

# Effects of Stimulus Duration and Intensity on Simple Reaction Time and Response Force

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Previous research indicates that response force increases with stimulus intensity in simple reaction time (SRT) tasks. This result contradicts the common view that the perceptual system activates the motor system via a punctate go signal of fixed size. An elaborated view assumes that the size of the go signal depends on stimulus intensity so that more intense stimuli yield more forceful responses. In order to examine the latter hypothesis, the present experiments manipulated stimulus duration as well as intensity. Response force increased with duration even beyond a critical value of about 60 ms at which stimulus duration no longer affected SRT. In addition, increasing the duration of a stimulus also increased the duration of force output. These findings argue against models with punctate transmission of activation to the motor system. Certain continuous models and variable output models with prolonged go signals provide acceptable accounts of these effects.

Models of simple reaction time generally assume that detection responses result from the operation of two sequential processes: stimulus detection and motor activation (e.g., Luce, 1986). The former accumulates perceptual information from the environment and culminates in the decision that a stimulus has been presented (e.g., Pins & Bonnet, 1996). At that point, a punctate go signal is transmitted to the motor system, which produces some final activation needed to trigger a preplanned movement. Because these two processes occur sequentially, simple reaction time (SRT) is the sum of two components corresponding to the durations of these two processes,  $SRT = D + M$  (cf. Luce, 1986; Smith, 1995). One component,  $D$ , is assumed to represent the time needed to detect the onset of the stimulus, whereas the other component,  $M$ , is thought to reflect the time needed to initiate the motor response after the stimulus has been detected. Given this partitioning of SRT, it is natural to suppose that  $D$  would be affected only by characteristics of the stimulus and that  $M$  would be affected only by characteristics of the response. For example, stimulus intensity would be expected to have its effect on  $D$ , but movement complexity would be expected to influence  $M$ . Thus, traditional models of SRT imply two general assumptions. First, the whole reaction process is divided into at least two function-

ally independent and sequentially arranged processing stages. Second, the output from the decision stage is invariant of the characteristics of the stimulus. The latter assumption is analogous to the assumption of constant stage output underlying the additive factor method (cf. Sanders, 1990; Sternberg, 1969).

Two distinct types of evidence suggest that this conception is too simple, however, at least with respect to the variable of stimulus intensity. The first type of evidence consists of various facts suggesting that intensity has a larger effect on SRT than on the latency of perceptual processes. For example, intensity has a larger effect on SRT than on strictly perceptual tasks such as temporal-order judgment (Menendez & Lit, 1983; Roufs, 1974; Sanford, 1974), suggesting that intensity influences the speed of both the perceptual processing common to both measures and the motor processes contributing only to SRT (but for alternative interpretations, see Jaśkowski, 1996; Neumann, Koch, Niepel, & Tappe, 1992; Sternberg & Knoll, 1973). In addition, the latencies of early components of the evoked potential are sometimes found to be less affected by stimulus intensity than SRT, especially for auditory stimuli (Jaśkowski, Rybarczyk, & Jaroszyk, 1994; Krauskopf, 1972). This suggests that stimulus intensity may influence later central and distal stages as well as early sensory ones (but see Jaśkowski, Pruszewicz, & Świdzinski, 1990; Vaughan, Costa, & Gilden, 1966; Wilson & Lit, 1981). Moreover, Hughes and Kelsey (1984) reported that saccade latencies were less dependent on visual intensity than were manual response latencies. Because the same retinal position was stimulated in both response conditions, the stronger effect of intensity on manual responses suggests that stimulus intensity may exert its effect beyond early stages of visual processing. The second type of evidence is that intensity affects movement characteristics, at least under some conditions. For example, several studies have reported that more intense stimuli produce more forceful responses (e.g., Angel,

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1973; Jaśkowski, Rybarczyk, Jaroszyk, & Lemanski, 1995; Mattes & Ulrich, 1997; Miller, Franz, & Ulrich, in press), and Ulrich and Stapf (1984) found that more intense stimuli produce bimanual responses that are better synchronized.

It is easy to see that the effects of intensity on response force and the inferred effects on motor time are inconsistent with the above-mentioned class of go signal (or discrete) models, which assume that intensity effects are entirely localized at a perceptual level. One possibility is that the model is wrong because processing is not truly sequential, as assumed by these models. Instead, the detection and motor stages might operate with some temporal overlap, as assumed by continuous models (e.g., McClelland, 1979). However, even according to the most elaborated formulations of this model class (e.g., Busemeyer & Townsend, 1993; McClelland, 1979; Smith, 1995), stimulus intensity should not affect response force and thus cannot account for intensity effects on force output without further modification. The reason is that models within this class generally assume that a response is emitted as soon as the accumulated activation in a final response stage attains a threshold value. Because all responses are elicited at the same threshold level of activation regardless of intensity, intensity cannot affect the force output.<sup>1</sup>

A second theoretical possibility, which motivated the present experiments, is that the model is wrong because the characteristics of the stimulus influence  $M$  as well as  $D$ . This could happen if, for example, the characteristics of the go signal depended on those of the stimulus. The goal of the present article, then, was to consider whether the effects of intensity on force can be reconciled with a version of the discrete model, abandoning the assumption of constant output.

Below, we consider various elaborations of the discrete model derived from specific stochastic mechanisms that have been of particular importance in the reaction time (RT) modeling literature (e.g., Luce, 1986). Three elaborations are derived from criterion models, which are most commonly used in modeling SRT, and one elaboration is derived from the less common framework of counting models. Each elaboration rejects the assumption of constant output and proceeds from the idea that the size of the go signal depends on the physical characteristics of the stimulus. Specifically, intense stimuli are assumed to produce larger and hence more effective go signals and may thereby not only shorten the motor time but also enlarge the force output of a response. We refer to elaborations of this type as "variable stage output" models. As discussed further below, three of the four elaborations also retain the assumption of a punctate go signal, but one allows a prolonged go signal, with activation transmitted into the motor system over an extended period of time. In the remainder of the introduction, we show how each elaboration accounts for the observed intensity effects on the motor system and how these elaborations can be further tested by manipulating stimulus duration as well as intensity.

Almost all SRT models are variants of a prototypical criterion model (for a review, see Luce, 1986).<sup>2</sup> These models assume that the physical stimulation is transduced into some

internal activation that is accumulated over time. A central decision mechanism establishes a criterion value, and a go signal is released to initiate motor processing as soon as the accumulated information reaches this value (e.g., Grice, 1968; Luce, 1986; Schwarz, 1989; Smith, 1995). The temporal interval from stimulus onset until the accumulated activation reaches the criterion value denotes the detection time. The setting of the criterion value reflects a compromise between the level of accuracy and the speed of the response. If this value is lowered, SRTs will shorten, but false alarms due to spontaneous activity will increase. When stimulus intensity increases, more neuronal impulses are generated, and consequently, the rate of the central accumulation process increases. It is obvious that increasing stimulus intensity shortens the detection time and thus SRT. However, it is not obvious how this model class can account for intensity effects on the motor system without introducing further assumptions. We discuss three elaborated criterion models, each of which accounts for such motoric effects.

### Rate-Dependent Criterion Models

One elaboration assumes that the strength of the go signal only depends on the initial rate of the accumulation process but not on the total amount of accumulated activation. Given that the rate of accumulation increases with stimulus intensity, intense stimuli should produce larger and hence more energetic go signals than weak stimuli. For example, the size of the go signal might be determined solely by change detectors, which monitor changes in the flow of sensory information. Because the onsets of intense stimuli create a larger change in this ongoing flow, change detectors would produce a stronger output when an intense stimulus is turned on. Thus, this elaboration predicts especially rapid and forceful responses for intense stimuli.

