

# On the Locus of Speed–Accuracy Trade-Off in Reaction Time: Inferences From the Lateralized Readiness Potential

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Lateralized readiness potentials (LRPs) were used to determine the stage(s) of reaction time (RT) responsible for speed–accuracy trade-offs (SATs). Speeded decisions based on several types of information were examined in 3 experiments, involving, respectively, a line discrimination task, lexical decisions, and an Erikson flanker task. Three levels of SAT were obtained in each experiment by adjusting response deadlines with an adaptive tracking algorithm. Speed stress affected the duration of RT stages both before and after the start of the LRP in all experiments. The latter effect cannot be explained by guessing strategies, by variations in response force, or as an indirect consequence of the pre-LRP effect. Contrary to most models, it suggests that SAT can occur at a late postdecisional stage.

There is little doubt that people can control their perceptual, cognitive, and motor processes, as well as the communication between these processes. Some notable examples involve attention and preparation. Focusing attention can influence what perceptions guide cognition or action, and preparation can help select what cognitions or actions are so guided. Such control by individuals over their own information-processing dynamics has concerned experimental psychologists since the late 19th century. For example, Lange (1888) argued that participants in reaction time (RT) tasks can adopt either a sensorial or a motor “set” (Einstellung) depending on whether their attention is focused on the stimulus or on the response (see also James, 1890, Vol. I, pp. 92–94). That is, they may strategically emphasize either their sensory or motor processes.

One important type of control occurs under conditions in which there is an inverse relation between speed and accuracy, referred to here as a speed–accuracy trade-off (SAT). People can often control their level of SAT, that is, select or change their position along

a continuum of speed versus accuracy. Lange (1888) believed that accurate but slow performance could be achieved by adopting a sensorial set, whereas a motor set would lead to fast but inaccurate performance. Not only did SAT phenomena attract pioneers of psychology (e.g., Henmon, 1911; Lange, 1888; Woodworth, 1899), but they have remained also an active research topic up to the present. Among the contemporary work are RT studies covering a wide range of information processing, including perception (e.g., Ratcliff, 2002; Ratcliff & Rouder, 2000; Ratcliff, van Zandt, & McKoon, 1999), memory retrieval (e.g., Doshier, McElree, Hood, & Rosedale, 1989; Hacker, 1980; Hintzman & Caulton, 1997; Kounios, Montgomery, & Smith, 1994), and problem solving (e.g., Kounios & Smith, 1995).

## Models of SAT

Given the centrality of SATs to human information processing, it is not surprising that several models of RT have attempted to explain these phenomena (for a review, see Luce, 1986; Pachella, 1974; Sanders, 1998). At the most general level, these models can be divided into two classes: mixture models and accumulation models. *Mixture models* regard SAT as the result of mixing two or more types of responses, whereas *accumulation models* explain SAT through the accumulation of sensory information. Perhaps the most well-known models of the first class are the fast-guess and deadline models. The *fast-guess* model (Ollman, 1966; Yellott, 1971) assumes that participants make either a complete guess or a highly accurate stimulus-controlled response based on a complete analysis of the stimulus. In other words, guesses are sampled from a population of responses with fast RTs and chance accuracy, whereas stimulus-controlled responses are sampled from a population of highly accurate responses with longer RTs. Different levels of SAT are achieved by merely changing the proportion of these two types of responses, that is, the mixing parameter for sampling from the two distributions.

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The *deadline* model (Ollman, 1977; Ollman & Billington 1972; Swensson, 1972) postulates that participants set a deadline on each trial. If the deadline has not yet passed, they initiate a response as soon as sufficient stimulus information has accumulated to make a highly accurate response. If sufficient information has not accumulated by the deadline, they make their best guess. The mixture here consists of highly accurate responses and deadline-generated guesses, with the mixing parameter equal to the probability that stimulus processing reaches completion (or some criterion level) before the deadline. Different levels of SAT are achieved by changing the deadline. Changes in the deadline influence both the mixing parameter and the two sampled populations. Moving the deadline earlier not only increases the probability of a guess, but also results in faster guesses (which are initiated earlier) and faster accurate responses (which must be faster to beat the deadline).

The conditions under which a fast-guess or deadline model can provide a complete explanation of SAT would appear to be, at best, limited. First, according to the fast-guess model, RTs of incorrect responses should not vary with the level of speed stress (Pachella, 1974). Yet, mean RT of incorrect responses usually decreases with speed stress (e.g., Link & Tindall, 1971). Second, the deadline model implies slower incorrect responses than correct responses. Data, however, do not generally support this prediction (cf. Luce, 1986, p. 233; Ratcliff et al., 1999). Third, both models postulate guesses at chance accuracy. Meyer, Irwin, Osman, and Kounios (1988) developed a procedure for isolating guesses under speed stress and discovered that such guesses are often not at chance accuracy. Finally, Ruthruff (1996) derived a new prediction from both models regarding the shape of RT distributions and reported data violating this prediction.

The above findings can be accommodated by the second class of models, the accumulation models, which have also been able to account for SAT under a wide range of conditions. These models explain the identification or classification of stimuli through the accumulation of evidence over time and are also referred to as cumulative models (Pachella, 1974). Three prominent and related examples within this class are random walk models; the diffusion model; and the leaky, competing accumulator model. *Random walk* models have been developed to account for SAT effects in two-alternative forced-choice tasks (Laming, 1968; Link, 1975; Link & Heath, 1975; Stone, 1960). They describe the accumulation of evidence as a random walk between two thresholds as evidence is collected for the two response alternatives. At stimulus presentation, this walk starts at a certain point between both thresholds. The random walk tends to drift to the threshold associated with the correct alternative. When this random walk hits one threshold, the corresponding response will be prepared and elicited. Random walk models usually account for differences in SAT by changes in the separation of the two thresholds.

The *diffusion* model was developed by Ratcliff (1978, 1985, 1988). It can be seen as an extension of earlier versions of the random walk model, because it is a continuous variant of this model in the sense that evidence is accumulated continuously over time rather than sampled at discrete time points (cf. Luce, 1986). Relative to its predecessors, the diffusion model has explicit mathematical expressions allowing rigorous empirical tests. The diffusion model has been successfully applied to a wide range of experimental paradigms (cf. Ratcliff et al., 1999). Usher and McClelland (2001) have recently developed an accumulation

model that includes the diffusion model as a special case. Their *leaky, competitive accumulator* model assumes that perceptual information is accumulated in a gradual, leaky, stochastic, and competitive fashion. In contrast to the diffusion model, the accumulation process is subject to loss or decay of the accumulated information. Moreover, the model not only applies to a two-choice situation, but also generalizes to situations involving more than two response alternatives.

### Locus of SAT

Models of SAT seek to characterize the mechanism by which it occurs. The present article focuses on a closely related question: the locus of SAT within the information-processing system. In the context of an RT task, this concerns the stage (or stages) at which SAT occurs. Not only is this a basic theoretical question for the understanding of SAT, but it also bears on the adequacy of accumulation models. These models posit a mechanism that trades accuracy in return for time spent prior to motor processing. The savings in time precede motor processing because accumulation of evidence must reach a threshold before a response is initiated, and SAT involves changes in the level of this threshold. If changes in SAT were found to influence the duration of motor processes, current formulations of accumulation models would need to be modified. To inform these models and to enhance their further development, a better understanding of the locus of SAT within the processing stream would therefore be most useful.

Because of its theoretical importance, a number of previous studies have already sought to address this issue. For example, Swanson and Briggs (1969) found that SAT did not change the effect of memory load on RT in a stimulus-categorization task. From this result, they concluded that SAT occurs primarily at an initial stimulus-encoding stage not involved in the categorization of the stimulus. Further support for this conclusion was obtained by Briggs and Shinar (1972), who found speed stress to have a larger effect on choice RT when visual noise obscured recognition of the response signal than when the display was essentially noise free. Using the additive factors method (AFM; Roberts & Sternberg, 1993; Sternberg, 1969, 2001), Briggs and Shinar interpreted this interaction as implying an early locus of SAT, presumably at the level of stimulus encoding. Although this conclusion would seem to be consistent with accumulation models of SAT, it does not preclude the possibility that SAT can occur also at motoric stages of processing. To show that SAT is limited to premotor stages, as required by accumulation models, it is necessary to demonstrate that it does not occur at motoric stages.

One may also question whether SAT does in fact occur at an early stage of processing. Briggs and Shinar's (1972) interpretation of the interaction between speed stress and stimulus quality assumed a serial-stage model. In such a model, the output of one stage provides the input for the next, and each begins only after all preceding stages have reached completion. Given a serial-stage model, along with other ancillary assumptions, the AFM interprets interactions as being due to several factors that affect the duration of a common stage (Sternberg, 1969). There are, however, models of RT in which interactions are interpreted differently. An example with which we will be concerned later in this article is the *cascade model* (McClelland, 1979; see also Schwarz, 2003). This model assumes that each stage transmits its output continuously to the

subsequent stage in a series. Given this type of information transmission between stages, two manipulations that affect the duration of different stages can nevertheless interact in their joint effects on RT. Hence, in a cascade model, if speed stress affected the duration of a motoric stage only, it might nevertheless interact in its effects on RT with manipulations that affected the duration of perceptual stages only.<sup>1</sup>

There is yet another reason to question the conclusion that SAT operates at an early perceptual stage. Two recent studies (Osman et al., 2000; Van der Lubbe, Jaśkowski, Wauschkuhn, & Verleger, 2001) reached exactly the opposite conclusion, that is, that SAT operates exclusively at a late motor stage. This latter conclusion is difficult to reconcile with either mixture or accumulation models because both postulate an effect of SAT on premotor processes, either on their presence or on their duration. Because of the wide-reaching implications of this conclusion, the studies by Osman et al. (2000) and Van der Lubbe et al. (2001) will be described in some detail. Both studies, like our own, used a psychophysiological measure known as the lateralized readiness potential (LRP) to infer the stage (or stages) responsible for experimental effects on RT. In order to explain the basis for their conclusions, as well as the inferential procedure used in the present study, we must provide first some background about the LRP.

### LRP

As its name suggests, the LRP is believed to be related closely to the lateralized portion of the readiness potential (RP; Coles, 1989; Eimer, 1998; Eimer & Coles, 2003). The RP is a slow negative potential that precedes spontaneous voluntary movements of the distal limbs (Kornhuber & Deecke, 1965; Vaughan, Costa, & Ritter, 1968). The later part of the RP is larger over the side of the head contralateral to a moved hand. Both magnetic and intracranial recordings in humans indicate that the lateralized portion of the RP arises mainly from primary motor cortex (Ikeda & Shibasaki, 1992; Lang et al., 1991).

The LRP is measured in choice RT tasks, in which a stimulus signals that a response should be made with one of two effectors (usually the hands). Recordings are made from two electrode sites (C3' and C4') located respectively over the left and right hand areas of primary motor cortex. On every trial, the recording at the site contralateral to the signaled effector is subtracted from the recording at the ipsilateral site. The LRP is the result of this subtraction averaged across trials. Like other event-related potentials, the LRP is a waveform that represents voltage over time. Let the potentials recorded at the contralateral and ipsilateral sites at time  $t$  be denoted as  $\text{Contra}(t)$  and  $\text{Ipsi}(t)$ . The LRP at time  $t$  is then defined as  $\text{LRP}(t) = \text{Average}[\text{Contra}(t) - \text{Ipsi}(t)]$ . The resulting LRP will be negative when the response is performed with the correct (signaled) hand and positive when the response is performed with the wrong hand.

A useful property of the LRP arises from alternative definitions of time,  $t$ . The LRP can be either stimulus locked or response locked. *Stimulus locked* (S-locked) means that each point in the LRP is based on points from individual trials that follow the response signal by the same amount of time ( $t = 0$  at response signal onset). *Response locked* (R-locked) means that each point in the LRP is based on points from individual trials that precede the overt response (RT) by the same amount of time ( $t = 0$  at RT). The

interval between the response signal and S-locked LRP onset (S-LRP interval) is related to the duration of the processes that occur before the start of the LRP, and the interval between R-locked LRP onset and RT (LRP-RT interval) is related to the duration of processes that occur after the start of the LRP. By examining which of these two intervals is affected by an experimental manipulation, it is possible to determine whether the manipulation's effects on RT occur before or after the start of the LRP.

Such LRP fractionation of RT effects has proved extremely useful for mental chronometry. This usefulness stems from the fact that the lengths of the S-LRP and LRP-RT intervals can be independently manipulated (see Sternberg, 2001 on separate modifiability). Experimental manipulations have been found to affect one of the two intervals without propagating onto the other in numerous studies (e.g., Hackley & Valle-Inclan, 1999; Miller & Low, 2001; Miller, Ulrich, & Rinkenauer, 1999; Mordkoff, Miller, & Roch, 1996; Müller-Gethmann, Rinkenauer, Stahl, & Ulrich, 2000; Osman et al., 2000; Osman & Moore, 1993; Smulders, Kok, Kenemans, & Bashore, 1995; Sommer, Leuthold, & Schubert, 2001; Van der Lubbe et al., 2001). For example, Smulders et al. (1995) manipulated stimulus quality and response complexity within the same experiment and found the former to affect the S-LRP interval only, the latter to affect the LRP-RT interval only, and the combined manipulations to affect RT additively.

### SAT Effects on the S-LRP and LRP-RT Intervals

Because the S-LRP and LRP-RT intervals can be influenced selectively, they can provide evidence about which stages are responsible for an effect on RT. LRP fractionation has thus far been used to discover the locus of a wide variety of RT effects, including those resulting from stimulus intensity (Miller et al., 1999), ancillary and redundant signals (Hackley & Valle-Inclan, 1999; Mordkoff et al., 1996), number of stimulus-response alternatives (Miller & Ulrich, 1998), advance information provided by precues (Leuthold, Sommer, & Ulrich, 1996; Müller-Gethmann et al., 2000; Osman, Moore, & Ulrich, 1995), and the psychological refractory period (Osman & Moore, 1993; Sommer et al., 2001). Moreover, as mentioned earlier, it has been used to determine the locus of SATs in the two studies to which we now turn.

