic origin of criterion setting. Specifically, apart from uncertainty and intertrial transitions, Strayer
and Kramer’s blocked versus mixed manipulation may have affected even a third psychologically relevant variable, denoted here as effective memory load. This concept refers to the number of memory targets that must be necessarily memorized (and possibly rehearsed) for adequate task performance, which could be quite different from the objective memory load. For instance, in the pure-CM condition subjects can perform perfectly well without memorizing any specific target, because extensive CM-training yields an automatic segregation of targets and distractors. By contrast, to obtain adequate performance in the pure VM-condition subjects must actively memorize each individual memory target due to varied mapping training. For the same reason, VM targets must be memorized in mixed blocks, but CM targets need not. In effect then, the effective memory load is equal to the number of VM targets in the memory set. This suggests the possibility that the criterion is not adjusted on the basis of uncertainty, but on the basis of effective memory load. 2 As it seems difficult to rule out this plausible alternative account on the basis of Strayer and Kramer’s (1994a, 1994b) data, the significance of uncertainty in their studies remains unclear.

Finally, some limitations should be pointed out concerning the value of a variable criterion model as a general account of mixing costs. Most notably, Grice’s model predicts that mixing costs, if at all observed, should be asymmetric, as can be easily verified in Fig. 1. Although the model does not a priori exclude symmetric mixing costs, these could only be obtained from a unique ordering of the criteria used in the different blocks, and thus should be regarded as relying on sheer coincidence. Nevertheless, the interaction between signal intensity and block type reported by Grice (1968) appears to be limited to the combination of a simple reaction task and auditory or tactile stimuli (Nissen, 1977; Sanders, 1977). Variations in visual stimulus intensity usually give rise to symmetric mixing costs (Sanders, 1977; Grice et al., 1979; Niemi, 1981; Van Duren and Sanders, 1988), as do variations in auditory stimuli in a choice reaction task, where a response is selected contingent on a task relevant aspect of the stimulus (e.g., Sanders, 1977). Thus, the interaction between block type and auditory stimulus intensity seems to be the exception rather than the rule, which questions the generality of Grice’s variable criterion interpretation (but see Grice et al., 1982, for additional work on the model to remedy its shortcomings). The pattern of results presented by Strayer and Kramer (1994a,b) is also not exemplary for results usually obtained in the blocked-mixed design. As will become apparent in the remainder of this paper, mixing benefits, as observed by Strayer and Kramer for VM probes, are usually not found, nor are clear-cut effects of speed-accuracy trade-off. Of course, these two exceptions in combination are well accounted for by a variable-criterion model, but the more commonly found data pattern rather less so.

2 It should be noted that Strayer and Kramer (1994b) may not disagree with this point of view, witness their statement that “The setting of response criteria through a long-term referent appears to be determined by the constituency of the memory set (or perhaps more generally by the difficulty of the task)” (p. 363). However, on the basis of this reasoning their earlier conclusion (1994a) that: “Uncertainty regarding whether the probe would be drawn from the CM or VM set disrupted performance relative to blocked conditions, in which there was no uncertainty about the set from which the probe would be drawn” (p. 336), comes to hang in thin air.
2.2.1.2. Immediate arousal. Sanders (1975, 1977, 1983) proposed a model based on a serial arrangement of computational stages in combination with an energetic supply, denoted as arousal. In its reliance on sequential stages, the model can hardly be called a criterion-based model, but for two reasons it is presently addressed. First, it will be shown that a stage model is not so different from a criterion model as proposed by Grice in the way preparatory state is regulated. Second, the model sheds light on some conflicting results mentioned above.

In Sanders's model, the serial arrangement of computational stages is based on the results of a large body of studies using the additive-factor method (Sternberg, 1969; Sanders, 1980, 1990). This method infers the independence of stages from consistent additive relations of variables affecting RT, whereas a single stage is thought to be affected when variables are found to interact. The additive-factor method has certainly not been left undisputed regarding this logic (e.g., McClelland, 1979; Pieters, 1983), but its results have been widely used as a heuristic for the level of processing affected by a variable. Thus, within this framework, a great deal of evidence suggests that the effect of signal intensity affects early perceptual processing (e.g., Sanders, 1980; Schweickert et al., 1988), whereas block type affects processing at a later stage (e.g., Meyer et al., 1988, Experiment 4; Sanders, 1977; Van Duren and Sanders, 1988). Sanders (1977) used this framework in his analysis of the conflicting data mentioned above, namely the finding of asymmetric mixing costs when in a simple reaction task auditory signal intensity is presented in the blocked-mixed design, but of symmetric mixing costs when auditory signal intensity is replaced by visual signal intensity, or the simple reaction task is replaced by a choice reaction task (e.g., Sanders, 1977). An analysis of these data in the framework of independent processing stages, as shown in Fig. IC, results in a formulation of the problem exactly opposite to the one reached on the basis of the variable-criterion model: Not an additive relation of signal intensity and block type is the exception, but an interaction between these variables, since block type and signal intensity are assumed to affect different processing stages.

At this point the concept of arousal is supposed to provide the missing link for a serial stage model. As an energetic impulse issued by stimuli, arousal is generally believed to be functional in its disposition to provoke an orientation response toward a potentially endangering stimulus, or, more radically, to prepare the organism for fight or flight (Pribram and McGuinness, 1975; Rohrbaugh, 1984). Similarly, Sanders (1975, 1977, 1983) proposed that arousal as evoked by the stimulus might immediately affect the subject's preparedness for action, without intervention of computational stages. The threshold of intensity beyond which a stimulus becomes arousing, is assumed to depend on the modality of the stimulus. It is extremely high for visual stimuli, intermediate for auditory stimuli (beyond 70 dBA), and relatively low for tactile stimuli (e.g., Posner, 1975; Nissen, 1977; Sanders, 1975, 1977; Van der Molen and Keuss, 1979, 1981). Thus, the interaction between auditory intensity and block type can be explained by arguing that a state of low preparedness, as assumed to occur in mixed blocks, is at least partially offset by arousal, which proceeds from loud signals but not from soft signals. This also clarifies why the interaction is limited to auditory (or tactile) stimuli in the context of a simple reaction task. The threshold at which visual stimuli become arousing is so high that it is normally not attained in experimental settings (e.g., Niemi, 1981),
thus precluding compensatory effects on the motor level. Furthermore, a nonspecific increment in preparedness for action is functional in a simple reaction task, but not in a choice reaction task, where the subject has to select one out of several responses, while suppressing any tendency to make an impulsive, error prone response (Van der Molen and Keuss, 1979, 1981; Nissen, 1977).

Although a variable-criterion model and a serial stage model obviously differ in their assumptions on human information processing, they are similar in how they see that block type affects the preparatory state of the subject. As stated earlier, the preparatory state in the context of the variable-criterion model is reflected in the adaptation of the criterion. By contrast, in the serial stage framework an absolute, invariant response criterion is usually endorsed, which is by some identified with the motor action limit (Näätänen and Merisalo, 1977; Niemi and Näätänen, 1981; Sanders, 1983). Yet, the mechanism of preparing on the basis of expectancy is similar to that assumed in the variable-criterion model. Instead of varying the criterion, the base level of activation is assumed to vary, thus determining the subject’s preparedness. Low preparedness is the state in which activation is remote from the motor action limit, high preparedness the state in which this distance is small. Barring the effect of immediate arousal, preparedness is thought to be under strategic control of the subject, with the constraint that a state of high preparedness is hard to maintain (e.g., Gottsdanker, 1975; Näätänen, 1972). Thus, where in the variable-criterion model the criterion is adjusted in accord with the level of uncertainty, in the serial stage model the distance of motor activation to a stable motor action limit is adjusted. The net result is similar, however: Preparedness is reflected by the difference between base activation and the criterion prior to the occurrence of the stimulus.

Finally, the immediate arousal account of mixing costs is not free from objections in its reliance on an exclusive relation between block type and motor preparation. One of the key notions underlying the additive stage structure is that factors affect the reaction process selectively (see Fig. 1C). Ideally, the influence of a factor can be pinpointed at a single stage, as indicated by interactive effects with other factors affecting that stage and additive effects with factors affecting other stages. This ideal is reasonably approximated for a lot of variables, though for some it is not. Thus, it has been shown that the variable signal intensity has additive effects with many other variables, ignoring the cases in which arousing effects accompany the signal (e.g., Sanders, 1980, 1990). By contrast, the ideal of selective influence has not at all been shown to hold for the variable block type. As will become clear in the course of this paper, variables affecting RT beyond early preprocessing (as affected by signal intensity) generally interact with block type. Furthermore, using physiological measures Coles et al. (1985) found evidence that block type affects both processes of stimulus evaluation and response criterion setting. Thus, although block type may affect motor processes, its lack of selective influence prohibits an a priori link to this stage.

2.2.1.3. The deadline model. A final criterion model concerns a version of the deadline model (Ollman, 1966, 1977; Ollman and Billington, 1972), which has only occasionally been mentioned in the literature as an account of mixing costs (Duncan, 1978; Los, submitted a; Meyer et al., 1988). The deadline model assumes that a response is the
outcome of one of two processes, an analytic process and a fast guess process. The analytic process equals a full task relevant analysis of the imperative stimulus, and a response based on it is in principle correct. The fast guess process develops in parallel with the analytic process and has chance accuracy. Whether the response is based on the analytic process or on the fast guess process is determined by the deadline, which can be conceived as a criterion in the time domain. If the analytic process runs to completion before the deadline expires, the response is based on this process, if not, a guess is emitted. Similar to the criterion in the variable-criterion model, the deadline is assumed to be under strategic control, and may well be adjusted to the accuracy requirements to be met in a block of trials.

In the explanation of mixing costs the deadline model has the advantage over the variable-criterion model that it is self-evident how the deadlines used in the various blocks should be positioned relative to each other. Provided that subjects aim at an equal level of accuracy across pure and mixed blocks, they will adjust the deadline such that the proportion of fast guesses is about equally divided among blocks (cf. Ollman and Billington, 1972). It follows that in pure blocks the adjustment of the deadline is intimately related to the duration of the analytic process. So, in conditions where the analytic process is fast, the deadline is adjusted to an earlier point in time than in conditions where the analytic process is slow. It is also clear that in mixed blocks with an equal proportion of fast and slow events, the deadline should be adjusted about optimally for the time requirements of the slow event, because a sharper deadline would yield too many fast guesses in response to this event, thus forfeiting the aim of constant accuracy. This specific strategy will be denoted here as the 'worst-case mechanism', implying that in mixed blocks subjects opt for anticipating the 'worst' (or 'slowest') case. The obvious qualitative deduction from this model is that the fast level of a variable shows larger mixing costs than the slow level, because the deadline is adjusted too sloppy for the fast level in mixed blocks. Thus, a deadline model arrives necessarily at predicting an underadditive interaction between block type and the variable at issue (i.e., the combined effect of the slowest levels of two variables is less than predicted by additivity).

