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Effects of auditory stimulus intensity on response force in simple, go/no-go, and choice RT tasks

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In four experiments, increasing the intensities of both relevant and irrelevant auditory stimuli was found to increase response force (RF) in simple, go/no-go, and choice reaction time (RT) tasks. These results raise problems for models that localize the effects of auditory intensity on purely perceptual processes, indicating instead that intensity also affects motor output processes under many circumstances. In Experiment 1, simple RT, go/no-go, and choice RT tasks were compared, using the same stimuli for all tasks. Auditory stimulus intensity affected both RT and RF, and these effects were not modulated by task. In Experiments 2–4, an irrelevant auditory accessory stimulus accompanied a relevant visual stimulus, and the go/no-go and choice tasks were used. The intensity of the irrelevant auditory accessory stimulus was found to affect RT and RF, although the sizes of these effects depended somewhat on the temporal predictability of the accessory stimulus.

It is well known that subjects in reaction time (RT) tasks respond faster to bright or loud stimuli than to dim or soft ones (see, e.g., Kohfeld, 1971). This effect is not surprising, because sensory and perceptual processing are clearly faster for more intense physical stimuli (Levick, 1973). Indeed, it is often assumed that the effects of stimulus intensity on RT can be accounted for entirely within the sensory and perceptual systems (see, e.g., Burbeck & Luce, 1982; Hildreth, 1979; Smith, 1995; Sternberg, 1969; Vaughan, Costa, & Gilden, 1966).

Contrary to this view, however, there is evidence that stimulus intensity can affect response processes as well as perceptual ones. First, stimulus intensity has been found to influence the forcefulness of responses. For example, Angel (1973) examined stimulus intensity effects on RT and response force (RF) in simple RT tasks using visual, auditory, and tactile stimuli. In each trial, he recorded the full force–time function of the response and found that the peak of this function increased with stimulus intensity for all modalities. Ulrich, Rinkenauer, and Miller (1998) successfully replicated Angel's result for both auditory and visual stimuli, and Jaśkowski, Rybarczyk, Jaroszyk, and Lemański (1995) replicated it for auditory stimuli, although not for visual ones. Clearly, an influence of intensity on RF indicates that intensity must have some effect on the response system, even if this effect is contingent on and mediated by the perceptual analysis of the stimulus input. Using similar logic, Abrams and Balota (1991) and Balota and Abrams (1995) have demonstrated that response dynamics are influenced by more cognitive factors, such as word frequency and memory set size, and have therefore concluded that these factors influence motor stages as well as perceptual and decision-making ones.

Second, auditory stimulus intensity has been found to influence the variability of the response system in simple RT tasks. Ulrich and Stapf (1984) asked subjects to respond with both hands simultaneously in a simple RT task, and they computed the difference between the RTs for the two hands, arguing that this difference should be sensitive to the durations of response stages but not of perceptual ones. They found that the difference was less variable, from trial to trial, for loud stimuli than for soft ones. Like Angel's (1973) findings, this suggests that stimulus intensity directly influences response processes.

As discussed by Nissen (1977), postperceptual effects of stimulus intensity are important because they contradict models in which intensity influences only early perceptual processes. In these models, intensity cannot have

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even an indirect effect on downstream decision and motor stages, at least in tasks in which perceptual outputs are categorized independently of stimulus intensity (i.e., intensity is task irrelevant). The exact arrangement of processing stages in such models is not crucial for the present discussion, so we will ignore distinctions among simple serial-stage models (e.g., Sternberg, 1969) and more recent and elaborate stage models allowing various kinds of parallel processing structures (e.g., Liu, 1996; Schweickert & Townsend, 1989; Townsend & Ashby, 1983; Townsend & Nozawa, 1995; Townsend & Schweickert, 1989). As will be elaborated next, however, effects of stimulus intensity on motor output have thus far been established only for a very narrow range of experimental conditions, even with auditory stimuli, whose motoric effects are best documented. Thus, it is possible that models with strictly perceptual intensity effects may still be tenable in other cases. It is clearly of interest to investigate possible intensity effects on motor output in a wider range of conditions, both to find out whether the effects of intensity are ever strictly localized within perceptual processes and to help identify the mechanisms responsible for the effects of intensity on motor output.

The present experiments addressed two questions about the generality of the effect of auditory stimulus intensity on response processes. First, is the effect of intensity on force robust across tasks? Previous demonstrations that stimulus intensity affects response processes have only used the simple RT task, in which the subject makes the same response to any stimulus (Angel, 1973; Jaśkowski et al., 1995; Ulrich & Stapf, 1984). Obviously, this task requires very limited perceptual discrimination and response selection processes (Donders, 1868/1969), allowing a relatively direct connection between sensory and response processes. It is easy to imagine that the effect of intensity on force depends on the directness of this connection, in which case the effect might disappear when the task is made more complex, consistent with models in which auditory intensity effects stop short of response processes. This suggestion is quite consistent with the analysis of Nissen (1977), who reviewed various differential effects of stimulus intensity on simple versus choice RT . She noted that these differential effects may be explained by a two-pathway model in which intensity effects on simple RT are mediated by an energy-based pathway, whereas intensity effects on choice RT are mediated by a nonenergy-based pathway. If the former pathway mediates the effect of intensity on RF, the effect should be absent in choice tasks. In Experiment 1, then, we varied auditory stimulus intensity in go/ no-go and choice RT tasks, as well as in simple RT tasks, to see whether intensity would still affect force in these more complex tasks.

Second, is RF influenced by the intensity of irrelevant stimuli as well as relevant ones? In previous studies demonstrating that stimulus intensity affects response output, experimenters have always varied the intensity of a task-relevant stimulus. In most cases, this relevant stimulus has been the imperative stimulus itself (Angel, 1973; Jaśkowski et al., 1995; Ulrich & Stapf, 1984). Ulrich and Mattes (1996) found that intensities of warning signals (both auditory and visual) also influence RF, but these warning signals were also task relevant because they conveyed timing information about the occurrence of the upcoming imperative stimulus. Thus, previous results only show that RF is influenced by the intensity of a relevant stimulus.

It is also of theoretical interest to find out whether the intensities of irrelevant stimuli affect RF, and Experiments 2–4 were designed to answer this question. There is ample evidence that task-irrelevant stimuli do receive postperceptual processing (see, e.g., Eriksen, Coles, Morris, & O'Hara, 1985), so it is certainly possible that their intensities would affect response output. Indeed, one explanation of intensity effects on RF is that they are mediated by intensity-driven changes in arousal (Giray, 1990; Mordkoff, Miller, & Roch, 1996; Ulrich & Mattes, 1996). If arousal is influenced by the physical characteristics of irrelevant as well as relevant auditory stimuli, as seems likely (Brunia & Boelhouwer, 1988; Sanders, 1983; Scheirs & Brunia, 1982), intensities of irrelevant stimuli should influence RF just as intensities of relevant stimuli do. On the other hand, the effects of relevant-stimulus intensity on force might alternatively be attributed to changes in the asymptotic activation levels of internal representations of the task-relevant stimuli (McClelland, 1979). On this view, stronger stimuli produce stronger perceptual outputs, which feed onward through the decision-making system and eventually lead to greater response activation (i.e., higher force). If this is the explanation of intensity effects on force, such effects may not be found when the intensities of irrelevant stimuli are varied.