As a more specific example of this idea, one might hypothesize that stimulus intensity effects on response force are merely due to startle reflexes. Specifically, if stimulus onset reaches a sufficiently high intensity in a sufficiently brief time, the stimulus will elicit a startle response (Blumenthal & Berg, 1986b). The present manipulation of stimulus duration also provides a test of this hypothesis because studies of such reflexes have shown that they depend mostly on the transient characteristics of a stimulus. In contrast, increases of stimulus duration beyond 40 to 50 ms affect neither probability, amplitude, nor latency of the startle reflex (Blumenthal & Berg, 1986a; Marsh, Hoffman, & Stütt, 1973). Thus, if the effect of intensity on response force is another manifestation of the mechanisms underlying the startle reflex, one would expect response force to be rather uninfluenced by the sustained characteristics of a stimulus,

<sup>1</sup> In the General Discussion, we consider in more detail whether modifications of such models are compatible with intensity effects on the motor system, including some new effects demonstrated here.

<sup>2</sup> This class is sometimes called *timing models* in the RT literature (cf. Luce, 1986, p. 379).

like its duration beyond 50 ms, as examined in the present study.

In conclusion, then, the rate-dependent model suggests that response force should be unaffected by a manipulation of stimulus duration—at least when stimulus intensity is well above the detection threshold. Thus, the strongest version of this elaboration suggests that response force would depend on stimulus intensity but not on stimulus duration.

The rate-dependent criterion models assume that the sensory system can compute rates for the sensory accumulation process. This would require a rather stable (i.e., not noisy) accumulation process to provide accurate estimates of the rate because rate must be computed on brief samples of neural activity. Consistent with this assumption, certain data suggest rather stable sensory responses to stimulus input. First, psychophysical experiments (e.g., Sakitt, 1972) have shown that humans are able to detect one quantum of light; it seems inappropriate to characterize overall sensory processing as very noisy if a single quantum can be detected. In addition, the human visual system is renowned for its excellent overall resolution (Wandell, 1995). This seems to be accomplished by summing signals from individual receptors, yielding a summed signal which is extremely precise, both spatially and temporally. Second, physiological data from early sensory systems indicate that the response to a stimulus is rather stable. For example, intracellular flash responses of individual rods and cones are sufficiently precise that intensity effects can clearly be seen in single-trial recordings (e.g., Schnapf & Baylor, 1987). Even with very weak light flashes, the resulting intracellular rod responses are sufficiently larger than the noise so that they are clearly visible on single trials (Fain, 1976). Thus, these findings seem to be compatible with the assumption of rather stable sensory signals, as needed to compute the rate of accumulation with sufficient accuracy.

### Total-Dependent Criterion Models

An alternative elaboration of the criterion model assumes that the size of the go signal is positively related to the total amount of accumulated activation at the point when the criterion value is crossed. In addition, it denies the commonly made assumption that the criterion remains constant while the accumulation process is active. In the presence of speed stress, it might be advantageous to lower the criterion gradually during the accumulation process in order to speed the response. If that happened, more intense stimuli would produce more forceful as well as more rapid responses because the criterion would be crossed sooner—and therefore at a higher level—when activation built up quickly.

According to this elaboration, both SRT and response force should be sensitive to stimulus duration, and they should be sensitive to it over the same range. To see this property, first imagine the accumulation process elicited by a relatively short stimulus. Accumulation will build up continuously until the stimulus is switched off, at which point the accumulated information will still not be sufficient to satisfy the criterion. In this case, the detection process cannot

release the go signal until the criterion is lowered to the level of the accumulated information. Thus, the detection time will be long and the go signal will be small, implying a slow and weak response. Now imagine the accumulation process of a relatively long stimulus of the same intensity. The accumulation process will reach the criterion at some critical duration before stimulus offset, and the length of the stimulus beyond this critical duration will influence neither detection time nor go-signal size. Thus, both latency and force depend on duration up to but not beyond this critical duration. Therefore, this elaboration implies that both SRT and response force should be sensitive to stimulus duration over the same range, and both should saturate beyond the same critical stimulus duration.

This model assumes that the criterion must start being lowered during the foreperiod; it would be too late to start lowering the criterion when the signal was detected because in the SRT task, signal detection is sufficient for response initiation. Consistent with this assumption, studies have shown that SRT diminishes rapidly with foreperiod length and attains a minimum at about 150 ms (Alegria, 1974; Bertelson & Tisseyre, 1968; Ulrich & Mattes, 1996). This result is compatible with the assertion that participants might lower their criterion in anticipation of the stimulus to speed up the response.

### Gating Model

Like the traditional formulation, this version assumes that the detection process does not output any information to the motor system until the accumulation process reaches the criterion. However, in contrast to the original model, this model assumes that a gate opens once the criterion is reached and that any further incoming sensory information is forwarded through the open gate to the motor system. For example, the initial burst of activation provided by the stimulus might be sufficient to start the process of recruiting motor units for the response (i.e., open the gate), and yet further activation from the stimulus could further increase the number of units recruited. The length of time that the gate stays open is a free parameter within this model; for example, it could be assumed that the gate closed after a fairly short duration (say, 50 ms), that the gate stayed open until the termination of the response, or anything in between. Although the initial burst of activation provided by the stimulus would be sufficient to trigger the response and therefore determine SRT, the rate of subsequent activation from the stimulus into the motor system would still influence response force. Thus, this model predicts that stimulus intensity would affect the rate of the accumulation process not only before but also after the criterion is reached, thus influencing both SRT and the size of the go signal (and hence response force).

This elaboration clearly suggests that response force should be sensitive to stimulus duration because the size of the go signal is affected by the amount of activation arriving while the gate to the motor system is open. When a stimulus is switched off before the gate is closed, it will contribute less additional activation to the motor system than will a

long stimulus that contributes activation throughout the period when the gate is open. Unlike the preceding elaborations, this elaboration allows response force and SRT to be sensitive to stimulus duration over somewhat different ranges. It seems evident that the size of the go signal will increase with stimulus duration even after the criterion is reached, whereas detection latency will depend only on the amount of time until the gate is opened. Thus, response force will be sensitive to a larger range of stimulus durations than SRT. Furthermore, if the gate stayed open long enough, one could imagine that stimulus duration might influence the shape of the force output profile as well as the total force output. If additional motor units were recruited for the entire duration of the stimulus, for example, then the duration of the force pulse would clearly increase with the duration of the stimulus.

### Total-Dependent Counting Models

Although most models of SRT belong to the class of criterion models considered above, it is also reasonable to consider an alternative class of counting models that have been suggested to account for stochastic stimulus detection (McGill, 1963). This class assumes a fixed time interval, the observation period, during which activation is accumulated. The total amount of activation arriving during the observation period provides an estimate of the perceived intensity, and it is used to judge whether or not a stimulus was presented. Although this model has usually been applied in situations where participants try to detect weak signals and where accuracy is the dependent variable, it could also be used to model SRT simply by letting the detection time  $D$  be the length of the observation period. Because the observation period is selected by the participant prior to stimulus onset, however, this model makes the surprising prediction that the length of the observation period does not depend on stimulus intensity. Hence, according to this model, all of the effect of intensity on SRT would have to be due to the effect on  $M$ . Indeed, the model is quite compatible with an effect of intensity on  $M$ , assuming that the size of the go signal reflects the amount of activation arriving during the observation period. Because this amount would increase with stimulus intensity, a more intense stimulus would produce a larger go signal, leading to smaller  $M$  and more forceful responses. The idea that intensity effects may manifest at distal rather than proximal stages is clearly compatible with the findings mentioned above that stimulus intensity affects response force.