In view of the opposite overadditive interaction between auditory intensity and block type, discussed earlier, the prospect of a deadline model might seem scant. Even if the overadditive interaction is considered to be an exception, as suggested by the immediate arousal account, the view that additivity between intensity and block type is the rule, is not in line with the predictions of the deadline model. On the other hand, underadditive relations with block type are commonly found for variables that, according to the stage structure inferred by the additive-factor method, call upon processes beyond early perceptual analysis. Thus, in line with the predictions of the worst-case mechanism of the deadline model, underadditive interactions with block type have been reported almost without exception for the variables stimulus quality, S-R compatibility, task control and foreperiod. Notably, Duncan (1978) presented compatible and incompatible S-R relations in the blocked-mixed design and found much larger mixing costs for compatible than for incompatible S-R relations. On the basis of this result, he suggested that "subjects may tend to make all responses of a given task at an approximately fixed speed, so that, if the tasks involve S-R pairs differing in difficulty, performance is
slowed for easy pairs, but not for difficult pairs (p. 439)”; an idea very similar to the deadline model.

Duncan (1978) referred to this mechanism as ‘highly plausible’, but one feature of his data suggests that it is not. Setting the deadline in mixed blocks in accordance with time demands of the slow event, implies that less guessing should occur for the fast event. Thus, mixing costs for RT should be offset by mixing benefits for accuracy, but if anything, Duncan (1978) observed a lower accuracy for compatible S-R relations in mixed blocks than in pure blocks. Of course, Duncan did not commit himself explicitly to a deadline model, but whatever view one holds, it should account for what subjects do in the extra time they take to arrive at their response. A plain ‘more extensive processing’ seems only satisfactory if the ensuing response proves less error prone.

More explicit evidence against a deadline model has been obtained by Meyer et al. (1988). In their Experiments subjects had to make lexical decisions with respect to visual letter strings. On regular trials subjects were instructed to respond fast while avoiding errors. On signal trials, the presentation of the letter string was quickly followed by the presentation of a tone, which represented a physical deadline and required subjects to respond immediately. Meyer et al. derived the strong prediction that the cumulative RT-distribution becomes increasingly steeper as the (physical) deadline is set more sharply, due to increasingly cutting short on responses that would normally be initiated at moments beyond the deadline. This prediction born out convincingly on signal trials (Experiments 1, 2, 3 and 5). However, the prediction was disconfirmed when the comparison was between RT-distributions of regular trials when mixed with signal trials and of regular trials when presented in a pure block (Experiment 4). That is, in mixed blocks the deadline as set on signal trials did not transfer to regular trials, thus disconfirming the deadline model as an account of mixing costs. This finding is especially important, since mean performance measures of regular trials showed mixing benefits for RT in combination with mixing costs for accuracy, which would as such fit a deadline model quite well. On the basis of the distribution analysis, Meyer et al. concluded instead, that the observed mixing benefits were due to adaptations in the analytic process, rather than to a tendency of more guessing.

2.2.2. Structural models

Structural models differ from criterion-based models in their specification of stages or processes that are supposed to fulfill a specific task in the goal-oriented processing of information. It is assumed that the stage or process can be prepared or preset in anticipation of a forthcoming event. The two models addressed next serve as examples along this line of thinking.

2.2.2.1. The two-stage model. The first structural model to be discussed is the two-stage identification model as proposed and tested by Forrin and Morin (1967) for different categories of S-R relations in the blocked-mixed design (see also Morin and Forrin, 1962; Forrin and Morin, 1966; Forrin, 1975; Duncan, 1978). The central assumption of this model is that in mixed blocks a preselection between categories (i.e., stage 1) must precede the selection of the unique S-R relation within categories (i.e., stage 2).
Additional assumptions concerning these stages are that (a) stage 1 is time consuming and error prone and (b) the nature of the selection process at stage 2 is determined by the nature of the S-R relations of the category: Responses that have a highly familiar relation with the stimulus can be selected directly, whereas responses that are otherwise related to the stimulus are arrived at by search in memory, or by the application of an S-R transformation rule that characterizes the set (Forrin and Morin, 1967; Forrin, 1975; Duncan, 1978; Kornblum et al., 1990). Finally, the principle of pure insertion is assumed to hold for stage 1, implying that the all or none involvement of this stage is of no influence on the qualitative aspects of the remainder of the processing. Stage 1 is thought to be included in mixed blocks, where the forthcoming category is not predictable, but omitted in pure blocks, where the subject anticipates a single category.

The two-stage model predicts either additive or underadditive relations between effects of block type and a variable, and does thereby even not exclude the occurrence of mixing benefits for the slow event. Consider, for instance, the situation whereby two categories are presented in the blocked-mixed design, each comprising eight S-R relations. The number of alternatives is kept at eight across blocks, by presenting only four of the S-R relations of either category in each mixed block. According to the two-stage model, the response selection in pure blocks bypasses stage 1, and concerns a within-category selection among eight alternatives at stage 2. In mixed blocks a selection between categories takes place first, whereby the number of alternatives to select among at stage 2 is reduced from eight to four. Whether this two-step selection is less effective than the one-step selection followed in pure blocks, depends on the S-R relations of the category. If these are highly familiar, their number is immaterial to the duration of stage 2, but if not, stage 2 takes more time as the set of S-R relations increases. Consequently, for highly familiar S-R relations mixing costs reflect the duration of stage 1, whose pure insertion distinguishes mixed from pure blocks. For arbitrary S-R relations, on the other hand, the time loss in mixed blocks due to the insertion of stage 1 is offset by a faster subsequent search through the halved number of relevant S-R alternatives, thus reducing mixing costs. So, whereas considerable mixing costs are predicted for highly familiar S-R relations, these should decrease or even turn into benefits as the S-R relations become less compatible, especially when the set of S-R relations is large.

An attractive feature of this model is that it provides a clear theoretical basis for the occurrence of mixing benefits, which have incidentally been reported in the literature (e.g., Forrin and Morin, 1967; Strayer and Kramer, 1994a,b; Van Duren and Sanders, 1988). Duncan (1978) considered the two-stage model a serious candidate to account for the mixing costs he obtained for spatial S-R compatibility, although he was reluctant to explain the asymmetry of these costs by assuming differential compensatory effects of compatible and incompatible S-R relations at stage 2 (an asymmetry which he preferred to explain in terms of a tendency of the subject to respond at a regular pace, as mentioned in Section 2.2.1). The status of the characteristics attributed to stage 2 is probably less critical than the theoretical status of stage 1, however. A general scepticism prevails in the literature over the principle of pure insertion that is assumed to hold for this stage (see Ilan and Miller, 1994 for a recent discussion). Furthermore, Van Duren and Sanders (1988) questioned the feasibility of stage 1 for variables that do not
have a rule-based category distinction, like signal contrast or signal quality, but that have been shown to produce mixing costs when presented in the blocked-mixed design.

Empirical tests provided by Forrin and Morin (1967; see also Forrin, 1975) and Stoffels (submitted) failed to support the model. The methods of testing used in these studies were basically the same, and aimed at varying the load both at stage 1, by comparing a mixed to a blocked presentation of compatible and incompatible S-R relations, and at stage 2, by varying the number of incompatible S-R relations to select from. Forrin and Morin found dependencies in their data that are not in line with the two-stage model. First, the estimated duration of stage 1 was dependent on the particular S-R category that was selected, whereas the model predicts that stage 1 is only affected by the number of categories to be distinguished. Second, the duration of stage 2 for compatible stimuli was affected by the number of incompatible S-R relations occurring in the same block, which according to the model should have been selected out at stage 1. In turn, Stoffels compared mixing costs in a two-choice task and a four-choice task (as dissociated by precuing either two or four potential alternatives), and found equal mixing costs in these conditions for incompatible S-R relations. This finding disconfirms the central prediction of the two-stage model that mixing costs should be smaller in the four-choice task than in the two-choice task, because the two-choice task does not allow as much compensation at stage 2 as the four-choice task, while the costs at stage 1 are supposed to be equal. This led Stoffels to prefer an alternative routes account of mixing costs as proposed by Van Duren and Sanders (1988).

2.2.2.2. The alternative routes model. Van Duren and Sanders (1988) presented visual digits for speeded identification, of which they varied the signal intensity (high vs. low luminance), stimulus quality (intact vs. noise-degraded) and S-R compatibility (compatible vs. incompatible digit naming) in the blocked-mixed design. The results showed that mixing costs were about equal for these variables, though differentially distributed across the two levels of each variable. Specifically, mixing costs were symmetric for signal intensity, moderately asymmetric for stimulus quality, in that they were larger for intact than for degraded stimuli, and highly asymmetric for S-R incompatibility, in that they were considerable for compatible stimuli but absent for incompatible stimuli. These mixing costs patterns are prototypical in that they have been observed several times before and since (e.g., Sanders, 1977; Niemi, 1981; Los, 1994, submitted a; Duncan, 1978; Forrin and Morin, 1967; Forrin, 1975; Stoffels, 1996a,b, submitted). Notwithstanding their differences in exhibiting asymmetric mixing costs, the three variables showed mutually additive effects both in the pure and mixed condition. This finding is prototypical in the context of additive-factor research, which has strongly suggested that these variables affect independent processing stages, supposedly running from early preprocessing, affected by signal intensity, via encoding, affected by stimulus quality, to response selection, affected by S-R compatibility (e.g., Sanders, 1980, 1990). Combining the perspectives of differential mixing costs distributions and serial subsequent processing stages, brought Van Duren and Sanders (1988) to the following summary of their data: The asymmetry of mixing costs increases as processing proceeds from perception to action.

To account for this result, Van Duren and Sanders (1988) proposed a model here
denoted as the alternative routes model. Referring to Sternberg (1969) they interpreted the occurrence of an underadditive interaction as an indication for the involvement of separate processing routes. Thus, they postulated a ‘fast’ route for the ‘fast’ level of a variable and a ‘slow’ route for the ‘slow’ level. Processing along the fast route relies on associative relations 3, whereas processing along the slow route needs a time consuming additional process that has a more analytical character, similar to that proposed for stage 2 of the two-stage model. For instance, the authors suggested that at the level of encoding a process might exist that is engaged in separating relevant from irrelevant features of noise-degraded stimuli, while intact stimuli can be detected directly. Similarly, at the level of response selection they envisaged a process that searches for the proper incompatible S-R relation, while compatible relations are elicited directly. The selection of a processing route is assumed to rely on two principles: (a) processing routes can be preset and (b) subjects preset the slow route in mixed blocks – the worst-case mechanism applied to a specific processing route. Thus, in pure locks subjects are able to preset the route that is optimal for the required processing, but in mixed blocks the slow route is always preset, causing a reduction in the efficiency of processing fast events. 4 Due to this bias in mixed blocks, asymmetric mixing costs naturally derive. Furthermore, the strategic nature of the worst-case mechanism has a straightforward implication for the growing asymmetry of mixing costs observed when going from perception to action: This reflects an increasing strategic influence from perception to action, enabling an increasing specificity in presetting the slow route.