In summary, the present experiments investigated the generality of the finding that auditory stimulus intensity influences RF. Specifically, in Experiment 1, we sought to determine whether this influence is present in go/no-go and choice tasks as well as in simple RT tasks, and in Experiments 2–4, we examined whether the effect is present for irrelevant stimuli as well as relevant ones. The answers to these questions will help identify the circumstances under which chronometric models can or cannot explain auditory intensity effects solely in terms of sensory and perceptual processes. Obviously, if intensity influences RF, the effects of intensity cannot be solely perceptual. In addition, these answers should help elucidate the mechanisms by which intensity influences RF. It should be noted that there were two main reasons for our decision to vary the intensities of auditory, rather than visual, stimuli. One reason was that the intensities of auditory stimuli tend to have particularly large and reliable effects on RF (see, e.g., Jaśkowski et al., 1995). If intensity has different effects on force in different tasks, it would seem easiest to document this interaction in a situation in which the effects were large in the first place. A second reason for studying the effects of auditory stimuli is that task-irrelevant auditory stimuli often have much larger effects on RT than do task-irrelevant visual ones (see, e.g., Bernstein, 1970). It seems plausible that the intensities of irrelevant stimuli are most likely to influence force when such stimuli are known to have larger effects on other measures.

EXPERIMENT 1

The purpose of this experiment was to see whether auditory stimulus intensity would influence RF in go/no-go and choice RT tasks, as well as in simple RT tasks. On each trial, the subjects were presented with a single pure tone at one of two possible frequencies and one of three possible intensities. In the simple RT task, the subjects made the same response to all tones. In the go/no-go task, the subjects responded to tones of one frequency and withheld responses to tones of the other frequency. In the choice RT task, the subjects responded with the left or the right hand to indicate the frequency of the tone.

To our knowledge, the influence of stimulus intensity on RF in choice and go/no-go tasks has only been examined once before: Miller, Ulrich, and Pfaff (1991) found no effect of visual intensity on RF in either of these tasks, but also found no effect in a simple RT task. Their results suggest that the previously obtained effects of stimulus intensity on RF may be specific to certain kinds of stimuli, responses, or procedures. Given their failure to replicate the effect of intensity on force in simple RT tasks, however, their results must be interpreted with caution. Thus, the present studies mimicked the procedure of Angel (1973) more closely, in order to replicate the effect of intensity on force in simple RT tasks. Once effects of intensity on force are obtained in simple RT tasks, the same stimuli and procedures can be used in go/no-go and choice RT tasks to see whether intensity effects disappear in more complex tasks, which would be consistent with models in which intensity effects are localized entirely within perceptual processes.

Method

Subjects. The subjects were 36 undergraduate students (17 females, 19 males) from the University of California, San Diego. They received course credit for their participation.

Stimuli. Each stimulus was a 600 or 1000 Hz pure tone, presented binaurally via headphones for 150 msec. These frequencies were chosen to be easily discriminable. Each tone was presented at one of three intensity levels: approximately 55, 75, or 90 dB, with a background noise of approximately 45 dB.

Apparatus. The subjects responded with a brief flexion of the left or the right index finger, depending on experimental condition. The force of this flexion was measured by force-sensitive keys similar to telegraph keys. A leaf spring (140 × 20 × 2 mm) was held in a clamp at one end of the force key, and the subjects pressed on the other, free end with the index finger. A force of 15 N bent the free end of the leaf spring approximately 2 mm. The response key was mounted on a board that provided full forearm support. One response key was used for each hand, and both boards were angled at the subject's convenience. Strain gauges (Type 6/120 LY 41, manufactured by Hottinger Baldwin Messtechnik, Darmstadt, Germany) were attached near the fixed end of the leaf spring, so force applied to the leaf spring at the free end was reflected in an analog signal, with a resolution of approximately 2.8 mN. The digitized force signal was recorded at 100 Hz, starting 150 msec before stimulus onset and continuing for 2,500 msec. This allowed RT to be measured to the nearest 10 msec, and this resolution is more than adequate in studies of effects on mean RT (Ulrich & Giray, 1989).

Procedure. Three tasks (simple RT , go/no-go, and choice RT) were employed in a single session lasting approximately 45 min. In the simple RT task, the subjects responded to any auditory signal; in the go/no-go task, they responded to tones of one frequency but not to the other; and, in the choice task, they responded with one hand to tones of each frequency. The assignments of frequency to hand in the choice task and to the go response in the go/no-go task were counterbalanced over subjects, as was the order of tasks.

Each task was run in two successive blocks of trials, with each combination of signal intensity and frequency occurring seven times randomly intermixed within each block, yielding a total of 28 trials per subject for each combination of task and intensity. The interval between two successive signal presentations was never less than 7.5 sec. A random duration drawn from the exponential distribution with a mean of 1 sec was added to this 7.5-sec interval to prevent anticipatory responses.

Task instructions for each block were presented on the computer screen at the beginning of the block, and the subjects initiated the block by pressing a footswitch when they felt ready to proceed. The first five trials of each block were considered practice, to familiarize the subjects with the new task. The subjects were instructed to respond as quickly as possible without making too many errors, and they were instructed not to press the response key during the intertrial interval.

Method of analysis. RT was defined as the first moment at which force exceeded a criterion of 40 cN (about 40 g) after response signal onset. This value was selected because it is approximately the force needed to trigger a response with many common setups for measuring RT. Responses with RTs of less than 100 msec were considered anticipations and were discarded from data analysis (0.09% of trials). There were no responses with RTs greater than our predetermined cutoff for slow outliers, 2,300 msec.

In each trial, peak force (PF) was determined from the recorded force–time function to assess potential effects on RF. Other force measures could also be taken (e.g., the total size of the force impulse), but these tend to be highly correlated with PF and slightly noisier than it (cf. Giray & Ulrich, 1993).

For each subject, mean values of RT and PF were computed across all correct-response trials within each condition (task × intensity). Only right-handed response trials were included from the choice task, for comparability with the simple RT and go/no-go tasks in which all responses were made with the right hand. These individual-subject means were analyzed, using repeated measures analyses of variance (ANOVAs) with factors of task and intensity, separately for RT and PF.

Results and Discussion

Trials with response errors were discarded from the data analysis. In the go/no-go task, there were 4% false alarms in no-go trials. The subjects responded with the wrong alternative in 6% of the trials in the choice task. Table 1 shows the percentage of correct responses as a function of task and stimulus intensity for all of the experiments reported in this article, and it is apparent that stimulus intensity did not have much effect on response accuracy.

