Stimulus intensity and information processing

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The physiological and behavioral literature regarding effects of stimulus intensity on the time course of information processing is reviewed. The physiological data describe intensity effects on the sensory pathway. Reaction time studies show that the effect of intensity on behavioral responses also depends on and may be mediated by more cognitive processes. The degree to which intensity affects simple reaction time varies directly with the response criterion subjects use. The lack of this dependence in choice reaction time may indicate different intensity effects on energy and nonenergy pathways. The literature suggests that intensity affects the time course of information processing not only by influencing the speed of processing in sensory pathways, but also by affecting alertness and the time required to direct attention to a stimulus.

Stimulus intensity has been used extensively as an independent variable in psychological research, but its use has been most closely associated with the field of psychophysics. As part of their general interest in the relation between stimulus magnitude and subjective magnitude, psychophysicists have relentlessly searched for the true law relating stimulus intensity to perceived intensity. There has been no doubt that the relationship is nonlinear. Rather, the questions have involved the type of nonlinearity that best describes the psychophysical data (logarithmic vs. power functions), the level in the processing system at which the nonlinear transformation occurs, and the dependence of the input-output relationship on such things as stimulus modality, duration, and size.

The thoroughness of the psychophysicists' investigations of the effect of stimulus intensity on perceived intensity has not been paralleled by investigations of intensity effects on other psychological processes. It has been known since 1886 that reaction time decreases with stimulus intensity (Cattell, 1886). Recent studies in cognitive psychology have concentrated not on understanding how intensity affects reaction time but instead on using manipulation of intensity as a tool with which to investigate other cognitive factors. In Sternberg's (1969) influential stage model of information processing, stimulus intensity is explicitly assumed to affect only the earliest stages of encoding. Without questioning this assumption, psychologists have used intensity manipulations within the framework of the additive factors logic (Sternberg, 1969), arguing that any variable which interacts with

stimulus intensity must also affect encoding. Considering the number of theoretical arguments that have been based on the assumption that intensity only affects the earliest stage of processing, it is important to know, specifically, whether that assumption is valid, and generally, how intensity effects on response latency are mediated.

The first section of this paper will examine the pathway effects of intensity, i.e., its influence on processing within the sensory system. Physiological data are useful here and will be briefly summarized. Models which attempt to account for intensity effects on response latency solely in terms of pathway variables will also be discussed. The second and major part of the paper will consider central factors involved in the manifestation of intensity effects: the interaction of intensity and response criterion, and the immediate influence of intensity on alertness and attention. It is hoped that this analysis will show the complexity of processes which may mediate what is usually considered a purely sensory effect.

PATHWAY EFFECTS

Cattell's (1886) observation of an inverse relation between visual stimulus intensity and reaction time (RT) has been replicated many times. From an analysis of data from several studies, Vaughan, Costa, and Gilden (1966) claimed that simple RT decreases as a power function of light intensity, with the exponent near $-.3$. More recent studies by Mansfield (1973) and Ueno (1977) generally agree with that formulation, although the value of the exponent varies somewhat with stimulus size and duration. Teichner and Krebs (1972) have provided a review of the effects of stimulus intensity, size, duration, and viewing condition (monocular vs. binocular) on simple RT. Their analysis shows that asymptotic reaction time (RT to stimuli of sufficient

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duration to produce an asymptotically fast response) is a power function of intensity, with exponents of $-.06$ for small stimuli and $-.02$ for larger stimuli. Simple RT to small, relatively dim stimuli ranges from 290 to 500 msec over a 3-log-unit change in intensity. The range in experiments using larger and generally brighter stimuli is from 160 to 240 msec over a 4-log-unit intensity change. Simple RT to auditory stimuli also decreases with intensity, and in some cases the relation appears to follow a power law (Angel, 1973; Chocholle, 1945).

Simple RT has been considered a measure of perceptual latency; it has seemed that this dependent variable ought to directly reflect sensory processing time. Thus, the decrease in RT with visual intensity has been attributed to faster processing within the visual system. And occasionally, the effect has been attributed entirely to retinal processes (Vaughan et al., 1966).

There is ample evidence that visual intensity affects the amplitude or rate of response throughout the visual pathway, from the initial photoreceptor response to cells in the striate cortex. The earliest recordable effect of light on the visual system is the early receptor potential (ERP), which is generated by the initial light-induced changes in photopigment molecules. The amplitude of this response increases linearly with stimulus intensity (Cone, 1964; Debecker & Zanen, 1975). The amplitude of the a-wave of the electroretinogram, which presumably reflects receptor output, also increases with intensity. At this stage, the relation between intensity and response amplitude becomes nonlinear, approximating either a logarithmic (Brown, Watanabe, & Murakami, 1965) or a power function (Boynton & Whitten, 1970).

The dependence of the firing rate of retinal ganglion cells and optic nerve fibers on light intensity has been studied extensively (Barlow & Levick, 1969; Cleland & Enroth-Cugell, 1970; Hartline, 1938; Marrocco, 1972; Stone & Fabian, 1968; Stone & Fukuda, 1974; Winters & Hamasaki, 1972). There is a nonlinear increase in the response with intensity, but the precise form of the relationship seems to depend on the type of ganglion cell recorded from, the contribution of antagonistic surround mechanisms, the range of intensities used, and the portion of the response that is considered (initial burst vs. steady state response). There is better agreement on the relation between response latency and intensity: the time to the initial impulse decreases approximately 10 msec with each log unit increase in intensity (Cleland & Enroth-Cugell, 1970; Hartline, 1938; Levick, 1973).

A group of studies has shown that at the level of ganglion cells (Barlow & Levick, 1969; Stone & Fukuda, 1974), lateral geniculate nucleus (Marrocco, 1975), and striate cortex (Bartlett & Doty, 1974)

there exist subgroups of cells which seem specialized for coding intensity. In the monkey lateral geniculate nucleus (LGN), for example, most cells respond differentially to stimulus intensities covering a range of only 1.5 log units (Jacobs, 1965; Winters & Hamasaki, 1972). Marrocco (1975), however, found a few cells which showed a much wider operational range, with firing rate increasing over an intensity range of 5 log units. Similarly, a subgroup of ganglion cells termed "luminance units" by Barlow and Levick (1969) or tonic "W-cells" by Stone and Fukuda (1974) shows a maintained firing rate that varies regularly over a wider range of intensity than do most units at that level. It has been suggested that these cells are involved in controlling pupil diameter rather than contributing to brightness perception. Yet, such specialized neurons appear even at the cortical level. Bartlett and Doty (1974) reported that, of the monkey striate cells they tested with diffuse light, only 40% showed an intensity-dependent response. The firing rate of these "luxotonic" units in light was at least twice that in dark. Furthermore, 70% of the luxotonic units were also luminance units, defined as cells in which the rate of discharge increased monotonically with light intensity over a range of at least 3 log units.¹