If stimulus duration and intensity are varied, counting models predict that response force should also increase with duration. A shorter stimulus is more likely to terminate before the end of the observation period than a longer one, so a longer stimulus will tend to cause more activation to accumulate during the observation period, on average, leading to both faster and more forceful responses. There is a limit to the effect of duration, however. Beyond a critical duration, the stimulus will be so long that it always extends past the end of the observation period, so further increases in stimulus duration will have no further effect on go-signal

size and therefore no effect on SRT or force. For the present purposes, the crucial prediction of counting models is that the critical stimulus duration should be the same for effects on both SRT and force. Both of these variables depend on the amount of activation accumulated during the observation period, so each will saturate only when the stimulus is so long that it always extends past the end of the observation period. Thus, saturation should occur at the same stimulus duration for both SRT and force.<sup>3</sup>

In conclusion, the standard discrete model cannot account for intensity effects on response force because it proceeds from the assumption that the go signal is independent of stimulus intensity. We therefore considered various extensions of the standard model, retaining the assumption of sequential processing but rejecting the assumption of an invariant go signal. Each elaboration assumes that more intense signals produce more energetic go signals, which may not only shorten the motor time but also produce especially forceful responses (the variable output assumption). Three of the elaborations retain the assumption of a punctate go signal, but the fourth (gating model) allows transmission of activation into the motor system over an extended period of time. Although all four elaborations account for the intensity effects on response force, they may be distinguished when stimulus duration and stimulus intensity are varied (see Table 1). In the present two experiments, we factorially manipulated the intensity and the duration of the stimulus to assess these various elaborations of the standard model and thereby gain further insight into the mechanisms underlying the influence of intensity on force.

### Experiment 1

In the first experiment, we used auditory stimuli. Stimulus duration was manipulated in the range from 5 to 320 ms and was factorially crossed with three levels of stimulus intensity (56.6, 71.5, and 86.6 dB).

#### Method

*Participants.* Thirty participants were volunteers (mean age = 28.8 years) recruited on the campus of the University of Konstanz. They were tested in a single session and received 7.50 deutsche marks. All participants were naïve about the experimental hypothesis. All but one participant claimed to be right-handed.

*Apparatus and stimuli.* Participants were seated in a dimly illuminated room. A microcomputer controlled stimulus presentation, recorded response force, and produced a background noise of 36 dB(A) as measured at the participant's ear.

The auditory stimulus was a 1000-Hz tone presented binaurally via headphones. Stimulus duration was either 5, 10, 20, 40, 80, 160, or 320 ms. Stimulus intensities were 56.3, 71.5, or 86.8 dB(A), which were well above detection threshold. The temporal profile of

<sup>3</sup> This prediction rests on the additional assumption that response force and SRT are sensitive to go-signal size over the same range, so the model could predict different critical durations if force and SRT saturated at different go-signal sizes. We ignore this complication in the present study because the intensities used in the present study were low enough to avoid saturation on either measure.

Table 1  
Predictions of Various Variable Output Models

Model	Prediction		
	Effect of stimulus intensity on response force	Effect of stimulus duration on response force	Relationship of critical durations
Rate-dependent criterion	Response force increases with intensity	Duration should not affect response force	
Total-dependent criterion	Response force increases with intensity	Response force increases with duration	Identical critical durations for both response force and SRT
Gating	Response force increases with intensity	Response force increases with duration	Critical duration is longer for response force than for SRT
Total-dependent counting	Response force increases with intensity	Response force increases with duration	Identical critical durations for both response force and SRT

Note. SRT = simple reaction time.

the auditory stimulus resembled the shape of a sine wave. This function always started with a zero crossing and attained its first maximum after 0.5 ms. When the stimulus was switched off, it turned into an underdamped motion for less than 0.5 ms. Thus, both the onset and the offset of the stimulus were rather abrupt.

Response force was measured by means of a force key of the same sort used previously (e.g., Giray & Ulrich, 1993). One end of a leaf spring (110 × 19 mm) was held fixed by an adjustable clamp, and the other end remained free. The participant's forearm rested comfortably on a table while his or her index finger bent down the free end of the leaf spring in response to the stimulus. A force of 10 N bent the free end by about 1 mm. The resolution of this device was about 2 cN (approximately 2 g). Strain gauges were attached to the leaf spring, so force applied to its free end caused changes in an electrical signal that was digitized with a sampling rate of 500 Hz. Reaction time was scored as soon as response force crossed the criterion level of 50 cN.

*Procedure.* There were 21 blocks of 21 trials each. A single block contained all possible factorial combinations of intensity by duration in a random order. The first block served as a practice block and was excluded from data analysis. There was a short rest after each block, during which the computer presented feedback about mean SRT and response accuracy in the previous block. The participant initiated the next block when she or he felt ready to proceed.

To minimize stimulus anticipation, the intertrial interval between stimulus onsets was random with a mean duration of 5 s. The interval was the sum of a constant basetime of 4 s and an exponentially distributed random variable with a mean of 1 s. Participants were asked to respond as quickly as possible without making anticipations, and anticipations were further discouraged by visual feedback presented when participants responded before stimulus onset. Trials with SRT less than 90 ms or larger than 800 ms were considered outliers and were excluded from the data analysis.

Each dependent variable reported below was submitted to a repeated-measures analysis of variance (ANOVA) with factors of intensity and duration. The significance levels of the ANOVAs were adjusted according to the procedure of Greenhouse and Geisser (1959) as necessary to compensate for violations of the sphericity assumption.

## Results and Discussion

*Response errors.* The percentages of anticipations (RTs < 90 ms) and inattention errors (RTs > 800 ms) were 6.6

and 3.1, respectively. The percentage of anticipations increased slightly with stimulus intensity,  $F(2, 58) = 4.9, p = .024$ , with percentages of 5.4, 5.7, and 8.7 for the three intensity levels. This main effect indicates that a small percentage of true SRTs were mistakenly classified as outliers. There were no further significant main effects on these response errors.

*Reaction time.* The upper panel of Figure 1 shows SRT as a function of stimulus duration and intensity.<sup>4</sup> As expected, SRT decreased as duration increased,  $F(6, 174) = 21.9, p < .001$ , with the effect of duration saturating between 20 and 60 ms as in the studies of Hildreth (1973, 1979) and Raab (1962). SRT also decreased with increasing intensity,  $F(2, 58) = 198.4, p < .001$ , and the effect of duration on SRT diminished as intensity increased,  $F(12, 348) = 7.6, p < .001$ . A similar interaction was reported by Hildreth (1973).

*Response force amplitude.* The maximum force value and the total force integrated over time were determined for each trial. Both measures assessed the forcefulness of a response. The middle graph of Figure 1 depicts mean peak force (PF), and the lower graph depicts mean integrated force (IF), as a function of duration and intensity. As in the study of Angel (1973), PF increased with intensity,  $F(2, 58) = 66.6, p < .001$ . It also increased with stimulus duration,  $F(6, 174) = 8.2, p < .001$ . IF also increased with intensity,  $F(2, 58) = 52.7, p < .001$ , and with duration,  $F(2, 58) = 13.9, p < .001$ . In addition, the interaction of duration and intensity was highly significant for both PF,  $F(12, 348) = 3.5, p = .003$ , and IF,  $F(12, 348) = 5.1, p < .001$ . In contrast to SRT, duration had a stronger effect on both measures when stimulus intensity was high.

The correlation coefficients among the dependent mea-

<sup>4</sup> The error bars in each plot are equal to two times SE of the mean. The SE was computed from the error terms of the repeated-measures design according to a suggestion made by Loftus and Masson (1996). In short,  $SE = \sqrt{MSE/n}$ , where  $n$  is the number of scores averaged to get the corresponding mean at the level of ANOVA. *MSE* represents the pooled error terms combining the sums of squares for the Intensity × Participants interaction, the Duration × Participants interaction, and the Intensity × Duration × Participants interaction.