Figure 1 shows mean RT and PF as a function of stimulus intensity and task. Separate two-way ANOVAs, with factors of task and intensity, were carried out for RT and PF.

Table 1
Percentage of Correct Responses as a Function of Stimulus Intensity (Low, Medium, High) and Task for Experiments 1–4

	Task								
	Simple RT			Go/No-Go			Choice RT		
Experiment	Low	Med	High	Low	Med	High	Low	Med	High
1	100	99	100	98	99	98	93	97	93
2				99	99	99	97	96	97
3				99		100	97		97
4							99		98

The ANOVA on RT indicated that both main effects were highly significant ($p < .001$) but that the interaction was not [$F(4,120) = 1.89$, $MS_e = 3{,}590$, $p = .12$]. Post hoc comparisons indicated that RT was significantly greater in the low-intensity condition than in the medium- and high-intensity conditions, which did not differ significantly from each other. In addition, RT was significantly less in the simple RT task than in the go/no-go and choice tasks. The difference between go/no-go and choice tasks was barely reliable ($.04 < p < .05$) by the Newman–Keuls test.

The ANOVA on PF indicated that the main effect of stimulus intensity was highly significant [$F(2,60) = 7.32$, $MS_e = 2{,}369$, $p < .001$], and post hoc comparisons indicated that PF was significantly lower in the low-intensity condition than in the medium- and high-intensity conditions, which did not differ from each other. Neither the main effect of task nor the task × intensity interaction approached significance ($p > .3$ in both cases). Further analyses compared low-intensity stimuli against the average of medium- and high-intensity stimuli, considering each task separately. These yielded significant effects of intensity in the simple and choice tasks ($p < .05$) and a marginally significant effect in the go/no-go task ($p < .10$). Clearly, then, the effect of auditory intensity on RF is not limited to simple RT tasks but extends to more complex tasks as well.

Three stronger statistical tests for a task × intensity interaction were also carried out, but none yielded significant evidence of an interaction ($p > .20$). One examined the interaction of task with a two-level intensity factor, using low intensity as one level and the average of medium and high intensities as the other level. The second looked for differences between tasks in the linear trend across the three levels of intensity. The third tested for a linear trend across the three tasks in the slope of the function relating PF to intensity.

For each subject, the correlation of RT and PF was computed across all the trials within each task by intensity combination, to see how force and RT are related when all experimenter-manipulated variables are held constant. Across subjects and conditions, the average correlation coefficient was .01, indicating that response speed is not linearly related to RF within a single condition. Near-zero correlations between RT and PF have been reported previously (e.g., Giray & Ulrich, 1993).

In summary, the results of this experiment indicate that there are effects of auditory stimulus intensity on RF in go/no-go and choice tasks, extending the results of Angel (1973) and others. These results indicate that auditory intensity affects motor output processes—not merely perceptual ones—in go/no-go and choice tasks, as well as in simple RT tasks.

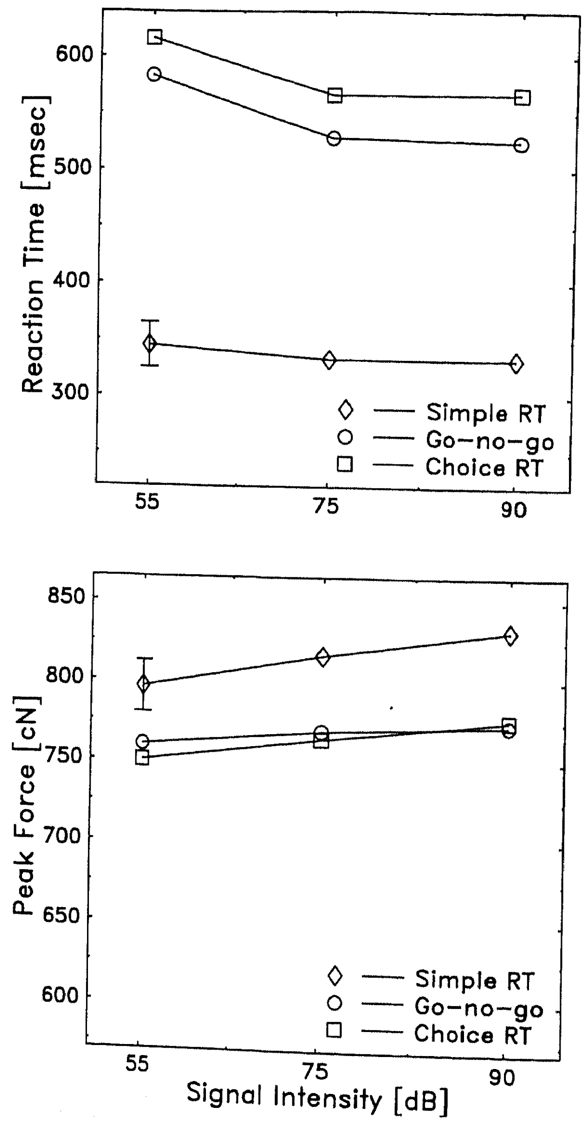

Figure 1. Experiment 1: Mean reaction time (RT) and peak force (PF) as functions of task and stimulus intensity. The vertical bars indicate deviations of two standard errors in each direction from the condition means. The estimate of error was obtained by pooling across the intensity × subject and intensity × task × subject interaction terms, which were virtually identical in the analyses of both RT and PF, so the error bars are appropriate for judging differences between intensities and for judging differences in the effect of intensity across tasks. Note that the error bars are not appropriate for judging differences between tasks; the task × subject interaction was not included in the error term, because it was substantially larger than the others and because main-effect comparisons between tasks are of subsidiary interest.

EXPERIMENT 2

As was noted earlier, previous studies of the effects of intensity on force have varied only the intensities of relevant stimuli. This experiment examined whether the intensity of irrelevant auditory stimuli would also influence RF. If so, we can conclude that the intensities of irrelevant stimuli can also influence motor output processes, as do the intensities of relevant stimuli.

Method

Subjects. The subjects were 28 undergraduate students (17 females, 11 males) from the University of California, San Diego. They received course credit for their participation.

Apparatus. The apparatus was identical to that in Experiment 1.

Stimuli. The characters X and O served as response signals on the computer screen. These characters were 2 cm high and were presented for 150 msec at an intermediate brightness (37 cd/m^2). In each trial, an accessory auditory stimulus preceded the visual signal by 50 msec. The physical parameters of the accessory auditory stimuli were identical to those of the auditory stimuli employed in Experiment 1. Intensity and frequency levels of the accessory stimuli were randomly intermixed within each block of trials.

Procedure. Two tasks (go/no-go and choice RT) were employed in a single session, and each task was run in two successive blocks of trials. In the go/no-go task, the subjects responded to one visually presented character but not to the other, and in the choice task, they responded with one hand to one character and with the other hand to the other character. The assignments of character to hand in the choice task and to go-trials in the go/no-go task, as well as the order of tasks, were counterbalanced over subjects. Each combination of visual character, auditory stimulus intensity, and auditory stimulus frequency occurred five times within a single block. A session lasted about 50 min. In all other respects, the procedure of this experiment was identical to that of Experiment 1.