Despite general questions about the reliability and origins of scalp-recorded evoked potentials, the amplitude and latency of evoked responses recorded over primary sensory cortex are usually believed to reflect the strength and speed of processing within the sensory pathways. The amplitude of these responses is almost invariably found to increase with the intensity of visual (Tepas & Armington, 1962; Vaughan & Hull, 1965) and auditory (Klingaman & Anch, 1972; Teas & Kiang, 1964; Tepas, Boxerman, & Anch, 1972) stimuli. It has also been shown that the latency of the evoked response is inversely related to intensity. Vaughan and his associates (Vaughan, Costa, & Gilden, 1966; Vaughan & Hull, 1965) measured the peak latency of component P1, which was about 100 msec for the visual stimuli they used. Their data suggested that P1 latency was a power function of intensity, with an exponent of $-.3$.

This brief review indicates that there are reliable effects of intensity on neural processing at every level of the visual system and at least at the cortical level of the auditory system. There have been attempts (Mansfield, 1976; Vaughan et al., 1966) to make a quantitative comparison of intensity effects on the neural pathway and on simple reaction time and thus to prove that the behavioral effect originates entirely within the sensory pathway. The one study which obtained a physiological (evoked response) and behavioral (simple RT) response simultaneously (Vaughan et al., 1966) and found identical intensity effects supports that view. However, the precise form of the functions relating intensity to the neural

response and to reaction time depends strongly on other stimulus variables. For this reason, convincing comparisons across experimental subjects, cell groups, and stimulus conditions seem difficult. Nevertheless, given such strong pathway effects and little reason to postulate central effects of intensity, models of reaction time have been proposed which show how a stronger response in the sensory pathway could be translated to a faster reaction time.

Models

A theory developed by Luce and Green (1972) models several decision processes which make use of the output of the sensory system. The decision processes they consider include those for recognition and discrimination of intensity, detection, magnitude estimation, and simple reaction time. Only their model for simple RT will be considered here. Although the model was developed to account for responses to auditory stimuli (pure tones, in particular), it presumably could be applied to vision as well.

The Luce and Green model assumes that the information used by the decision mechanism consists of a series of interarrival times (IATs) corresponding to the interspike intervals of the neural pulses generated by the sensory system in response to a stimulus. Based on physiological data, it is assumed that the distribution of the IATs is a Poisson process, and that the expected value of the IAT distribution varies inversely as a function of stimulus intensity. Decisions based on stimulus intensity are made by sampling one or more IATs from one or more sensory channels and comparing the observed IAT to a criterion.

A simple RT task is essentially a speeded detection task. Subjects must respond as soon as a stimulus which is discriminably different from the background noise level is detected. Luce and Green (1972) propose that subjects set a decision criterion and initiate a response at the end of the first IAT that does not exceed that criterion. The difference in RT to strong vs. weak signals reflects the difference in IATs generated by strong vs. weak signals. In fact, in the Luce and Green model, IAT is the only intensity-dependent variable influencing reaction time. The other components of RT include: the time to transduce stimulus energy into pulses (receptor latency), the time required for a pulse to travel from the receptor to the central decision mechanism, and response execution time. Although Luce and Green assume that none of these components of RT varies with stimulus intensity, the physiological data discussed above suggested that the latency to the initial pulse (which presumably corresponds to the travel time) is intensity-dependent.

Another model of simple reaction time which is quite similar to that of Luce and Green has been

outlined by McGill (1963). While the former model may be termed a neural timing model in that the intensity-dependent decision variable is the inter-arrival *time*, McGill's is a neural counting model: Decisions are based on a *count* of neural events occurring within a prescribed time, with the count varying directly with stimulus intensity. Like Luce and Green, McGill assumes that only the decision time is intensity-dependent. Neither the neural passage time nor the time for response execution is thought to depend on intensity. The decision mechanism consists of two neural counters, one accumulating an impulse count in noise and one accumulating counts of the expected signal. A decision to respond is made as soon as the difference between the two counters exceeds a specified criterion.

According to the neural counting model, the code for detection is the number of events occurring within a fixed period of time; the neural timing model suggests that the relevant code is the amount of time required for a fixed number of events to occur. In a recent comparison of these two models, Wandell (1977) proposes that both of these methods of detection are available to subjects. He shows that experimental conditions (specifically, the time deadline in a speed-accuracy tradeoff situation) determine which method the subject uses.

CENTRAL EFFECTS

McGill's model assumes that the subject's decision criterion is maintained at a constant value. Luce and Green argue that the variability in the criterion is very small in comparison to the IAT variability, although they acknowledge the possibility that the criterion is not constant. We turn now to an examination of the theory and data regarding the role of the response criterion in the manifestation of intensity effects.

Interaction of Intensity and Response Criterion

Theory

Although Wilhelm Wundt considered the components of simple RT to include both a peripheral latency, consisting of the time required for the sensory impulse to reach a decision mechanism, and a central latency, which included attentional and response initiation times, he believed that the peripheral latency was negligible. Consequently, he was unwilling to attribute large effects of stimulus intensity to peripheral factors. To lend support to his belief that some intensity effects were due to attentional factors, he conducted a simple auditory RT experiment (Wundt, 1874). Tones of two intensities were used and were presented in either a regular or random order. In the former condition, subjects

knew which intensity would be used on each trial, and the difference in RT to the loud and soft tones was 11 msec. When subjects were uncertain of the intensity to be used, the difference was 109 msec. Furthermore, overall RT increased 137 msec in the uncertain condition. Wundt argued that the increase in RT and in the intensity effect was due to the inability to direct attention to a certain loudness in the uncertain condition.

The dependence of stimulus intensity effects on the use of pure vs. mixed blocks of trials has been replicated many times, as we shall see. The first theory in modern psychology to deal with this interaction was proposed by Grice and Hunter (1964), who described it as an adaptation level effect: When the same intensity is used in a series of trials, the adaptation level is near the stimulus value, whereas when two intensities are used in a single session, the adaptation level must lie midway between the two stimulus values. The larger intensity effect in the latter condition results from the greater departure of the stimulus values from the adaptation level.