The alternative routes model as proposed by Van Duren and Sanders (1988) is highly ambitious in that it pretends to be applicable to a wide range of phenomena occurring at various levels of processing. This pretension revolves around the principle of increasing strategic influence when going from perception to action. However, as noted by Los (submitted b) the data obtained by Van Duren and Sanders (1988) do not provide a clear empirical basis for this principle. The proposed increasing strategic involvement in the course of processing relies on the comparison of interactions between block type and different variables (i.e., signal intensity, stimulus quality and S-R compatibility) that are supposed to load different processing stages. These variables have very different characteristics and cause main effects that differ in size. Thus, in absence of a valid metric, it is questionable whether the strengths of their interactions with block type should be compared at all, and even whether the meaning of these interactions is the

3 Frith and Done (1986) proposed to distinguish between a ‘fast’ and a ‘direct’ route. In this proposal, the fast route is a short-cut between sensory registration and response initiation, which might be used in a simple-RT task. The direct route includes stages of stimulus identification and response specification, though skipping response selection due to highly overlearned stimulus-response relations. Thus, Van Duren and Sanders’s ‘fast’ route would be called ‘direct’ by Frith and Done.

4 The nature of reduced processing efficiency in mixed blocks can be modeled in several ways. Van Duren and Sanders suggested that in mixed blocks fast events are suboptimally processed along the slow route, whereas Los (1994, submitted a) preferred to think in terms of a loss of time when a shift takes place from the initially preset slow route to the fast route on behalf of the fast event. The mechanism proposed by Los is probably somewhat more flexible, because mixing costs are also observed when stimuli of a different type of degradation are presented in the blocked-mixed design, whose specific processing requirements cannot, presumably, be taken over by an alternative process.
same for each variable. A more general question left open in Van Duren and Sanders's (1988) study is how symmetric mixing costs, like those for visual signal intensity, should be interpreted. Perhaps one might reverse the argument of Van Duren and Sanders, and interpret the absence of an underadditive interaction between block type and signal intensity as an indication that only one processing route is involved. This inference would be in line with physiological evidence that signal intensity affects the firing rate along a single input channel (Nissen, 1977; Luce and Green, 1972). Furthermore, the finding of symmetric mixing costs once again raises the question of the locus of these costs, given that the additive-factor method inferences from additive effects that different processing stages are affected (Sternberg, 1969). As was argued in Section 2.2.1 the suggestion of a motor locus of mixing costs is not convincing, due to the lack of selective influence of the variable block type. The finding of robust interactions of block type with the variables stimulus quality and S-R compatibility underscores the need for independent evidence for this suggestion.

2.3. Summary

This section sets out with a reflection of the concept of uncertainty that, defined as the extent to which events are unpredictable to the subject, underlies a large group of accounts of mixing costs. The central idea is that a state of low uncertainty, as met in pure blocks, enables the subject to achieve a state of high preparedness by presetting mental structures that will be used in forthcoming processing. High uncertainty encountered in mixed blocks prevents subjects to achieve a similar high preparatory state. Several models based on this principle have been discussed. Criterion models assert that stimulus induced activation is sampled until a response criterion as set by the subject is met. The criterion is assumed to be sensitive to the anticipated processing demands of pure and mixed blocks. Discussed are variable-criterion models (Grice, 1968; Strayer and Kramer, 1994a,b), the deadline model (Ollman and Billington, 1972) and, though not a typical criterion-model, a stage model supplemented with an immediate arousal component (Sanders, 1975, 1977, 1983). Structural models are characterized by the involvement of specific processes that are differentially prepared in pure and mixed blocks. Two models have been discussed. The two-stage model (Forrin and Morin, 1967) proposes that a category selection precedes the selection of the eventual task relevant alternative. The alternative routes model (Van Duren and Sanders, 1988) distinguishes a fast and a slow route for processing a fast and a slow event, respectively, whereby in mixed blocks the slow route is preset (so as to deal with the 'worst case').

3. Intertrial variability and mixing costs

The viewpoint of uncertainty, examined at length in the previous section, took the global difference between pure and mixed blocks in the predictability of forthcoming events as the starting point for theorizing. The present section examines the prospect of the more dynamical view that transient variations in mental state due to intertrial variability are stronger in mixed than in pure blocks. The relevance of this view is
suggested by research into sequential effects, which has indicated that individual trials do not independently contribute to mean RT but are affected by preceding trials. Thus, if sequential effects differ between pure and mixed blocks, they necessarily contribute to mixing costs as well. This section starts with a brief exposition on sequential effects and evaluates how they might differentially affect mean RT in pure and mixed blocks. Next, possible mechanisms are described that rely on the notion of intertrial variability.

3.1. Sequential effects

Research into sequential effects implies the analysis of RT on a given trial as a function of the similarity of the events of that trial to events dating one or more trials back. This research has revealed that responding on a trial is generally faster as more features of the preceding trial are repeated; a phenomenon called the (intertrial) repetition effect. Ever since its first demonstration (Bertelson, 1961), a major issue of research has been the location of the effect in the course of information processing. One approach to this problem has been to examine the persistence of the repetition effect by various degrees of overlap between successive trials. Thus, beside ‘identical repetitions’, of which both the stimulus and the response are repeated (e.g., Bertelson, 1961; Remington, 1969), research has focussed on ‘response repetitions’, of which the response but not the stimulus is repeated (e.g., Bertelson, 1965; Pashler and Baylis, 1991; Campbell and Proctor, 1993), ‘stimulus repetitions’, of which the stimulus is repeated but not the response (e.g., Pashler and Baylis, 1991; Campbell and Proctor, 1993) and ‘category repetitions’, of which only the category to which the stimulus belongs is repeated, while both the stimulus and the response are different (e.g., Rabbitt and Vyas, 1973; Rabbitt et al., 1977; Marcel and Forrin, 1974; Los, 1994). Another approach to identify the locus of the repetition effect has been the study of sequential effects at different levels of a variable whose relationship to a specific processing stage is well established (e.g., Bertelson, 1963; Kornblum, 1969, 1975; Hansen and Well, 1984). Finding sequential effects modified by this variable would, according to the additive-factor logic (Sternberg, 1969), pinpoint the repetition effect at the level of processing affected by the variable. From these two approaches, converging evidence has established the response selection stage as a main locus for sequential effects.

To understand the repetition effect on a more theoretical level, it is useful to consider two principles put forth by Pashler and Baylis (1991). The first is the pathway-specific speedup principle. A pathway is conceived as the execution of a specific stage of processing with a given input and a given output. So, on a trial of a choice reaction task a chain of specific pathways, running from early perceptual processing to response execution, is traversed before a response is emitted. The principle of pathway-specific speedup asserts that the processing along a pathway can be selectively enhanced without affecting other pathways in the chain. Thus, discerning the response selection stage as the locus of the repetition effect implies that repeated processing along a response selection pathway proceeds relatively fast, whereas repeated processing along pathways of other stages does not. Pashler and Baylis’s second principle is what will be called here the weakest-link principle. This principle asserts that the pathway that is most susceptible to speedup is the one that is initially the weakest in the chain of pathways.
This principle puts the finding of the response selection stage as the main locus of the repetition effect in a different perspective. The generality of this finding does not so much reflect a specific nature of the response selection stage as it identifies this stage as the weakest link in many choice reaction tasks. Indeed, in the majority of experiments highly overlearned stimuli have been coupled to highly practiced responses, but their connection has often been new and rather arbitrary. So, according to the weakest-link principle it should be possible to demonstrate repetition effects on perceptual or motor stages of processing as well, provided that complex stimuli or responses are used (see Los, 1994, Experiment 3, for a confirmation of this prediction).

Apart from providing a useful framework for understanding sequential effects, the two principles of Pashler and Baylis (1991) have also implications for the nature of the repetition effect. In particular, the repetition effect seems to proceed from residual activation of pathways that have been activated on a previous trial. In that quality it is stimulus-driven, or caused by preceding activity, rather than strategic, or based on an irrational stronger expectancy of repetitions than alternations. This view is not generally valid, however, given the evidence that irrational expectancies may, under circumstances, indeed play a role in the occurrence of sequential effects. For instance, Soetens et al. (1985) found in a two-choice reaction task that a positive repetition effect turned negative as the response-stimulus interval between subsequent trials increased from 50 to 1000 msec. They attributed this result to a bias to expect an alternation, analogous to the gamblers fallacy (Jarvik, 1951), that builds up in time and comes to dominate an initially stimulus-driven repetition effect. There have also been proposals to explain the common positive repetition effect in terms of a strategic mechanism. Thus, Kirby (1975, 1976a,b) proposed that this effect could reflect a strategy to use the event of the last trial as a point of reference for the forthcoming trial. As remarked by Soetens (1990), this proposal leaves open the question under what circumstances subjects are led to expect a repetition or an alternation. However, the possibility of strategic mechanisms of this kind prevents an a priori connection of sequential effects to a stimulus-driven mechanism as derives from the principles put forth by Pashler and Baylis (1991).

From these considerations two tentative conclusions can be drawn related to mixing costs. First, due to greater intertrial variability, mixed blocks are very likely to produce less positive sequential effects than pure blocks, which necessarily translates into mixing costs. This is particularly clear when the number of alternatives is not kept equal across blocks. For instance, in the experiment of Grice and Hunter (1964), mentioned in Section 2.2.1, only identical repetitions (of either loud or soft tones) occurred in pure blocks, whereas these were about halved in mixed blocks. Equating the number of alternatives across pure and mixed blocks, as is often strived for in the blocked-mixed design (see for instance the illustrative experiment described in Section 1.1), accordingly equates the frequency of occurrence of identical repetitions, but not the frequency of occurrence of category repetitions. Thus, whatever control measures are taken, differential intertrial transitions between pure and mixed blocks are inherent to the blocked-mixed design, and constitute a potential source for mixing costs. Second, although sequential effects are most elegantly explained by a stimulus-driven mechanism, like pathway speedup, it is still possible that they are caused by irrational expectancies or strategies to use the last trial as a point of reference for the forthcoming trial. This prohibits an a
priori connection between differential sequential effects in pure and mixed blocks and a stimulus-driven account of mixing costs.

3.2. Mechanisms based on intertrial variability

In this section two mechanisms are discussed stemming from the perspective of differential intertrial variability. Common to these mechanisms is that they both rely on a stimulus-driven principle, in that mixing costs are conceived of as a consequence of residual activity of previous trials. The mechanisms differ in what they assume to be the cause of sequential effects. The first mechanism discussed below assumes that mental structures related to a specific event are not activated in isolation. Rather, a process of associative priming causes a coactivation of semantically similar structures, which aids subsequent processing to the degree it makes use of these structures. The second mechanism assumes that the mental apparatus is inert, and reluctant to change. Thus, the adaptation of a process takes time, so that mental actions are impeded to the degree they require adjustments of preceding actions.