Results and Discussion

Response errors occurred in 2% of all trials. Two percent false alarms were observed in no-go trials; in the choice task, the subjects responded with the wrong hand in 3% of all trials. There were no anticipatory responses (RT < 100 msec) or slow outliers (RT > 2,300 msec). These percentages are very similar to those of Experiment 1.

Figure 2 shows mean RT and PF as a function of task and accessory intensity. An ANOVA on RT indicated that the effect of intensity was statistically reliable [$F(2,48) = 3.91$, $MS_e = 707$, $p < .05$], and post hoc comparisons with the Newman–Keuls procedure indicated that responses were significantly faster with high intensity than with medium or low intensity, with the latter two conditions not differing from one another. The 43-msec difference between go/no-go and choice tasks was also significant [$F(1,24) = 28.57$, $MS_e = 2,766$, $p < .001$], but the interaction between intensity and task was not ($F < 1$).

An ANOVA on PF revealed a significant interaction of task and intensity [$F(2,48) = 3.82$, $MS_e = 1,708$, $p = .029$], with no other significant sources of variance. Separate ANOVAs for each task showed that PF increased with accessory intensity in the go/no-go task [$F(2,48) = 6.56$, $MS_e = 1,262$, $p < .01$], whereas there was no effect of accessory intensity on PF in the choice task [$F(2,48) = 0.387$, $MS_e = 1,689$, $p = .68$].

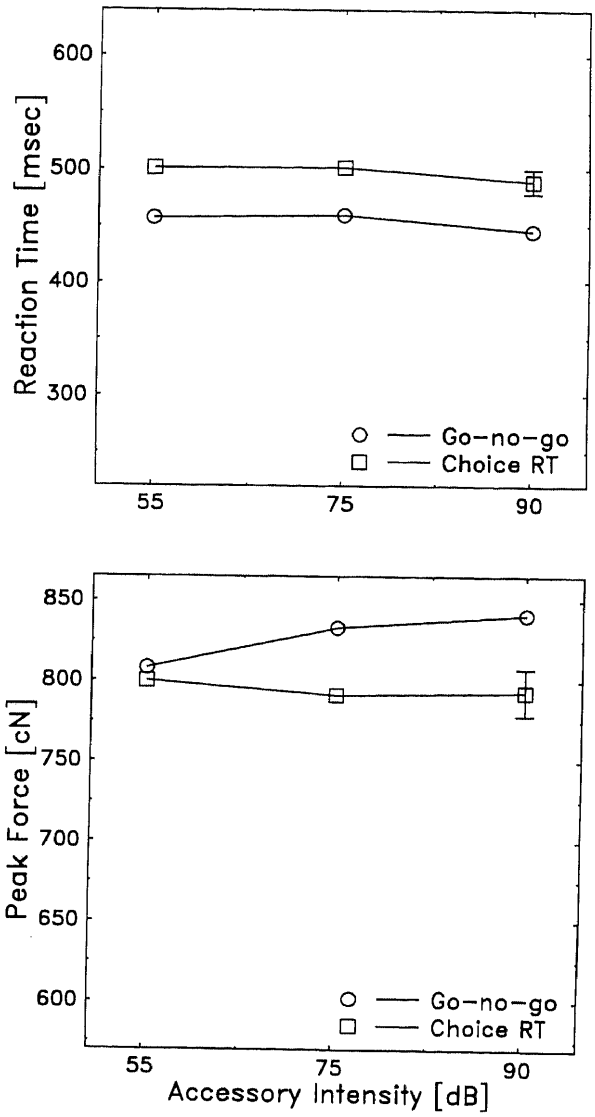

Figure 2. Experiment 2: Mean reaction time (RT) and peak force as functions of task and the intensity of a task-irrelevant accessory stimulus. The vertical bars indicate deviations of two standard errors in each direction from the condition means, computed in the same way as those for Figure 1.

Because the same auditory stimuli were used in Experiments 1 and 2, it is possible to compare the effects of intensity on force across the two experiments to see whether intensity has different effects when it is conveyed by relevant rather than by irrelevant auditory stimuli. On average across the go/no-go and choice tasks, the effect of intensity on force was numerically larger with relevant than with irrelevant auditory stimuli (20 vs. 13 cN), but this difference did not approach significance ($p > .2$). There was a three-way interaction of intensity, relevance, and task, however, suggesting that stimulus irrelevance reduces the effect of intensity more for choice tasks than for go/no-go tasks [$F(1,62) = 4.67$, $MS_e = 9{,}797$, $p < .05$]. In the choice task, the overall effect of intensity was larger for relevant stimuli (26 cN) than for irrelevant stimuli (−7 cN), although the difference between these two effects only approached significance [$F(1,62) = 3.1$, $MS_e = 5{,}777$, $p < .10$]. In the go/no-go task, in contrast, the overall effect of intensity was actually smaller for relevant stimuli (13 cN) than for irrelevant stimuli (33 cN), although these two values were again not reliably different ($p > .10$).

EXPERIMENT 3

The pattern of results obtained in Experiment 2 was unexpected, in that intensities of irrelevant auditory stimuli influenced RF for the go/no-go task but not for the choice task. To clarify this pattern, Experiment 3 was basically a replication of Experiment 2, except that it used randomly varying delays between the onsets of the relevant stimuli and the irrelevant accessories. These random delays were introduced to test two possible explanations of the observed differences between the go/no-go and the choice tasks.

According to one explanation, the intensities of unattended stimuli really have no effect on force, and the obtained intensity effect in the go/no-go task was an artifact. Because the accessory always occurred 50 msec prior to the relevant stimulus, the accessory was temporally relevant, and it could have been used to optimize the time of response preparedness (Bertelson & Tisseyre, 1969; Nickerson, 1973; Niemi & Näätänen, 1981; Requin, Brener, & Ring, 1991). Optimal preparedness may be more useful in the go/no-go task, in which the overt motor response is known in advance, than in the choice task, in which it is not. Thus, the extra usefulness of the accessory in the go/no-go task may have caused the subject to pay some attention to the accessory when performing this task. If the accessory was attended, of course, its intensity would be expected to have an effect on RF, just as would the intensity of any other relevant stimulus.

Experiment 3 tested this explanation by varying the temporal relation of the accessory to the relevant stimulus, in order to minimize temporal cuing. If the effect of accessory intensity on RF in the go/no-go task resulted from attended processing because of its temporal relevance, the effect should be greatly reduced or eliminated in the go/no-go task of Experiment 3, because of the varying stimulus onset asynchronies (SOAs).