Because of the appearance of data that would be difficult to handle within an adaptation level approach (and perhaps because of the emergence of modern cognitive psychology), Grice redefined his theory 4 years later (Grice, 1968). The new approach was based on McGill's model of simple RT. In both McGill's and Grice's models, the only effect of the intensity of a stimulus on the subject's response *to that stimulus* is mediated by the rate of buildup of information. But while McGill viewed the response criterion as being generally constant, Grice proposed that it was a variable criterion. More importantly, Grice argued that the magnitude of intensity effects manifested in subjects' responses varied directly with the response criterion. Because the buildup of information about a strong stimulus rises more steeply than that for a weak stimulus, the two hypothesized functions diverge over time. Thus, the difference in the time it takes the two to reach a criterion value will be less if only a small amount of information is needed for a decision to respond than if this criterion is higher (see Figure 1).²

To apply Grice's model to Wundt's data, one could postulate that the response criterion is higher when two intensities are presented in a random order than when presented in pure blocks. In the latter condition, subjects have knowledge of the noise characteristics of the system and of the expected excitation from the signal, allowing them to use a low criterion for both strong and weak signals. Alternatively, they may set the criterion somewhat higher in blocks of strong signals than in blocks of weak signals, but this higher criterion would be compensated by the faster buildup of information from strong signals. The general stimulus uncertainty in mixed intensity blocks, however, would lead sub-

jects to use a criterion higher than that used in either of the pure blocks. This higher criterion would have three consequences: slower overall RT; a larger intensity effect; and a larger effect of criterion on RT to weak signals than to strong signals (because of the shallower slope of the information function for weak signals). All three effects are evident in Wundt's data.

Before turning to more recent data relevant to Grice's theory, a few more of its characteristics should be noted. First of all, it does not postulate any difference in the initial latencies of neural responses to strong and weak signals; the buildup of stimulus information begins at the same time for both of them, the only difference occurring in the rate of buildup once it has begun. The physiological data discussed above suggest that this feature of the model may be inaccurate.

Secondly, Grice's model can be contrasted to the additive factors model (Sternberg, 1969). Within the additive factors framework, response latency is considered to reflect the sum of the times required by several serial stages of information processing. In the case of simple RT, the stages are assumed to include sensory registration, decision to respond, and response execution. The power of this framework, in terms of its use as an empirical tool, depends on the assumption that if two independent variables affect different stages, their effects on RT should be additive. In Grice's theory, the buildup of sensory information and the response criterion may be viewed as independent "stages," in that the criterion value does not affect information buildup and vice versa. Yet Grice predicts that variables affecting the two should interact.

Data

The initial impetus for Grice's theory came not from reaction time, but from the classical conditioning literature. Recording the number of conditioned responses (CR) to visual and auditory condi-

Figure 1. Grice's model of criterion-intensity interactions.

tioned stimuli (CS) during extinction, Grant and Schneider (1948, 1949) found that although CR frequency tended to increase with CS intensity, the effect was small and not significant. Grant and Schneider, however, had varied CS intensity in a between-subjects design. When Beck (1963) paired tones of various intensities with air puffs to the eye to produce a conditioned eye-blink response, she used a within-subjects design and found a large and significant effect of CS intensity on the number of anticipatory responses. Using the same stimuli that Beck had used, Grice and Hunter (1964) varied CS intensity both randomly within a block of trials and in a between-subjects design. The former condition showed a significantly larger intensity effect. Obviously, this is the same effect that Wundt found on simple RT and is the prototype of data that nourish Grice's model.

Most of the simple RT data which follow have been collected by Grice and his colleagues, and most involve presumed manipulations of the response criterion. In most of the studies, anticipatory key-presses are reduced by the use of either random foreperiods or catch trials. Error rates are either very low or not reported and thus cannot be considered in conjunction with RT data. Unless otherwise noted, the experiments to be reported used auditory stimuli.

Pure vs. mixed blocks. Grice and Hunter (1964) found a significantly greater effect of stimulus intensity on simple RT when tones of two different intensities were presented in random order to the same subjects than when the two intensities were presented to different subjects. Speiss (1973) used an entirely within-subjects design and found that the difference in RT to tones of 40 and 100 dB was 82 msec when trials were blocked by intensity, and 100 msec when intensity was randomized within blocks. Using visual stimuli, Thrane (1960b) found a 1-msec intensity effect in pure blocks and a 15-msec effect in mixed blocks. In Thrane's study, the interaction was primarily due to the fact that weak stimuli were hurt more by mixed presentation than were strong stimuli: RT to the bright light increased 7 msec in mixed blocks, whereas RT to the dim light increased 21 msec.

In all of these studies, overall RT is significantly slower in mixed blocks. However, Murray (1970) has demonstrated that the interaction does not depend on an overall RT difference. In his data, RT was equally fast in the two conditions, but the intensity effect was significantly greater in mixed blocks. He argued that, in pure blocks of weak tones, subjects used a very low criterion; in pure blocks of strong tones, they used a very high criterion; and in mixed blocks, they used a single criterion that was midway between the other two. That arrangement could lead to little or no intensity effect

in pure blocks and a much larger one in mixed blocks (see Figure 2).

The energy in a flash of light is determined by both its luminance and its duration. When stimuli are presented for less than a particular critical duration, simple RT decreases as duration increases. Beyond this critical duration, reaction time is unaffected by duration. Although the critical duration depends on luminance (Raab & Fehrer, 1962; Ueno, 1977), values near 10 msec are frequently cited (Kietzman & Gillam, 1972; Mansfield, 1973).

If the critical duration is considered as the interval during which the subject samples stimulus information, rather than as a biologically fixed integration time, one might expect it to be manipulable in much the same way as the response criterion of Grice's theory. Bernstein, Futch, and Schurman (1973) found an effect of pure vs. mixed blocks on the critical duration for simple visual RT. When stimuli of only one luminance were presented in a block, the critical duration was 10 msec; when three luminance levels were presented randomly, it increased to 20 msec. One interpretation of these data is that the increased stimulus uncertainty lengthened the sampling interval.

Preknowledge. Several investigators have asked whether the effective difference between pure and mixed blocks simply involves whether or not the subject has advance knowledge of the intensity to be used on each trial. Two studies (Speiss, 1973; Thrane, 1961) have compared the effect of intensity under three conditions: intensity randomized within blocks; intensity randomized within blocks but with the subject informed before each trial of the intensity to be used; and trials blocked by intensity. Both Speiss and Thrane found that overall RT and the size of the intensity effect were equivalent in the latter two conditions. The randomized-without-preknowledge condition produced slower RT and a larger intensity effect than the other two conditions.

Figure 2. Variable criterion model account of Murray's (1970) results. Dashed lines represent criteria used in three conditions.

These results would suggest that the criterion can be changed voluntarily and quite flexibly before each trial. However, there is contradictory evidence. Murray (1970) found that the preknowledge condition showed the same overall RT and intensity effect as did the randomized condition without preknowledge. The source of this discrepancy is undetermined.