3.2.1. Associative priming

Marcel and Forrin (1974) presented four digits and four letters for speeded identification in mixed blocks and studied the nature of the category repetition effect. On half of the trials they provided preknowledge about the category to be presented on the forthcoming trial by means of a valid cue, announcing the presentation of a digit or a letter. They found a considerable category repetition effect in the uncued condition, but this effect was virtually abolished in the cued condition. In a subsequent experiment the authors demonstrated that the mechanisms underlying effects of cuing and category repetition could be dissociated when the cue provided invalid information on a limited number of trials. Specifically, invalid information was very harmful to category alternations (i.e., informing the subject on a forthcoming category repetition, but presenting a category alternation), but hardly at all to category repetitions (i.e., informing the subject on a forthcoming alternation, but presenting a repetition). These experiments constitute a highly interesting couple. The first experiment shows that the category repetition effect can be reduced when preknowledge is provided about the forthcoming category, suggesting that this effect is strategic in nature. However, the second experiment reveals a flaw in the logic underlying this conclusion: A reduction of the repetition effect in the cued condition merely indicates that this effect can be strategically compensated whatever its nature, but not necessarily that the effect itself relies on a strategic mechanism. In fact, the category repetition effect recurred when the cue provided invalid information, suggesting that the category repetition effect and the cuing effect rely on different mechanisms.

Marcel and Forrin (1974) accounted for these results by assuming that symbols, like letters and digits, have abstract representations, or logogens (Morton, 1969), in memory. When the activation level of a logogen exceeds a threshold, a corresponding response is made available, implying that responding is faster as the initial level of activation is closer to threshold. Activating a logogen may occur in two independent ways, either in a stimulus-driven way, by the presentation of an external representation of the logogen, or
in a strategic way, as endogenously proceeding from the subject (see also Miller, 1979). Conversely, when an elevated activation level is not maintained in either of these ways, it decays passively and monotonically over time. Furthermore, Marcel and Forrin (1974) assumed that logogens are organized in an associative network, implying that an elevated state of activation of one logogen spreads to adjacent logogens by a process of associative priming (Meyer and Schvaneveldt, 1976), the strength of which decreases as the distance from the originally activated logogen increases. Marcel and Forrin (1974, Experiment 4) lend support to this assumption by demonstrating a gradual reduction of the priming effect as the numerical distance between subsequently presented digits increased.

According to this model, the category repetition effect stems from a fully stimulus-driven process. Upon stimulus presentation, the level of activation of the corresponding logogen is elevated, which in turn gives rise to a spread of activation that elevates the levels of activation of related logogens. Thus, a presentation of a stimulus from the same category as its predecessor will profit from this state of elevated activation and allow a relatively fast response. A stimulus from another category than its predecessor will generally find the initial level of activation of the logogen relatively low, thus giving rise to slow responding. Consequently, the category repetition effect is observed. This effect is abolished, however, when valid preknowledge is timely provided, as it enables subjects to strategically raise the initial activation level of the logogens belonging to the forthcoming category. Again, invalidly cuing the forthcoming category revives the original category repetition effect, because the effects of the strategic and the stimulus-driven mechanism are independent. Specifically, the response to an actual repetition is not delayed by invalid cuing, as the activation level of related logogens has been raised on the previous trial in a stimulus-driven way. By contrast, the response to an actual alternation is delayed by invalid cuing, because related logogens have been deprived of any mechanism to elevate their relatively low levels of activation prior to the onset of the stimulus.

This account of mixing costs has not received additional testing, although it gives rise to the remarkable and interesting conclusion that subjects perform best when they prepare for another category than the one presented on the last trial. Using this strategy, the highest total level of activation is obtained, as raised in a stimulus-driven way for the category presented on the last trial and in a strategic way for the alternate category. Of course, this conclusion is not remote from the data obtained by Marcel and Forrin, which showed that invalid preknowledge yields costs for an actual alternation, but not for an actual repetition. Yet, it seems that subjects do not use this 'alternate-category' strategy of their own accord, witness the pronounced category repetition effect in Marcel and Forrin's uncued condition. Therefore, it would be an interesting test for the associative-priming account to instruct subjects to use the alternate-category strategy in mixed blocks.

3.2.2. Mental inertia

Inertia has been an important theoretical concept in physics ever since its formulation by Newton in his classical mechanics. It refers to the disposition of a physical body to persist in a state of steady motion or rest. The present section pursues a qualitative
analogue of this concept in contemporary cognitive psychology, denoted as mental inertia. Mental inertia is conceived of as the disposition of perceptual and cognitive activity to persist in its actual state. As such, mental inertia might appeal to the common-sense experience that in order to perform most efficiently, we prefer to organize our activities in similar rather than in dissimilar clusters. Conversely, when we are forced to repeatedly adjust our actions to changing demands on subsequent occasions, our performance might become rather inefficient. In such a case, inertia induced by actions that have finished shortly before should be overcome before new demands imposed by the environment can be addressed.

Recently, Allport et al. (1994) came to endorse this principle in their study on shifting task set. In their Experiment 5, they used incongruent color words (e.g., the word ‘red’ printed in blue), of which they sequentially presented two exemplars (S1 and S2) on each trial. Subjects had to orally name the word (word reading) or the color in which the word was printed (color naming). In pure blocks, subjects had to execute the same task with respect to S1 and S2 (i.e., either word reading or color naming), whereas in mixed blocks they had to execute alternate tasks with respect to S1 and S2 (i.e., word reading/color naming or color naming/word reading). The response stimulus interval (RSI) between S1 and S2 was either 20, 550 or 1100 msec, so as to vary the opportunity to prepare for the task demands of S2 after completing the task with respect to S1. Regarding the time to respond to S2 (RT2), the results showed the typical asymmetry of mixing costs, namely sizable mixing costs for the fast word reading task, but no mixing costs for the slow color naming task. Furthermore, mixing costs decreased only slightly when RSI increased from 20 to 550 msec, and remained constant thereafter. Although subjects were well aware of forthcoming task demands, they were, apparently, hardly capable to strategically disengage from preceding task demands, not even when RSI was as long as 1100 msec.

On the basis of these and similar results Allport et al. (1994) developed their concept of task-set inertia, which is here conceived of as a specific case of mental inertia. In that quality, task-set inertia is the disposition of a task set to persist in its actual state, implying a greater efficiency of reusing a task set than of shifting to another task set. A crucial feature of task-set inertia is that disengagement from the previous task set does not occur autonomically, but only upon occurrence of the subsequent stimulus. This feature was evident in the experiment described above, in that mixing costs were hardly reduced as RSI increased. To account for the finding of asymmetric mixing costs, Allport et al. (1994) assumed that individual task features are more subject to inertia as they demand more control. In theoretical contributions to the Stroop task it is commonly assumed that color naming is a control demanding activity, whereas word reading proceeds rather automatically (e.g., Posner and Snyder, 1975; see MacLeod, 1991, for a review). Thus, contrary to word reading, color naming is subject to inertia, and so,

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5 An interesting feature of this result is that the asymmetry of mixing costs is opposite to the asymmetry of the well known Stroop interference. The latter asymmetry implies that color naming of incongruent color words is much more retarded relative to color naming of amorphous patches than is reading incongruent color words relative to reading black color words (e.g., Stroop, 1935; see MacLeod, 1991, for a review).
mixing costs are only found for word reading, reflecting a time consuming shift from color naming. Allport et al.'s observation of asymmetric mixing costs is not an isolated case, since for a great variety of variables it has been found that mixing costs are larger for the fast, and possibly automatically processed level of the variable than for the slow, control demanding level (e.g., Duncan, 1977a,b, 1978; Forrin and Morin, 1967; Los, 1994, submitted; Stoffels, 1996a, submitted; Van Duren and Sanders, 1988). These observations then, are in support of a connection between mental inertia and controlled processing.  

This task-set inertia account has recently been criticized by Rogers and Monsell (1995). They found evidence that mixing costs disappear by the first time a task set is repeated in a mixed block (Experiment 6). They considered this finding not in line with task-set inertia, which in their view should have persisted over a considerable number of trials, referring to Allport et al.'s (1994, Experiment 4) finding that mixing costs persisted over a considerable time scale. However, this feature may not be very crucial to the concept of task-set inertia after all, witness Allport et al.'s remark that "whether the amount of task-set interference depends simply on the temporal recency of alternative (divergent) S-R mappings, or whether there is some form of context-dependent 'release', across different experimental settings, is a subject to future research" (p. 436). It seems more crucial to the concept of task-set inertia that mixing costs represent a time loss to disengage from previous task demands, rather than to engage into new task demands. In their experiments, Rogers and Monsell (1995) basically replicated Allport et al.'s (1994) result that costs of task switching were reduced as RSI increased up till about 500 msec, though very little thereafter. In addition, they presented evidence that the reducible part of these mixing costs reflects a subject-driven task-set reconfiguration, rather than a passive decay of inertia (Experiments 2 vs. 3), whereas the residual mixing costs reflect a stimulus-driven completion time of the task-set reconfiguration. This finding leaves open, however, to what degree these two components represent disengagement and engagement costs. A way to study this, is to find out whether or not mixing costs observed for a single task set are dependent on the precise nature of the preceding deviant task set. If disengagement has been completed before new task demands are addressed, the residual part of mixing costs should be independent of the nature of a deviant preceding task set. In that case the task-set inertia hypothesis would be falsified (see also Allport et al., 1994).

Inertia conceptions similar to that of Allport et al. (1994) have also been reported in the realm of visual perception. Thus, mental inertia is implicit in the Sanocki (1987, 1988, 1991) descriptions model of letter recognition. This model postulates that the perceptual system is tuned to abstract regularities that characterize the type font in which text strings are set. Specifically, font specific parameters are preserved across the subsequent analyses of text strings and only adjusted when the perceptual system fails to   

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6 The assumption that mental inertia proceeds from controlled processing is not at odds with the notion that mixing costs proceed from mental inertia in a stimulus-driven way. In this view, controlled processing may render specific mental structures inert, and constitutes as such a condition for the occurrence of mixing costs. However, it is the disengagement from these inert task features, as triggered by the subsequent stimulus, that gives rise to mixing costs and that renders mixing costs their stimulus-driven nature.
bring about a satisfactory transformation of a character to match an abstract letter code. Stated differently, the perceptual system is inert in its resistance to change font-specific parameters from one occasion to the next. To test this principle, Sanocki (1988, Experiment 2) tachistoscopically presented on each trial a string of four letters. After a presentation, subjects were asked to identify these letters by means of a forced choice between two newly presented alternatives at each string position. In pure blocks, the type font of the letters was invariant across trials, but in mixed blocks two highly distinct type fonts alternated between successive trials. The results showed that letter identification was less accurate in mixed blocks than in pure blocks. These mixing costs indicate that the perceptual system is less sensitive to font specific characteristics in mixed blocks than in pure blocks, thus supporting the tuning principle of the descriptions model.