Osman et al. (2000) used instructions to manipulate SAT (which they referred to as the "macro-tradeoff"). Participants were en-

<sup>1</sup> To demonstrate this point, we performed a simulation of the study by Briggs and Shinar (1972) using a two-stage version of McClelland's (1979) cascade model. The first stage was assumed to represent early perceptual processes and the second stage to represent motor processes extending to just before overt response execution. Stimulus quality was assumed to affect only the activation growth rate of the early process (noise-free =  $0.008 \text{ ms}^{-1}$  and noisy =  $0.004 \text{ ms}^{-1}$ ). Speed stress was assumed to influence the level of an activation criterion applied to the second process to determine when an overt response should be triggered (low stress = 0.8 and high stress = 0.4). These assumptions yielded a simulation in which the effect of stimulus quality on RT decreased with increasing speed stress (187 ms under low stress and 94 ms under high stress). Thus, a cascade model can produce the interaction observed by Briggs and Shinar (1972) even when stimulus quality and speed stress affect different stages, with the latter involving motor processes only.

couraged to go fast on some blocks of trials and to be highly accurate on others. The experiment used a type of choice-RT task often referred to as the *flanker task* (B. A. Eriksen & Eriksen, 1974). In this task, participants were instructed to respond with their left or right hand depending on the identity of a target letter (H or S) appearing in the center of a five-letter horizontal array. Letters that flanked the target could be the same letter as the target (HHHHH or SSSSS) or the alternative letter (SSHSS or HSHSH). In line with previous studies, mean RT was shorter when the flankers matched the target with which they were presented than when they matched the alternative. The general interpretation of this finding is that participants cannot sufficiently focus their attention on the target to entirely preclude the influence of the flankers (B. A. Eriksen & Eriksen, 1974). Osman et al. (2000) found this target-flanker compatibility effect to occur solely on the S-LRP interval.

Of most relevance for the present discussion, Osman et al. (2000) found that the RT changes caused by speed stress involved only changes in the LRP-RT interval. Surprisingly, there was no effect on the S-LRP interval. That is, speed stress exclusively shortened motor processes. Osman et al. (2000, pp. 192–193) cautioned, however, that this pattern of results might be specific to their particular experimental conditions, including the type and level of speed stress, as well as the particular RT task.

Nevertheless, the same pattern of SAT effects on the S-LRP and LRP-RT intervals was found by Van der Lubbe et al. (2001) in the context of a different type of speed stress applied to different choice-RT tasks. Specifically, SAT within a choice-by-location task and a Simon task was manipulated by setting different response deadlines. In the choice-by-location task, a letter could appear on the left or right side in the display and a filler stimulus on the other side. Participants responded with their left hand when a letter appeared on the left side and with their right hand when the letter appeared on the right side. By contrast, letter identity, but not letter location, defined the response hand in the Simon task. Consistent with the bulk of RT studies on the Simon task, a clear Simon effect was obtained. That is, RT was shorter when letter side and response side corresponded than when they did not correspond. This Simon effect arose solely during the S-LRP interval. More important, and analogous to what was found by Osman et al., speed stress influenced the LRP-RT, but not the S-LRP, interval in both tasks.

Thus, two studies applying different SAT manipulations to different choice-RT tasks both found speed stress to affect the LRP-RT interval, but not the S-LRP interval. The effects on the LRP-RT interval are consistent with a motor locus of SAT, a hypothesis supported by the finding of more forceful responses under speed stress (Jaśkowski, Van der Lubbe, Wauschkuhn, Wascher, & Verleger, 2000; Jaśkowski, Verleger, & Wascher, 1994; Van der Lubbe et al., 2001). If this is true, accumulation models of SAT would need to be revised. The absence of an SAT effect on the S-LRP interval is more problematic, because it suggests the absence of the premotor locus postulated by both mixture and accumulation models.

### *Present Study*

As reviewed above, most models of SAT posit an effect of speed stress on early premotor stages of RT. The LRP results of Osman

et al. (2000) and Van der Lubbe et al. (2001), however, suggest that speed stress affects only later motor stages. Thus, these LRP results appear to be at variance with most models of SAT. For this and a number of other reasons, it may be premature to conclude just yet that SAT phenomena involve late motor processes only.

First, the SAT effects on speed and accuracy in the two studies were relatively small. A wider range of speed stress may be necessary to detect effects at premotor stages. Second, details of the RT tasks used in the two studies may have discouraged participants from trading speed for accuracy at an early stage of processing, thus forcing them to do so at later stages. The flanker and Simon tasks involve irrelevant stimuli or stimulus features that are associated with response alternatives. There is ample evidence that such stimuli or features can automatically activate the response system (e.g., Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988). Their presence may necessitate an especially thorough accumulation of information to prevent them from evoking a response (Gratton et al., 1988) or capturing attention (e.g., Folk, Leber, & Egeth, 2002; Shiu & Pashler, 1994, 1995). Thus participants may have been reluctant to adapt to increased speed stress by lowering the decision threshold applied to accumulating information. Finally, the automatic activation of the motor system by stimuli may involve a different information-processing pathway than more deliberate, controlled response selection based on information explicitly signaled by the stimulus (Kornblum, Hasbroucq, & Osman, 1990). Which of these pathways underlies task performance may influence the opportunities available for SAT.

These considerations provided part of the motivation for the present study. Like the Osman et al. (2000) and Van der Lubbe (2001) studies, the present study examined the effects of SAT on the S-LRP and LRP-RT intervals. The immediate overall goal was to determine with more confidence which of these two intervals was affected by SAT, and under what conditions. More specifically, we extended the studies of Osman et al. (2000) and Van der Lubbe et al. (2001) in several ways. First, the present experiments used several levels of speed stress covering a wide range of SAT. This was achieved by a more controlled method of speed stress that involved an adaptive algorithm for tracking target levels of accuracy. Second, SAT was examined in the context of three quite different tasks. The first task emphasized perceptual processing (Experiment 1), and the second emphasized more cognitive (linguistic) processing (Experiment 2). Both involved simple stimulus displays that varied along only a single dimension related to the responses, the one used to signal the responses. To examine the influence of automatic processing of distracter stimuli on SAT, the third task (Experiment 3) was the flanker task used by Osman et al. (2000). A further advance provided by the present study concerns a new method for removing the contribution of lucky correct guesses to the LRP (see the Appendix). This method was used to remove the contribution of guessing strategies to SAT effects on the S-LRP and LRP-RT intervals in each of the three tasks.

In sum, the current study should significantly broaden the database for inferring the locus of SAT effects. The results should allow a systematic evaluation of whether SAT operates on processes that occur before or after LRP onset. Further specification of the locus of SAT will aid in the evaluation and development of models of SAT. More broadly, identifying the stage (or stages) of information processing at which SAT can occur will aid in better



understanding an important way in which humans control their own perceptions, thoughts, and actions.

### Experiment 1

It has been assumed that in line-length discrimination tasks, the decision process is based on perceptual information (e.g., Link & Tindall, 1971; Luce, 1986). Link and Tindall (1971), for example, studied the same–different discrimination of pairs of line segments presented successively. They combined different levels of discriminability with different levels of speed stress and concluded that speed stress affects the processing of the stimulus information fed to a decision process. Therefore, to maximize the role of perceptual processes in SAT, we used a line-length discrimination task in Experiment 1.

Participants discriminated between two line segments on each trial in a two-alternative forced-choice task. A vertical line of fixed length presented in the middle of the display was divided by a horizontal line into two segments. Participants responded with one hand if the upper segment was longer than the lower segment and with the other hand if the lower segment was longer than the upper one. The vertical orientation and central location of the judged line segments were chosen to avoid LRP artifacts caused by horizontal eye movements. Three levels of speed stress were used. If SAT in this task occurs solely at the level of perceptual processing, we would expect an effect of speed stress on the S-LRP interval, but not on the LRP-RT interval.

### Method

**Participants.** Twelve participants (mean age = 27 years) were each tested individually in three 2-hr sessions. All had normal or corrected-to-normal vision and no apparent sensorimotor or neurological problems, and satisfied inclusion criteria applied to their performance and electrophysiological recordings (see *Procedure*). Each was paid 31.5 € (approximately \$39) plus an additional 22.0 to 28.0 € (\$27 to \$34) based on their performance.

**Stimuli, behavioral responses, and trial events.** Stimulus presentation and the acquisition of behavioral responses were controlled by a PC. Visual stimuli were presented on a 15-inch (38.1-cm) monitor located 70 cm in front of the participant. Each trial began with the appearance of a white fixation point (40 cd/m<sup>2</sup>) at the center of the computer screen (0.06 cd/m<sup>2</sup>). This point was replaced after 500 ms by the warning signal, which consisted of a white horizontal line (4.4 mm, 40 cd/m<sup>2</sup>). The response signal was a vertical line (23 mm, 40 cd/m<sup>2</sup>) bisecting the horizontal line. The time interval between the onsets of the warning and the response signal was 500 ms. The vertical line was displayed for 50 ms, with its midpoint either slightly (1.8 mm) above or below the horizontal line. The participant's task was to indicate the vertical position of the response signal relative to the warning signal. Half of the participants responded with the left index finger when the vertical line segment above the horizontal line was longer than the segment below and with the right index finger when the segment below was longer. For the other half of the participants, this stimulus–response assignment was reversed. Response force was measured with force-sensitive response keys.

Trial feedback was provided 1,450 ms after the offset of the response signal. In each trial, one of six possible messages appeared in the center of the screen: (a) If the response was correct and the corresponding RT was shorter or equal to a certain deadline (see below), the expression “sehr gut” (very good) appeared in the center of the screen. (b) By contrast, the feedback message “zu langsam” (too slow) was presented if the RT was longer than this deadline and the response was correct. In case of a wrong response, the participant received either (c) the message “falsche Taste”

(wrong key) when the response was fast enough or (d) the message “zu langsam, falsche Taste” (too slow, wrong key) if it was too slow. (e) The message “Nur eine Taste drücken” (press one key only) appeared if both keys had been pressed. (f) Anticipations resulted in the error message “Bitte auf das Signal warten” (please wait for the signal). In addition to this feedback, RT and the required deadline were also presented after each trial.

**Design.** Participants were tested in 12 blocks of 80 trials each during each of three experimental sessions. Trials requiring left- and right-hand responses occurred equally often within each block and in a random order. The mapping between the two response hands and the two response stimuli remained the same throughout the experiment for each participant and was counterbalanced across participants. On any given block, a participant was placed under one of three levels of speed stress (low, medium, or high). The 12 blocks in a session were divided into four groups of 3 consecutive blocks. Except for the initial group during the first session (see *Procedure*), each group of 3 blocks consisted of 1 block tested under each level of speed stress. Each participant received the same order of speed-stress conditions for each group within all sessions. A Latin square was used to counterbalance the order of speed-stress conditions across participants.

**SAT tracking algorithm.** The three levels of speed stress were distinguished by the RT deadlines that participants tried to beat. The deadlines for each speed-stress condition were determined by a tracking algorithm, which was applied separately for each participant in each speed-stress condition. The algorithm was set to track deadlines producing 97.5%, 82.0%, and 66.0% accuracy, respectively, in the low, medium, and high speed-stress conditions. Each block of trials used a single fixed RT deadline, which depended on (a) the deadline on the previous block in which the participant had experienced the same nominal speed-stress condition, and (b) the participant's accuracy on that previous block. The deadline was adjusted upward or downward by a fixed amount or remained the same, depending respectively on whether the participant had performed at 2.5% or more below target accuracy, 2.5% or more above target accuracy, or within  $\pm 2.5\%$  of the target accuracy. The deadlines were adjusted by a step size of 30 ms during the first session and by a step size of 15 ms during the second and third sessions.

**Procedure.** The first three blocks of the first session were used to estimate the initial RT deadline for each participant. These blocks also provided the opportunity to familiarize the participant with the spatial discrimination task and the speed–accuracy emphasis typically used in RT tasks. The deadline for the first block was set at 1,000 ms, so as to exceed all reasonable RTs. The deadline for the second block was set at the 95th RT percentile for correct responses in the first block, and the deadline for the third block was set at the 95th RT percentile for correct responses in the second block.

The remaining nine blocks of the first session consisted of three groups of consecutive blocks, each group involving one block at each level of speed stress (see *Design*). The initial deadline values used for each level of speed stress in Blocks 4 through 6 were based on the RT distribution for correct responses in Block 3. The 95th, 64th, and 32nd RT percentiles were arbitrarily selected, on the basis of a deadline model,<sup>2</sup> as rough initial

<sup>2</sup> According to the deadline model, the probability  $p_c$  of a correct response in a speeded two-alternative forced-choice situation is computed as  $p_c = p + 0.5 \times (1 - p)$ , where  $p$  is the probability that the response is stimulus controlled. Thus the  $p$ th RT percentile in the low speed-stress condition provides an estimate for  $p$  if we proceed from the plausible assumption that approximately all responses are stimulus controlled in this condition. So, when the deadline is equal to the 64th RT percentile in the low speed-stress condition, the model predicts  $p_c = 0.64 + 0.5 \times (1 - 0.64) = 82\%$  correct responses in the medium speed-stress condition if this deadline is used. Analogously, a deadline associated with the 95th RT percentile would yield  $p_c = 97.5\%$  correct responses, and another associated with the 32nd RT percentile would yield  $p_c = 66\%$ .

estimates of deadlines that might yield levels of accuracy close to those tracked in the low, medium, high speed-stress conditions.

Participants' performance during the last six blocks of Session 1 was used to determine whether they were invited to participate in the remaining two sessions of the experiment. For further inclusion in the study, participants' performance needed to satisfy the following four criteria:

1. Their RTs of the correct or incorrect hand beat the deadline at least 75% of the time in each speed-stress condition.
2. The responses that beat the deadline were at least 59% accurate in the high speed-stress condition, at least 75% accurate in the medium speed-stress condition, and at least 90% accurate in the low speed-stress condition.
3. The response force on only one response key exceeded criterion force (i.e., one and only one manual response) on at least 95% of the trials in each speed-stress condition.
4. A robust LRP could be detected on the basis of recordings from all 12 blocks.

The last criterion was based on a single R-locked LRP calculated from all trials (approximately 960) on which a single manual response occurred (with "left" and "right" defined by the responding hand). The criterion for inclusion was an LRP amplitude larger than 1  $\mu$ V. One participant failed to meet Criterion 4 and was thus replaced.

**Payoffs and feedback.** In addition to their base pay (10.5 € per session), participants received a bonus based on their performance. The bonus was incremented after each block, according to the formula: payment =  $A \times B \times C$  €. Here, A is the number of "good" trials during the previous block, that is, trials on which only a single key press occurred and the RT beat the deadline. B indicates the proportion good trials that were correct minus chance (0.5), and C indicates the pay scale for the level of speed stress under which the block was performed. The pay scale for all participants was 0.02, 0.04, and 0.07 € for the low, medium, and high speed-stress conditions. These pay scales were chosen so that participants would earn approximately the same bonus in each condition.