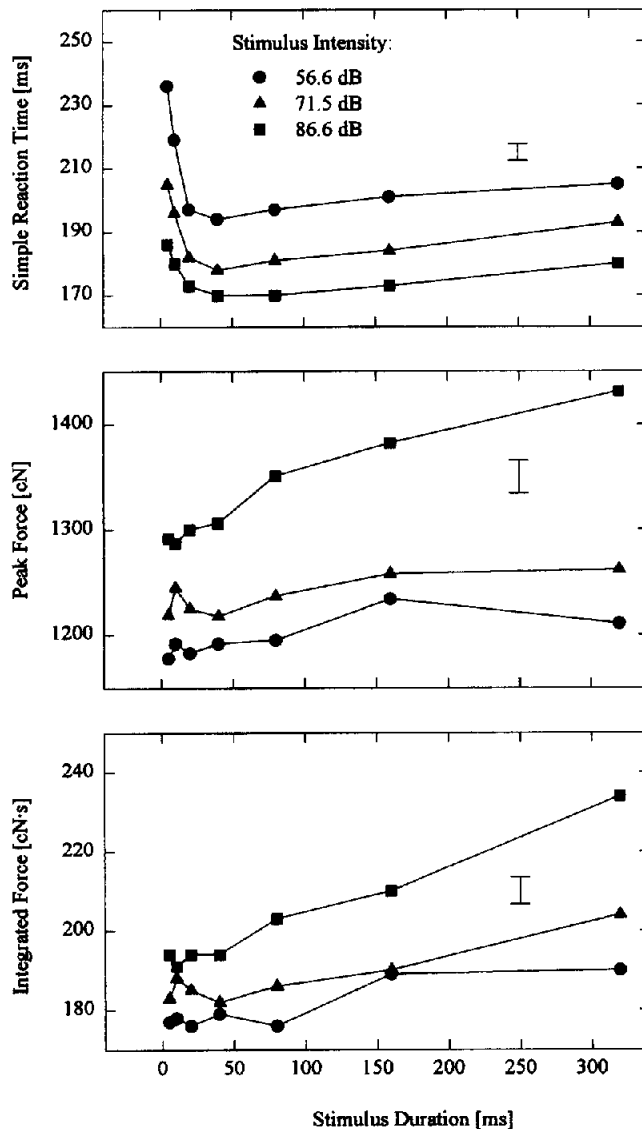


Figure 1. Experiment 1: simple reaction time, peak force, and integrated force as a function of stimulus intensity and duration.

sures SRT, IF, and PF were computed for each participant within each factorial combination of duration and intensity across trials. As has been found previously (e.g., Giray & Ulrich, 1993), the overall average correlations between reaction time and both force measures were almost zero,  $r(\text{SRT}, \text{PF}) = .00$  and  $r(\text{SRT}, \text{IF}) = .05$ , whereas the two force measures were strongly related,  $r(\text{PF}, \text{IF}) = .90$ .

This experiment replicated the basic finding of Angel (1973) that more intense stimuli produce more forceful responses. In addition, the results show that stimuli of longer durations also produce more forceful responses and that there is an interaction of stimulus intensity and duration, such that the effect of intensity on response force increases with stimulus duration.

The present findings are inconsistent with some versions

of the variable output model discussed in the introduction (see Table 1). First, contrary to the rate-dependent criterion model, stimulus duration affected response force. This finding argues against the view that intensity effects on response force are merely due to the initial speed with which sensory information accumulates within the perceptual stage.

Second, the present findings are also inconsistent with the predictions of the total-dependent criterion and total-dependent counting models because durations greater than approximately 40 ms yielded almost equivalent SRTs, whereas IF and PF continued to increase with duration all the way to 320 ms. This conclusion was supported by a separate two-way ANOVA, which included only stimulus durations of at least 80 ms. This analysis revealed that both PF,  $F(2, 58) = 4.3, p = .021$ , and IF,  $F(2, 58) = 12.1, p = .001$ , increased significantly with stimulus duration, whereas SRT,  $F(2, 58) = 4.2, p = .044$ , no longer decreased but actually slightly increased, exhibiting the so-called Broca-Sulzer phenomenon. Thus, this additional analysis clearly supports the theoretically important conclusion that response force continues to increase with stimulus duration beyond the critical duration at which SRT saturates.

Although the present findings rule out several versions of the variable output model, the differential effects on SRT and response force are in accord with at least one version, namely, the gating model. As noted in the introduction, this version allows a prolonged rather than a punctate go signal and thereby predicts a longer critical duration for response force than for SRT, in accordance with the present findings. Within this model, the fact that response force continues to increase with stimulus duration up to 320 ms suggests that the gate is actually open for quite a long period of time, possibly into the actual execution of the movement. Furthermore, the gating model can also account for the obtained intensity by duration interaction on response force. This is because sensory information should arrive at a higher rate while the gate is open for high than for low stimulus intensity. As a result, the size of the go signal should increase more rapidly with stimulus duration for more intense stimuli. Because the size of the go signal directly determines the amount of force output, increasing stimulus intensity should therefore magnify the effect of stimulus duration on response force. (We consider in the General Discussion how the gating model may account for the observed zero correlation between response force and SRT; at present, this finding does not seem to discriminate among the proposed models.)

*Shape analysis of force-time profiles.* The shapes of the force-time functions were also analyzed to test further the proposition that the motor system receives activation over a long period of time, as assumed by the gating model. It seems plausible that late-arriving activation should influence the shapes of the force-time functions, making them, for example, relatively longer lasting and less sharply peaked with long stimulus durations than with short ones.

We used seven different shape measures, divided into three sets, to assess this possibility. Each measure was computed for each trial, and then averages were computed

Table 2  
*Analysis of Variance Results of Shape Measures for All Levels of Stimulus Duration and for Durations of at Least 80 ms*

Measure	All levels of duration			Durations of at least 80 ms		
	D	I	I × D	D	I	I × D
Force duration	.001	.05	.10	.001	.05	.05
Time to peak force	.001			.001	.05	
Time from peak force	.01	.05		.001	.05	.10
Rate of force growth	.05	.001	.05	.10	.001	
Rate of force decay	.05	.001	.10		.001	
Skewness	.05	.01		.05	.05	
Kurtosis	.01	.10		.01		

*Note.* The table shows the significance levels of stimulus duration (D), stimulus intensity (I), and their interaction (I × D). All tail probabilities were rounded up to conventional significance levels of .001, .01, .05, and .10. An empty cell indicates a nonsignificant effect, that is,  $p > .10$ .

across trials within a condition for each participant.<sup>5</sup> The resulting averages were submitted to separate two-way ANOVAs with factors of duration and intensity. One ANOVA included all durations, and—analogue to the previous analyses of SRT, PF, and IF—a second ANOVA included only durations of at least 80 ms. Table 2 summarizes these statistical analyses, and Figure 2 shows mean values for each shape measure as a function of stimulus intensity and duration. It is important to note that the ANOVA results did not markedly change when only stimulus durations of 80, 160, and 320 ms were included.