Los (1994) used a design similar to that of Allport et al. (1994) to study mixing costs in the perceptual domain. On each trial subjects had to identify two different digits ($S_1$ and $S_2$) that were separated in time by an RSI of about 140 msec. $S_1$ and $S_2$ were either intact or degraded by noise (i.e., Fig. 2a vs. 2b), yielding four experimental conditions. Subjects had preknowledge about the forthcoming visual qualities of $S_1$ and $S_2$, as these were varied between blocks. The results showed that the time to identify $S_2$ (RT2) was shorter for pure pairs than for mixed pairs of stimulus quality (i.e., intact–intact vs. degraded–intact and degraded–degraded vs. intact–degraded). Los attributed these mixing costs to inertia-like properties of the visual system. Furthermore, in a control condition the visual $S_2$ was preceded by an auditory $S_1$, a pure tone, of which subjects had to identify the pitch. This prevented that subjects engaged in visual processing before $S_2$ was presented, and thus constituted a baseline against which the mixing costs of the experimental conditions could be evaluated. The results showed that RT2 only deviated from the baseline in conditions that involved a degraded $S_1$. In the degraded–intact condition, RT2 was longer than in the tone-intact condition, and in the degraded–
degraded condition, RT2 tended to be shorter than in the tone-degraded condition. This led Los to suggest that the specific processing demands called upon by a degraded S1 constitute a major source of mental inertia.

In a subsequent study Los (submitted a) explored in greater detail the significance of specific processing demands of visual stimuli for the occurrence of mixing costs. His subjects had to identify digits belonging to various categories of visual quality, which he pairwise presented in the blocked-mixed design. His purpose was to reveal the necessary and sufficient conditions for the occurrence of mixing costs in the perceptual domain. The results showed that any pairwise combination of intact, noise-degraded and segment-deleted qualities (i.e., Fig. 2a, 2c and 2e, respectively) yielded mixing costs. By contrast, mixing costs were not found when variations within a quality, related to the complexity of the quality (as defined by the number of noise dots – Fig. 2b vs. 2c) or to a trivial perceptual feature (i.e., Fig. 2c vs. 2d), were pairwise presented in the blocked-mixed design. These results suggest that mixing costs are due to time consuming shifts among different analytical processes for identifying stimuli of different categories, like ‘cleaning-up’ for noise-degraded stimuli, ‘filling-in’ for segment-deleted stimuli and neither of these for intact stimuli. Of course, these descriptions of analytical processes are merely illustrative and not meant to reflect genuine processes in the brain. They do indicate, however, at which level of visual processing mixing costs are assumed to take place: not at an ‘early’ level, where processing is bound to retinotopic coordinates, but at a later level, where processing is object-based, involving visual routines (Ullman, 1984; Trick and Pylyshyn, 1994). According to this view then, mixing costs reflect inertia to shift among visual routines.

To test this hypothesis, Los (submitted a) conducted another experiment in which he presented intact and segment-deleted digits as well as dice dots (i.e., Fig. 2f) pairwise in the blocked-mixed design for fast number identification. The major result was that mixing costs observed in the dice dots/segment-deleted condition were about the sum of the mixing costs observed in the dice dots/intact and the intact/segment-deleted conditions. This result is consistent with the hypothesis that mixing costs proceed from shifting among visual routines. First, in spite of a greater perceptual similarity between dice dots and segment-deleted digits than between dice dots and intact digits (i.e., in terms of the distribution of dots in the visual field), mixing costs were greater when the former two categories were combined than when the latter two categories were combined. This suggests that the source of these mixing costs is not the variability of perceptual features, but the variability of more abstract perceptual routines. Furthermore, the additive relationship of the mixing costs supports an interpretation in terms of a shifting mechanism. Thus, a ‘single’ shift between routines is needed to identify the number of dice dots upon identifying an intact digit, because enumeration processes probably rely on different routines than symbol identification (e.g., Trick and Pylyshyn, 1994).

To exclude the interpretation that mixing costs are due to greater confusion among the segment-deleted digits and dice dots than among intact digits and dice dots, Los had a control group carry out the same conditions with segment-deleted digits replaced by noise-degraded ones (i.e., Fig. 2c), which are maximally discriminable from dice dots. The results were basically the same as in the experimental group, thus disconfirming the confusion account.
1994). However, a ‘double’ shift is needed to identify dice dots upon identifying a segment-deleted digit: a shift away from the specific routine of ‘filling-in’ in addition to the shift from symbolic to enumeration routines.

Apart from providing evidence for specific perceptual processes, the data obtained by Los (1994, submitted a) constitute a challenge to describe a mechanism for mental inertia in greater detail. As an attempt in this direction, it could be assumed that visual routines operate in a competitive way to analyze an incoming visual signal. The nature of the competition is such that the increment of activity in one routine implies the suppression of alternate routines by means of lateral inhibitory pathways. The duration of the competition determines hereby the amount of transferred inhibition. That is, the longer it takes until the appropriate routine wins the competition, the more inhibition will have been transferred toward competing, inappropriate routines. Thus, in this proposal mixing costs reflect a reduced efficiency of the operation of visual routines due to inhibitory carry-over from previous calls on alternate visual routines. Furthermore, an asymmetry of mixing costs is explained by differential levels of competition between visual routines. For instance, when intact and noise-degraded stimuli are presented in the blocked-mixed design, the routines involved in identifying intact digits dominate the competition, and so do not need to suppress alternate routines. By contrast, more competition occurs during the analysis of a degraded digit, during which inappropriate, competing routines must be suppressed.

This proposal shares some crucial features with the proposal of Allport et al. (1994) discussed earlier in this section. In addition, it makes explicit that mental inertia serves to stabilize the ongoing activity by suppressing simultaneous actions that might interfere. This function might be realized in different ways, and there is no direct evidence for the proposed inhibition component. However, apart from being a logical solution, inhibition relates well to mechanisms proposed in the literature serving similar functions. For instance, it has been suggested that inhibition plays an important part to limit entrance of information in working memory (Hasher and Zacks, 1988). Furthermore, an important view in the literature on the phenomenon of negative priming is that distractors on a trial are inhibited to prevent interference with the target, which gives rise to slower responding when the distractor becomes the target on the subsequent trial (e.g., Tipper, 1985; Driver and Tipper, 1989).

3.3. Summary

This section examined the possibility to account for mixing costs from the perspective that mixed blocks exhibit stronger intertrial variability than pure blocks, and thus give rise to additional sequential effects. Because differential sequential effects between pure and mixed blocks necessarily translate into mixing costs, an account of sequential effects might also qualify as an account of mixing costs. Section 3.1 revealed that sequential effects are generally conceived of as relying on a stimulus-driven mechanism, or caused by residual activity of the preceding trial. However, mechanisms based on irrational expectancies or on a strategy to use the events on a previous trial as a point of reference for the subsequent trial should not be abandoned without testing. Next, two models were discussed that focus on the stimulus-driven dynamics that make pure and
mixed blocks distinct. According to the associative priming model the activation of a logogen spreads to adjacent logogens, thus aiding subsequent processing to the degree it makes use of the coactivated logogens. Mental inertia is the disposition of processing to persist in its actual state, thus impeding subsequent processing to the degree it is different from previous processing.

4. On the origin of mixing costs: A selective review

In the previous two sections, two perspectives on mixing costs have been discussed, one emphasizing the difference between pure and mixed blocks in the uncertainty of the subject about forthcoming events (Section 2) and another one emphasizing the difference between pure and mixed blocks in intertrial variability of the subject’s mental state (Section 3). In the present section these perspectives will be contrasted. This is a useful exercise, because a great deal of research that employed the blocked-mixed design has adopted the global perspective of uncertainty without considering the local perspective of intertrial variability. This section will start with the discussion of two methods on the basis of which the two perspectives can be distinguished. Then, a selective review is presented of studies in which either of the methods has been used.

4.1. Dissociation methods

From the perspective of uncertainty mixed blocks differ from pure blocks regarding the uncertainty subjects have about forthcoming events. The uncertainty is greater in mixed blocks than in pure blocks, which leads subjects to adjust their preparation by mechanisms like those discussed in the Section 2. According to this view, mixing costs are strategic in nature, because they are assumed to derive from variations in (subject-driven) preparation. By contrast, from the perspective of intertrial variability, pure blocks differ from mixed blocks in the extent to which processing adjustments have to take place on subsequent trials. Less trial-to-trial adjustments are necessary in pure blocks than in mixed blocks, enabling faster responding. According to this view, mixing costs are stimulus-driven in nature, because the necessary trial-to-trial adjustments are determined by the processing requirements of the stimuli.

Two methods seem particularly suitable to distinguish between the strategic and stimulus-driven accounts. First, the method of preknowledge aims at dissolving the confounding between uncertainty and intertrial variability by providing preknowledge in mixed blocks about the level of the variable to be presented on the forthcoming trial. Provided that the preknowledge is valid and leads the imperative stimulus by a sufficiently long time to enable full preparation, this method equates mixed blocks to pure blocks regarding the level of the subject’s preparedness for the forthcoming event. Consequently, a strategic account predicts the disappearance of mixing costs when preknowledge is provided. Because this method does not affect the intertrial variability, the obvious prediction of a stimulus-driven account seems to be that mixing costs persist when preknowledge is provided, but, as will be argued in the next paragraph, this inference is not necessarily true. Second, the method of sequential order analyzes RT in
mixed blocks separately for repetitions and alternations of the levels of the variable presented in the blocked-mixed design. As argued in Section 3, a stimulus-driven account of mixing costs predicts that RTs for repetitions should be shorter than RT for alternations. In its strong version a stimulus-driven account even predicts that mixing costs are absent on repetition trials. Because uncertainty about forthcoming events is independent of sequential order, strategic accounts do not have clear predictions regarding sequential effects.

The predictions deriving from these methods seem quite self-evident, but the next remarks indicate that some reservations are in order. Starting with the method of preknowledge, it should be emphasized that the results from this method are not as testing for the stimulus-driven account as they are for the strategic account. The reason for this asymmetry is analogous to the argument pointed out by Marcel and Forrin (1974) in their study on the category repetition effect (see Section 3.2.1): A reduction of mixing costs by preknowledge would merely indicate that these costs can be compensated whatever their nature, but not necessarily that these costs themselves rely on a strategic mechanism. Marcel and Forrin found the elimination of the category repetition effect when they provided valid preknowledge, but a strong revival of this effect when preknowledge was invalid. This led them to conclude that the category repetition effect is stimulus-driven in nature, although it could be strategically compensated. Thus, whereas the absence of an effect of preknowledge is harmful for the strategic account, its presence is not necessarily harmful for the stimulus-driven account. Another point of concern is what should count as 'sufficient' preparation time. If there is no reliable a priori criterion, any persistence of mixing costs in the preknowledge condition could be attributed to the failure of preparation processes to finish in time. The delicacy of this point has also been demonstrated by Marcel and Forrin (1974), who reported no reduction of the category repetition effect at preparation intervals of 500 msec, but its virtual elimination at intervals of 1000 msec. Subject-paced preparation intervals of even well above 1000 msec have been reported by Dixon and Just (1986), but the course of preparation in this study was nonspeeded and concluded by a motor response, thus prolonging the interval. It may seem then, that preparation intervals longer than 1000 msec should generally suffice to bring about a fully prepared state for simple processing requirements. If in that case mixing costs do not show clear signs of reduction relative to conditions in which no preknowledge is provided, their strategic basis should be severely doubted.