After each block, participants viewed a feedback page on the monitor screen. The page contained the bonus formula with the name and value of each term indicated. Also presented on the feedback page were the following statistics for all trials, excluding warm-up trials and error trials with double key presses on the previous block: (a) mean RT, (b) the number of RTs that failed to beat the deadline, (c) the number of trials with an incorrect response, and (d) the number of trials with responses that were both incorrect and failed to beat the deadline. A further statistic reported the number of trials on which either two responses or no response occurred.

**Instructions.** Before the first block of the first session, the line discrimination task was explained and participants were instructed how to produce the requisite amount of force to register a response on the force keys. They were told to respond on each trial as soon as they knew the response hand. The bonus formula was explained shortly after the participants had viewed the block feedback page for the first time. It was explained that, to maximize the bonus, they needed to maximize the number of trials with a single correct key press that beat the deadline. It was also explained that, for the moment, the deadline was set quite late, so that the optimum strategy was to concentrate on accuracy.

Just before the second block, participants were instructed about eye movements and eye blinks. They were first told about the negative effects of the resulting artifacts on electrophysiological recordings. They were then asked to fixate on the center of the screen during each trial and to avoid blinks and eye movements while this location was occupied by the fixation point, warning signal, or response signal (i.e., from the beginning of each trial until trial feedback occurred). They were advised to make any necessary blinks or eye movements during the 2,500-ms period between

feedback onset and the beginning of the next trial (i.e., during the intertrial interval).

After the first three blocks (all involving low speed stress), the concept of SAT was explained. Participants were told that before each of the remaining blocks, they would be asked to perform that block at one of three levels of speed stress, referred to as "accurate," "moderate speed-stress" and "high speed-stress." Before their first block with moderate or high speed stress, participants received further information about the consequences of different strategies. They were told that if they made complete guesses, they could always beat the deadline, but would be at chance accuracy. Alternatively, if they responded slowly enough to always be correct, they might never beat the deadline. Thus, performing at either extreme of the SAT would minimize the bonus.

Participants were then provided with the following advice (in German):

To make money on speeded blocks, you must find a middle way between these two extreme strategies. You need both to beat the deadline, as well as respond above chance accuracy on trials that beat the deadline. This is not easy, and it will certainly require some learning and practice. Precisely what you do is up to you. That's what this experiment is supposed to find out: how people trade between speed and accuracy.

**Psychophysiological recording.** Before each session, Ag-AgCl electrodes were attached to the participant's head to record electroencephalographic (EEG) and electrooculographic (EOG) activity on each trial. These signals were amplified by an SA Instrumentation (San Diego, CA) system and sampled at 100 Hz. EEG was recorded unipolarly from lateral electrode sites C3' and C4' (4 cm to the left and right of the vertex along the interaural line) and referenced to the right mastoid.<sup>3</sup>

Vertical EOG was recorded bipolarly from sites above and below the midpoint of the right eye, and horizontal EOG (hEOG) was recorded bipolarly from sites 2 cm external to the outer canthus of each eye. EEG, vertical EOG, and hEOG activity was filtered online with a bandpass (butterworth type,  $-12$ dB/octave) of 0.01 to 30.00 Hz. The impedance was below 5 k $\Omega$  for all EEG and EOG recordings. The recording epoch on each trial was 3 s, beginning 200 ms before the fixation point and lasting until 1,800 ms after the response signal.

**RT measurement.** The force-time function of each hand was recorded in each trial with a sampling rate of 100 Hz. Two force keys allowed for the near-isometric measurement of the flexion of each of the two index fingers. Each force key consisted of a leaf spring (55 mm long  $\times$  20 mm wide  $\times$  2 mm thick) held at one end by a clamp, with a strain gauge attached near the clamped end. Each force key was mounted on a board. The effective sensitivity of the force keys was 1.7 cN (about 1.7 g). At the beginning of each session, participants were asked to put their relaxed index fingers on the force keys to estimate the baseline force. The onset of the response was scored as soon as force exceeded a criterion of 50 cN above baseline force. The participants' forearms and palms rested comfortably on the table such that any body movements other than index finger movements were minimized. The index fingers were pointed out, each attached to a force key by an adjustable thimblelike holder mounted horizontally near the free end of the leaf spring. Response force for each hand was recorded on each trial. These recordings are considered in detail, but are discussed briefly in the General Discussion.

**Data reduction and analysis.** As mentioned, performance during the first 3 blocks of the first session was used to estimate the initial RT deadline for each the speed condition. Blocks 4–6 of the first session and Blocks 1–3 of the second and third session served as practice. Data from these 12 blocks was excluded from further analysis. Thus, the results to be

<sup>3</sup> We also recorded EEG from midline sites Fz, Cz, and Pz (International 10–20 System, Jasper, 1958). Because these recordings were not used to infer the locus of SAT, they are not reported here.

reported here were based on Blocks 7–12 of Session 1 and Blocks 4–12 of Sessions 2 and 3 for each participant. In sum, then, there were 24 blocks, or a total of 640 trials, per speed condition (8 blocks  $\times$  80 trials) for each participant.

Both mean RT and the percentage of correct responses were calculated for each participant and condition. RT was defined as the interval between response-signal onset and the moment force that exceeded the response criterion. RTs shorter than 100 ms were defined as anticipations, and RT longer than 1,000 ms as misses; such trials and trials with bimanual responses were discarded from data analysis. Finally, trials with eye blinks and eye movements were also excluded from data analysis; a threshold of 50  $\mu$ V in all EOG channels was chosen for artifact rejection.

Baselines were computed for each trial to adjust the recordings from each individual electrode site. Before averaging, each recording was adjusted by subtracting the baseline voltage from all time points. For S-locked averaging, the baseline corresponded to the mean voltage during the 200-ms interval preceding the response signal. For R-locked averaging, it corresponded to the mean voltage during the interval 600 to 400 ms before response onset.

As mentioned in the introduction, the LRP was determined by averaging the mean waveforms at C3' and C4' in a standard manner (Coles, 1989; De Jong, Wierda, Mulder, & Mulder, 1988). For each condition, the difference between contralateral and ipsilateral activity was computed (i.e., C3' minus C4' for trials in which the right-hand response was correct, and vice versa for correct left-hand responses). Both differences were then averaged to compute the LRP. The signals were time-locked either to the stimulus or to the response to compute the S-LRP and the LRP-RT, respectively (Osman & Moore, 1993). The averaged LRP waveforms were filtered (4 Hz low pass) before their onsets were estimated. The jackknife method (Miller, Patterson, & Ulrich, 1998) and its extension to factorial designs (Ulrich & Miller, 2001) were used to evaluate potential experimental effects on LRP onsets. As recommended by Miller et al. (1998), the onset for the S-LRP (LRP-RT) was defined as the point in time when a criterion of 50% (30%) of the amplitude was reached.

Usually, 60 trials per condition and participant are sufficient to compute a stable LRP waveform (e.g., Miller et al., 1998). Although the mean waveform is an unbiased estimator, the signal-to-noise ratio of this estimator increases with the number of trials used to compute the average waveform. Because the number of trials varies with speed condition, the highest signal-to-noise ratio occurs in the low-speed condition. Nevertheless, the number of trials contributing to the average waveform was always much larger than 60, even in the high-speed condition.

Horizontal EOG was computed in a manner analogous to that of the LRP in order to assess the contribution of possible eye-movement artifacts to the observed LRPs. Such artifacts may arise when there is a tendency for eye movements toward the responding hand. Specifically, eye movements correlated with the responding hand may mimic LRP activity.<sup>4</sup> In contrast, vertical EOG (caused mainly by eye blinks) does not systematically affect LRP recordings. Nevertheless, we discarded trials with either horizontal or vertical eye movements from data analysis in order to increase the signal-to-noise ratio of the EEG recording. Because vertical eye movements do not systematically influence the LRP, we only report waveforms of the hEOG.

All probability values obtained from the repeated measures analyses of variance (ANOVAs) were adjusted with the Greenhouse–Geisser correction (Huyhn, 1978) for violations of the sphericity assumption. The significance level was set at .05 throughout this study. For post hoc comparisons, 95% halfwidth intervals (HWI) of Scheffé's test were computed. A one-way factorial ANOVA with the factor speed stress was performed for the dependent measures. The three levels of speed stress were low (LS), moderate (MS), and high (HS). Finally, partial  $\eta^2$  is reported as a measure of effect size for all significant ANOVA results.

## Results

The measures to be reported include RT, accuracy, the S-LRP interval, the LRP-RT interval, and hEOG. Each was obtained separately for each participant in each condition. The RT and accuracy results allow us to assess the SAT induced by the speed-stress manipulation. The effects of speed stress on the S-LRP and LRP-RT intervals provide evidence concerning the locus of SAT within the information-processing system. We used hEOG to evaluate the possible effect of eye-movement artifacts on the LRP.

*Excluded trials.* All trials with eye movements (25.0%), anticipations (0.3%), misses (0.3%), and responses with both hands (2.1%) were discarded from the analysis. The percentage of eye movements did not vary with speed stress,  $F(2, 22) = 1.9, p = .17$ ; LS = 22.9%, MS = 25.8%, and HS = 25.8%. The mean number of trials remaining after trials with eye movements, anticipations, misses, or responses with both hands were excluded was LS = 488, MS = 461, and HS = 456. Note that the trials remaining in each speed-stress condition were composed both of trials on which the response was made with the correct hand and trials on which the response was made with the incorrect hand. These latter two types of trials, which consist only of trials not excluded, are referred to as *correct response trials* and *incorrect response trials*, respectively.

*RT and accuracy.* A strong SAT effect was observed. The mean RT for correct responses decreased with speed stress,  $F(2, 22) = 127.5, p < .001, \eta^2 = .92$  and was accompanied by an increase in the number of incorrect responses,  $F(2, 22) = 209.4, p < .001, \eta^2 = .95$ . The mean RT was LS = 434 ms, MS = 368 ms, and HS = 321 ms (HWI = 18.7 ms), and the mean percentage of incorrect responses was LS = 4.1%, MS = 15.7%, and HS = 27.8% (HWI = 3.0%). These latter percentages are based on the number of nonexcluded trials with an incorrect response divided by the total number of nonexcluded trials and are close to the intended targets of the tracking algorithm (error rates of 2.5%, 18.0%, and 34.0%). In contrast to what would be predicted by the fast-guess model, mean RT for incorrect responses decreased with speed stress,  $F(2, 22) = 62.3, p < .001, \eta^2 = .85$ ; LS = 419 ms, MS = 321 ms, and HS = 278 ms (HWI = 43 ms). In contrast to what would be predicted by the deadline model, RT was faster for incorrect responses (339 ms) than for correct (374 ms) responses,  $F(1, 11) = 44.5, p < .001, \eta^2 = .80$ .

*S-locked LRP.* The average S-locked LRP for correct responses in each speed-stress condition is shown in the upper panel of Figure 1. Analysis with the jackknife-based scoring method revealed a significant effect of speed stress on the S-locked LRP onset latency,  $F(2, 22) = 33.2, p < .001, \eta^2 = .75$ . This latency was LS = 293 ms, MS = 264 ms, and HS = 228 ms. A modified Scheffé's test (Ulrich & Miller, 2001) for LRP latency yielded a

<sup>4</sup> Because the retina is more negative than the cornea, looking to one side produces a lateral shift in electrical potential across the head. Through volume conduction, recordings at lateral scalp sites can be systematically contaminated by ocular potentials. In fact, voltage-topography studies have shown that about 20% of the hEOG activity propagates to lateral central sites (e.g., Elbert, Lutzenberger, Rockstroh, & Birbaumer, 1985).



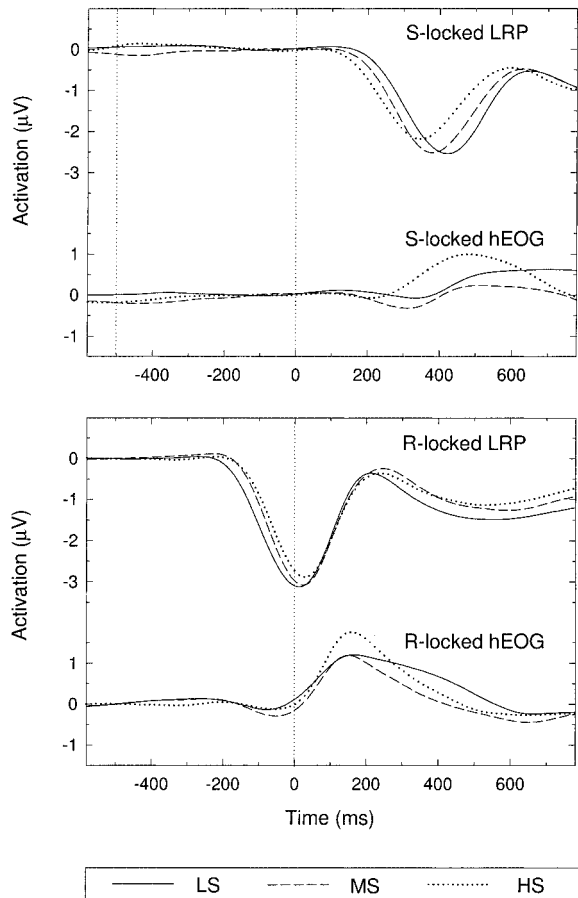


Figure 1. Grand average stimulus-locked (S-locked; upper panel) and response-locked (R-locked; lower panel) lateralized readiness potential (LRP) and grand average stimulus-locked (upper panel) and response-locked (lower panel) horizontal eye movements (hEOG) as a function of speed stress in Experiment 1. LS = low speed stress; MS = moderate speed stress; HS = high speed stress.

corrected HWI of 21 ms, suggesting that all latencies differed significantly from each other.<sup>5</sup>

**R-locked LRP.** The lower panel in Figure 1 depicts the R-locked LRP waveforms for correct responses. Speed stress produced a significant effect on the LRP-RT interval,  $F(2, 22) = 18.6$ ,  $p < .001$ ,  $\eta^2 = .63$ ; LS = -135 ms, MS = -109 ms, and HS = -101 ms. This effect indicates that speed stress also shortens processes after LRP onset. A post hoc analysis revealed that the LRP-RT interval between LS and MS and between LS and HS differed significantly (HWI = 15 ms). In conclusion, then, speed stress shortened the duration of processes not only before, but also after, the onset of the LRP.<sup>6</sup> The effect of speed stress on the LRP-RT interval saturated when speed stress attained a medium level. Such saturation, however, was not obtained for the S-LRP interval.