According to the second explanation, the intensities of irrelevant stimuli do influence RF, but the lack of effect in the choice task of Experiment 2 was artifactual. This artifact would operate if intensity effects are extremely short lived with irrelevant accessory stimuli—a possibility consistent with the short-lived timecourse of the accessory effect on RT (Bernstein, Clark, & Edelstein, 1969). Specifically, intensity effects of irrelevant stimuli may have been absent in the choice task of Experiment 2 because choice responses took so long that the effects of intensity had faded away. This view is consistent with the fact that effects were found in the go/no-go task, because the faster responses in this task may have been made while intensity was still having an effect. This explanation in terms of effect persistence requires a further assumption to handle the presence of relevant-stimulus intensity effects on force in Experiment 1: Intensity effects last longer for relevant than for irrelevant stimuli. This additional assumption is quite plausible, of course, because attended stimuli would be likely to be processed actively for longer than unattended ones. Experiment 3 tested this explanation by including conditions in which the accessory stimulus occurred later, relative to the choice stimulus, which should allow choice responses to be made before the accessory effect had faded.

Method

Subjects. The subjects were 28 undergraduate students (16 females, 12 males) at the University of Konstanz, Germany. In return for their participation, they received either course credit or a payment of 10 DM (approximately $7 US).

Stimuli. The visual stimuli were the characters X and O. These characters were 2 cm high and had a brightness of 37 cd/m^2, so they were easily discriminable and appeared at an intermediate intensity level on the screen. The characters were presented for 148 msec. Auditory stimuli were similar to those used in Experiments 1 and 2, except that there were only two levels of intensity (54 and 87 dB) and one frequency (1000 Hz). Tones were presented binaurally via headphones for 148 msec. One visual stimulus and one auditory stimulus were presented on each trial, with an SOA of -50, -16, 16, or 50 msec, measured from the onset of the visual stimulus to the onset of the auditory stimulus.

Apparatus. The apparatus was functionally identical to that used in Experiment 1, although there were minor physical differences in the equipment of the laboratories in San Diego and Konstanz. The response manipulanda and force measurement systems were nearly physically as well as functionally identical. Recording of force began 207 msec before visual stimulus onset and continued for 2,707 msec.

The procedure was nearly identical to that of Experiment 2, except for differences caused by the manipulation of SOA. Each combination of visual character, auditory stimulus intensity, and SOA was presented five times within a single block.

Results and Discussion

Response errors occurred in 2% of all trials, with 1% false alarms in no-go trials and 3% responses with the wrong hand in the choice task. No spuriously fast or slow RTs were observed. These percentages are very similar to those of Experiments 1 and 2.

Figure 3 shows mean RT and PF as a function of task, accessory intensity, and SOA, and Table 2 shows the task × intensity means, averaging over SOA. As expected, the 22-msec effect of intensity on RT was statistically reliable [$F(1,24) = 52.26$, $MS_e = 1{,}050$, $p < .001$], as was the 83-msec difference between go/no-go and choice tasks [$F(1,24) = 144.26$, $MS_e = 5{,}276$, $p < .001$]. As in Experiment 1, the interaction between these two factors was not significant ($F < 1$). In addition, there was a significant

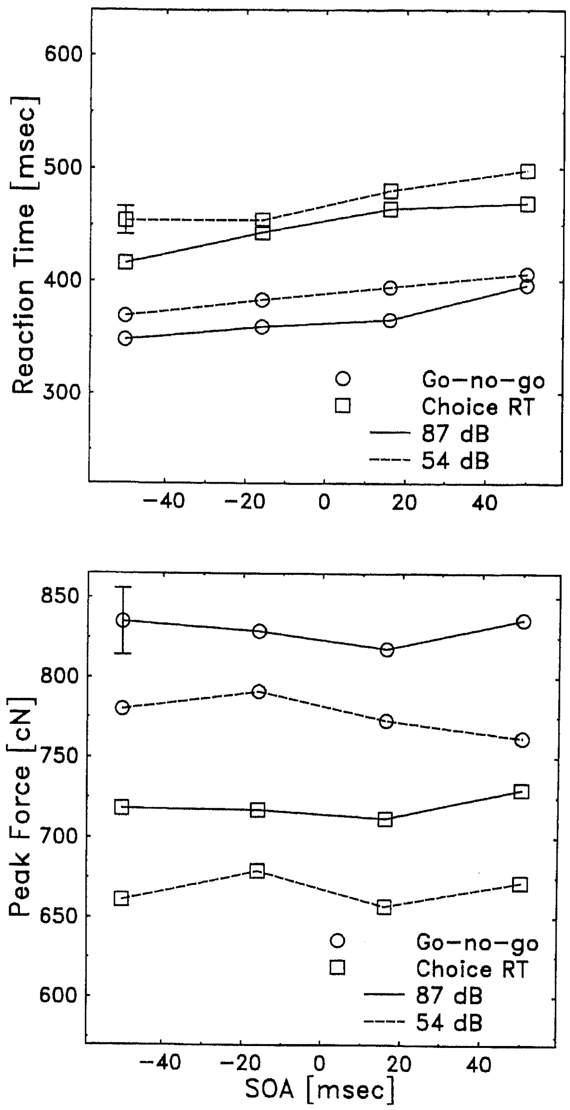

Figure 3. Experiment 3: Mean reaction time (RT) and peak force as functions of task, stimulus onset asynchrony (SOA), and the intensity of a task-irrelevant accessory stimulus. The vertical bars indicate deviations of two standard errors in each direction from the condition means. As in Figures 1 and 2, error was computed by pooling across all sources of error variance, except for the task × subjects interaction, which was significantly larger than the other sources of error variance.

effect of SOA [$F(3,72) = 40.94$, $MS_e = 1{,}063$, $p < .001$]. None of the other effects reached significance, although there was a tendency toward an intensity × SOA × task interaction [$F(3,72) = 2.09$, $MS_e = 1{,}089$, $p = .10$].

An ANOVA on PF revealed a significant 52-cN effect of intensity [$F(1,24) = 28.44$, $MS_e = 10{,}882$, $p < .001$], as well as a significant 110-cN effect of task [$F(1,24) = 11.06$, $MS_e = 121{,}458$, $p < .01$]. The interaction of task and intensity was again nonsignificant ($F < 1$). The interaction of SOA, task, and intensity did not approach significance ($F < 1$), although the main effect of SOA did [$F(3,72) = 2.11$, $MS_e = 1{,}846$, $p = .11$]. No other sources of variance were significant. PF was also analyzed with data from the go/no-go and choice tasks considered separately, and the results indicated that the effect of intensity was highly significant within each task ($p < .01$ for each).

The present experiment demonstrates an effect of irrelevant stimulus intensity on RF in both go/no-go and choice RT tasks. Thus, it seems clear that motor output can be influenced by the intensities of irrelevant auditory stimuli as well as relevant ones. Moreover, the effect of intensity on force in the go/no-go task of Experiment 2 does not appear to have been mediated by the task relevance of timing information, because the effect was also obtained in this experiment with more temporally uncertain irrelevant stimuli.