Instructions. It would seem that the most direct way to vary a subject's criterion would be to vary the instructions, emphasizing either speed or accuracy. The former instruction should lead to a lower criterion. Henderson (1970) presented tones of 40 and 90 dB within blocks. When subjects were urged to "go fast," the intensity effect was 40 msec; when urged to "be accurate" (to make no false alarms), the intensity effect was 82 msec. Murray (1970) manipulated the response criterion by either emphasizing speed and using no catch trials or using 10% catch trials. Reaction time was faster and the intensity effect smaller in the former condition. There is evidence that Grice's theory can be applied to monkeys as well as humans. When Stebbins and Miller (1964) trained monkeys to press a key in response to tones of various intensities, they found that the intensity effect was greater when every response was rewarded than when only fast responses were rewarded. Finally, Henriksen (1971) attempted to manipulate his (human) subjects' response criterion by presenting either no feedback regarding their reaction time or feedback which was false but credible. He thought that by telling the subjects their responses were slower than normal, he could get them to lower their criteria. Likewise, subjects who were told their responses were unusually fast might raise their criteria. Although the groups receiving false fast and false slow feedback showed no difference in overall RT or intensity effects, both groups demonstrated a faster RT and smaller intensity effect than the group receiving no feedback. Feedback in general seems to lower the response criterion.

Individual differences. The effect of intensity varies among individuals. Part of the variation may be due to differences in the rate of buildup of information, but Grice's theory would suggest that it may also depend on criterion differences. Thrane (1960a), using visual stimuli, found no difference in the effect of intensity on "slow responders" and "fast responders." The difference has been demonstrated for auditory stimuli: subjects with fast RTs showed less effect of auditory intensity than subjects who responded more slowly (Kohfeld, 1969b).

Reaction time tends to increase with age. Hines and Posner (Note 1) attribute this effect not to an increase in peripheral latency, but to the fact that older people tend to have higher response criteria. In agreement with this notion, Botwinick (1971)

has shown that stimulus intensity effects on simple RT are greater among older subjects (64-79 years old) than among younger subjects (17-22 years old). It is possible that the greater effect of stimulus intensity shown by mental retardates (Baumeister, Hawkins, & Kellas, 1965a, 1965b; Kellas, 1969) can also be attributed to criterion differences.

Practice. Performance on tasks as simple as simple reaction time improves with practice. If part of the reduction in RT is due to the lowering of the response criterion, intensity effects ought to decrease with practice. Using visual stimuli, Thrane (1960a) found no reduction in the intensity effect with practice. However, Henderson (1970) and Kohfeld (1969b), who both used auditory stimuli, found a greater effect of intensity on the first day of the task than on the second day.

Distribution of stimulus intensities. Assuming that subjects adopt a single criterion within blocks of trials in which more than one intensity is presented, the height of that criterion ought to depend on the proportion of strong and weak signals that are used. For example, if most of the stimuli are weak, subjects could decrease their RT by using a low criterion. When most stimuli are strong, they could maintain a fast RT and presumably decrease the false alarm rate by using a higher criterion. When Murray (1970) and Sanford (1972) varied the proportion of loud and soft tones presented in a block, they found a larger intensity effect in blocks having a high proportion of loud stimuli. In Sanford's data, the difference between RT to loud and soft tones was 83 msec when 75% of the stimuli were loud and 33 msec when 75% were soft.

Preadaptation and warning signal intensity. Two studies (Kohfeld, 1968; Murray & Kohfeld, 1965) have investigated the effect of preadaptation to tones of various intensities on simple auditory RT. Before performing a reaction time task, subjects listened to 12 tones presented once every 20 sec. In a control condition, no tones were presented. The preadaptation session was immediately followed by a simple RT task to tones of different intensities. Both studies showed that RT was slowest when the preadapting tone was 100 dB and RT was fastest when it was 35 dB. One possible explanation of this effect is that a loud preadapting tone raised subjects' response criterion to tones in the RT task. However, this explanation would predict an interaction between the intensities of the preadapting stimulus and the stimulus to which subjects responded (the imperative stimulus). This interaction was not obtained in either study. An alternative account is that preadaptation affects a peripheral stage and increases the latency of information accrual. Two aspects of the data seem to rule out this hypothesis. First, the effect of preadaptation intensity persisted on the second day of

Kohfeld's RT experiment, without a repetition of the preadaptation session. And second, in the control condition when no preadaptation was used, RTs were intermediate between those produced by a strong and a weak preadapting stimulus.

Kohfeld (1969a, 1969b) has reported some effects of warning signal intensity which are similar to those of the preadaptation intensity. When he presented subjects with visual or auditory warning signals of various intensities and then, after a foreperiod of 1 to 3 sec, presented tones of various intensities to which subjects responded, he found that more intense warning signals led to slower responses. A similar effect was reported by Baumeister, Dugas, and Erdberg (1967), who used auditory warning and imperative stimuli and a foreperiod of either 2 or 15 sec. There exists a discrepancy among these experiments regarding the interaction of the intensities of the warning and the imperative signals. Whereas one of Kohfeld's experiments (1969b) produced additivity between the two variables, both Kohfeld (1969a) and Baumeister et al. (1967) found greater effects of imperative intensity when a strong warning signal was used. Kohfeld has attempted to explain both the preadaptation and warning signal data in terms of Grice's theory, arguing that when an imperative stimulus is preceded by an intense signal, a higher response criterion is adopted. Considering the inconsistencies in the data, that argument seems tenuous.

The main effect of warning signal intensity reported in these experiments is opposite the effect that is frequently found: Stronger warning and accessory signals lead to faster responses (Behar & Adams, 1966; Bernstein, Chu, Briggs, & Schurman, 1973; Keuss, 1972). At least part of the difference may depend on the foreperiods used. Keuss (1972) found that increases in the intensity of the first stimulus only reduced RT when the interval between the first and second stimuli was between 50 and 350 msec; with a delay of 500 msec, there was no effect. Perhaps an even longer delay is necessary to show an increase in RT with a stronger warning signal.