**Horizontal EOG.** We analyzed the hEOG to assess whether the effects of speed stress on the LRP could have been due to eye movements. Therefore, the hEOG was computed in exactly the same way as the LRP. The resulting hEOG waveforms are depicted in Figure 1 beneath the LRP waveforms in each panel. As

can be seen, the hEOG did not systematically vary with speed stress. In addition, hEOG activity started clearly, if at all, after the onsets of the LRP waveforms. The amplitudes of the hEOG waveforms were no more than about  $1 \mu\text{V}$ . Because approximately 20% of hEOG activity propagates to the C3' and C4' sites, its possible contribution to the observed LRP was  $0.2 \mu\text{V}$  or less. To assess whether hEOG activity differed from baseline, we calculated the averaged amplitude for the S-locked waveforms in the range from 0 to 300 ms after stimulus onset and for the R-locked waveforms in the range from -200 to -50 ms before response onset. Neither the averaged S-locked hEOG amplitude,  $F(1, 11) < 1$ , nor the averaged R-locked amplitudes,  $F(1, 11) < 1$ , differed significantly from baseline. Therefore, it seems unlikely that horizontal eye movements contaminated the LRP onset latencies.

### Discussion

The objective of Experiment 1 was to locate the SAT effect on RT in a perceptual discrimination task. Participants had to decide between the lengths of two line segments and to indicate their decision with either the left or right hand. The SAT manipulation required participants to control the speed of their responses in order to beat a deadline while maintaining as high a level of accuracy as possible. Three levels of speed stress were used, each involving a different deadline. The deadline at each level was determined individually for each participant by a tracking algorithm. This algorithm produced a strong SAT effect on RT and accuracy. Three virtually equidistant levels of accuracy, close to those intended, were obtained. To examine SAT effects on the duration of both motor and premotor stages, we measured the S-LRP and LRP-RT intervals at each level of speed stress.

The S-LRP interval was shortened by speed stress, which suggests an early premotor locus of SAT. The S-LRP differed between the LS and MS conditions and between the MS and HS conditions. These S-LRP findings support the hypothesis that SAT occurs at an early stage of processing, as is assumed by the majority of SAT models. These findings are what one would expect if speed stress shortens the decision process and the LRP does not begin before this process has finished. They are in line with accumulation models, because such models posit that SAT is controlled by

<sup>5</sup> Because the mean number of trials for incorrect hand responses was insufficient, it was not possible to obtain stable estimates of the LRP waveforms for these responses. Thus these data are not reported.

<sup>6</sup> Some may wonder why the SAT effect on mean RT was larger than the sum of the SAT effects on the S-LRP and LRP-RT intervals. For example, mean RT decreased by 66 ms from LS to MS, whereas the sum of the S-LRP and LRP-RT intervals decreased by only 55 ms (29 and 26 ms, respectively). A direct comparison of effect sizes on mean RT and parameters of an average ERP waveform is problematic for several reasons. Among these is trial-by-trial variability in the latency of ERP components, which causes a temporal smearing of the components observed in waveforms averaged over trials. Because of this smearing, the onset latency of an ERP component in an average waveform is not equivalent to the mean onset latency of the components on individual trials, but instead is biased toward the minimum (Meyer, Osman, Irwin, & Yantis, 1988). Recall also that the S-LRP interval is measured from the average of S-locked waveforms, whereas the LRP-RT interval is measured from the average of R-locked waveforms. The sources of latency variability that contribute to temporal smearing are different for the two types of average waveform.



adjusting a decision criterion applied to accumulating information and that this criterion must be reached before motor processing can begin. An early locus of SAT is also predicted by fast-guess and deadline models, because both attribute the effects of speed stress to an increase in the proportion of guesses. The perceptual and decision processes required to make a response should be either missing or abbreviated in a guess.

Speed stress also shortened the LRP-RT interval, a finding also reported by Osman et al. (2000) and Van der Lubbe et al. (2001). This finding suggests that not only premotor, but also motor, processes were shortened by speed stress. Because a guess could plausibly involve shorter motor processes than a more considered response, this finding is not incompatible with fast-guess or deadline models. It is, however, troublesome for accumulation models as currently formulated, because these models posit that SAT occurs only at the level of premotor decision processes.

There are at least two possible classes of explanation of how speed stress could have affected the LRP-RT interval. One class involves a direct influence on the duration of postdecision processes. For example, Osman et al. (2000) suggested that participants may select one response alternative after a tentative decision (thus producing an LRP) and then recheck the selected response. Slow, but accurate, performance would result when the final execution of the response was withheld until rechecking was completed. Speed stress would shorten the LRP-RT interval and decrease accuracy by inducing participants to skip or reduce rechecking. Another explanation within this class holds that speed stress induces advance motor preparation in addition to changes in the decision criterion. Such advance motor preparation could shorten the duration of postdecision processes and thus the LRP-RT interval (Leuthold et al., 1996; Sanders, 1998).

Direct effects of speed stress on the speed and/or accuracy of postdecision processes do not preclude similar effects on decision processes. Thus, this class of explanation is not necessarily incompatible with the basic notion of accumulation models, wherein SAT occurs at the level of an encapsulated decision process. Such explanations of the observed effects of speed stress on the LRP-RT interval merely require that accumulation models be extended to accommodate additional effects on postdecisional processes.

The second class of explanation is more difficult to reconcile with accumulation models. This class holds that speed stress influences postdecision processes, but only indirectly, through a direct effect on decision processes. Models that involve a cascade-like information-processing stream (e.g., C. W. Eriksen & Schulz, 1979; Grice, Nullmeyer, & Spiker, 1982; McClelland, 1979) would allow such indirect effects. A decision process conceived within the framework of these models could, from its start, continuously activate the motor system. An LRP would arise early in the course of motor system activation, and an overt response would be emitted when this activation reached a fixed criterion (Coles, 1989; McClelland, 1979). A direct effect of speed stress on the rate of processing within the decision stage could then propagate to the motor stage, thus indirectly influencing its duration (see Miller et al., 1999, p. 1456, for a similar line of reasoning). The result would be to shorten the LRP-RT interval, even if there were no direct effect of speed stress on motor processes.

Figure 2 illustrates an indirect-influence account derived from a two-stage version of McClelland's (1979) cascade model (cf. Ulrich, Mattes, & Miller, 1999, pp. 68–72). The first stage can be

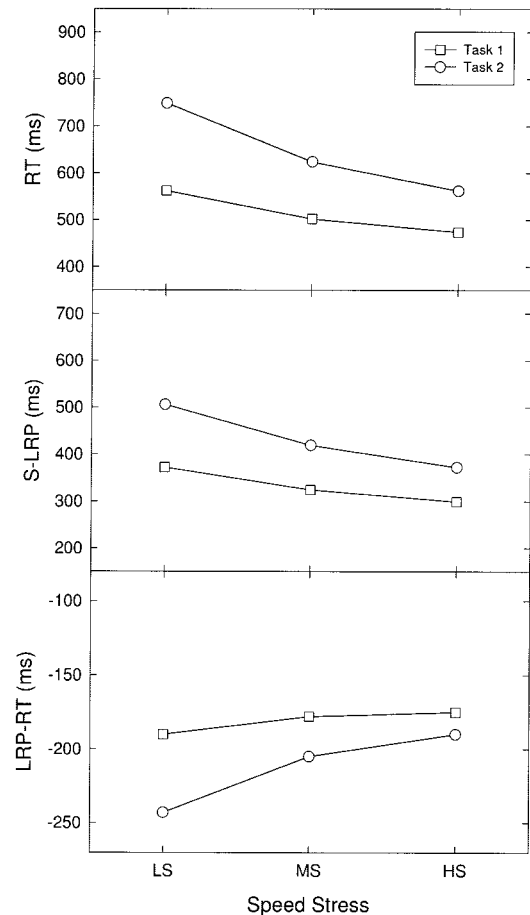


Figure 2. Predictions of the cascade model for mean reaction time (RT; upper panel), mean stimulus-lateralized readiness potential (S-LRP) interval (middle panel), and mean LRP-RT interval (lower panel) as a function of speed stress and task. Task 1: The growth rates for the first stage were 0.008, 0.012, and 0.016  $\text{ms}^{-1}$  for low, moderate, and high speed stress (LS, MS, and HS), respectively. Task 2: The growth rates for the first stage were 0.004, 0.006, and 0.008  $\text{ms}^{-1}$ , respectively. The growth rate for the second stage was 0.004 for both tasks and all speed conditions. The response criterion for RT was set to 80% of asymptotic activation of the second stage, whereas the LRP threshold was set to 60% of asymptotic activation.

thought of as comprising premotor processes (perceptual and decision processes), and the second stage as involving motor processes. The growth rate of activation for the first stage increased with speed stress, whereas the growth rate of the second stage did not. Shown in Figure 2 are predictions for two tasks that differ only in overall growth rate of the first stage. Specifically, its overall growth rate is faster in Task 1 than in Task 2. The upper panel shows predicted RT as a function of speed stress and task. As to be expected, RT decreases with increasing speed stress. The panel in the middle depicts the predicted S-LRP interval as a function of speed stress and task. Like RT, this interval becomes shorter as speed stress is increased. Most important for present purposes are the predicted LRP-RT intervals, which are shown in the bottom panel. Though the growth rate of the motor stage was kept constant in all conditions, LRP-RT interval was nevertheless indirectly

influenced by the direct effect of speed stress on the growth rate of the premotor stage. In addition, the cascade model predicts that this indirect effect becomes amplified when speed stress directly affects relatively slow premotor processes (as for Task 2 compared with Task 1).

In conclusion, effects of speed stress were observed in Experiment 1 on both the S-LRP and LRP-RT intervals. The effect on the S-LRP interval is consistent with both mixture and accumulation models, whereas the effect on the LRP-RT interval is somewhat problematic for accumulation models. Two alternative classes of explanation for the LRP-RT effect were discussed. They differed with respect to whether speed stress directly affects the duration of motor processes or instead produces an indirect effect by means of premotor processes.

## Experiment 2

This second experiment was motivated by two goals. The first was to see whether the results obtained in the previous experiment would generalize to a more cognitively oriented task. In Experiment 1, the decision processes were based on perceptual information. The present experiment involved a decision based on information from a lexical retrieval process. Specifically, on each trial, a German noun was presented and participants had to judge the gender of the noun. Each noun was either masculine or feminine. A speeded decision on the gender of the noun was required, and was made by pressing one of two buttons.

Second, we assumed that the present task is more complex than the one in the previous experiment. This assumption is supported by neuroimaging studies of cerebral activation in word processing (for a review, see Levelt, 2001), which suggest that such tasks involve several distinct neural processes besides those involved in a visual discrimination task (e.g., Yaguchi et al., 2000). We therefore expected that the decision process would be slower in the present task than in the previous one. That is, the accumulation of information from the lexical retrieval process would proceed at a slower rate than the accumulation of perceptual information in Experiment 1. If the effect of speed stress on the LRP-RT interval reflects an indirect effect on the duration of motor processes, caused within a cascadelike processing architecture by direct effects on the rate of an earlier decision process, it should be larger in Experiment 2 than in Experiment 1 (see Figure 2). By contrast, if speed stress influences postdecision processes directly, then a similar-sized effect on the LRP-RT interval would be expected.

## Method

The method was identical to that of Experiment 1, with a few exceptions described below.

**Participants.** A fresh sample of 12 students was tested (mean age = 25.4 years). As in Experiment 1, all had normal or corrected-to-normal vision and no apparent sensorimotor or neurological problems, and satisfied inclusion criteria applied to their performance and electrophysiological recordings. Two participants were replaced because their LRP amplitude was less than 1  $\mu$ V and because of too many eye movements.

**Stimuli.** The response signal was a noun consisting of three, four, five, or six letters approximately 8.6 mm in height. On each trial, a noun was randomly drawn without replacement from a sample of 480 masculine and 480 feminine words. This sample was selected from a large corpus of approximately 10,000 nouns provided by the Institute for the German

Language in Mannheim (*Mannheimer Korpus 2*, n.d.). Words that are ambiguous with respect to their gender were eliminated from the sample (e.g., *der/die See*). Words that are identical in singular and plural were also eliminated (e.g., *der/die Kuchen*). Feminine and masculine words were selected from this reduced sample such that word length was matched for both classes. Thus, the final sample contained a total of 15 words of three letters, 82 words of four letters, 199 words of five letters and 184 words of six letters for each gender. Stimulus duration was slightly increased to 100 ms to allow sufficient time for reading.

## Results

First, we present the results of Experiment 2 to assess the generality of the findings from Experiment 1. We then compare the results of both experiments to determine whether speed stress exerts a direct or indirect effect on postdecision processes.

**Excluded trials.** The number of trials excluded was similar to that in Experiment 1. Eye movements were observed on 24.0% of all trials, anticipations on 0.1%, misses on 0.2%, and responses with both hands on 0.9%. Consistent with Experiment 1, the percentage of eye movements did not vary with speed stress,  $F(2, 22) = 0.9$ ,  $p = .36$ ; LS = 25.1%, MS = 24.0%, and HS = 22.4%. After excluding these trials, the mean number of trials remaining was LS = 476, MS = 482, and HS = 491, which is similar to that in Experiment 1.

**RT and accuracy.** As expected, the overall mean RT for correct responses was longer in this experiment than in the previous one (622 vs. 374 ms), and a strong SAT was obtained. Mean RT for correct hand responses decreased with speed stress,  $F(2, 22) = 126.7$ ,  $p < .001$ ,  $\eta^2 = .92$ , whereas the percentage of incorrect hand responses increased,  $F(2, 22) = 93.7$ ,  $p < .001$ ,  $\eta^2 = .89$ . The tracking algorithm again produced three levels of accuracy close to those intended and thus close to those obtained in Experiment 1. The mean percentage of incorrect hand responses was LS = 4.7%, MS = 13.6%, and HS = 24.2% (HWI = 3.7%). The mean RT for correct hand responses was LS = 726 ms, MS = 612 ms, and HS = 528 ms (HWI = 33 ms). Consistent with Experiment 1, speed stress also shortened the RT for errors  $F(2, 22) = 83.3$ ,  $p < .001$ ,  $\eta^2 = .88$ ; LS = 779 ms, MS = 611 ms, and HS = 490 ms (HWI = 59 ms). In contrast to Experiment 1, mean RT for incorrect responses (626 ms) did not differ significantly from mean RT of correct responses (622 ms),  $F(1, 11) = 0.4$ ,  $p = .53$ .