At the suggestion of an anonymous reviewer, we also examined the go/no-go tasks of Experiments 2 and 3 to see whether there were any detectable effects of accessory intensity on the no-go trials. One possibility is that the subjects might incorrectly respond on no-go trials more often when accessory intensity is high than when it is low. There was barely a trend in this direction in Experiment 2 (2.65% vs. 2.86% false alarms, $p > .2$), but this effect was significant in Experiment 3 (5.36% vs. 2.95%, $p < .01$). A second possibility is that subjects generate partial, subthreshold forces on no-go trials and do so to a greater extent with high than with low accessory intensity. To check this, we computed both mean force and PF in various time intervals following stimulus onset. Again, some analyses suggested an intensity effect in Experiment 3 ($p < .06$) but not in Experiment 2 ($p > .20$). Overall, these analyses suggest that measures of RF on no-go trials are relatively insensitive measures of the effects of intensity on motor output.

Although the present experiment differed from the previous one, in that the choice task also showed an effect of intensity on force, the present results do not support the idea that intensity effects faded away because of slow choice responding in the previous task. If that were the explanation of the previous results, the effect of intensity on force would have been expected to increase across SOAs in the present choice task, but it did not. Moreover, the present observations fail to replicate the previous experiment, because a 57-cN effect of intensity on force was found at the −50-msec SOA in the choice task, which previously revealed virtually no effect. Thus,

Table 2
Mean Reaction Time (RT; in Milliseconds) and Mean Peak Force (PF; in Centinewtons) as a Function of Stimulus Intensity and Task, Averaging Across SOA, in Experiment 3

	Task			
	Go-No-Go		Choice RT	
Intensity	RT	PF	RT	PF
87 dB	367	830	448	719
54 dB	388	777	472	667

the presence of intensity effects on force in the choice task of Experiment 3 appears to depend on the change from a constant SOA of −50 msec to randomly varying SOAs, suggesting that the temporal information conveyed by the accessory stimuli in Experiment 2 actually interfered with the effect of intensity on force. Although Experiments 2 and 3 differed with respect to both subject populations and many subtle procedural details, one possible explanation of this discrepancy relies on the fact that high arousal is known to interfere with response selection in choice RT tasks with arbitrary stimulus–response mappings (see, e.g., Sanders & Andriessen, 1978). The subjects in Experiment 2 might have adopted a strategy of delaying slightly their processing of the relevant stimulus, in order to let the problematic arousal fade. This strategy would be much less attractive in Experiment 3, however, because the relatively later onset of accessory stimuli would require much greater delays and, therefore, greater increases in RT.

EXPERIMENT 4

The main purpose of the previous experiment was to decouple the temporal relationship between the visual imperative stimulus and the auditory accessory. Nevertheless, one could still argue that this manipulation was unsuccessful. Perhaps the subjects used the auditory stimulus as a temporal cue for the visual stimulus (cf. Nickerson, 1973) because the SOA values were too narrowly spaced.

In this experiment, we further diminished the predictability of the target from the accessory and thus further reduced the accessory's potential to function as a temporal reference for the imperative visual stimulus. To accomplish these objectives, we reduced the probability of the occurrence of the accessory and increased the range of SOAs between the accessory and the imperative stimulus. Thus, in contrast to Experiment 3, the accessory was presented in only 50% of all trials, and the range of SOAs was increased by a factor of eight. (To keep the number of total trials comparable between Experiments 3 and 4, the subjects performed only the choice task in Experiment 4.) If the same pattern of intensity effects on PF occur under these conditions of reduced temporal cuing, this would provide stronger support for the claim that intensity affects RF even when the auditory stimulus is not relevant to task performance.

Method

Subjects. The subjects were 26 undergraduate students at the University of Wuppertal. There were 16 females and 10 males, ranging in age from 21 to 37 years (M = 26.9). In return for their participation, they received either course credit or a payment of 10 DM.

Stimuli. The physical properties of the visual and auditory stimuli were exactly the same as those in Experiment 3. However, in half of the trials, no accessory was presented. In the other half of the trials, the SOA between the visual stimulus and the accessory was −400, −50, 50, or 400 msec, with a negative SOA indicating that the accessory was presented before the imperative stimulus, as in Experiment 3.

Apparatus. The apparatus was identical to that used in Experiment 3.

Procedure. The choice RT task of Experiment 3 was employed in four successive blocks of 64 trials. In half of the trials, each combination of visual character, auditory stimulus intensity, and SOA was presented twice. In the other half, the imperative signal was presented without the auditory accessory. The order of the 64 trials was randomized for each block. A session lasted about 50 min. In all other respects, the procedure was identical to that of Experiment 3.

In the earlier experiments, the left-handed responses in choice task were excluded from the data analyses, because these trials could not be compared to the right-handed responses in the go/no-go and simple RT tasks. Experiment 4, having only the choice task, did not

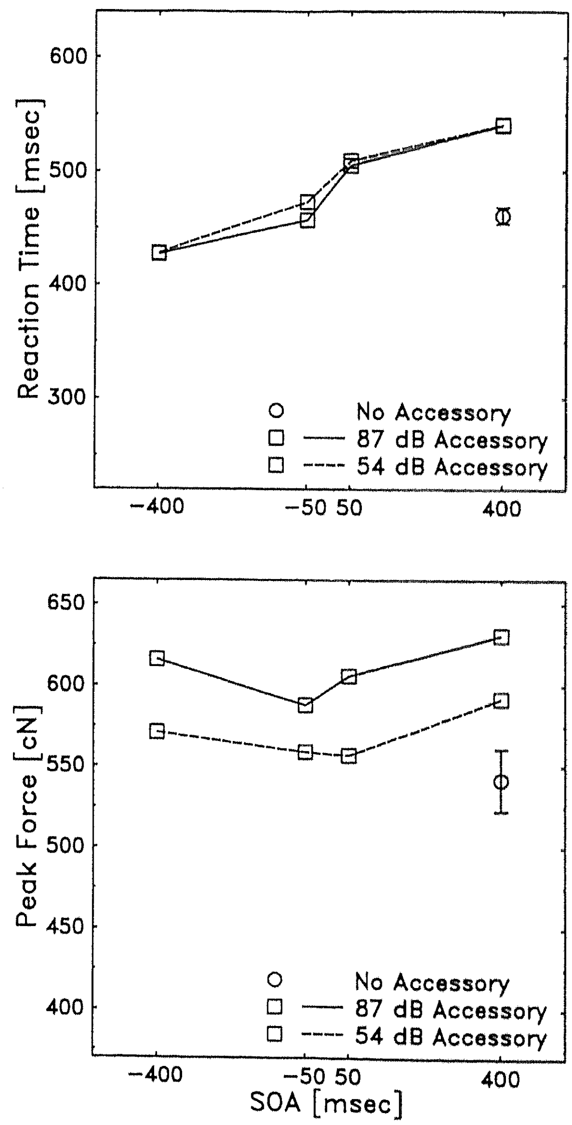

Figure 4. Experiment 4: Mean reaction time and peak force as functions of stimulus onset asynchrony (SOA) and the intensity of a task-irrelevant accessory stimulus. The vertical bars indicate deviations of two standard errors in each direction from the condition means. As in Figures 1–3, error was computed by pooling across all sources of error variance.

pose this problem, and so left-handed responses were included in the data analyses.