Turning to the method of sequential order, it should be emphasized that this method is more testing for stimulus-driven accounts than for strategic accounts — an asymmetry opposite to that for the method of preknowledge. Whereas the absence of sequential effects would strongly argue against a stimulus-driven account of mixing costs, their presence is not necessarily harmful for the strategic account. As indicated in Section 3.1, sequential effects might be explained by assuming that subjects are led to expect a repetition of events (cf. Kirby, 1975, 1976a,b) or in some cases an alternation (Soetens et al., 1985). Yet, it is doubtful whether these assumptions are generally true, and so sequential effects should be considered as at least slightly embarrassing for a strategic account of mixing costs.

To summarize, it is proposed that the combined results deriving from the method of
preknowledge and the method of sequential effects are necessary and sufficient to reveal the strategic or stimulus-driven nature of mixing costs. If the provision of preknowledge has the effect of decreasing mixing costs and no sequential effects are observed, the nature of the mixing costs can be confidently attributed to a strategic cause. Instead, if clear sequential effects are found and preknowledge proves ineffective, mixing costs should be attributed to a stimulus-driven cause.

Nevertheless, even the latter pattern of results did not restrain Strayer and Kramer (1994a,b) from a strategic interpretation of their mixing costs. As was discussed in Section 2.2.1, they presented consistently mapped (CM) and variedly mapped (VM) memory targets in the blocked-mixed design, and observed that block type mainly affected the level of the criterion in Ratcliff’s (1978) retrieval theory. This is what led them to adopt the strategic point of view, even though they found that preknowledge was completely ineffective in reducing mixing costs (Strayer and Kramer, 1994b, Experiments 1, 2 and 3), whereas considerable sequential effects were found (Experiments 1, 2, 6 and 7). They concluded that subjects cannot set the criterion dynamically on the basis of preknowledge, though they can do so on the basis of information provided by the previous trial. This conclusion seems indeed inescapable if it is assumed that the setting of the criterion is the exclusive prerogative of the subject. However, on the basis of the strategy concept under present consideration, these results should be interpreted differently. It is suggested that subjects, in their undeniable effort to perform optimally, may take advantage of a well tuned criterion. However, the tuning of the criterion is brought about by activities that took place on the previous trial(s), and thus should be considered stimulus-driven.

Finally, useful additional information about the nature of mixing costs can be obtained by varying the time interval between subsequent events. From the strategic point of view, the time course of preparation could be studied by varying in mixed blocks the interval between the presentation of preknowledge and of the imperative stimulus. Similarly, from the stimulus-driven point of view, the dissipation of activation or inhibition could be studied by varying the interval between subsequent trials, when preknowledge is not provided. It should be remarked, however, that time course data should be interpreted with care. In particular, there are no generally accepted standards of how activation or inhibition should dissipate in time, and recently Hasher et al. (1991) failed to find a reliable reduction of inhibition in an interval ranging from 500 to 1200 msec. Thus, by themselves, time course data seem to be insufficient to provide conclusive evidence on the strategic or stimulus-driven nature of mixing costs.

4.2. A selective review of mixing costs

This section presents a review of mixing costs reported in the literature and examines whether the nature of these costs is strategic, as derives from the uncertainty perspective, or stimulus-driven, as derives from the intertrial variability perspective. Because it has been argued that strategic influence increases as processing proceeds from perception to action (e.g., Sanders, 1983; Van Duren and Sanders, 1988), the review is structured according to the stages of processing affected by the variables presented in the blocked-mixed design (cf. Sanders, 1990). For this reason, the review is limited to
variables whose selective influence to stages of information processing has been well established by additive factors research (e.g., Sanders, 1980, 1990). In the next three subsections mixing costs will be examined that occur at the levels of perception, response selection and motor behavior. In each subsection, three issues will guide the inquiry. First, whether mixing costs occur and whether they are symmetrically or asymmetrically divided across the levels of a variable. Second, whether or not mixing costs are reduced by preknowledge. Third, whether RTs in mixed blocks show sequential effects. Because relatively little research has been devoted to these issues, the review has also the function of indicating empirical voids and of suggesting alternative views.

4.2.1. Perception

According to the additive stage structure, signal intensity is a variable that affects early perceptual processing (e.g., Sanders, 1980; Schweickert et al., 1988). As a variable in the blocked-mixed design, signal intensity has shown several properties not shared by variables that are assumed to affect later stages of processing. First, although a main effect of block type is usually found, this effect shows either no interaction or an overadditive interaction with the effect of signal intensity, contrary to the underadditive interaction commonly reported for block type and other variables when presented in the blocked-mixed design. As has been argued in Section 2.2.1, the overadditive interaction is commonly found when the levels of the variable differ in their surmised arousing properties (e.g., Sanders, 1977), whereas additive effects are commonly found when this is not the case (e.g., Niemi, 1981; Van Duren and Sanders, 1988). Second, sequential effects have been shown to be consistently deviant from those of other variables. Instead of a general beneficial effect of repetitions, it has been found that trials containing a signal of low intensity are likely to speed up the response on the subsequent trial, regardless of the intensity of the signal occurring on that trial. These results have been found for both the auditory (e.g., Murray, 1970; Henriksen, 1971) and the visual (e.g., Niemi, 1981) modality, although some studies failed to find sequential effects (Murray and Kohfeld, 1965, Kohfeld, 1969). A possibly related finding is that preadaptation to soft auditory tones in the beginning of the experiment entails faster responding later in the experiment than preadaptation to loud tones (Murray and Kohfeld, 1965; Kohfeld, 1968). Finally, studies using the method of preknowledge have shown inconclusive results. In two studies mixing costs disappeared when preknowledge was provided in mixed blocks (Thrane, 1961; Speiss, 1973), though in one study they did not (Murray, 1970). For additional experimental findings, see Nissen (1977) for a review.

Within the framework of Grice’s (1968) variable-criterion model (see Section 2.2.1), the finding of sequential effects has raised two distinct hypotheses. The first hypothesis is strategic in its statement that subjects adjust their response criterion in accord with the intensity of the stimulus presented on the preceding trial (e.g., Murray, 1970; Henriksen, 1971; Nissen, 1977; Niemi, 1981). Specifically, it has been argued that upon processing a loud signal, subjects might adopt a higher criterion on the next trial, so that the response to a forthcoming signal is delayed irrespective of its intensity. The second hypothesis is stimulus-driven in its statement that more neural noise is left behind as the intensity of a signal is higher, so that more processing is required on the subsequent trial to distinguish the stimulus from noise (e.g., Murray, 1970). In a direct test of these
hypotheses, Henriksen (1971) found his data more in agreement with the strategic hypothesis, because mixing costs proved resistant to increases in RSI from 6 till 15 seconds, during which neural noise would be expected to dissipate. Independent support for this view is lacking, however. The data deriving from the preknowledge experiments have not in all cases revealed strategic compensatory effects, and even if they did, this does not necessarily imply that the nature of mixing costs is strategic as well, as follows from Marcel and Forrin’s (1974) argument addressed in Section 4.1. The question of the strategic or stimulus-driven nature of mixing costs is not only relevant to Grice’s (1968) model, but also to a stage model as proposed by Sanders (1977, 1983), discussed in Section 2.2.1. Within this context, the question would be whether the level of response related activation relative to the motor action limit is regulated strategically or in a stimulus-driven way by preceding stimuli. In the literature there is a clear preference for the first option, but in Section 4.2.3 an alternative view will be presented.

In comparison to signal intensity, other perceptual variables have been relatively little studied in the blocked-mixed design, although relevant data are available. According to the additive stage structure, the variable *stimulus quality* affects a later perceptual stage than signal intensity (Sanders, 1980, 1990). As a variable in the blocked-mixed design stimulus quality has been found to yield asymmetric mixing costs, as reflected by its underadditive interaction with block type (Van Duren and Sanders, 1988; Los, 1994, submitted a; Van Duren, submitted). Recently, Los (submitted b) failed to find any reduction of mixing costs when preknowledge was provided. In addition, he found that these mixing costs were exclusively present on those trials of mixed blocks where the stimulus quality alternated relative to the previous trial, whereas they were absent on trials where the stimulus category was repeated. These results clearly demonstrate a lack of strategic involvement, which led Los to propose an explanation in terms of mental inertia, which has been discussed in Section 3.2.2.

Another perceptual variable that has been studied in the blocked-mixed design is *stimulus rotation*. There is good evidence that this variable induces a process of mental rotation when the task calls for a discriminative choice response between a normal and mirror reflected orientation of the stimulus when imaginary rotated upright (Shepard and Metzler, 1971). Within the additive stage structure, mental rotation has been identified as a late perceptual process (Sanders, 1990). Ilan and Miller (1994) studied mental rotation in the blocked-mixed design, and examined which factors affected the sizable mixing costs found for upright (unrotated) stimuli. Mixing costs proved completely resistant to the presentation of preknowledge about the forthcoming angle of orientation (Experiment 1 vs. 2), and only slightly less so to category repetition (Experiment 1). That is, these results seem neither consistent with a strategic account, nor with a stimulus-driven account. In Experiment 5, however, mixing costs were virtually abolished when the choice reaction task was replaced by a disjunctive reaction task. In this task subjects released a response when the stimulus (after rotation) proved normally oriented and withheld a response to a mirror reflected stimulus, or vice versa. From these data Ilan and Miller concluded that mental rotation is not a purely inserted process, but interferes with response selection processes. They conjectured that the mixing costs in their Experiments 1 and 2 reflect the need to maintain readiness for mental rotation, even when preknowledge about a forthcoming upright stimulus releases the subject from
this confinement, and that this maintenance interferes somehow with the maintenance of two alternative responses in a choice experiment. This explanation relates to a bottleneck property of the response selection stage (Pashler, 1993), or, in terms of capacity theory, to concurrence costs (Navon and Gopher, 1979; see also Noble et al., 1981). A similar idea was also suggested earlier as an account of the mixing costs observed by Strayer and Kramer (1994a,b) in Section 2.2.1.