Sequential dependencies. A problem related to preadaptation and warning signal intensity is the question of whether RT and the effect of imperative stimulus intensity depend on the stimulus intensity of the preceding trial. The use of a loud stimulus on trial $n-1$ might lead subjects to adopt a higher criterion on trial n , producing longer RTs and larger effects of stimulus intensity on trial n . In his warning signal experiment, Kohfeld (1969a) found no sequential dependencies based on imperative stimulus intensity. That negative finding is not surprising, since the warning signal intervening between two imperative stimuli would presumably have the dominant effect on the criterion. However, the preadaptation experi-

ment of Murray and Kohfeld (1965), in which no auditory warning signals intervened between imperative stimuli, also failed to demonstrate sequential dependencies of imperative intensity. Kellas (1969) and Murray (1970) reported that RT was faster when a soft tone was used on the previous trial, and that this effect was greater on responses to weak stimuli than to strong stimuli, as Grice's model would predict. Henriksen (1971) found small sequential dependencies and noted that they did not decrease with the intertrial interval, tending to rule out the possibility that these effects are due to the "neural noise" produced by the preceding trial.

It may seem that the effects of preadapting and warning signal intensity, on one hand, and preceding imperative stimulus intensity, on the other, should be mediated by the same mechanism. There are theoretical reasons why that may not be the case. In a study of sequential dependencies on choice RT, Keele and Boies (1973) postulated that stimulus repetitions yield faster reaction times because subjects tend to expect repetitions, i.e., sequential dependencies are mediated by expectancy. If this were true in the case of simple RT to tones of various intensities, the use of a loud tone on the preceding trial could lead subjects to expect another loud tone and to raise their response criterion. In this sense, the sequential dependency effects (when they exist) are more similar to the effects of pure vs. mixed blocks and preknowledge of stimulus intensity. The fact that the effects are not very robust may reflect a weaker tendency for subjects to develop these expectancies in simple RT tasks. Warning signal intensity, however, may not influence expectancies regarding the imperative stimulus, and the intensity of a tone used in a preadapting session almost certainly would not. Thus, these variables would not be expected to affect the response criterion in the same way as sequential dependencies. The absence of an interaction between preadapting and imperative signal intensity confirms the notion that the effect is not on the criterion. The question of why strong warning and preadapting stimuli lead to longer RTs is still unanswered.

Type of catch trial. In an experiment which led him to postulate a theory that is quite similar to Grice's, John (1966, 1967) found that reaction time to an imperative stimulus varies directly with the intensity of catch trial stimuli. He asked subjects to press a key in response to a light but not to respond when they heard a tone. Tone intensity was varied between blocks of trials. John found that RT to the light was 23 msec slower when loud tones were used on catch trials than when soft tones were used. In a control condition using the same stimuli, subjects responded to both the auditory and visual stimuli. In that case, visual RT did not depend on the

intensity of the tone that was used. John argued that when loud tones were used in the first task, subjects raised their response criterion to avoid making false alarms.

Grice (1972; Grice, Hunt, Kushner, & Morrow, 1974) has suggested that both the intensity of catch trial signals and their similarity to the imperative stimulus affect the subject's criterion. LaBerge (1971) reported an experiment in which the imperative stimulus was a 1,000-Hz tone and, in different conditions, catch trials involved the presentation of a red light, white noise, a 1,200-Hz tone, or nothing. Grice (1972) reanalyzed these data in terms of his model, computing both the response criterion and the "sensory recruitment" or information buildup function in each condition. Assuming the same sensory recruitment function in all conditions but differences in criteria, with the blank catch trial condition having the lowest and the 1,200-Hz tone condition the highest, he could successfully predict the RT distributions that LaBerge obtained.

If the criterion increases with the similarity between imperative and catch trial signals, the effect of imperative signal intensity ought to increase with it. Grice et al. (1974) tested this notion by varying tone intensity and using catch trials consisting of a red light, white noise of different intensities, tones of different intensities, or nothing. They succeeded in finding a larger effect of imperative intensity when a light was used on catch trials than when blank trials were used. However, results from conditions in which auditory catch trials were used did not conform to Grice's predictions. In fact, RT to loud imperative stimuli was frequently longer than RT to soft stimuli. Grice et al. remark that, in those conditions, different processes than elevation of the criterion must be involved.

Extensions of Grice's Model: Choice RT

Different processes, indeed. In comparing the conditions Grice used, it is essential to examine the type of stimulus information on which subjects base their responses and to consider how that information depends on the type of catch trial that is used. When the design involves either no catch trials or blank catch trials, subjects can respond on the basis of what may be called energy pathways. That is, they may respond to any increase in the amount of energy in the system. When the imperative stimulus is auditory and catch trials are visual, they might respond to modality-specific energy pathways—to any increase in energy within a modality. However, when imperative and catch trial stimuli are within the same modality, and especially when they are similar to each other, the situation changes drastically. For example, when tones of two frequencies are used as imperative and catch trial signals, the subject can no

longer respond on the basis of energy pathways, but must respond on the basis of tonal frequency.

Grice et al. (1974), in an attempt to understand the rather anomalous results of their auditory catch trial conditions, demonstrated their subjects' use of both energy pathways and frequency information. The imperative stimulus was a 1,000-Hz tone of 50, 80, or 100 dB. The catch signal was an 1,800-Hz tone of 50, 80, or 100 dB. Grice et al. computed the time course of information transmitted by the relevant (frequency) and irrelevant (intensity) stimulus dimensions. For very fast responses, they found that the response information was largely noise, as one would expect. But the portion of information in these early responses that was dependent on the stimulus was constrained by intensity rather than frequency. That is, when subjects responded very quickly, their responses seemed to be based on energy pathways such that they responded to both loud imperative and loud catch signals. Later responses were based on the relevant frequency dimension. Grice et al. report that their subjects were aware of this tendency to respond to loud signals regardless of frequency. Their caution is reflected in the unusually slow and variable responses to loud imperative signals.

A question that arises is whether Grice's model can account for responses that are not based on energy pathways. Specifically, when responses must be made on the basis of information about tonal frequency, visual form, or stimulus location, is there still an interaction of stimulus intensity and criterion?

Most of the available data indicate that there is not. Grice, Hunt, Kushner, and Nullmeyer (1976) measured RT to 1,000 Hz tones of 50 or 100 dB when the catch signal was an 1,800-Hz tone of either 50 or 100 dB. In one condition, subjects were instructed to respond quickly enough to beat a time deadline. In a second condition, there was no deadline, and subjects were instructed to avoid errors. These instructions presumably influenced the response criterion: mean RT was 31 msec slower in the accuracy condition. However, the use of a higher criterion did not result in a larger intensity effect. In fact, the difference between RT to the loud and soft tones was actually slightly larger with speed instructions (68 msec) than with accuracy instructions (52 msec).