Results and Discussion

Response errors occurred in 1.5% of all trials. No spuriously fast or slow RTs were observed. These results are very similar to those of Experiments 1, 2, and 3.

Figure 4 depicts mean RT and PF as a function of accessory intensity and SOA. This figure also includes mean RT and mean PF for the control condition in which no accessory accompanied the imperative stimulus.

Two ANOVAs were performed for each dependent variable (i.e., RT and PF). The first set of ANOVAs examined the conditions in which the accessory was presented, and it tested for effects of auditory intensity and SOA. The ANOVA on RT revealed a significant effect of SOA [$F(3,75) = 53.67$, $MS_e = 4{,}741$, $p < .001$], as was obtained in Experiment 3. Specifically, responses were faster when the accessory preceded rather than followed the imperative stimulus. It seems possible that detection of the accessory interfered with the processing of the imperative stimulus, at least for a short period after accessory onset. Unlike the previous experiments, however, there was only a 6-msec effect of intensity on RT [$F(1,25) = 3.09$, $MS_e = 962$, $p = .09$]. Relative to Experiments 2 and 3, this smaller intensity effect is consistent with the idea that diminished predictability of the accessory reduced the subjects' reliance on it as a temporal cue. Also, left-handed responses were 18 msec slower than right-handed responses [$F(1,25) = 5.45$, $MS_e = 6{,}307$, $p < .05$]. No other effects approached significance (all $ps > .25$).

Although accessory intensity did not significantly affect RT, it nevertheless had a highly significant effect on PF [$F(1,25) = 24.31$, $MS_e = 6{,}946$, $p < .001$]. The size of the intensity effect on PF was 40 cN, which is similar to that observed in Experiment 3. Hence, diminishing the predictability of the accessory apparently reduces the intensity effect on RT but not on PF. This is strong evidence that accessory intensity affects PF, whether the accessory is temporally relevant or not. PF also varied slightly yet significantly with SOA [$F(3,75) = 6.32$, $MS_e = 4{,}474$, $p < .01$], and the effects of intensity and SOA were approximately additive ($F < 1$). No other sources of variance were significant.

The fact that accessory intensity affects force but not RT provides a new example of the sorts of dissociations that can arise between the two measures (cf. Mattes & Ulrich, 1997). These dissociations raise problems for models that assume that force effects are mediated by the speed of processing. For example, Jaśkowski and Verleger (1993) suggested that people want to compensate for slowness by generating "more impetuous and forceful responses" (p. 173). Of course, this hypothesis also has difficulty with the effect of intensity on force in general, because it predicts more force for weaker than for more intense stimuli.

The second set of ANOVAs included trials without an auditory accessory, treating these as a third level of the accessory intensity factor (i.e., no accessory vs. a 56-dB accessory vs. an 87-dB accessory). Response hand was also included as a factor, and data from different SOAs within each accessory-present condition were pooled together. Although, as mentioned before, there was virtually no RT difference between the 87- and 56-dB accessories, RT was clearly shorter in trials with no accessory [$F(2,50) = 25.94$, $MS_e = 391$, $p < .001$]. This decrease in RT in trials without an accessory supports the assumption that the presence of an accessory interferes with the processing of the imperative stimulus. As in the previous analysis, there was a reliable effect of hand on RT. No other effects approached significance.

The analogous ANOVA for PF revealed a clear and monotonic effect of accessory intensity on RF [$F(2,50) = 26.22$, $MS_e = 2{,}336$, $p < .001$]. As an arousal explanation would suggest, the largest PFs were obtained for the high-intensity accessory, the second largest for the low-intensity one, and the smallest for trials without an accessory. This graded intensity effect is dissociated from the pattern of accessory effects on RT and, thus, clearly supports the interpretation that stimulus intensity enhances RF via nonspecific mechanisms.

In conclusion, the present experiment shows that effects of auditory accessory intensity on RF are still demonstrable when the accessory is virtually useless as a predictor of the time of imperative stimulus onset. Although the reduction in predictability seems to eliminate the intensity effect on RT, it does not eliminate the effect on PF. This dissociation suggests that the intensity effect on RF is mediated by mechanisms other than those that determine RT.

GENERAL DISCUSSION

The main finding of the present experiments is that RF is sensitive, not only to the intensities of auditory stimuli in simple RT tasks (see, e.g., Angel, 1973; Jaśkowski et al., 1995), but also to the intensities of both relevant and irrelevant auditory stimuli in go/no-go and choice RT tasks. This persistent influence of auditory intensity on motor output indicates that intensity effects are not limited to perceptual processes under a much wider range of circumstances than has been previously demonstrated. Clearly, these findings raise problems for models that localize the effects of auditory stimulus intensity entirely within perceptual processes. As will be discussed next, there are at least two possible avenues by which the effects of intensity on motor output might be explained: coding models and arousal models.

Coding Models

According to coding models, the intensity of an auditory stimulus is coded as part of the internal representation of that stimulus, and the forcefulness of the response is influenced by this intensity code. One possibility, consistent with discrete-coding models, is that information about stimulus intensity is included in a categorical representation of the stimulus and that the response system then responds harder to more intense stimuli because of the natural mapping of higher intensity to higher force (Romaiguere, Hasbroucq, Possamai, & Seal, 1993). A second possibility, consistent with continuous models, is that internal representations vary continuously in strength, with the strength of a stimulus's internal representation increasing directly with the intensity of that stimulus (see, e.g., Eriksen & Schultz, 1979; McClelland, 1979). Under the metaphor that the internal representation provides energy to activate the response, it would be quite natural for stimulus intensity to influence RF within such a system. Balota and Abrams (1995) have recently suggested two further variants of continuous-coding models that could also explain more forceful responses to more intense stimuli. According to one, which they called the *confidence model*, force is greater when the subject is more confident in the correct response. Assuming that subjects are more confident when intensity is high than when it is low, this clearly predicts more forceful responses for more intense stimuli. According to the other, which they called the *enabled response model*, force is determined by the rate at which activation builds up, not by the total amount of activation. Assuming that the rate increases with intensity, this variant also predicts more forceful responses for more intense stimuli.

Although coding models are generally compatible with an effect of intensity on motor output, certain aspects of the present results raise difficulties for such models. One problem is that the effects of auditory stimulus intensity on force do not depend greatly on the task (Experiment 1). Given that go/no-go and choice RT tasks require much different stimulus coding than in simple RT tasks, it would seem to be a remarkable coincidence that intensity-dependent codes should have the same effect on force in all three tasks.