**S-locked LRP.** Figure 3 depicts the average S-locked LRP for correct responses in each speed-stress condition. A jackknife-based analysis identical to that in Experiment 1 revealed a significant effect of speed stress on the S-LRP interval,  $F(2, 22) = 21.5$ ,  $p < .001$ ,  $\eta^2 = .66$ ; LS = 514 ms, MS = 462 ms, and HS = 408 ms. The modified Scheffé's test suggests that all S-LRP intervals differed significantly from each other (HWI = 42 ms). As expected, the overall mean S-LRP interval was longer in this experiment than in the previous one (462 vs. 262 ms).

**R-locked LRP.** R-locked LRP waveforms for correct responses are shown in the lower panel of Figure 3. Speed stress again produced a significant effect on the LRP-RT intervals,  $F(2, 22) = 20.0$ ,  $p < .001$ ,  $\eta^2 = .65$ ; LS = -133 ms, MS = -109 ms, and HS = -102 ms. Thus, as in Experiment 1, speed stress shortened the duration of the processes after the LRP onset. Indeed, the LRP-RT intervals were virtually identical to those in Experiment 1. Effects of speed stress on this interval once again saturated at high levels. Post hoc analysis revealed that the LRP-RT interval

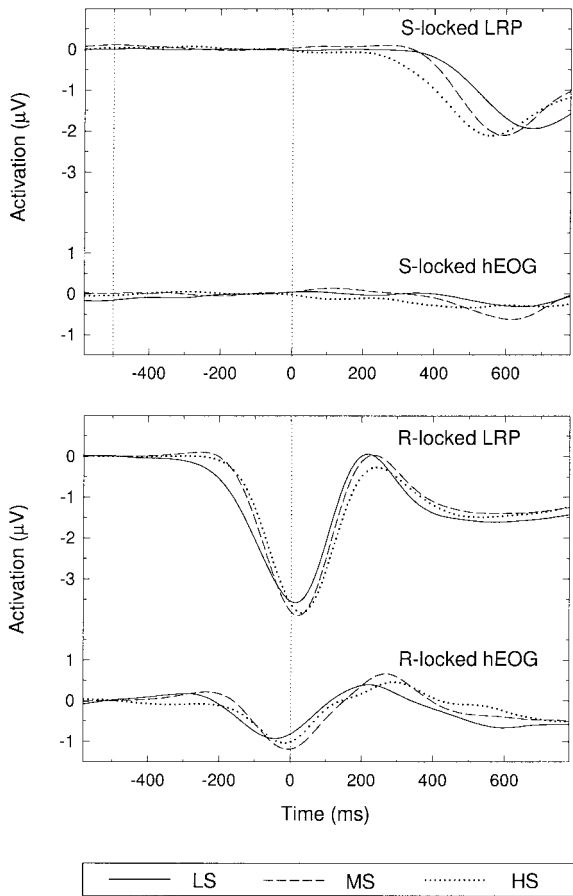


Figure 3. Grand average stimulus-locked (S-locked; upper panel) and response-locked (R-locked; lower panel) lateralized readiness potential (LRP) and grand average S-locked (upper panel) and R-locked (lower panel) horizontal eye movements (hEOG) as a function of speed stress in Experiment 2. LS = low speed stress; MS = moderate speed stress; HS = high speed stress.

differed significantly between LS and MS, but not between MS and HS (HWI = 13 ms).

*hEOG.* Figure 3 also depicts the hEOG activity. The amplitude of the S-locked hEOG waveform (upper panel) differed significantly from baseline hEOG in the range from 250 to 550 ms after stimulus onset,  $F(1, 11) = 7.7, p = .02, \eta^2 = .41$ . Nevertheless, speed stress affected neither the amplitudes of these waveforms  $F(2, 22) = 1.1, p = .34$ , nor their onsets,  $F(2, 22) = 1.5, p = .26$ . The averaged amplitude of the R-locked hEOG waveforms (lower panel) differed significantly from baseline hEOG in the range from -200 to -50 ms before response onset,  $F(1, 11) = 5.9, p = .03, \eta^2 = .35$ . Yet neither the amplitudes,  $F(2, 22) = 1.2, p = .31$ , nor the latencies ( $F < 1$ ), of these waveforms were affected by speed stress. Thus it seems unlikely that the effect of speed stress on either the S-LRP or LRP-RT interval was due to eye movements.

*Experiment 1 versus Experiment 2.* As mentioned, a comparison between the results of Experiments 1 and 2 should help determine whether the effects of speed stress on the LRP-RT interval were caused by a direct effect on motor processes or were

an indirect consequence of an effect on premotor processes. An ANOVA with the factors speed stress and experiment was conducted on RT, the S-LRP interval, and the LRP-RT interval. Figure 4 depicts these variables for both experiments. As expected, mean RT for correct responses was significantly longer for the more complex linguistic task in Experiment 2 (622 ms) than for the perceptual discrimination task of Experiment 1 (374 ms),  $F(1, 22) = 81.5, p < .001, \eta^2 = .79$ , HWI = 57 ms. The effect of speed stress on mean RT was also stronger in Experiment 2 than in Experiment 1, as indicated by a significant interaction between speed stress and experiment,  $F(2, 44) = 17.2, p < .001, \eta^2 = .44$ . Given the similar accuracies at each level of speed stress in the two experiments, this would seem to indicate a slower rate of information accumulation in Experiment 2. That is, the same increase in accuracy required trading more time in Experiment 2 than in Experiment 1.

Consistent with the notion that the cognitive task in Experiment 2 requires a longer decision process, the average S-LRP interval in

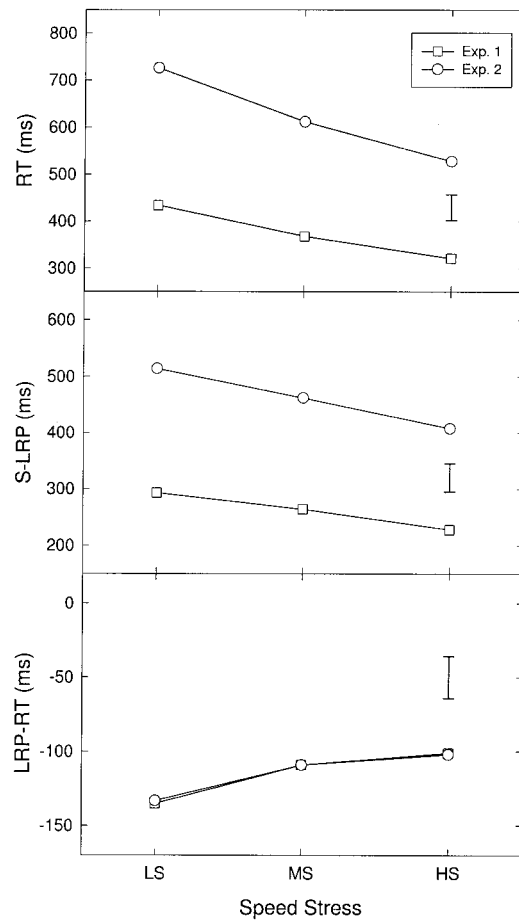


Figure 4. Mean reaction time (RT; upper panel), mean stimulus-lateralized readiness potential (S-LRP) interval (middle panel), and mean LRP-RT interval (lower panel) as a function of speed stress and experiment (Exp.). The error bar in each plot is equal to two times the standard error. Standard errors were computed from the error terms in the manner suggested by Loftus and Masson (1994) and Ulrich and Miller (2001). LS = low speed stress; MS = moderate speed stress; HS = high speed stress.



Experiment 2 (462 ms) was longer than in Experiment 1 (262 ms),  $F(1, 22) = 63.5$ ,  $p < .001$ ,  $\eta^2 = .74$ ,  $\text{HWI} = 51.7$  ms. Although the SAT effect on the S-LRP interval was stronger in Experiment 2 than in Experiment 1, the interaction of speed stress and experiment was only marginally significant,  $F(2, 44) = 2.5$ ,  $p = .09$ . The mean LRP-RT interval was virtually identical in both experiments  $F(1, 22) < 1$ ;  $-115$  versus  $-114$  ms,  $\text{HWI} = 29.2$  ms. Consequently, and most importantly, the effect of speed stress on the LRP-RT interval did not differ significantly between both experiments,  $F(2, 44) < 1$ . Given the slower rate of information accumulation in Experiment 2, an indirect effect of speed stress on motor processes should have produced a more pronounced effect on the LRP-RT interval than in Experiment 1 (cf. lower panel of Figure 2). Thus, these results argue against an indirect effect on the LRP-RT interval and therefore strengthen the notion that speed stress has a direct effect on motor processes.

### Discussion

Experiment 2 demonstrates the generality of a speed-stress effect on each of the two LRP intervals and that the effect on the LRP-RT interval is direct. The participants' task required a speeded decision on the gender of a German noun. The results confirm our expectations that this linguistic decision would take longer and would proceed more slowly than the perceptual decision in Experiment 1. Mean RT was longer in Experiment 2 than in Experiment 1. This was also true for the S-LRP interval, which presumably reflects the duration of premotor processes. In contrast, there appears to be no difference in mean LRP-RT interval between the two experiments, which suggests that the RT difference is due entirely to a difference in the duration of premotor processes. Speed stress produced a larger effect on RT in Experiment 2 than in Experiment 1. Because the accuracy at each level of speed stress is similar across the two experiments, this would imply a shallower SAT function in Experiment 2 and, therefore, a slower rate of information accumulation.

Consistent with the notion that it shortens motor processes, speed stress again shortened the LRP-RT interval. Because the absolute size of the LRP-RT interval at each level of speed stress was virtually identical to that in Experiment 1, the effects of speed stress on this interval in both experiments were very close numerically. We again found a significant difference between low and medium levels of speed stress, but not between medium and high levels.

Experiments 1 and 2 in combination demonstrate that the magnitude of the speed-stress effect on the LRP-RT interval can be invariant across decision type. The LRP-RT intervals at each level of speed stress were virtually identical in the two experiments, despite the decisions (a) being based on qualitatively different types of information, (b) having different durations, and (c) involving different rates of information accumulation. This finding does not support the idea of an indirect effect, wherein the shortening of the LRP-RT interval is a consequence of a direct effect of speed stress on premotor decision processes. As noted, effects on the growth rate of decision processes could influence the time course of subsequent motor processes within a cascadelike processing architecture. Such an indirect effect should, however, be inversely proportional to the rate of the decision process. Thus, were the effects of speed stress on the LRP-RT interval indirect,

they should be larger in Experiment 2 than in Experiment 1. The equivalence between LRP-RT intervals in the two experiments therefore supports the notion that speed stress directly affected the duration of motor processes after LRP onset.

### Experiment 3

Experiment 3 addressed a discrepancy between the results of Experiments 1 and 2 and those of previous studies examining effects of SAT on the S-LRP and LRP-RT intervals (Osman et al., 2000; Van der Lubbe et al., 2001). As mentioned in the introduction, these studies found that speed stress shortened only the LRP-RT interval, whereas an effect of speed stress was found on both the S-LRP and LRP-RT intervals in Experiments 1 and 2. Also mentioned in the introduction were two possible explanations for the absence of an S-LRP effect in previous studies.

First, the SAT effects in these studies were relatively small. In the study by Osman et al. (2000), speed stress decreased RT by 67 ms and increased the error rate by 11%. SAT effects of similar size (i.e., 44 ms and 6%) were reported by Van der Lubbe et al. (2001). In contrast, the SAT effects obtained in both Experiments 1 and 2 were much larger. Averaged over the two experiments, RT decreased from LS to HS by 156 ms, and error rate increased by 22%. To determine whether the limited extent of the SAT in previous studies was responsible for the lack of an S-LRP effect, in Experiment 3, we replicated the study of Osman et al. (2000) with a wider range of speed stress.

The other potential explanation attributes the lack of an S-LRP effect to a particular property of the stimulus displays in previous studies. Specifically, these complex displays included stimuli or features of the response signal that could possibly trigger an incorrect response. With such displays, lowering a decision criterion to gain speed may be especially costly in terms of errors. Avoiding distraction by extraneous noise may require focusing attention to achieve a thorough accumulation of task-relevant information. For example, Shiu and Pashler (1994, 1995) provided strong evidence that a spatial attentional mechanism is used when the display includes decisional noise that has to be filtered out. Thus, participants in the studies by Osman et al. (2000) and Van der Lubbe et al. (2001) were perhaps reluctant to lower their decision criteria, especially because they also had the option of adapting to speed stress at a postdecisional level.

To assess the validity of this explanation, we extended the standard flanker paradigm by including a further experimental condition. We reasoned that if the flankers were identical to the target across an entire block of trials, participants would not have to filter out irrelevant information. Thus, in Experiment 3, each participant was tested in two conditions. In the standard flanker condition, compatible (HHHHH, SSSSS) and incompatible (SSHSS, HSHHH) response signals were mixed across trials within a block. In the compatible-only condition, the flankers were always identical to the center letter for all trials within the block. If the lack of an SAT effect on the S-LRP interval in the previous studies was due to the need to guard against responses triggered by extraneous information, an effect of SAT on the S-LRP interval should (a) still be absent in the standard flanker condition, but (b) emerge in the compatible flanker condition.

## Method

The method was virtually identical to the two previous experiments. The major change concerned the stimulus displays.

**Participants.** A fresh sample of 9 students took part in this experiment (mean age = 27 years). As in the two previous experiments, all had normal or corrected-to-normal vision and no apparent sensorimotor or neurological problems, and satisfied the same inclusion criteria applied to their performance and electrophysiological recordings.

**Stimuli conditions, responses, and trial events.** In the standard flanker condition, the stimulus consisted of a five-letter horizontal array (HHHHH, HSHHH, SSSSS, or SSHSS). The center letter was the target letter, and the remaining letters were task-irrelevant flankers. Each letter was 5 mm high and 3 mm wide. All letters within the array were spaced so that the distance between adjacent letters was 1 mm. The stimulus array was presented in the middle of the screen. The temporal course of a single trial was as in Experiment 2.

Participants responded with the index finger of one hand to the target letter H and with the index finger of the other hand to the target letter S. Assignment of letter name to hand was balanced across participants. A single block consisted of 40 trials with compatible stimulus arrays and 40 trials with incompatible stimulus arrays, which were randomly mixed. In the compatible-only condition, a single block consisted of 80 trials with response-compatible flankers (40 HHHHH and 40 SSSSS).