In choice RT, as in simple RT, the presentation of stimuli of different intensities within a block of trials leads to slower responses than when trials are blocked by intensity (Brebner & Tiivas, 1975). In both types of task, the increased stimulus uncertainty present in mixed intensity blocks evidently raises the response criterion. However, Posner (Note 2) found that in a choice RT task, stimulus intensity did not

interact with the use of pure vs. mixed blocks. He presented subjects with a visual $\times$ to the left or right of fixation, and asked them to indicate the stimulus position by pressing one of two keys. Stimulus intensity was varied either between or within blocks. Posner's data showed a main effect of intensity, but it was the same in pure and mixed blocks. Furthermore, although RT decreased with practice, the intensity effect did not, and there was no evidence in the mixed blocks of sequential dependencies based on intensity.

Pachella and Fisher (1969) presented subjects with one of 10 lights arranged horizontally and asked them to press one of 10 corresponding keys to indicate the position of the light. Stimulus contrast against the background and spatial confusability, manipulated by the distance between lights, were varied between subjects. The response criterion was manipulated by the use of different time deadlines: In different blocks of trials, the deadline was 0.4, 0.7, or 1.0 sec. An unspeeded condition was also used. Their data show that the accrual functions for high- and low-contrast stimuli are parallel, differing only in intercept; the effect of stimulus contrast on information transmission was the same in all deadline conditions. On the other hand, the effect of spatial confusability was larger in conditions employing slower deadlines (higher criteria).

Lappin and Disch (1972) have used a slightly different technique to study the rate of accrual of information from bright and dim stimuli in a choice task. Reaction times from a single speed-emphasis condition are rank ordered from fastest to slowest. Reaction times are then grouped within this rank ordering, so that the fastest 75 responses would constitute one group, the next fastest 75 responses the next group, and so on. For each group, the error rate and average RT are plotted against each other. Lappin and Disch performed this analysis on the data of a two-choice RT task in which subjects responded to the position of a visual stimulus that was either bright or dim. In contrast to Pachella and Fisher (1969), Lappin and Disch found that the accrual function for dim stimuli had both a larger intercept and a lower slope than that for bright stimuli. They attribute the inconsistency to the fact that the task Pachella and Fisher used was a more complex cognitive task in which intensity was relatively unimportant. Perhaps tasks involving highly compatible responses can make greater use of energy pathways.

Why is it that stimulus intensity should appear to affect the rate of accrual of information in a simple RT task but not in a choice task? Grice et al. (1976) have recently addressed this question in a model of disjunctive reaction time. Basically, their argument is this. The empirical accrual functions represent the sum of a sensory growth function and an associ-

ative growth function. The growth of sensory strength is assumed to be exactly the same in choice tasks as it is in simple RT tasks; the slope of the sensory function is higher for strong than for weak stimuli. The associative process serves to selectively strengthen the accrual of information from imperative stimuli.³ The sum of these sensory and associative processes, which could be viewed as the total excitatory strength reaching the decision mechanism, will thus be greater for imperative stimuli than for catch signals. As in simple RT, subjects can respond by employing a single criterion. In this case, the criterion must be above the asymptotic excitation from catch signals but below that of imperative signals.

With the exception of the Lappin and Disch (1972) study, the experiments cited above suggest that the rate of accrual of information is not affected by intensity in a choice RT task or in the disjunctive task reported by Grice et al. (1976). Given that this empirical function reflects the sum of sensory and associative growth functions, and given that the slope of the sensory function is greater for stronger signals, it follows that the slope of the associative function must be less for strong signals than for weak ones. That is what Grice et al. (1976) propose: Associative strength accrues more rapidly for weak stimuli. Although this notion is quite counterintuitive, Grice's extended model does fit his disjunctive RT data. It remains to be seen how Grice will model intensity effects in RT tasks in which two different responses must be made.

An alternative way to account for the lack of intensity-criterion interactions in choice RT tasks is this: While intensity affects both the latency and rate of accrual of activity in energy pathways, it only affects the latency of information about more complex stimulus properties. Because the accrual functions in these nonenergy pathways are parallel, the intensity effect will be constant regardless of the height of the criterion. It should be noted that this alternative is much closer to Sternberg's (1969) conceptualization of the role of stimulus intensity in his stage model. Intensity affects the duration of an early encoding stage, and thus affects the time at which higher-level processes can begin to analyze the encoded representation in greater detail. Intensity does not, however, affect the rate of processing at these higher levels.

Alertness

The interaction of intensity and response criterion demonstrates the importance of central processes in the *manifestation* of pathway effects. Those data do not necessitate the postulation of intensity effects on anything other than the input pathway. This section will consider the possibility that intensity has an immediate effect on alertness.

Posner (1975) has described alertness as a state in which an organism's central decision mechanism is activated and made ready to respond to incoming information. The consequences of this state include a decrease in reaction time but an increase in errors, since information has had less time to build up. In RT tasks, alertness is frequently manipulated by presenting a warning signal at various intervals before the imperative stimulus. In a similar paradigm, the warning signal (termed an accessory stimulus in this situation) is presented simultaneously with the imperative stimulus. The facilitation in RT to the imperative stimulus found in this paradigm was originally attributed to an increase in the discriminability of the imperative stimulus. However, Nissen (1974) showed that the effect of an accessory stimulus is the same as that of a warning signal: faster reaction time but an increase in errors. Thus, a more recent view of this "intersensory facilitation" is that the accessory stimulus increases alertness (Nickerson, 1973; Nissen, 1974).

If one stimulus presented simultaneously with another can affect the time at which the decision mechanism responds, then presumably a single stimulus can, by affecting alertness, influence the speed with which it is responded to. Stimuli with greater alerting properties should produce faster but less accurate responses. Based on warning signal experiments which show that, at least when relatively short foreperiods are used, more intense warning signals lead to faster responses, it seems possible that the alerting properties of a stimulus would increase with its intensity. Thus, in addition to pathway effects, the influence of intensity on reaction time might be mediated by alertness.

It has been proposed that visual and auditory stimuli differ in their alerting characteristics (Posner, Nissen, & Klein, 1976; Sanders, Note 3): Visual stimuli seem to produce little or no automatic alerting. Consequently, it may be that auditory, but not visual, intensity effects are partially mediated by alertness. With this hypothesis in mind, the relevant data will be examined by modality.

Audition

Posner and Boies (1971) and Posner, Klein, Summers, and Buggie (1973) have shown that alertness is greater at foreperiods of about 200-500 msec than at longer foreperiods. Because the alerting properties of the imperative stimulus should be less effective when alertness is already high, stimulus intensity should have less effect at short foreperiods than at longer foreperiods. Bernstein, Chu, Briggs, and Schurman (1973) measured simple RT to loud and soft tones presented at foreperiods of .5 and 5.5 sec and found intensity effects of 32 msec at the shorter foreperiod and 55 msec at the longer fore-

period. Several other studies (Botwinick, 1969; Kellas, 1969; Kellas, Baumeister, & Wilcox, 1969; Sanders, 1975, Note 3) reported similar results: When simple RT was measured to tones of various intensities presented at several foreperiods, the effect of stimulus intensity was greatest when alertness was lowest. Baumeister, Hawkins, and Kellas (1965a, 1965b) found no interaction between foreperiod and intensity, but the foreperiods they used were all rather long (4-6 sec), and the data showed no main effect of foreperiod, suggesting that alertness did not vary with these long intervals.