A second problem is that irrelevant stimuli influenced RF approximately as much as did relevant ones. One would expect irrelevant stimuli to be attenuated or filtered somewhere prior to the response system, to avoid causing errors (cf. Broadbent, 1958; Deutsch & Deutsch, 1963). But if irrelevant stimuli were indeed attenuated or filtered, their codes would presumably have substantially smaller effects on motor output than would codes obtained from relevant stimuli. Nor would irrelevant stimuli be expected to have much effect on confidence or on the rate of information buildup, as would seem to be required in the models considered by Balota and Abrams (1995). Of course, effects of irrelevant stimuli on motor output processes have been demonstrated before (e.g., Eriksen et al., 1985), and these effects can be explained if irrelevant stimulus codes are not greatly attenuated before responses are activated (see, e.g., Cohen, Dunbar, & McClelland, 1990). But in these previous examples, the irrelevant stimuli were actually target letters that appeared in to-be-ignored positions of the display, and their status as targets may have been responsible for maintaining the strengths of their codes. In the present experiments, on the other hand, it is difficult to argue that anything would have maintained the strengths of the irrelevant stimulus codes, because these codes were not inherently task relevant, or even in a task-relevant modality!

Arousal Models

Arousal models provide an alternative way to account for the effects of intensity on RF (see, e.g., Giray, 1990; Jaśkowski et al., 1995). According to these models, intensity has an influence outside the usual chain of information-processing stages, on mechanisms controlling the subject's overall arousal level. Affective stimuli, for example, seem to have nonspecific effects on the response system mediated by changes in autonomic arousal (Kramer & Spinks, 1991; Öhman, 1987). Similarly, it is generally believed that high-intensity auditory stimuli also increase arousal more than do low-intensity ones (see, e.g., Gopher & Sanders, 1984; Jaśkowski, Rybarczyk, & Jaroszyk, 1994; Keuss & Van der Molen, 1982; Niemi & Näätänen, 1981; Sanders, 1975, 1977; Ulrich & Mattes, 1996; Van der Molen & Orlebeke, 1980). As another example, Graham and Hackley (1991) distinguish four types of reflexes—orienting, defense, startle, and transient-detecting—any one of which could in principle modulate arousal in an intensity-dependent manner. However high-intensity stimuli increase arousal, the level of arousal would be expected to influence the forcefulness of motor output, thus producing an effect of intensity on RF mediated primarily by processes outside the information-processing system. Note that this explanation still implies the conclusion that the effects of intensity on information processing are not exclusively perceptual; although the effects are mediated by processes along a different route than those responsible for information processing, they nonetheless modulate the final phase of information processing: motor output. This multiple-route conception of RT models is consistent with various recently developed alternatives to strictly serial architectures (e.g., Schweickert & Townsend, 1989; Townsend & Schweickert, 1989).

Arousal-based models provide a simple and plausible explanation of the effect of stimulus intensity on RF, and these models also have firm theoretical precedents. On the basis of a variety of evidence, Sanders (1983) argued for a cognitive–energetical model to explain arousal effects on information-processing tasks (see, also, Molenaar & Van der Molen, 1986). In this model, informational properties of stimuli are processed by traditional stages, such as feature extraction and response choice. In addition, however, energy-related stimulus properties (e.g., intensity) have an influence on a parallel system of energetical mechanisms, such as arousal and activation. Although these effects are generated via a pathway that bypasses the information-processing stages translating a stimulus to a response and are thus independent of regular stimulus processing, energetical mechanisms still feed activation back to the information-processing stages, thereby influencing task performance. More generally, the idea that intensity effects on force may be mediated by processes outside the usual information-processing chain is consistent with theories in which there are different possible processing routes from stimulus to response, with some routes involving more direct activation and other routes involving more abstract coding (see, e.g., Frith & Done, 1986; Kornblum, Hasbroucq, & Osman, 1990; Kramer & Spinks, 1991; Öhman, 1987; Van Duren & Sanders, 1988).

Models attributing auditory intensity effects on force to pathways outside of the normal information-processing stream have several advantages over those attributing intensity effects to the propagation of intensity through the information-processing system. First, as is demonstrated in the present experiments, the intensity of irrelevant as well as relevant stimuli can affect RF. Second, as found here and previously (e.g., Giray & Ulrich, 1993), RT and force are generally uncorrelated across trials within a condition. Clearly, this lack of correlation is easier to understand if force is determined outside rather than inside the information-processing stages that determine RT. Third, the separate-pathways explanation can account for the effect of intensity on force in terms of an arousal-based mechanism that has already been clearly demonstrated by a number of other well-documented effects. Warning signals, for example, affect reflex amplitudes and EEG (see, e.g., Brunia, 1993) as well as RT and RF (see, e.g., Ulrich & Mattes, 1996), and some of these effects are known to depend on the intensity of the warning signal (see, e.g., Keuss, 1972). Warning signal effects are typically interpreted as evidence that warning stimuli produce nonspecific alerting or arousing effects that influence information-processing stages (see, e.g., Nissen, 1977)—precisely the same interpretation offered here for the effect of stimulus intensity on RF. Besides the effects of warning signals, similar arousal-based interpretations have been offered for the effects of sleep loss and noise (see, e.g., Broadbent, 1971), the threat of electrical shock (see, e.g., Jaśkowski, Wroblewski, & Hojan-Jezierska, 1994), knowledge of results (see, e.g., Steyvers, 1987), amphetamines and barbiturates (see, e.g., Trumbo & Gaillard, 1975), speed stress (Jaśkowski, Verleger, & Wascher, 1994), and preparatory muscle tension (see, e.g., Brebner & Welford, 1980). Given the strong precedents for the idea of arousal effects on information processing, it is parsimonious to use the same idea to account for the effect of intensity on RF. Fourth, Valle-Inclan and Hackley (1997) and Hackley and Valle-Inclan (1998) have recently found evidence that irrelevant auditory accessories do not influence the speed of motor processing, in contrast to the present evidence that they clearly influence force output. These investigators measured the lateralized readiness potential (LRP), a psychophysiological marker of hand-specific response preparation. They found that accessory stimuli had no effect on the time from LRP onset to the overt keypress, an interval that is commonly regarded as a fairly direct reflection of the time consumed by motor processing in choice RT tasks (cf. Coles, 1989). A dissociation between accessory effects on RT and those on PF is, of course, quite consistent with the general idea that force is determined by pathways outside the stream of information processing that determines RT.

In conclusion, the present experiments contribute to the growing trend of using measures of response dynamics in the study of human information processing (see, e.g., Abrams & Balota, 1991; Balota & Abrams, 1995; Coles, Gratton, Bashore, Eriksen, & Donchin, 1985; Giray & Ulrich, 1993; Jaśkowski et al., 1995; Mordkoff, Miller, & Roch, 1996). Such measures are clearly useful supplements to traditional RT measurement, especially for the purpose of probing within the black boxes of information-processing models to localize experimental effects. The clues they provide may be particularly pertinent for constructing a description encompassing nonchronometric as well as chronometric properties of the system underlying human information processing.

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