The first set of measures assessed the duration of force output. The results were as follows: (a) Force duration measures how long response force exceeds the criterion force of 50 cN. As expected, this measure increased with stimulus duration, and it also increased slightly with stimulus intensity. Force duration can be decomposed into the time from the criterion to the peak force and the time from the peak force back down to the criterion. We conducted separate analyses of these components to determine whether the initial or final portion of the force pulse was affected by each factor. (b) The initial portion of the force pulse (i.e., time to peak force) clearly increased with stimulus duration and also increased slightly with stimulus intensity for the longest durations only. It is interesting to note that the grand mean of this measure was 112 ms, which is close to the minimal attainable value of about 90 ms (Freund & Büdingen, 1978; Siegel, 1988; Ulrich & Mattes, 1996). Thus, the responses were quite rapid. (c) The final portion of the force pulse (i.e., time from peak force) increased slightly but reliably with both stimulus duration and stimulus intensity. In sum, consistent with our expectation, longer stimuli prolonged the force output of a response. This prolongation affected both the initial and the final portion of force output. An analogous but weaker effect was found for stimulus intensity.

Of course, it is hardly surprising that responses with greater peak force would last longer; indeed, increased duration seems almost a necessary biomechanical conse-

quence of a larger peak, especially when durations are near the minimum possible. Thus, with the second set of kinetic measures we examined the rates of force growth and decay to see whether force changes consist of more than just a simple rescaling of force and time (cf. Ulrich, Wing, & Rinkenauer, 1995). The results were as follows: (a) For each force pulse, we determined the ratio of the peak force to the time to peak force. This ratio was conceived as a measure of the rate of force growth. This rate increased with both the intensity and the duration of the stimulus, although the effect of duration was especially strong for intense stimuli. (b) The ratio of the peak force to the time after peak force provides an index of the rate of force decay. Force decayed especially quickly for intense stimuli, which is not surprising because the decay phase starts at larger peak forces for these stimuli. In contrast, however, the decay rate was only slightly affected by stimulus duration. In conclusion, then, the rate of force rise and decay was clearly modulated by stimulus intensity but only slightly by stimulus duration.

The last set of measures used central moments as shape descriptors (Cacioppo & Dorfman, 1987). These measures were recently used by Ulrich et al. (1995) to assess the shape of force pulses. If the force-time function on each trial is normalized to have an area of 1, it can be thought of as analogous to a probability distribution, and its shape can be described by standard measures of skewness and kurtosis. Each of these two shape descriptors was scored on the force-time function for each trial. The results were as follows: (a) Pulses generally exhibited a positive skewness; that is, they were skewed to the right and became more positively skewed as stimulus intensity increased. Pulses were more symmetrical at longer stimulus durations. (b) Kurtosis is commonly used as an index of peakedness. As this index increases, the peakedness of a pulse is thought to increase. This analysis indicated that pulses were flatter with longer stimulus durations. This finding agrees with the idea that longer lasting stimuli produce a continued force output, leading to less peaked pulses.

In general, the results of the shape analyses are consistent with the idea that prolonged stimuli not only increase the amplitude of the force-time functions but also increase the duration of force output, thereby causing systematic shape changes. Interestingly, these changes resemble the changes produced when participants are explicitly instructed to prolong the force output of brief isometric pulses. Ulrich et al. (1995) asked participants to vary pulse duration from trial to trial, and distinct shape changes emerged for longer pulses. First, the time to peak force increased with the pulse duration. Second, longer pulses were more symmetrical and usually flatter. Because the force-time functions for longer stimuli were similar to those observed when participants were instructed to produce longer pulses, it seems plausible

<sup>5</sup> It should be noted that the shape characteristics of an average of single-trial force-time functions are usually distorted relative to the shape characteristics of the individual signals entering into the average. Hence, we preferred to score single-trial signals and average their scores instead of scoring average force-time functions.

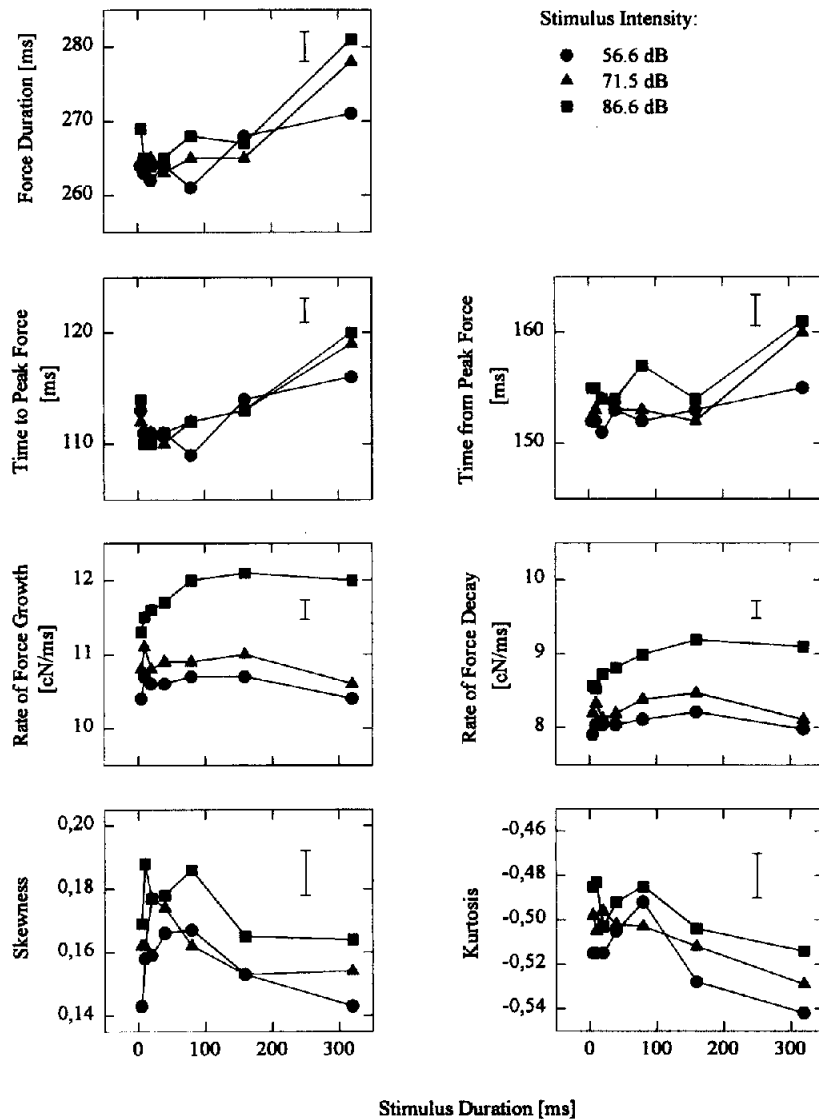


Figure 2. Experiment 1: shape measures as a function of stimulus intensity and duration.

to conclude that stimulus duration not only increased the magnitude of the go signal but also increased its duration. This particular finding agrees with the gating model's prediction of continued transmission of activation into the motor system while the gate is open.

### Experiment 2

It is known that auditory stimuli exert an immediate arousal effect, facilitating the processing of incoming information at either central (Nissen, 1977; Posner, 1978) or distal (Sanders, 1983) stages of information processing. There is also evidence that response force is sensitive to immediate arousal (Miller et al., in press, Mordkoff, Miller, & Roch, 1996; Ulrich & Mattes, 1996). Thus, it is quite possible that immediate arousal changes are necessary for a continuing flow of activation to the motor system. If that is the case, the results obtained in Experiment 1 may well be limited to the auditory modality and thus will not

generalize to other sensory modalities. To test this possibility, in Experiment 2 we used visual stimuli, which appear much less likely to produce immediate arousal effects (Nissen, 1977). Stimulus duration was manipulated in the range from 2 to 320 ms and was again factorially crossed with three levels of stimulus intensity (0.022, 0.220, and 2.200 cd/cm<sup>2</sup>).