Vision

Posner (Note 2) has obtained evidence that alertness does not increase with visual stimulus intensity. He used a two-choice RT task in which subjects responded to the position of the visual stimulus, and on some trials presented a visual accessory signal simultaneously with the imperative stimulus. More intense accessory signals did not produce faster responses. This finding was replicated in a task in which subjects determined whether the imperative stimulus, which was a digit, was odd or even.

Regarding the relation between foreperiod and visual intensity effects, there seems to be no doubt that the effects are additive. In simple RT tasks, stimulus intensity has the same effect at all foreperiods used (Bernstein, Chu, Briggs, & Schurman, 1973; Koster & Peacock, 1969; Raab, Fehrer, & Hershenson, 1961; Sanders, Note 3). Niemi (1975) has obtained additivity of foreperiod and visual intensity in a choice task. Furthermore, errors do not increase with the intensity of a visual imperative stimulus in a choice task (Posner, Note 2).

Limitations and Extensions of Alertness Model

These data support the hypothesis that auditory signals exert an automatic alerting effect which increases with stimulus intensity but that visual signals do not. However, it is possible that the differences found between vision and audition result from the use of visual intensities of a generally lower level or smaller range than the auditory intensities used. Sanders (1975) investigated this possibility in a simple RT task to visual and auditory stimuli in which stimulus intensity and foreperiod were varied. Using a wide range of visual and auditory intensities, he found an interaction of foreperiod and intensity in both modalities. When very bright visual signals are used, RT is less sensitive to foreperiod manipulations. Although it is possible that visual stimuli of extreme intensity exert an alerting effect, it seems that within the intensity range used in most reaction time studies, visual stimuli do not exert an automatic alerting effect. In short, it seems reasonable to maintain the hypothesis that the effect of auditory, but

not visual, intensity is partially mediated by alertness.

A more difficult theoretical problem is raised by the results of choice RT to auditory stimuli. When auditory intensity and foreperiod are varied and subjects base their responses on either the pitch (Keuss, 1972) or spatial location (Sanders, Note 3) of a tone, intensity and foreperiod have additive effects.

The similarity in the pattern of results obtained within the framework of Grice's (1968) theory and the framework of alertness is striking: The predicted interactions are obtained in simple but not choice reaction time. When one considers that Posner's (1975) conceptualization of alertness is basically equivalent to a change in response criterion, the thought of a unification of the two frameworks becomes irresistible. Two alternative attempts will be outlined here.

(1) In the first approach, both sets of results—those pertaining to Grice's model and those dealing with foreperiod effects—will be handled in terms of alertness. It will be assumed that alertness and the variables manipulated by Grice and his colleagues similarly affect the response criterion. It will also be assumed that increases in stimulus intensity, at least for auditory stimuli, lead to greater alertness and thus, lower response criteria.

If auditory intensity and practice, for example, both affect the response criterion, the two variables should interact. The alerting properties of a stimulus should be less effective when the response criterion is already at a low value, such as when subjects have had much practice on a task. Thus, intensity effects should decrease with practice. The same argument applies to the interaction of intensity and instructions, the use of pure vs. mixed blocks, preknowledge of intensity, age, and so on. If alertness does not increase with visual intensity, however, intensity should not interact with these variables when visual stimuli are used. Unfortunately, there have been only three simple RT studies using visual stimuli in this context. Sanders (1975) found no interaction between visual intensity and pure vs. mixed blocks. Thrane (1960b) demonstrated the existence of such an interaction for vision, but it was weak. And in a second study (Thrane, 1960a), she found no interaction of visual intensity with either practice or individuals (fast vs. slow responders). Thus, the simple RT data obtained within Grice's framework seem consistent with the notion that auditory intensity and these other variables interact because both affect the response criterion.

But what about choice reaction time? If visual stimuli produce little automatic alerting, results showing no interaction of visual intensity with foreperiod (Niemi, 1975), practice, pure vs. mixed

blocks, or sequence (Posner, Note 2) in choice reaction time are easily explained. However, the additivity between foreperiod and auditory intensity in choice RT (Keuss, 1972; Sanders, Note 3) is not. Sanders suggests that "the effect of immediate arousal is not effective whenever the information flow involves the response choice mechanism" (Sanders, Note 3).

(2) The alternative way to incorporate the two sets of data assumes that none of the effect of stimulus intensity is mediated by alertness. Although auditory stimuli might exert an immediate alerting effect, it is assumed that either immediate alerting does not vary with stimulus intensity or the alertness produced does not influence the criterion used in responding to the alerting stimulus. Furthermore, this approach argues that Grice's theory can explain the interactions found in simple RT between intensity and all other variables investigated so far—including foreperiod. At optimal foreperiods, the subject's response criterion is lower than at longer foreperiods and, thus, intensity effects are smaller. The way in which Grice's model can account for the additivity between criterion manipulations and intensity in choice RT has been discussed in an earlier section of this paper: Intensity may affect only the latency and not the rate of information accrual in nonenergy pathways.

This approach has difficulty in accounting for the lack of interactions found with visual intensity in simple RT tasks. But the fact that such interactions occasionally appear, especially when a wide range of intensities is used (Sanders, 1975), is promising.

Attention

Both of the alternatives just discussed place the locus of visual intensity effects in the input pathway, attributing little or no influence of visual intensity to alertness. Further support for the notion that visual intensity only affects the input pathway comes from evidence that it is additive with stimulus-response compatibility (Biederman & Kaplan, 1970; Posner, Note 2), number of stimulus alternatives (Posner, Note 2), and response type (Miller & Pachella, 1973), which are thought to influence later stages of processing. Bartlett (1963) has shown that visual intensity does not affect response execution: The interval between the muscle action potential and the completion of a response is constant over intensities. However, evidence of an interaction between intensity and expectancy suggests that visual intensity may influence the time it takes to turn attention to an unexpected stimulus.

Miller and Pachella (1973) varied stimulus contrast and probability in a memory-scanning task and found that the effect of contrast was greater on responses to low-probability stimuli. The same inter-

action was obtained when subjects were shown a digit on each trial and simply had to say the name of the digit. In a later study, Pachella and Miller (1976) looked at the effects of stimulus intensity and probability in a letter matching task. Although there was some evidence of the expected interaction, it was not statistically significant.