Each participant was tested on 48 blocks, 24 for the standard flanker condition and 24 for the compatible-only condition. These 48 blocks were subdivided into four sessions of 12 blocks each that were conducted on 4 consecutive days. One stimulus condition was tested in Sessions 1 and 2, and the other condition was tested in Session 3 and 4, with the order of the two conditions counterbalanced across participants. As in the two previous experiments, the 12 blocks of a single session were further subdivided into four groups of 3 successive blocks. As before, the level of speed stress was changed from block to block within each group, such that all three levels of speed stress were administered to each group. As in the previous two experiments, the first 3 blocks in each stimulus condition were used to estimate the initial RT deadline. The SAT tracking algorithm was again used in the remaining 21 blocks of a single stimulus condition.<sup>7</sup>

## Results

**Excluded trials.** As in the two previous experiments, all trials with eye movements (7.8%), anticipations (0.1%), misses, (0.7%), and responses with both hands (2.2%) were discarded from the analysis. As in the two previous experiments, the percentage of eye movements did not vary with speed stress,  $F(2, 16) = 0.5, p = .55$ ; the mean percentage of eye movements in the different speed conditions was LS = 8.2%, MS = 7.9%, and HS = 7.2%. The main effect of stimulus condition, however, approached statistical significance,  $F(1, 8) = 4.6, p = .06, \eta^2 = .37$ ; there were 5.5% eye movements in the standard flanker condition and 10.0% in the compatible-only condition. This smaller percentage in the former condition may be attributed to the need for a more precise fixation on the task-relevant information located in the center of the stimulus array. There was no significant interaction between the factors on the percentage of eye movements ( $F < 1$ ). After trials were excluded, the mean number remaining was LS = 522, MS = 505, and HS = 507 in the standard flanker condition, and LS = 489, MS = 485, and HS = 484 in the compatible-only condition.

**RT and accuracy.** RT and percentage of correct responses were submitted to separate two-way ANOVAs with the factors stimulus condition (standard flanker vs. compatible-only condition) and speed stress (LS, MS, HS).<sup>8</sup> An SAT effect similar to that

in Experiments 1 and 2 was obtained. Mean RT for correct responses again decreased with speed stress,  $F(2, 16) = 271.1, p < .001, \eta^2 = .97$ , whereas the number of incorrect responses increased with speed stress,  $F(2, 16) = 337.8, p < .001, \eta^2 = .98$ . Mean RT was LS = 380 ms, MS = 336 ms, HS = 301 ms (HWI = 9.1 ms). The percentage of incorrect responses was LS = 4.0%, MS = 17.0%, HS = 28.8% (HWI = 2.6%), again close to the intended accuracy levels. Stimulus condition produced a significant main effect on RT,  $F(1, 8) = 26.7, p = .001, \eta^2 = .77$ , but not on the percentage of incorrect responses ( $F = 1$ ). As one might expect, mean RT of correct responses was shorter in the compatible-only condition (314 ms) than in the standard flanker condition (364 ms). Mean RT in the standard flanker condition was slightly, yet significantly, more affected by speed stress than in the compatible-only condition,  $F(2, 16) = 5.1, p = .027, \eta^2 = .39$ . There was no significant interaction between the factors on the percentage of incorrect responses ( $F < 1$ ).

As in Experiment 1, and thus again in contrast to the predictions of a deadline model, mean RT for incorrect responses (301 ms) was significantly shorter than mean RT for correct responses (339 ms),  $F(1, 8) = 175.7, p < .001, \eta^2 = .96$ . As in Experiments 1 and 2, and thus again in contrast to the predictions of fast-guess models, mean RT for incorrect responses decreased with speed stress,  $F(2, 16) = 207.8, p < .001, \eta^2 = .96$ ; LS = 355 ms, MS = 290 ms, and HS = 257 ms (HWI = 13.2 ms). Furthermore, mean RT of incorrect responses was shorter in the compatible-only condition (270 ms) than in the standard flanker condition (331 ms),  $F(1, 8) = 47.1, p < .001, \eta^2 = .85$  (HWI = 20.3 ms). The interaction of these factors on mean RT of incorrect responses approached statistical significance,  $F(2, 16) = 3.0, p = .104$ . Speed stress tended to affect RT in the standard flanker condition more than in the compatible-only condition, which resembles the interaction effect on RT for correct responses.

**LRP.** The analysis of the S-LRP interval was of particular interest for discriminating between the two potential explanations that motivated this experiment. As mentioned earlier, the decision-noise hypothesis holds that participants will be reluctant to adapt to speed stress by lowering a decision criterion under conditions in which response-incompatible flankers may lead them astray. According to this hypothesis, the S-LRP should be more affected by speed stress in the compatible-only condition than in the standard flanker condition. In contrast, the presence of equal-sized S-LRP effects in both flanker conditions would favor the alternative

<sup>7</sup> All blocks from the four sessions were included in the data analysis, except for the first three blocks in Sessions 1 and 3. As a result, the number of trials per participant in each (Speed Stress × Stimulus Type) condition of Experiment 3 was approximately the same as in each speed-stress condition of Experiments 1 and 2.

<sup>8</sup> Compatible and incompatible trials in the standard flanker condition were not analyzed separately, as this was not germane to the two alternative hypotheses under consideration (see introduction to Experiment 3). Nevertheless, to assess whether the flanker manipulation was successful, we performed a separate analysis of RTs in the standard flanker condition. In agreement with previous studies (e.g., B. A. Eriksen & Eriksen, 1974), mean RT was longer on trials with response-incompatible flankers than on trials with response-compatible flankers (382 vs. 350 ms),  $F(1, 8) = 87.2, p < .001, \eta^2 = .92$ .

hypothesis that the absence of an S-LRP effect in previous studies was due to a small SAT.

The upper panel in Figure 5 shows the mean S-locked LRP waveforms for correct responses as a function of stimulus condition and speed stress.<sup>9</sup> A two-way ANOVA analogous to the RT analysis was performed for the S-LRP interval, again using the jackknife-based scoring method. This analysis revealed a significant effect of speed stress on the S-LRP interval,  $F(2, 16) = 26.9$ ,  $p < .001$ ,  $\eta^2 = .77$ ; LS = 289 ms, MS = 268 ms, and HS = 229 ms (HWI = 19 ms), and a significant effect of stimulus condition,  $F(1, 8) = 19.9$ ,  $p = .002$ ,  $\eta^2 = .71$ . The S-LRP interval was shorter in the compatible-only condition (241 ms) than in the standard flanker condition (282 ms). Most important, however, the interaction of stimulus condition and speed stress was insignificant ( $F < 1$ ). This result is not in accord with the decision-noise hypothesis, supporting instead the notion that the degree of speed stress in previous studies was insufficient to produce a noticeable effect on the S-LRP interval.

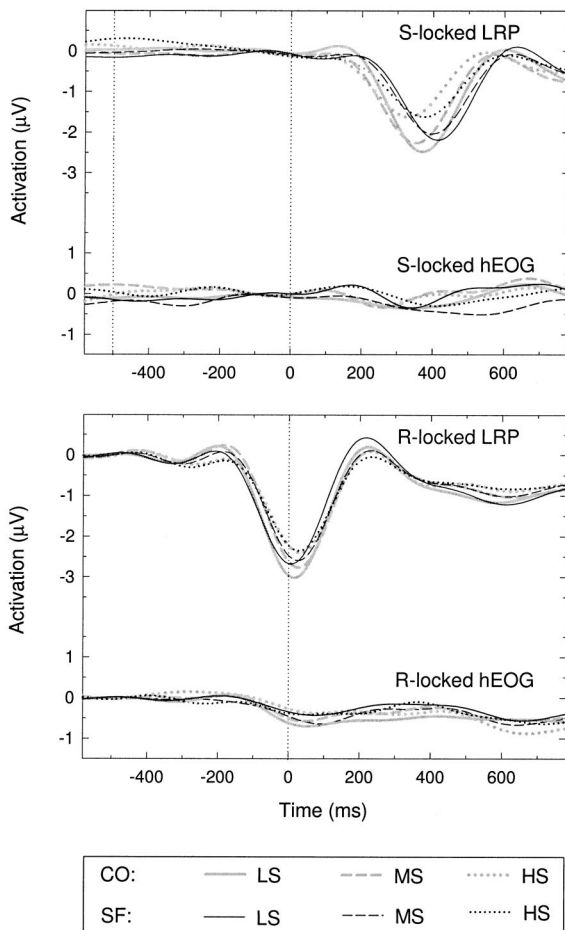


Figure 5. Grand average stimulus-locked (S-locked; upper panel) and response-locked (R-locked; lower panel) lateralized readiness potential (LRP) and grand average S-locked (upper panel) and R-locked (lower panel) horizontal eye movements (hEOG) as a function of speed stress and stimulus condition (compatible-only [CO] vs. standard flanker [SF] conditions) in Experiment 3. LS = low speed stress; MS = moderate speed stress; HS = high speed stress.

The lower panel in Figure 5 depicts the average R-locked LRP waveforms for correct responses as a function of stimulus condition and speed stress.<sup>10</sup> Speed stress again produced a significant effect on the LRP-RT interval,  $F(2, 16) = 12.9$ ,  $p < .001$ ,  $\eta^2 = .62$ ; LS = -84.5 ms, MS = -67.7 ms, and HS = -68.9 ms.<sup>11</sup> Thus, as in Experiments 1 and 2, speed stress shortened the duration of the processes after the LRP onset. Analogous to the two previous experiments, the effect of speed stress on this interval saturated at high levels. Post hoc analysis revealed that the LRP-RT interval differed significantly between LS and MS, between LS and HS, but not between MS and HS (HWI = 10 ms). There was neither a main effect of stimulus condition,  $F(1, 8) = 1.4$ ,  $p = .260$ , nor a significant interaction of Stimulus Condition  $\times$  Speed Stress ( $F < 1$ ).

*hEOG.* As in the previous two experiments, hEOG was analyzed to assess whether the effects of speed stress on the LRP could have been due to eye movements. This analysis was identical to the one in Experiment 1. Neither the averaged S-locked hEOG amplitude nor the averaged R-locked amplitude differed significantly from baseline ( $ps > .1$ ). Therefore, it is unlikely that horizontal eye movements contaminated the LRP onset latencies.

## Discussion

An effect of speed stress on the S-LRP interval was present and of equal size in both flanker conditions. Apparently, neither the presence of flankers per se, nor the possibility that they might signal an incorrect response, prevented participants from trading speed for accuracy at a premotor stage. The results of Experiment 3 suggest that, with a greater degree of speed stress, previous LRP studies (Osman et al., 2000; Van der Lubbe et al., 2001) might likewise have found an effect on the S-LRP interval.

Evidence to be presented in the General Discussion demonstrates that the SAT effect on the S-LRP interval was qualitatively different in Experiment 3 than in Experiments 1 and 2. Specifi-

<sup>9</sup> Compatible and incompatible trials were collapsed in the standard flanker condition to increase the signal-to-noise ratio. Nevertheless, we did perform a separate two-way (Compatibility  $\times$  Speed Stress) ANOVA on results from this condition. Consistent with Osman et al. (2000), there was a compatibility effect on the S-LRP interval,  $F(1, 8) = 9.7$ ,  $p = .014$ ,  $\eta^2 = .55$ . This interval was 267 ms for compatible trials and 311 ms for incompatible ones. There was also a significant speed effect,  $F(2, 16) = 4.8$ ,  $p = .020$ ,  $\eta^2 = .37$ , LS = 308 ms, MS = 297 ms, HS = 263 ms. The interaction between the two factors was not significant,  $F(2, 16) = 2.3$ ,  $p = .130$ .

<sup>10</sup> Because of the greater degree of noise in the LRP baselines, a more conservative criterion for R-locked LRP onset was used to calculate the LRP-RT interval than in Experiments 1 and 2. Specifically, to minimize the possibility of a false alarm, we increased the criterion from 30% to 50% of peak LRP amplitude.

<sup>11</sup> Compatible and incompatible trials in the standard flanker condition were again collapsed to increase the signal-to-noise ratio. Again, a separate two-way (Compatibility  $\times$  Speed Stress) ANOVA was performed on results from this condition. Consistent with the study by Osman et al. (2000), there was no main effect of compatibility on the LRP-RT interval ( $F < 1$ ). The LRP-RT interval was significantly reduced by speed stress,  $F(2, 16) = 7.7$ ,  $p = .005$ ,  $\eta^2 = .49$ , LS = -90 ms, MS = -69 ms, HS = -73 ms. This effect was somewhat stronger for compatible versus incompatible trials,  $F(2, 16) = 4.6$ ,  $p = .026$ ,  $\eta^2 = .37$ .



cally, when the S-locked LRP waveforms were corrected for the contribution of lucky guesses, the SAT effect on the S-LRP almost vanished in Experiment 3. This would imply that participants in Experiment 3 controlled SAT at a premotor stage primarily by a strategy of mixing in guesses. As will be seen, this was not the case in Experiments 1 and 2.

Perhaps, the perceptual discrimination and lexical access tasks in Experiments 1 and 2 allowed a more graded accumulation of the information necessary to select a response than the flanker task in Experiment 3. The letter identification that signaled the response hand in the flanker task might have been so quick and/or automatic as to proceed in close to an all-or-none fashion. If so, it may have been difficult to control SAT at a premotor stage by adjusting a criterion, thus forcing participants to rely on a strategy of mixing in guesses.

### General Discussion

SAT is an important and pervasive type of cognitive self-control that has challenged researchers since the beginning of experimental psychology. Yet, despite the considerable theoretical effort devoted to better understanding the mechanisms underlying SAT, surprisingly few attempts have been made to locate where it occurs in the information-processing system (Briggs & Shinar, 1972; Osman et al. 2000; Swanson & Briggs, 1969; Van der Lubbe et al., 2001). This is surprising, because many of the RT models developed to explain SAT phenomena proceed explicitly or implicitly from the assumption that the trade-off occurs solely at a premotor stage (for reviews, see Luce, 1986; Pachella, 1974; Sanders, 1998). The present study helps remedy this situation.

To determine the locus of SAT, we relied on latency measures of the LRP. More specifically, we examined effects of speed stress on the duration of two intervals related to LRP onset: the S-LRP and LRP-RT intervals. These two intervals reflect, respectively, the durations of RT processes before and after the onset of hand-specific response activation. We therefore reasoned that effects of speed stress on the S-LRP interval would index changes in the combined duration of the perceptual, cognitive, and decisional processes that precede hand-specific activation, whereas effects on the LRP-RT interval would index changes in the duration of motor processes after the start of such activation.