### Method

**Participants.** A fresh sample of 35 participants (mean age = 25.2 years) was tested.<sup>6</sup> All participants claimed to be right-handed.

<sup>6</sup> In Experiment 2, we added a further level of stimulus duration and therefore had to reduce the number of replications per factorial combination to keep the total trials per session constant across the two experiments. To compensate for the potential loss of statistical power, we increased the sample size from 30 to 35 participants in Experiment 2.



**Apparatus and stimuli.** Participants were stimulated by two red LEDs (Hewlett Packard, HLMP-8150, wavelength peak at 650 nm, diameter = 13.3 mm); that is, each LED stimulated one eye. These LEDs permitted an accurate timing of stimulus durations over a reasonable range of intensity levels. Onset and offset of the stimuli were practically instantaneous. Each LED was attached at one end of a grey tube (length = 140 mm, diameter = 25 mm). The tubes were parallel and fixed at eye level. Participants viewed the LEDs from padded open ends of the tubes. The distance between tubes as well as the tubes' inclination were adjusted for each participant so as to maximize comfort. Participants were asked to keep their eyes pressed against the tubes throughout a single block. The weakest intensity level could not be detected with eyes closed, so participants were required to keep their eyes open at the expected moment of stimulus presentation. The low percentage of misses testifies that our participants were cooperative and followed these instructions.

**Procedure.** The procedure was essentially the same as in Experiment 1 with the following exceptions. First, participants were dark-adapted for 5 min before the first block started. Second, an additional stimulus duration, 2 ms, was added to the set of durations used in the previous experiment because Mansfield (1973) showed that SRT may already level off at a stimulus duration of about 10 ms for visual stimuli. Third, a single block comprised 24 trials; that is, each factorial combination occurred one time within a single block. There were 18 blocks.

### Results and Discussion

**Response errors.** The percentages of anticipations (RTs < 90 ms) and inattention errors (RTs > 800 ms) were 1.0% and 2.2% and were thus considerably smaller than those in Experiment 1. There were no significant effects of intensity or duration on these response errors.

**Reaction time.** Mean SRT is depicted in the upper panel of Figure 3. Compared with the previous experiment, stimulus duration had a much smaller yet analogous effect on SRT,  $F(7, 238) = 3.6, p = .004$ . The effect leveled off within the 10–20 ms range. SRT decreased with stimulus intensity,  $F(2, 68) = 125.7, p < .001$ , and the interaction of these two factors was not significant,  $F < 1$ .

**Response force.** Mean PF and IF are shown in the middle and lower panels of Figure 3. As in the previous experiment, PF and IF increased with stimulus intensity,  $F(2, 68) = 16.0, p < .001$ , and  $F(2, 68) = 15.2, p < .001$ , respectively. Stimulus duration again enhanced PF and IF,  $F(7, 238) = 3.5, p = .009$ , and  $F(7, 238) = 5.9, p = .004$ , respectively. The interaction of duration and intensity approached statistical significance for PF,  $F(14, 476) = 2.0, p = .084$ , and was significant for IF,  $F(14, 476) = 2.6, p = .032$ . As in Experiment 1, duration had a stronger effect on both measures when stimulus intensity was high.

Separate ANOVAs with stimulus durations of at least 40 ms were conducted for SRT, IF, and PF. There was no significant main effect of stimulus duration on SRT,  $F(3, 102) = 2.4, p = .087$ . However, IF was still enhanced,  $F(3, 102) = 4.4, p = .021$ , by an increase of stimulus duration beyond the 20-ms level, although the slight increase of PF did not attain statistical significance,  $F(3, 102) = 2.1, p = .122$ . Thus, Experiment 2 essentially replicated the critical result of Experiment 1: Prolonging the stimulus increases

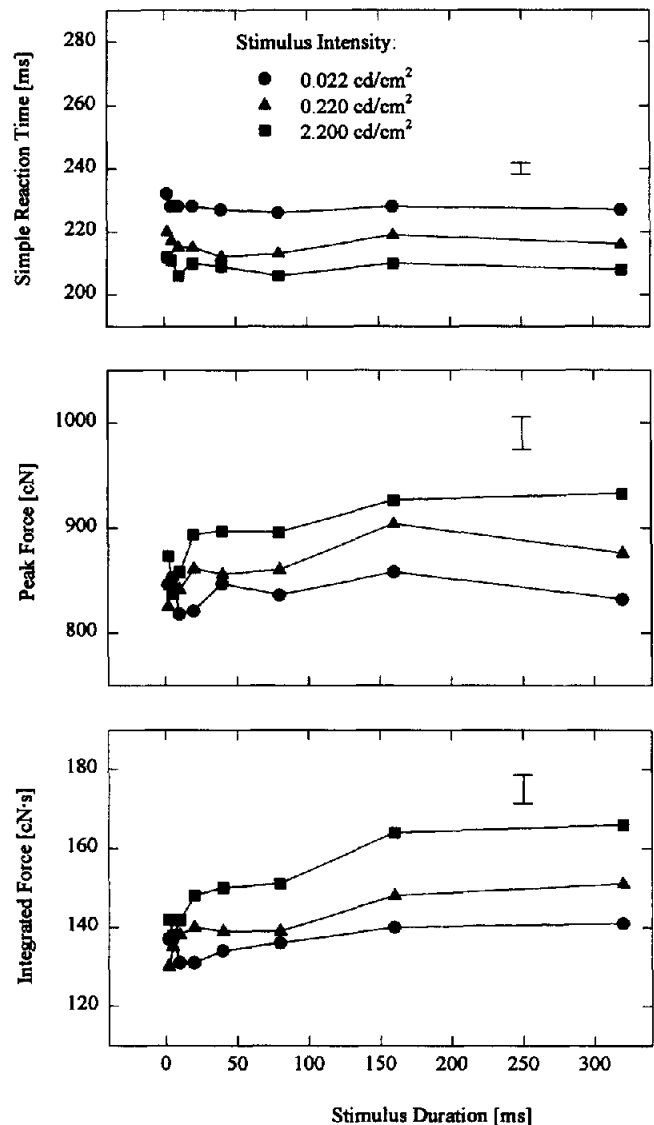


Figure 3. Experiment 2: simple reaction time, peak force, and integrated force as a function of stimulus intensity and duration.

the total force output even beyond the point at which the effect of duration on SRT has already saturated.

A correlation analysis identical to Experiment 1 was performed, and the average correlations were as follows:  $r(\text{SRT}, \text{PF}) = -.06$ ,  $r(\text{SRT}, \text{IF}) = -.01$ , and  $r(\text{PF}, \text{IF}) = .92$ . These values are in accord with those obtained in Experiment 1.