When subjects are asked to determine whether a string of letters is a word or a nonword, reaction time to a word is faster when it is preceded by a semantically related word. Neely (1976) has demonstrated that part of this facilitation is mediated by attentional processes. Presumably, subjects attend to an area of memory representing the meaning of the previous word. When a semantically related word is presented on the next trial, it takes less time to switch attention to it. Meyer, Schvaneveldt, and Ruddy (1975) found that the magnitude of this facilitation is greater for "degraded" stimuli than for intact stimuli. Becker and Killion (1977) replicated this result by varying stimulus intensity rather than degradation.

Additional evidence of an interaction between intensity and attention comes from the evoked potential (EP) literature. Schechter and Buchsbaum (1973) measured the amplitude of the evoked response to lights and tones of various intensities under several instructional conditions designed to affect the amount of attention subjects paid to the visual and auditory stimuli. The amplitude of the EP component with a latency of 120 msec increased with intensity. For visual stimuli, that increase was greatest when subjects were presumably ignoring the lights, and it was smallest when they attended to the lights. One could argue that the interaction may have been an artifact of the background EEG in the various conditions. The pattern of results from EPs to tones makes this unlikely: Tone intensity increased EP amplitude by the same amount in all conditions. An evoked potential study by Schwent, Hillyard, and Galambos (1976) provides further confirmation that Schechter and Buchsbaum's results were not artifactual and also indicates that EPs to auditory stimuli may demonstrate an interaction of attention and intensity. A series of tone pips was delivered from three spatial locations. Subjects counted the number of tones occurring at one location and ignored the other two channels. The N1 wave of the EP was larger to attended tones, and the difference between attended and unattended tones was greater when the tones were soft than when they were loud.

If one assumes that stimulus probability, semantic relatedness, and instructions to attend to a given source of stimuli all affect the direction of a subject's attention, then these data demonstrate an interaction of intensity and attention. But they do not indicate the locus of that interaction. Within the additive

factors logic, two possibilities exist. Attention could affect the input pathway preceding central stages of processing. Or intensity could affect the time it takes an unexpected or previously unattended stimulus to draw attention to itself. Physiological data indicate that intensity affects the input pathway, but the locus of attentional effects has not been specified as convincingly. Thus, most of these experiments were conducted under the assumption that an interaction of intensity and attention would mean that attention affects the input pathway. The opposite interpretation seems equally likely, however, and the available evidence (what there is of it) points in its favor.

Several investigators, including Schwent et al. (1976) have shown that evoked potentials recorded from the vertex are influenced by attentional manipulations. Evoked potentials measured over the occipital lobe presumably reflect an earlier stage of processing, corresponding to activity within the visual system. Begleiter, Porjesz, Yerre, and Kissin (1973) recorded EPs to visual stimuli simultaneously from the vertex and occipital lobe and found that although stimulus expectancy had a significant effect on the vertex EP, it did not affect evoked responses at the occipital site. This result suggests that expectancy does not influence these early stages of processing.

When subjects in a reaction time task are given a cue indicating with a certain probability what the following imperative stimulus will be, both costs and benefits result: In comparison to a neutral condition, responses to expected stimuli are facilitated, but responses to unexpected stimuli are retarded (Posner & Snyder, 1975). Posner and Snyder have proposed that the benefit produced by the cue results from an activation of the input pathways involved in processing the expected imperative stimulus, and the cost results from the additional time it takes to turn attention to the unexpected stimulus. When Posner, Nissen, and Ogden (Note 4) varied stimulus intensity and expectancy in a cost-benefit paradigm, the interaction of expectancy and intensity that was obtained was limited entirely to the cost portion of the results. The facilitation of responses to expected stimuli was the same regardless of stimulus intensity, but responses to unexpected stimuli suffered less if those stimuli were bright than if they were dim. The implication of these data is that it takes less time to switch attention to a bright stimulus. The locus of intensity-attentional interactions seems to be the attentional mechanism rather than the input pathway.

CONCLUSIONS

Physiological data indicate that stimulus intensity affects the latency and rate of processing in the

sensory pathway. If intensity and a seemingly more cognitive variable, such as stimulus probability, foreperiod, or speed-accuracy instructions are both manipulated in a reaction time task and are found to interact, what does this interaction tell us? Does the "cognitive" variable affect the input pathway, as is frequently assumed? Does intensity affect central processes? Or can the empirical interaction be explained without assuming any processing interaction?

In simple RT tasks, when responses can be based on energy pathways, two possibilities exist. According to Grice, the interaction of intensity and variables affecting the response criterion is a necessary consequence of the difference in the rate of sensory growth from strong and weak signals. The height of the criterion has no effect on the accrual of information, and intensity only affects the input pathway. The two variables produce an empirical interaction without affecting a common aspect of information processing.

The alternative account of interactions in simple RT tasks is that intensity affects both the rate of processing in sensory pathways and the response criterion. Intensity increases alertness, which lowers the criterion and leads to faster responses to more intense stimuli. Intensity and criterion variables interact because the portion of intensity effects mediated by alertness will be less evident when the criterion is already low. According to this view, the interaction implies a central effect of stimulus intensity.

Because visual stimuli are thought to be less automatically alerting, this second alternative predicts an intensity-criterion interaction only for auditory stimuli; Grice's account predicts an interaction for both modalities. The literature lacks a convincing demonstration of whether visual intensity and criterion variables produce additive or interactive effects on simple RT. Future research should indicate which of these theories is more adequate.

In most choice RT tasks, there seems to be no interaction between intensity and variables that affect the response criterion. One way to account for these data is to assume that intensity affects the latency but not the rate of processing in nonenergy pathways. Yet, in these choice tasks, there are interactions between intensity and attentional variables. The evidence available suggests that these interactions result from an intensity effect on attentional processes rather than an attentional effect on input pathways.

In short, the possible consequences of differences in stimulus intensity on information processing seem much broader than before. Perhaps future research should use stimulus intensity less as an empirical tool and more as a target of investigation itself.

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NOTES

1. Bartlett and Doty (1974) also reported inhibitory luxotonic and luminance units, in which firing rate decreased with increases in luminance. Units showing intensity-dependent inhibition have also been found in the optic tract and LGN (Marrocco, 1972).
2. The growth of sensory strength has been drawn as a linear function here for simplicity. In Grice's model, sensory strength grows according to a negatively accelerated function.
3. Grice, Hunt, Kushner, and Nullmeyer (1976) note that for some subjects the associative process selectively inhibits information from catch signals.

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