The present study provides a systematic examination of SAT effects on the two LRP intervals. Three experiments were conducted that required participants to make decisions on the basis of different types of information. The decisions were based on perceptual information about line length in Experiment 1 and on linguistic information about noun gender in Experiment 2. Experiment 3 required participants to extract task-relevant information from a letter array with distracting flanker information. Three levels of speed stress covering a wide range of SAT were used in each experiment. Participants were required to control the speed of their responses in order to beat a deadline while maintaining as high a level of accuracy as possible. Deadlines were adjusted by an adaptive tracking algorithm, so as to obtain approximately the same three target levels of accuracy in each experiment.

### Summary of Main Findings

A robust SAT was obtained in all experiments, with approximately equal accuracy across experiments at each level of speed

stress. The LRP results in all three experiments indicate an effect of speed stress on both the early and late stages of RT. Both the S-LRP and LRP-RT intervals decreased with speed stress in each experiment. Thus, speed stress affected the duration of processes both before and after the onset of hand-specific response activation, regardless of (a) whether the decision was based on perceptual or linguistic information, (b) whether the decision was based on the rate at which information was accumulated, or (c) whether the stimulus displays contained irrelevant information that might influence decision processes or trigger the wrong response.

The effects on the LRP-RT interval appear to be a direct rather than an indirect consequence of an SAT at the level of premotor (e.g., decision) processes. A simulation (see Experiment 1, *Discussion*) demonstrated that such an indirect effect on motor processes could occur within a cascadelike processing architecture, but that its size would then depend on the overall rate of the earlier premotor processes. The equivalent-sized effects of speed stress on the LRP-RT interval in Experiments 1 and 2, despite the different processing rates of the decisions involved in their respective tasks, is therefore inconsistent with such an indirect effect. The LRP results thus indicate that speed stress directly affected both motor and premotor stages of RT, rather than a single premotor stage.

The complete pattern of results is problematic for any single model of SAT described so far in this article. Neither the fast-guess nor the deadline model alone can account for the detailed pattern of RTs. The fast-guess model does not predict the decrease in RT found for incorrect responses with speed stress. The deadline model predicts that incorrect responses should be slower than correct ones, also contrary to our findings. Accumulation models cannot account for the effect of speed stress observed on the LRP-RT interval, because they postulate that SAT occurs solely at the level of premotor decision processes.

But perhaps the demand that a single model explain the entire pattern of results is overly severe. As noted by Osman et al. (2000), a demonstration that a single SAT mechanism cannot account for the entire pattern of data does not mean that it was not used at all. The SAT mechanisms implied by mixture and accumulation models are not mutually exclusive. Indeed, as further noted by Osman et al., a person might control his or her level of SAT by mixing in fast guesses, deadline-generated guesses, and setting a criterion, all within the same block of trials. In the following section, we therefore consider whether an accumulation model in combination with fast and/or deadline-generated guesses can account for our findings.

### Accumulation and Mixture Models Combined

Suppose that SAT was primarily controlled in the manner postulated by accumulation models, but also to a lesser degree by mixing in guesses. We might then obtain the observed effects of speed stress on RT and the two LRP intervals. Accumulation models can produce incorrect responses that are both faster than correct ones and become faster with speed stress. If a criterion applied to accumulating information were the dominant means of controlling SAT, we might thus expect the observed pattern of RTs.

Mixture models can explain the effects of speed stress on both LRP intervals. Like accumulation models, they are consistent with an effect of speed stress on the S-LRP interval. Both fast and

deadline-generated guesses should involve shorter perceptual and cognitive processes than nonguesses. Indeed, these processes might be entirely absent for fast guesses. Given that the proportion of correct responses that are due to lucky (correct) guesses increases with speed stress, the S-LRP interval should decrease. Unlike accumulation models, however, mixture models are also consistent with an effect of speed stress on the LRP-RT interval. Guesses could involve shortened motor processes.

One way guessing could shorten the motor processes that determine the LRP-RT interval is if it led to preparation of a response by one of the two hands before the response signal. As has been shown by numerous studies (De Jong et al., 1988; Leuthold et al., 1996; Osman et al., 1995; Sangals, Sommer, & Leuthold, 2002; Ulrich, Leuthold, & Sommer, 1998; Ulrich, Moore, & Osman, 1993), such advance preparation would result in an LRP prior to the response signal. Moreover, the amplitude of the presignal LRP would be expected to increase with speed stress, as a result of an increase in the proportion of guesses. To test these predictions, we performed an additional analysis but found no sign of a presignal LRP, at least not in Experiments 1 and 2.<sup>12</sup>

Yet, there remain other ways in which guessing might shorten the LRP-RT interval. Motor process might, for example, be speeded by advance preparation that did not activate a response hand. Although such preparation would not produce an LRP before the signal, it could result in especially short LRP-RT intervals. Regardless of precisely how guessing might shorten the LRP-RT interval, the presence of such effects can nevertheless be evaluated by removing the contribution of guesses to the LRP. Any remaining effects of speed stress on either the S-LRP or LRP-RT intervals would then have to have been caused by some other mechanism.

### *Correcting the LRP for Lucky Guesses*

One property of the LRP especially well-suited to the study of SAT is that the contribution of responses based on pure guesses can be removed. This property stems from the definition of the LRP, which reflects the correlation between the hand signaled by the stimulus and the left–right direction of lateralization in the readiness potential. For correct responses, guesses and nonguesses alike lead to a response by the signaled hand, and hence both contribute to the LRP. Thus, when based on correct responses only, as is typically the case, the LRP waveform, as well as the S-LRP and LRP-RT intervals, can be influenced by the presence of guesses.

To remove the contribution of guesses, the key is to calculate the LRP in such a way that it is no longer correlated with the hand signaled by the stimulus. This can be done by basing the LRP on all trials, not just correct ones, while continuing to define left- and right-hand trials in terms of the hand signaled by the stimulus. Because the response hand of a pure guess is by definition uncorrelated with the signaled hand, the contribution of the pure guesses to the LRP will cancel out in the LRP calculation. A full explanation of this cancellation is provided in the Appendix, which also examines the effects of speed stress on the guess-free LRPs.

It is shown in the Appendix that the S-LRP intervals in Experiments 1 and 2 still decrease with speed stress, even when the contribution of pure guessing is removed. Thus, guesses cannot account for the entire effect of speed stress on this interval. In contrast, when the guessing contribution was removed in Experi-

ment 3, the effect of speed stress on the S-LRP interval almost disappeared. This reveals a fundamental difference in SAT control between Experiment 3 and the first two experiments. As mentioned earlier (Experiment 3, *Discussion*), it indicates that SAT at a premotor level was controlled in Experiment 3 primarily by mixing in guesses. It also supports the conjecture by Osman et al. (2000) that the mechanism of SAT is likely to be task specific.

The effects of speed stress on the LRP-RT intervals cannot be attributed entirely to guessing in any of the three experiments. In each case, this interval continued to decrease with speed stress after the contribution of guessing was removed. Although accumulator models can account for guess-corrected effects on the S-LRP interval, those on the LRP-RT interval remain to be explained. Further hypotheses are considered below.

### *LRP-RT Interval and Response Force*

Previous research has shown that participants respond more forcefully with increasing speed stress (Jaśkowski et al., 1994). Thus, another possibility is that the effect of speed stress on the LRP-RT interval is merely a by-product of its effect on response force. More specifically, motor processes leading up to a more forceful response might also proceed more rapidly. Perhaps responding more forcefully is a strategy that participants adopt under speed stress in the hope of achieving faster RTs. There are reasons, however, to doubt that the effects of speed stress on force caused its effect on the LRP-RT interval.

First, there is converging evidence that the temporal and kinetic aspects of the motor system are unrelated (e.g., Miller et al., 1999; Mordkoff & Grosjean, 2001). If more forceful responses speed up motor processing, one should expect a negative correlation between RT and the magnitude of force. The magnitude of response force, however, is uncorrelated with RT on a trial-to-trial basis (Giray & Ulrich, 1993; Mordkoff et al., 1996). Indeed, increases of force can even be associated with an increase in RT (e.g., Mattes, Ulrich, & Miller, 2002). There are also some theoretical reasons to believe that an increase of response force is not accompanied by a decrease of motor duration (Ulrich & Wing, 1991).

Second, we analyzed the response force data from all experiments in the present study and observed a dissociation between the effects of speed stress on response force and the LRP-RT interval: A larger increase of response force was observed between MS and HS than between LS and MS, at least in Experiments 1 and 2, whereas the reverse pattern of results was obtained for the LRP-RT interval. Moreover, and contrary to the hypothesis that more forceful responses are always associated with shorter RTs, correct

<sup>12</sup> Amplitude of the prestimulus LRP for correct responses was averaged across the interval from 210 to 10 ms before response onset and referred to a 200-ms baseline before warning signal onset. The average prestimulus amplitudes were LS = 0.031  $\mu$ V, MS = -0.071  $\mu$ V, and HS = -0.003  $\mu$ V,  $F(2, 22) < 1$ , HWI = 0.25  $\mu$ V, in Experiment 1, and LS = 0.022  $\mu$ V, MS = 0.065  $\mu$ V, and HS = -0.022  $\mu$ V,  $F(2, 22) < 1$ , HWI = 0.18  $\mu$ V, in Experiment 2. Only in Experiment 3 did the effect of speed stress approach statistical significance,  $F(2, 16) = 3.0$ ,  $p = .09$ ; LS = 0.046  $\mu$ V, MS = 0.020  $\mu$ V, HS = -0.143  $\mu$ V.

responses were generally slower but more forceful than incorrect ones.<sup>13</sup>

Third, were the effects on the LRP-RT interval due merely to a change in response force, it is hard to imagine how a decrease in the LRP-RT interval with speed stress could contribute to a less accurate response choice. In other words, how could the decrease in the LRP-RT interval be part of a trade-off between speed and accuracy? It might be argued that only premotor decision processes contributed to the SAT in the present study, with effects of speed stress on the LRP-RT interval caused by additional changes in processing speed that had no consequence for accuracy. Both Osman et al. (2000) and Van der Lubbe et al. (2001) observed an effect of speed stress that was exclusively on the LRP-RT interval. The SAT observed in these experiments could therefore not have involved premotor processes. These studies demonstrate that processes during the LRP-RT interval can contribute to an SAT. It is reasonable to assume the same processes also contributed to the SAT observed in the present experiment.

### *Direct Versus Indirect Effects*

In the discussion of Experiment 1, we considered two classes of explanation of how speed stress might affect the duration of the LRP-RT interval. One class assumed that speed stress influences this interval indirectly, through its influence on premotor decision processes. According to this account, the decision processes continuously transmit information to postdecisional motor processes. As mentioned before, this account can be rejected because it predicts that the overall rate of the decision processes should influence the effect of speed stress on motor processes. Despite differences in the processing rates of their respective decisions, virtually identical effects of speed stress on the LRP-RT intervals were found in Experiments 1 and 2. Thus, it seems unlikely that the effect on the LRP-RT interval was an indirect consequence of effects on premotor processes.

It is interesting that the same pattern of results also rejects the hypothesis that the effects of speed stress on the S-LRP interval were indirect consequences of effects on motor processes. Such indirect effects from motor to premotor processes might be possible within a common-coding framework (e.g., Hommel, Müsseler, Aschersleben, & Prinz, 2001). It is difficult to imagine, however, how the equivalent effects of speed stress on the LRP-RT interval in the three experiments could result in the different effects of speed stress on their S-LRP intervals.

It seems likely that the other class of explanation, wherein speed stress exerts a direct effect on the LRP-RT interval, is the correct one. This is supported by our observation that the size of the speed-stress effect on the LRP-RT interval did not depend on the size of this effect on the S-LRP interval. As discussed previously, speed stress might directly influence the LRP-RT interval in several ways. For example, as suggested by Osman et al. (2000), participants might select one response alternative after a tentative decision (thus producing an LRP) and then recheck the selected response. Slow but accurate performance would result when the final execution of the response was withheld until rechecking was completed. Speed stress would shorten the LRP-RT interval and decrease accuracy by inducing participants to skip or reduce rechecking.

Another possibility is that speed stress might enhance motor preparation that is not specific to either hand. Previous studies have shown that such preparation can shorten the LRP-RT interval (Leuthold et al. 1996; Müller-Gethmann et al., 2000; Osman et al., 1995). Though not specific to either hand, such preparation might create a (more central) bias in favor of one of the response alternatives, thus increasing its chances of being emitted as an error (Falmagne, Cohen, & Dwivedi, 1975).

### *Multiple Effects of Speed Stress*

All things considered, speed stress probably affects at least two different stages of RT. The duration of the earlier stage is indexed by the S-LRP interval, and the duration of the later stage is indexed by the LRP-RT interval. It is also likely that the early and late effects can both be selectively influenced. The present findings demonstrate a selective influence on the magnitude of the early effect: Experiments 1 and 2 differed only in the size of the speed stress effect on the S-LRP interval, while exhibiting virtually identical effects on the LRP-RT interval. Likewise, increases in speed stress did not uniformly influence the duration of processes before and after LRP onset. In each experiment, a moderate level of speed stress was found to shorten the duration of both early and late processes. At higher levels of speed stress, however, only the duration of the early processes was shortened. It may even be possible for the two effects to occur independently of one another. As mentioned, speed stress has been found to influence the LRP-RT interval only (Osman, et al. 2000; Van der Lubbe et al. 2001). To the best of our knowledge, however, sole effects of SAT on the S-LRP interval have yet to be reported.

### *Conclusions*

Though people usually cannot control their speed and accuracy independently, they may be able to control separately the SAT settings of early and late processes. Such a view is reminiscent in some ways of Lange's (1888) early theory of SAT. Both posit a role for motor and premotor processes. However, whereas Lange explained SAT by shifts between modes of processing (set or Einstellung) that emphasized either sensory (accurate) or motoric (fast) performance, we propose separate SAT mechanisms involving either premotor or motoric stages.