**Shape analysis of response-force profiles.** Shape analyses analogous to those of Experiment 1 were conducted (see Figure 4 and Table 3). The general pattern of results was rather consistent with the one obtained in Experiment 1. As in Experiment 1, longer stimuli prolonged force duration and also produced more symmetrical and flatter force-time functions. In contrast to Experiment 1, however, stimulus intensity had a relatively strong influence on force duration

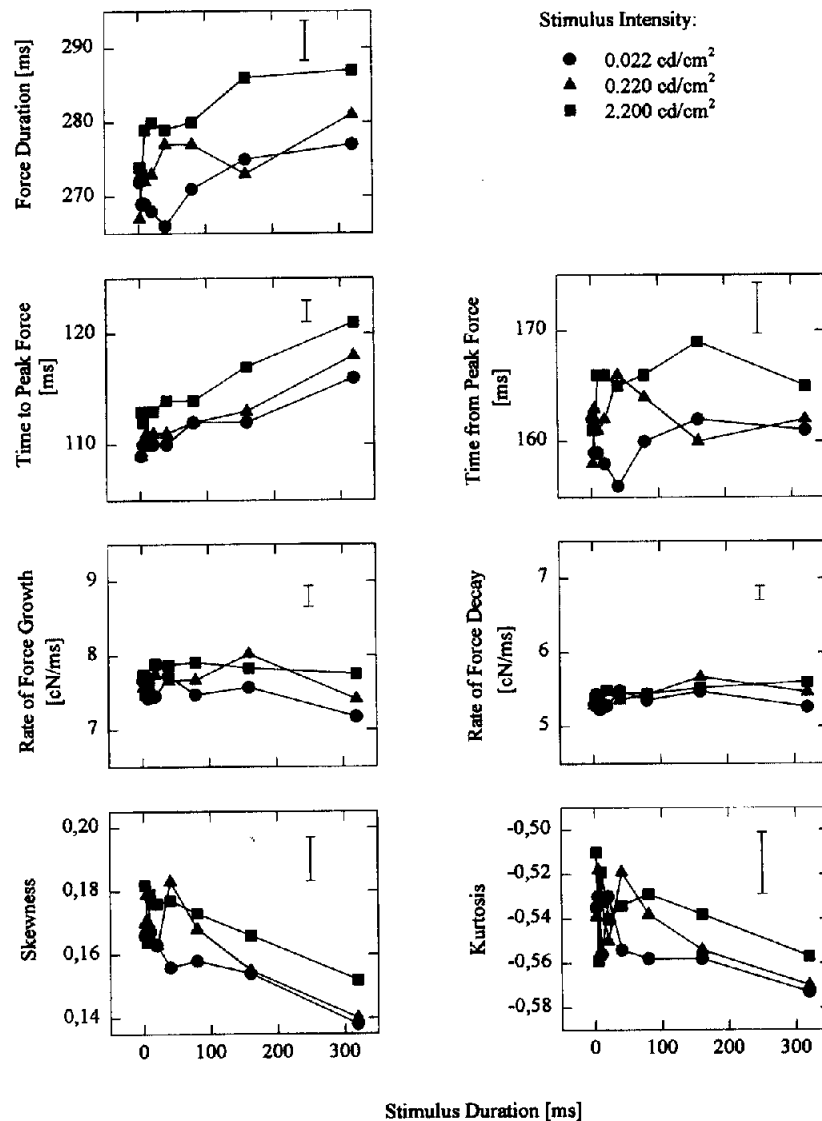


Figure 4. Experiment 2: shape measures as a function of stimulus intensity and duration.

and a relatively weak effect on the rates of force growth and decay.

The full pattern of results agrees nicely with the results of Experiment 1. There were effects of intensity and duration on both SRT and force, but duration clearly had an effect over a larger range for force. There were two main differences between the results of the two experiments, however. First, auditory stimuli produced generally faster SRTs (mean difference = 29 ms),  $t(63) = 2.93$ ,  $p < .001$ , and more forceful responses: mean PF difference = 363 cN,  $t(63) = 2.09$ ,  $p < .025$ ; mean IF difference = 44 cN · s,  $t(63) = 1.28$ , *ns*. Second, auditory but not visual stimulus intensity enhanced the rate of force growth and decay. Both differences may be attributable to the immediate arousing property of auditory stimuli, which might augment the information transmission from the sensory to the motor system.<sup>7</sup> Despite these differences, however, Experiment 2 demon-

strates that the idea of prolonged output from the perceptual into the motor system is not limited to the auditory modality but also applies to other sensory modalities.

<sup>7</sup> One might argue that these differences between the two experiments do not reflect arousing properties of auditory stimuli but would disappear if stronger visual intensity levels had been used in Experiment 2 such that equal SRT means were obtained in both experiments. Although we cannot completely rule out this possibility, there is evidence against such an account. The mean SRT for the highest visual intensity level in Experiment 2 was 209 ms, and the mean SRT for the lowest auditory intensity level in Experiment 1 was 207 ms. Even though these means were virtually identical, responses were still more forceful for the auditory than for the visual stimuli. The respective means of PF were 1,198 cN and 839 cN. Hence, it seems unlikely that the difference in response force between experiments was simply a matter of psychophysically unmatched intensity levels in the two sensory modalities (Kohfeld, 1971).

**Table 3**  
*Analysis of Variance Results of Shape Measures for All Levels of Stimulus Duration and for Durations of at Least 40 ms*

Measure	All levels of duration			Durations of at least 40 ms		
	D	I	I × D	D	I	I × D
Force duration	.001	.001		.05	.001	
Time to peak force	.001	.001		.001	.001	
Time from peak force		.01			.001	
Rate of force growth	.10	.01		.05	.001	
Rate of force decay	.10					
Skewness	.001	.05		.001	.05	
Kurtosis	.05			.10		

*Note.* The table shows the significance levels of stimulus duration (D), stimulus intensity (I), and their interaction (I × D). All tail probabilities were rounded up to conventional significance levels of .001, .01, .05, and .10. An empty cell indicates a nonsignificant effect, that is,  $p > .10$ .

### General Discussion

The present study clearly revealed that response force is sensitive not only to the intensity of a stimulus (Angel, 1973; Jaskowski et al., 1995; Mattes & Ulrich, 1997; Miller et al., in press; Ulrich & Mattes, 1996) but also to its duration. In both experiments, increasing stimulus duration enlarged both the response amplitude and the effect of stimulus intensity on response force. Of particular theoretical importance is the fact that response force is sensitive to duration over a much larger range than is SRT. The effects of duration on force were apparent not only in overall force amplitude but also in analyses of the shape of force-time profiles. These analyses suggest that the characteristics of a response can still be altered even after the moment of response initiation because in our experiments a longer stimulus prolonged force output and increased its amplitude, even up to durations of 320 ms. This prolonged force output was reflected in systematic changes of shape parameters resembling the changes that occur when participants are explicitly instructed to prolong the force output of their responses (Ulrich et al., 1995). The effects of duration on force output have several implications for models of SRT, which we discuss in the next few sections.

The present results also extend the findings of previous studies concerning intensity effects on response force in two ways. First, they show that the effect of stimulus intensity on response force depends on the duration of the stimulus. The intensity effect is stronger with long than with short stimuli. Second, the present results also show that response force and reaction time can be dissociated in that in both experiments, the effect of intensity was largest at short stimulus durations for SRT but was largest at long durations for response force. This pattern argues against the notion that response speed and response force are merely two different sides of one coin, showing instead that they reflect somewhat different aspects of processing. The zero within-condition correlation between speed and force is also consistent with this conclusion.

### Constant Stage Output Models

The present results provide further evidence against certain kinds of discrete-stage models of SRT (e.g., Grice, 1968; Luce, 1986; Smith, 1995; Sternberg, 1969). As mentioned in the introduction, such models assume the operation of two sequential processing stages, stimulus detection and motor execution. According to this modal view, the stimulus-detection stage accumulates sensory information and releases a punctate go signal as soon as the accumulated information attains a certain threshold value. The go signal is transmitted to the motor system to start the execution of the response. Because both processes are assumed to operate in a strictly serial fashion, SRT is conceived to be the sum of the durations of these two processes. Within this framework, stimulus manipulations are assumed to affect only detection but not motor processes. The finding that stimulus intensity and duration affect response force argues strongly against the transmission of a constant go signal to the motor system within this conception, although as is elaborated later, this evidence does not necessarily indicate that stimulus intensity influences the duration of motor processes.