Taken together, there seems to be little unity in the nature of mixing costs observed for perceptual variables in the blocked-mixed design. In particular, mixing costs for signal intensity are in almost all respects different from mixing costs for variables affecting later perceptual processing. These differences include: (a) the nature of the combined effect of block type and signal intensity, which is either additive or overadditive rather than underadditive; (b) the qualitative characteristics of sequential effects, implying fast responding following a signal of low intensity, rather than a general repetition advantage and (c) the impact of preknowledge, which often proved to reduce RT rather than being ineffective. Both within the framework of the variable-criterion model and of a stage model these effects are believed to be related to the variable distance between activation and a criterion, whether by adjusting the criterion or the baseline of motor activation. However, it is not yet clear how this distance is affected, by strategic adaptation, by preceding processing or by both. The variables stimulus quality and stimulus rotation are similar in that their mixing costs are not reduced by preknowledge. However, whereas the mixing costs for stimulus quality are subject to strong sequential effects, the mixing costs for stimulus rotation are not. Thus, the mixing costs for stimulus quality are adequately accounted for by a stimulus-driven mechanism, whereas the mixing costs for stimulus rotation may reflect the requirement to maintain task demands on the level of response selection.

4.2.2. Response selection

The response selection stage is also denoted as decision stage. Both names bring to expression the strategic properties that are commonly attributed to this stage, in accord with its function to connect input to output. Indeed, since myriads of stimuli and myriads of responses are continuously available, there must be a strategic principle that connects them in a meaningful way, that is, in accord with our intentions or task demands. Thus, the response selection stage is inconceivable without strategic involvement. However, the strategic nature of selection need not imply that mixing costs deriving from various selection rules are also strategic in nature. As has been indicated in the discussion about mental inertia (Section 3.2.2), it may well be that mixing costs reflect the need to overcome the residual activation of preceding strategic processing (see footnote 6). Therefore, it is useful to investigate the nature of mixing costs even at stages where strategy is believed to reign.

A variable that has been closely associated with the response selection stage is stimulus-response compatibility (S-R compatibility) (Sanders, 1980, 1990), which expresses the degree to which the stimulus and the response are naturally connected, or, more formally, are based on dimensional overlap (cf. Kornblum et al., 1990). Section 1.1 described an experimental design that has been employed in various studies that presented spatial S-R compatibility in the blocked-mixed design (Duncan, 1977a,b,1978;
Stoffels, submitted). Other studies used symbolical S-R compatibility as a variable in this design, by presenting in pure and mixed blocks symbolical stimuli that are naturally or unnaturally mapped onto their responses (Morin and Forrin, 1962; Forrin and Morin, 1966, 1967; Forrin, 1975; Van Duren and Sanders, 1988; Stoffels, 1996a). Since spatial and symbolical S-R compatibility are theoretically related by the principle of dimensional overlap (Kornblum et al., 1990), no specific distinction will be made between them.

The typical finding in studies that used S-R compatibility as a variable in the blocked-mixed design is the occurrence of mixing costs that are more pronounced for compatible than for incompatible S-R relations, as reflected by an underadditive interaction between block type and S-R compatibility. Studies using the method of sequential effects have invariably shown faster responding to category repetitions than to category alternations, differing only in the degree to which mixing costs coincided with sequential effects. Forrin (1975; on the basis of results obtained by Forrin and Morin, 1967) found only a moderate contribution of his category repetition effect to mixing costs. The degree of overlap in Duncan’s (1977a) and Stoffels’s (submitted) studies was substantial, whereas a complete overlap was reported by Stoffels (1996a). Using the method of preknowledge, both Forrin and Morin (1967) and Stoffels (submitted) observed that cuing the response selection category in advance of the imperative stimulus reduced, though not abolished mixing costs. However, their results might not be too convincing because they used cues that were nonimperative members of the categories they referred to, possibly instigating stimulus-driven processes in addition to transferring preknowledge.

A design related to the blocked-mixed design was recently used by De Jong (1995; see also Shaffer, 1965). He presented two stimuli on each trial, an auditory S1 and a visual S2, that were separated by a stimulus onset asynchrony (SOA) ranging from 100 to 600 msec. Subjects responded to S2 using a compatible or incompatible stimulus-response mapping rule as indicated by the high or low pitch of S1. In pure blocks the same rule (i.e., either compatible or incompatible) was used on each trial, implying that S1 could be ignored. In mixed blocks the mapping rules were randomized across trials, so that processing of S1 was mandatory. The results revealed considerable mixing costs in responding to S2, the strength and asymmetry of which declined as SOA increased from 100 to 600 msec. The mixing costs at shorter SOA’s are beyond the scope of the present paper, as they are possibly related to the fact that the number of task-relevant stimulus-response relations was twice as large in mixed blocks as in pure blocks. However, on the assumption that De Jong’s maximal SOA of 600 msec suffices to bring about a fully prepared state on the part of the subject, the results deriving from this condition are of present interest as they reflect whether or not mixing costs persist when the subject’s preparedness is equated across pure and mixed blocks. The mixing costs in this condition were quite small (in the order of 15 to 25 msec) and about equal in size for repetitions and alternations. This suggests that mixing costs in De Jong’s study were predominantly strategic in nature. This is interesting in the light of Allport et al.’s (1994) and Rogers and Monsell’s (1995) failure to find a similar strong reduction of mixing costs as the response stimulus interval increased between subsequent tasks that, like S-R compatibility, seem to call on central processing (see Section 3.2.2).
In all, the nature of mixing costs for response-selection processes cannot be identified on the basis of the available data. The studies discussed generally showed moderate effects of both preknowledge and repetition, and not an absence of either of these effects, which would be most revealing as argued in Section 4.1. De Jong's (1995) results come closest to demonstrating a strategic origin, but the apparent deviation from the results of Allport et al. (1994) and Rogers and Monsell (1995) remains to be clarified.

4.2.3. Motor behavior

So far, no mention has been made of motor stages, although extensive material on mixing costs is on hand. For several reasons, the focus will be on the variable 'foreperiod', defined as the interstimulus interval between a warning signal and the imperative signal. Foreperiod is a variable that has been studied over a long time, and its late motor adjustment locus has been firmly established in the tradition of additive-factor research (Sanders, 1980, 1990). Furthermore, patterns of mixing costs related to this variable are also well established, and some clear-cut theoretical ideas have been proposed. Before starting the examination, it suffices to say that mixing costs enjoy interest at earlier motor stages as well. For instance, variables that affect the construction of motor programs have been studied in the blocked-mixed design, and the resulting mixing costs are in this literature referred to as contextual interference (cf. Shea and Morgan, 1979). In their review Magill and Hall (1990) attribute these mixing costs to the effort to retrieve and construct different motor programs on alternation trials in mixed blocks, whereas only repetitions of a single program occur in pure blocks. In this sense, their view seems related to the principle of inertia proposed by Allport et al. (1994) and Los (1994, submitted b), which is described in Section 3.2.2.

Returning to foreperiod, it is remarkable that this term is used interchangeably with the term 'time uncertainty' throughout the literature, thereby ignoring possible stimulus-driven factors as derives from the intertrial variability perspective. This is illustrated in Niemi and Näätänen's (1981) review, which concluded that "Although the nature of the foreperiod-RT relation is not entirely clear, it is obvious that the foreperiod is the time of preparation for a response. Therefore it is justifiable to call the foreperiod the preparatory interval." (p. 158). So, in view of these words, defending a stimulus-driven point of view is playing the devil's advocate; a role taken by the author to explore the foundations of current insights.

To specify a typical blocked-mixed design involving foreperiod, consider the presentation of a number of, say, six clearly distinct foreperiods in the blocked-mixed design. The moment immediately after the expiration of each foreperiod is a potential moment of stimulus presentation, here denoted as critical moment. In pure blocks each trial uses one and the same critical moment for stimulus delivery, whereas in mixed blocks each trial contains six critical moments, which have an equal chance of being used for stimulus delivery. Using this type of design, mixing costs have been reported that are far more pronounced for short foreperiods than for long ones, constituting again an underadditive interaction between block type and foreperiod. Specifically, in pure blocks, RT is shortest after short foreperiods (near 250 msec), and linearly increases thereafter. In mixed blocks, by contrast, RT is longest after the shortest foreperiod and
decreases as a negatively accelerating function as foreperiod increases. Barring exceptional situations, in which the foreperiods in mixed blocks have a nonrectangular distribution (e.g., Baumeister and Joubert, 1969) or mutually differ less than 100 milliseconds (e.g., Drazin, 1961), the data pattern described here has been repeatedly found and subject to theorizing (see Niemi and Näätänen, 1981, for a review).

To explain this data pattern, the strategic view assumes that an optimal preparatory state can be maintained for only a short period of time (e.g., Gottsdanker, 1975; Näätänen, 1972). This implies that the preparatory state is higher as uncertainty about the moment of stimulus delivery is lower. Two factors determine the uncertainty about the moment of stimulus delivery (e.g., Requin and Granjon, 1969; Niemi and Näätänen, 1981; Sperling and Dosher, 1986). The first factor is the length of the foreperiod, which is the only factor in pure blocks. As the foreperiod prolongs (i.e., between blocks), the subject's time uncertainty about the critical moment increases, which causes a greater variance in his or her preparatory state and an according increase in RT. This factor is dominated by a second factor in mixed blocks, namely, the conditional probability of occurrence of the imperative stimulus. If the stimulus has not been presented as critical moments pass by, the probability of its occurrence at one of the remaining critical moments increases, which reduces the subject's uncertainty. This in turn enhances the subject's preparatory state and accordingly reduces RT. From this plausible point of view, the above described data pattern fluently derives. In pure blocks, only time uncertainty affects RT, favoring short foreperiods (though above 250 msec) over longer ones. In mixed blocks, this factor is dominated by the conditional probability of stimulus occurrence, which favors long foreperiods over short ones.

Studies that used the method of sequential order have put some problems to this view, however. In mixed blocks, intertrial repetitions of foreperiods have commonly yielded shorter RTs than intertrial alternations, most pronouncedly so for short foreperiods. That is, sequential effects are asymmetric in that short foreperiods are more affected than long foreperiods. In their review, Niemi and Näätänen (1981) suggested a combination of two hypotheses to account for these sequential effects. The first hypothesis states that subjects tend to expect a repetition of the previous foreperiod in mixed blocks (cf. Drazin, 1961). However, as Niemi and Näätänen remark, this account by itself would predict symmetric sequential effects. The second hypothesis states that subjects may, in the case an event has not occurred on a specific critical moment, reprepare for later critical moments (Alegria, 1975; Baumeister and Joubert, 1969). From these two hypotheses, Niemi and Näätänen explained the typical asymmetry in sequential effects of foreperiods by assuming that subjects initially expect the previous foreperiod to repeat, and from there to reprepare for later critical moments in the case the stimulus has not yet occurred by that time. Thus, a low expectancy of a long foreperiod can be timely compensated by repreparation, a possibility that a short foreperiod lacks. However, in their discussion, Niemi and Näätänen (1981) considered the notion of expecting a repetition a weakness of this hybrid account.