The major conclusion of this study is that speed stress affected not only the duration of decision processes, but also that of postdecision processes. This conclusion follows from the observed

<sup>13</sup> Participants responded more forcefully with increasing speed stress in all experiments. The average force amplitude was LS = 364 cN, MS = 405 cN, HS = 487 cN,  $F(2, 22) = 12.5, p < .01, \eta^2 = .53$ , in Experiment 1; LS = 225 cN, MS = 246 cN, HS = 321 cN,  $F(2, 22) = 8.2, p = .01, \eta^2 = .43$ , in Experiment 2; LS = 262 cN, MS = 321 cN, HS = 370 cN,  $F(2, 16) = 9.1, p = .011, \eta^2 = .53$ , in Experiment 3. Post hoc comparisons revealed a significant difference between MS and HS, but not between LS and MS in Experiment 1 (HWI = 65 cN) and Experiment 2 (HWI = 73 cN). In Experiment 3, only the difference between LS and HS was significant (HWI = 68 cN). Correct responses were more forceful than incorrect ones in all experiments: Experiment 1 (418 vs. 327cN),  $F(1, 11) = 9.7, p = .01, \eta^2 = .47$ ; Experiment 2 (301 vs. 264 cN),  $F(1, 11) = 12.8, p < .01, \eta^2 = .54$ ; and Experiment 3 (318 vs. 239 cN),  $F(1, 8) = 51.3, p < .001, \eta^2 = .87$ .



effects of speed stress on both the S-LRP and the LRP-RT intervals. Our results indicate that effects on the LRP-RT interval (a) cannot be entirely explained by pure guesses; (b) are not a by-product of effects on force; and (c) are direct, that is, not an indirect consequence of effects on decision processes. The effects of speed stress on the LRP-RT interval cannot be explained at present by accumulation models, such as random walk models (Laming, 1968; Link, 1975; Link & Heath, 1975; Stone, 1960); the diffusion model (Ratcliff et al., 1999); or the leaky, competing accumulator model (Usher & McClelland, 2001), which assume that speed stress influences premotor decision processes only. Further formulation of such models might therefore benefit from considering the possibility that SAT can occur also at a later stage.

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Appendix

LRP Waveform Correction for Lucky Guesses

This appendix shows that the effects of speed stress on the S-LRP and LRP-RT intervals cannot be exclusively due to lucky guesses. As discussed in the main text, the fast-guess model assumes that a response is based either on a complete guess or on a complete analysis of stimulus information (see Figure A1). That is, guesses are sampled from a population of responses, which are fast and at chance accuracy and hence are called *fast guesses*. Fast guesses yield correct hand responses (lucky guesses) in 50% of all trials, and incorrect hand responses (unlucky guesses) in the remaining 50%. In contrast to fast guesses, stimulus-controlled responses are sampled from a population of highly accurate responses with longer RTs. Different levels of SAT are achieved by changing the probability *c* of these two types of responses. The same probability mixture holds for the deadline model. For both models, the probability *c* decreases from 1 to 0 as speed stress increases.

Let the expected unobservable LRP function for stimulus-controlled trials be  $E[LRP_{sc}(t)]$ . According to both models,  $E[LRP_{sc}(t)]$  can be estimated by averaging the LRP waveforms of correct hand and incorrect hand responses. We will call this average the expected total LRP waveform,  $E[LRP_{tot}(t)]$ . According to the Law of the Unconscious Statistician (e.g., Ross, 1980) and both models, the expected total LRP waveform is

$$E[LRP_{tot}(t)] = c \cdot E[LRP_{sc}(t)] + (1 - c) \times .5 \times E[LRP_{lg}(t)] + (1 - c) \times .5 \times E[LRP_{ug}(t)], \quad (A1)$$

where  $E[LRP_{lg}(t)]$  and  $E[LRP_{ug}(t)]$  are the expected LRP waveforms for lucky and unlucky guesses, respectively. Due to the definition of the LRP, waveforms for incorrect hand responses have a polarity opposite those for correct hand responses. Thus,  $E[LRP_{lg}(t)] = -E[LRP_{ug}(t)]$ , and Equation A1 simplifies to

$$E[LRP_{tot}(t)] = c \times E[LRP_{sc}(t)]. \quad (A2)$$

The last expression shows that the expected  $LRP_{tot}(t)$  is identical to a scaled version of the expected unobservable stimulus-controlled waveform  $LRP_{sc}(t)$ .

The panels in the left column of Figure A2 depict the average S-locked  $LRP_{tot}(t)$  for all experiments and each speed stress condition. Consistent with Equation A2, the largest amplitudes were observed for the LS condition, because here *c* should be close to 1. That is, only few guesses should occur in this condition. In contrast, the waveform in the HS condition shows the smallest amplitude, because *c* should be smaller.

The panels in the right column of Figure A2 show the estimated  $LRP_{sc}(t)$  waveforms. These were computed by rescaling the waveforms in the left column. More specifically, according to Equation A2, the expected total  $E[LRP_{tot}(t)]$  must be divided by an estimate of the mixture probability *c*:

$$E[LRP_{sc}(t)] = E[LRP_{tot}(t)]/c. \quad (A3)$$

This probability *c* was estimated with the relative frequency *p* of incorrect hand responses for each speed condition. The value *p* is identical to the relative frequency of unlucky guesses within the corresponding speed condition. Note that the relative frequency of unlucky guesses is given by  $p = .5 \times (1 - c)$ . Thus *c* can be estimated by  $c = 1 - 2 \times p$ .

Of most relevance for present purposes is the result that the estimated stimulus-controlled waveform  $LRP_{sc}(t)$  still varies with speed stress, at least in Experiments 1 and 2. The S-LRP interval of the estimated stimulus-controlled waveform was LS = 298 ms, MS = 272 ms, and HS = 252 ms (HWI = 23 ms),  $F(2, 22) = 14.2, p < .001, \eta^2 = .56$ , in Experiment 1, and LS = 513 ms, MS = 473 ms, HS = 441 ms (HWI = 37ms),  $F(2, 22) = 13.3, p < .001, \eta^2 = .55$ , in Experiment 2. Thus, the effect of speed stress on the S-LRP interval is still present after correction for guessing, that is, when the contribution of lucky guesses is removed.

In Experiment 3, however, the effect of speed stress on the S-LRP interval was strongly reduced after guessing correction and thus only

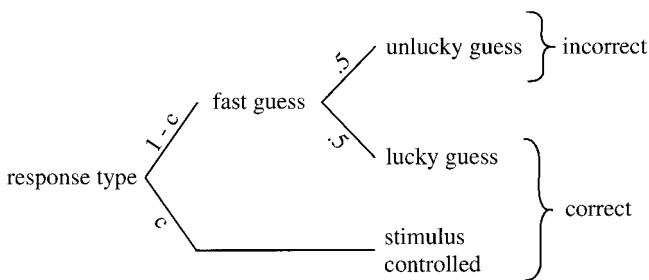


Figure A1. A tree diagram for response classification according to the guessing models (i.e., fast-guess and deadline models).



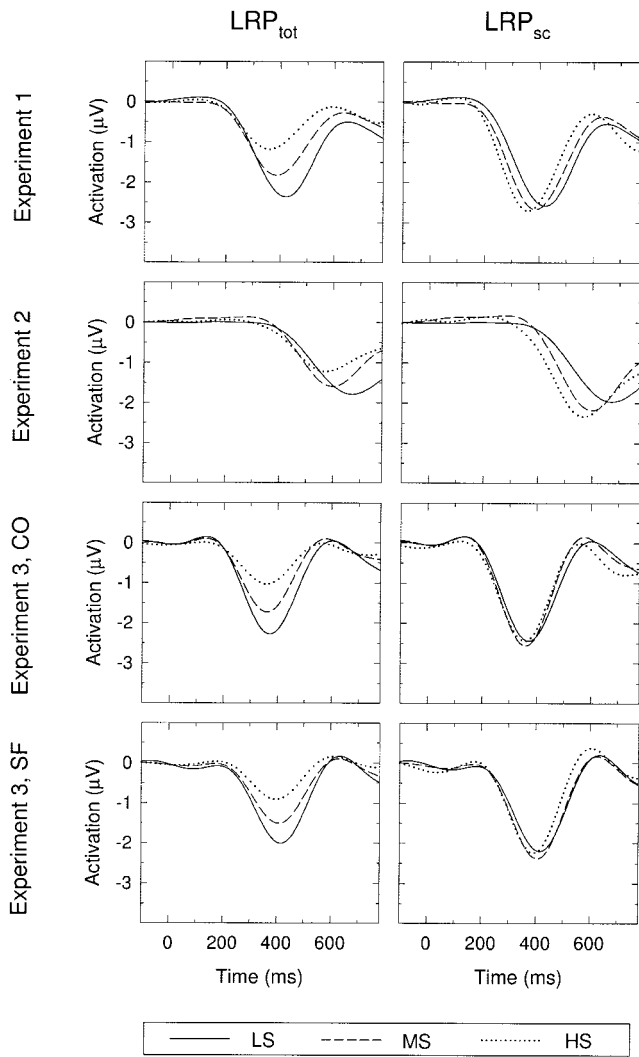


Figure A2. Guessing correction of stimulus-locked lateralized readiness potentials (LRPs). The graphs show total LRP ( $LRP_{tot}$ ; left column) and rescaled LRP ( $LRP_{sc}$ ; right column) as a function of speed stress for Experiment 1 (first row), Experiment 2 (second row), and Experiment 3 (third and fourth rows). The waveforms for Experiment 3 are separately depicted for the compatible-only (CO; third row) and the standard flanker (SF; fourth row) conditions. LS = low speed stress; MS = moderate speed stress; HS = high speed stress.

approached statistical significance, LS = 289 ms, MS = 282 ms, HS = 276 ms (HWI = 14 ms),  $F(2, 16) = 3.2, p = .07, \eta^2 = .29$ . The guessing-corrected S-LRP intervals in Experiment 3 were compared with those in Experiment 1, which had a similar overall RT, accuracy levels, and speed stress effect on the uncorrected S-LRP interval. A two-way ANOVA (speed condition by experiment) confirmed that speed stress had a smaller effect in Experiment 3,  $F(2, 38) = 4.9, p = .013, \eta^2 = .21$ . Guessing correction did not eliminate the effect of stimulus condition on the S-LRP interval in Experiment 3. The respective mean intervals were 262 ms and 303 ms (HWI = 18 ms) for the compatible-only and standard flanker conditions,  $F(1, 8) = 26.6, p < .001, \eta^2 = .77$ . As was the case for the uncorrected waveforms, stimulus condition did not modulate the effect of speed stress on the corrected S-LRP interval ( $F < 1$ ).

An identical analysis was performed for the R-locked LRP waveforms to evaluate whether the effect of speed stress on the LRP-RT interval is still present after correction for guessing. Analogous to Figure A2, Figure A3 depicts the total (left column) and stimulus-controlled (right column) versions of the R-locked waveforms for both experiments. This time, the effect of speed stress on the LRP interval was preserved in all three experiments. The mean LRP-RT intervals corrected for guessing were LS = -132 ms, MS = -108 ms, and HS = -92 ms (HWI = 16 ms),  $F(2, 22) = 22.5, p < .001, \eta^2 = .67$ , in Experiment 1; LS = -156 ms, MS = -116 ms, and HS = -104 ms (HWI = 21 ms),  $F(2, 22) = 23.3, p < .001, \eta^2 = .68$ , in Experiment 2; and LS = -83 ms, MS = -62 ms, and HS = -55 ms (HWI = 15 ms),  $F(2, 16) = 14.6, p < .001, \eta^2 = .65$ , in Experiment 3. In contrast to the S-LRP interval, the effect size of speed stress on the LRP-RT interval in Experiment 3 did not differ significantly

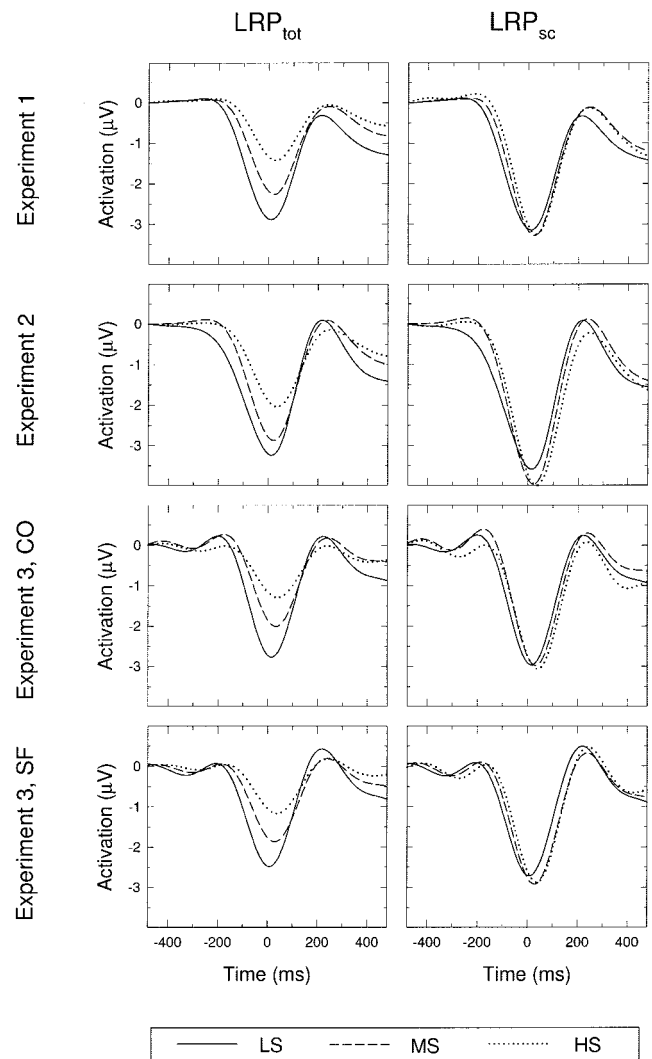


Figure A3. Guessing correction of response-locked lateralized readiness potentials (LRPs). The graphs show total LRP ( $LRP_{tot}$ ; left column) and rescaled LRP ( $LRP_{sc}$ ; right column) as a function of speed stress for Experiment 1 (first row), Experiment 2 (second row), and Experiment 3 (third and fourth rows). The waveforms for Experiment 3 are separately depicted for the compatible-only (CO; third row) and the standard flanker (SF; fourth row) conditions. LS = low speed stress; MS = moderate speed stress; HS = high speed stress.

from that in Experiment 1 ( $F < 1$ ). As with the uncorrected waveforms, there was neither a main effect of stimulus condition, nor did stimulus condition influence the size of the SAT effect on the LRP-RT interval ( $F_s < 1.3$ ).

In conclusion, the analyses in this appendix strongly support the idea that the LRP-RT effects observed in this study cannot be due entirely to guessing strategies. Shortening of the guessing-corrected LRP-RT intervals with speed stress would seem to reflect a genuine speed gain within the information-processing chain. The picture is somewhat more complex for

the S-LRP intervals. Guessing correction reduced only slightly the SAT effect on this interval in Experiments 1 and 2, but almost eliminated it in Experiment 3. This particular result suggests that guessing played a major role in the control of SAT in Experiment 3.

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