### Variable Stage Output Models

An alternative conception, which is more consistent with the effect of intensity on force, is that the go signal can vary in overall activation or strength and that the size of the go signal depends on stimulus intensity (e.g., Miller et al., in press; Ulrich & Mattes, 1996). For example, the decision system may release a stronger go signal to the motor system for intense stimuli. The strength of this go signal may influence the speed of motor execution and the output of response force. Such a response system might also account for the natural translation of higher intensity to higher force (Kornblum, Hasbroucq, & Osman, 1990; Romaignère, Hasbroucq, Possamai, & Seal, 1993).

In this article, we examined different versions of variable output model. These versions represent extensions of traditional reaction time models and each can account for the effect of intensity on response force. Common to all versions is the idea that the size and duration of the go signal increase with stimulus intensity, and each version specifies a mechanism by which this increase might be accomplished. Although all versions predict more forceful responses to more intense stimuli, they make different predictions with regard to stimulus duration (cf. Table 1).

One version, the rate-dependent criterion model, holds that the initial rate of sensory accumulation determines not only the speed of a response but also its force output. The larger the rate, the larger is the go signal released to the motor system. This version predicts that response force should be insensitive to stimulus duration, and the present data clearly rule out this version because response force was affected over a rather large range of stimulus durations.

Two other versions, the total-dependent criterion and total-dependent counting models, imply that the amount of force depends on the total amount of accumulated sensory information at the moment when the criterion to trigger the

motor system is reached. Both versions predict that SRT and response force should be sensitive to duration over approximately the same range. Because response force was sensitive over a much larger range of durations, we may also rule out these two versions.

The most promising version seems to be the gating model, which elaborates the standard criterion model by assuming that the detection process opens a gate through which activation flows to the motor system, thus allowing a prolonged rather than a punctate transmission of activation to the motor system. An initial burst of activation begins the response and thus determines SRT, but any further sensory information arriving while the gate is open will prolong and thus increase motor activity. Thus, the size of the go signal will increase not only with stimulus intensity but also with stimulus duration, at least up to the time when the gate is closed again. As discussed in the introduction, this model suggests that response force is sensitive to a larger range of stimulus durations than is SRT, and both experiments confirmed this prediction. Furthermore, this model provides a simple account for the finding that stimulus intensity enhances the effect of stimulus duration on response force because the rate of arriving activation while the gate is open increases with stimulus intensity, producing an overadditive effect of intensity and duration on the size of the go signal. Finally, the gating model also accounts for the evidence from shape analyses indicating that longer stimuli produce a prolonged activation of the motor system.

Although the gating model provides a simple and plausible account of the effects of stimulus intensity and duration, it is somewhat more difficult to see how the model explains the obtained zero correlation between response force and response speed. One could perhaps assume that there are instantaneous fluctuations in the rate of accumulation before the gate is opened (i.e., before the criterion is reached). These fluctuations could influence SRT but not force, whereas fluctuations during the time when the gate is open could affect response force but not response speed. Thus, this view allows the model to predict that SRT and response force would be uncorrelated. The difficulty with this view is that it seems inconsistent with the strong positive autocorrelations found in virtually all time-series of biological signals (e.g., electroencephalogram, electromyogram). Such autocorrelations also seem quite likely for the accumulation of sensory information, and thus any fluctuation in the rate of accumulation before the criterion would propagate to the accumulation of sensory information during the period when the gate is open. Thus, an autocorrelated accumulation process suggests a positive rather than a zero correlation between response force and response speed. Therefore, even though the gating model provides a satisfactory explanation of how stimulus intensity and duration affect response force, it seems somewhat difficult to explain how a zero correlation between response force and response speed can emerge within this particular model class. One possibility is that other variables produce a counteracting effect on the correlation, resulting in a zero correlation overall. For example, Mattes, Ulrich, and Miller (1997) found that when participants were highly prepared, their responses were faster yet

less forceful than when participants were relatively unprepared. Thus, trial-to-trial variation in the level of response preparation might produce a negative relation between response speed and response force, counteracting the positive relation predicted by the model to produce an overall correlation of zero. Clearly, further work is needed to develop and test correlation predictions in more detail.

### *Continuous Models*

So far, we have discussed traditional sequential stage models and have shown that elaborations of these models can account for the present findings. It seems important to ask whether the alternative class of stage models, the so-called continuous models, provide a more parsimonious account for the present findings. Like classical SRT models, continuous models (Eriksen & Schultz, 1979; McClelland, 1979) proceed from the assumption of serially arranged processing stages. However, unlike discrete-stage models, different stages can be active at the same time because each stage continuously processes partial output available from its predecessor stage. Within this framework it seems plausible that the motor stage is activated gradually by the perceptual system and that this might cause an increase of response force with more intense or prolonged stimuli.

Interestingly, more detailed analysis shows that some well-known examples of this model class, the cascade model (McClelland, 1979) and its elaborations (Bussemeyer & Townsend, 1993; Smith, 1995), cannot account for the present data without further modifications. The cascade model implies that the strength of a stage's input determines the strength of its output. Furthermore, this model holds that a response is emitted when the accumulated activation at the final response stage exceeds a certain threshold value. This simple version does not explain the basic effect of intensity on force because all responses are initiated at the same criterion activation value regardless of stimulus intensity. It is, however, possible to elaborate this model by assuming that (a) the onset of a response movement starts when activation in the response stage attains the threshold value and (b) response force depends on the amount of continued activation after the criterion is crossed. Such an elaboration may explain why intense and prolonged stimuli cause more forceful responses. First, within a given amount of time, intense stimuli forward more activation than weak ones to the response stage. This increased activation would cause stronger responses. Second, the amount of accumulated activation in the response stage would be larger for long than for short stimuli. Thus, longer stimuli would not only lengthen force output but would also enlarge the total amount of force output, that is, the integrated force. Although the elaborated cascade model might account for the observed force effects, it has difficulty accounting for the observed zero correlation between SRT and response force because random trial-to-trial variation of activation in the response stage should influence both measures, producing a correlation. As mentioned earlier, however, little weight can be placed on the absence of force-SRT correlations because it is difficult to know what other sources of trial-to-trial

variation might contaminate the correlation predicted from trial-to-trial variation in activation. We also note that this elaborated cascade model is quite similar to the gating model in allowing prolonged transmission of activation to the motor system. The main difference between the two models is in the onset of activation to the motor system. In the gating model, this onset is rather abrupt because of the requirement that an activation criterion be reached before any transmission of activation to the motor system. The cascade model involves no such criterion and therefore allows a gradual onset. As has been noted in previous studies (e.g., Molenaar, 1990), researchers can make gating models arbitrarily similar to the cascade model by using an arbitrarily small criterion.

In summary, the present results suggest that response force is sensitive to the duration of a stimulus as well as to its intensity and that the characteristics of a response can still be altered even after the timing of the response has been fully determined. This is evidence against models with punctate transmission of stimulus information to the response process and support for models that allow for prolonged activation of the motor system, continuing after the decision process has detected the stimulus and initiated the response. At this point, certain continuous models and certain variable output models provide acceptable accounts of these effects.

In conclusion, although our results indicate that traditional discrete-stage, constant-output models are not compatible with the effects of stimulus characteristics on response force, we must note that such models may still provide an adequate description of the temporal characteristics of processing.<sup>8</sup> More specifically, the fact that stimulus intensity and duration affect force output does not necessarily imply that they also affect the speed of motor processing. Indeed, the gating model, which provides an adequate description of the results, clearly suggests that response latency is determined by an initial burst of input to the motor stage, despite the fact that force is sensitive to more prolonged inputs. Thus, the present results leave open the possibility of making inferences from reaction time as prescribed by discrete-stage models (e.g., Sternberg, 1969), despite the fact that such models seem inconsistent with effects of stimulus characteristics on force.

<sup>8</sup> We thank Howard C. Hughes for pointing out this argument to us.

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