In view of the consensus that the foreperiod effect is strategic in nature, one expects to encounter a good deal of studies using the method of preknowledge, so as to confirm the prediction that mixing costs are abolished when preknowledge is provided. However, Niemi and Näätänen (1981) did not mention this manipulation in their review, nor has
its employment been common practice in more recent literature. As an exception, Van der Molen et al. (1987, Experiment 2) provided preknowledge in mixed blocks about the forthcoming foreperiod duration, which reduced RT relative to when preknowledge was withheld. In a recent pilot study at the Vrije Universiteit, which employed a full blocked-mixed design, this finding was replicated, but it was also found that mixing costs were only halved by preknowledge and certainly not abolished. This result suggests that uncertainty is not the sole determinant of mixing costs, still apart from the possibility that the effect of preknowledge reflects a strategic compensation of a stimulus-driven effect (cf. Marcel and Forrin, 1974). Taking up the gauntlet, one might question the basis of Niemi and Näätänen’s (1981) conviction about the preparatory nature of the foreperiod effect, given that they did not consider any account not based on preparation!

An attempt to account for the data on hand in terms of a stimulus-driven mechanism could start with questioning the assumption of the strategic view that it is strenuous to maintain a state of high preparedness. Alternatively, it could be that a peak in the subject’s disposition to respond evolves fairly automatically, as a time-conditioned response triggered by the onset of the warning signal. Thus, in the initial stage of the experiment, an elevation of response related activation at critical moments might get conditioned to the warning signal, because critical moments are time-locked to the warning signal. However, in mixed blocks this might lead to premature responding at critical moments where no stimulus is presented, which makes it necessary to inhibit this disposition. This inhibition in turn reduces the automatic activation at these critical moments for a subsequent occasion, analogous to extinction behavior of the conditioned response when the unconditioned stimulus is withheld. A crucial assumption is that the inhibition only affects those critical moments that are passed by on a trial, but not those critical moments that were not yet called at, due to earlier stimulus delivery.

This proposal offers an explanation for typical foreperiod effects without reliance on preparatory principles. In pure blocks, RT prolongs in accord with the length of the foreperiod, due to an increment of the variation of the conditioned response, analogous to the postulate in the preparatory view that the variation of the subject’s preparatory state increases in accord with the length of the foreperiod. In mixed blocks, the stimulus-driven account emphasizes the difference between short and long foreperiods regarding the frequency with which critical moments are bypassed in the course of a block. Thus, as critical moments occur later after the warning signal, they are less frequently bypassed in the course of a block of trials, and the automatic response activation associated with them is therefore less subject to inhibition. As a result the

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8 In its reliance on the classically conditioned response, which is nowadays believed to be cognitively mediated (e.g., Rescorla, 1988), the proposed account is not devoid of strategic elements. So, cognitive factors like expectancy are not excluded insofar as they are involved in the process of conditioning. However, in this context expectancy has a different function than in the traditional preparation view. In the preparation view, expectancy is assumed to trigger a preparatory mechanism on a trial basis, implying a short-lived enhancement of preparedness for action. In the present view, on the other hand, expectancy is assumed to play a global part in the development of the conditioned response, but it does not underly the within-trial fluctuations of activation, which are, rather, conceived as automatically elicited.
typical foreperiod-RT function of mixed blocks emerges. The asymmetry in sequential effects is accounted for similarly, without the necessity of an additional principle. The updating of the state of conditioning occurs on a trial basis, and differentially affects critical moments bypassed and critical moments not yet called at. Thus, the asymmetry of sequential effects reflects a relatively low activation for early critical moments following late ones, due to foregoing inhibition, but not for late critical moments following early ones.

Of course, this stimulus-driven account is speculative and cannot boast of tradition or robustness to testing. In addition, it may not be able to deal with results from studies using physiological measures, like the contingent negative variance of the EEG (e.g., Loveless and Sanford, 1974) and anticipatory heart rate deceleration (e.g., Van der Molen et al., 1987). These studies suggest the presence of preparation-based activity preceding the imperative stimulus. Still, it would be useful to confirm the relevance of preparatory activity on overt behavior by studying the nature of the effect of preknowledge about foreperiod duration on RT.

In conclusion, the study of foreperiod in the blocked-mixed design has never failed to emphasize the preparation point of view. This is not very surprising because mean effects are elegantly explained by concepts of time uncertainty and conditional probability of stimulus occurrence. However, considerable sequential effects are less readily accounted for. A combination of expecting the previous foreperiod to repeat and the possibility of repreparation when a signal does not occur at a critical moment, do not seem all too convincing. Yet, the findings of sequential effects apparently did not give rise to an explanation beyond uncertainty, as derives from intertrial variability. It is perhaps for this reason, that the method of preknowledge has hardly received attention in the long and rich tradition of research into the effect of foreperiod.

4.3. Summary

This section provided a selective review of mixing costs occurring at several stages of information processing. At almost all stages asymmetric mixing costs were found, as reflected by an underadditive interaction of block type and the variable loading the stage under investigation. A noticeable deviation from this pattern has been found at early perceptual processing, where the effects of the variables signal intensity and block type are as a rule additive, but overadditive when the intensity levels differ in their presumed arousing properties.

Two methods have been proposed to assess whether mixing costs are strategic or stimulus-driven in origin. The method of preknowledge aims to resolve the confounding between uncertainty and intertrial variability by providing preknowledge about the level of the variable to be presented on the forthcoming trial in a mixed block. The method of sequential order examines in mixed blocks whether intertrial repetitions of a level of a variable yield faster responding than intertrial alternations between levels, reasoning that a category repetition effect necessarily translates into mixing costs. It has been argued that a pronounced reduction of mixing costs in the preknowledge condition is a necessary but not sufficient result to decide in favor of the strategic account, since this result could well reflect a strategic compensation of stimulus-driven mixing costs (cf.
Marcel and Forrin, 1974). Conversely, a pronounced category repetition effect is a necessary but not sufficient result to decide in favor for a stimulus-driven account, since it could reflect a strategy to use the previous trial as a point of reference for the present trial (cf. Kirby, 1975, 1976a,b). Thus, the method of preknowledge and the method of sequential order should be applied in combination to obtain a complete picture of the strategic or stimulus-driven nature of mixing costs.

A tentative conclusion that may be drawn after exploring the limited number of studies that used either of these methods is that the stimulus-driven share in mixing costs has been either overlooked or insufficiently appreciated. Furthermore, there is as yet no clear evidence that the strategic share in mixing costs becomes more dominant from perception to action. Sequential effects constituted by the levels of the independent variable in mixed blocks are quite common, regardless of the stage of processing. These effects generally showed large and sometimes even complete (e.g., Los, submitted b; Stoffels, 1996a) overlap with mixing costs. In addition, the results deriving from studies that used the method of preknowledge did not always favor a preparation account. In some studies, mainly at the stage of perception, preknowledge was not at all effective in reducing mixing costs (Los, submitted b; Ilan and Miller, 1994), whereas in other studies, mainly at the stage of response selection, preknowledge reduced mixing costs to some extent, but not completely (Forrin and Morin, 1967; Stoffels, submitted). The only successful attempts to eliminate mixing costs have been reported for the variable auditory signal intensity (Thrane, 1961; Speiss, 1973; but see Murray, 1970, for a deviant result), while the method awaits more research regarding the foreperiod effect. On the basis of the available evidence, neither a strategic nor a stimulus-driven account can boast of unequivocal support.

5. Conclusions

The major objective of this paper was to examine the dynamics of information processing that gives rise to mixing costs. To this end, two opposing views on mixing costs have been discussed in Section 2 and Section 3. The strategic view holds that subjects are less well prepared in mixed blocks than in pure blocks, due to greater uncertainty about the level of the independent variable to be presented on the forthcoming trial. The stimulus-driven view holds that residual activation stemming from a preceding trial is more detrimental, or less beneficial, in mixed blocks than in pure blocks, due to greater intertrial variability.

The major conclusion of this paper is that manipulating block type is not equivalent to manipulating uncertainty, as has often been implicitly assumed in the literature. So, it is simply wrong to a priori attribute mixing costs to a strategic cause, since it is very well possible that stimulus-driven factors account for a large part of the mixing costs, if not completely. Thus, without additional information it should be taken into account that the variable block type confounds at least two factors, uncertainty and intertrial variability.

It should be emphasized, however, that this represents a minimal state of affairs. In passing it has become apparent that block type may embody even a greater set of
potentially confounded factors. Thus, Rogers and Monsell (1995) suggested that pure and mixed blocks might differ on dimensions like effort and arousal. Similarly, in the present paper, the notion of mental load has proved a viable candidate to be added to the set. This notion contains that the mental system is more loaded in mixed blocks than in pure blocks, due to the mere requirement to maintain readiness of all mental structures that could be called upon by either level of the independent variable. It deviates from both the stimulus-driven and the strategic view in that the load of maintaining mental structures is assumed to be static and independent of sequential order and state of preknowledge. Variations on this theme have been proposed in the literature (e.g., Ilan and Miller, 1994; Noble et al., 1981; Strayer and Kramer, 1994a,b, see also Section 2.2.1 and Section 4.2.1). It remains to be established, though, whether the mental load account has really independent significance, or only seemingly so, due to imperfections of the dissociation methods. For instance, it could be that the mental load account represents mental inertia that extends far beyond the borders of a single trial and even beyond the borders of a block (Allport et al., 1994). This could be revealed by studying longer sequences of repetitions in mixed blocks, or by analyzing performance in pure miniblocks embedded in a mixed block (Strayer and Kramer, 1994b; Los, submitted b; Rogers and Monsell, 1995). For the moment, however, all plausible factors that could be confounded by block type should be taken seriously.

It is emphasized, once more, that to disentangle the factors that are possibly confounded by block type, the methods of preknowledge and sequential order are inconclusive when applied in isolation, but powerful when applied in combination. As has been argued in Section 4.1 the weak and strong points of these methods seem to be complementary, and a clear picture may emerge only on the basis of the combined application of the methods. The great variety in patterns of results deriving from these methods underscores the importance of this conclusion. In fact, almost all possible patterns have been encountered in this paper: strong effects of preknowledge without sequential effects (as indicative for the strategic view), strong sequential effects without effects of preknowledge (as indicative for the stimulus-driven view), moderate effects of preknowledge and sequential order (indicating both strategic and stimulus-driven influences) and no effect of either of these methods (as predicted by the mental load view). Standardizing a combined application of these methods will certainly be of help in the future to disentangle the possible interpretations of mixing costs.

A final remark concerns the commonly found asymmetricity of mixing costs. This phenomenon has not received a central place in the conclusions because it is not diagnostic regarding the strategic or stimulus-driven nature of mixing costs. It leaves little doubt, however, that the phenomenon is of great importance in the development of a detailed account of mixing costs.

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