RESPONSE VARIABLES IN SUPRATHRESHOLD
STUDIES OF STIMULUS RECIPROCITY

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Studies of stimulus reciprocity necessarily involve four factors: three concern the stimulus, namely its intensity, duration and energy, and the fourth is the response. Typically, studies of stimulus reciprocity have emphasized the first three stimulus factors, plus other stimulus parameters, with little or no concern having been given to problems regarding the measurement or specification of the response. In the figures or the equations depicting reciprocity the response is not indicated; generally, the most said about it is that a constant response level is being used. This neglect of the response is particularly unwise since a survey of the history of the reciprocity relationship shows that the greatest changes in the concept have occurred with regards to the responses to which it applies. The earliest responses investigated by Bunsen and Roscoe were photochemical reactions to light. Some 30 years later their observations were applied successfully by Bloch to a different response -- the absolute visual threshold. This was followed 40 years later by reciprocity studies of a variety of physiological responses and of absolute and differential thresholds. Subsequently, the concept has been subjected to numerous further tests involving a wide range of physiological and behavioral response systems. In fact, it is the potential application of the simple stimulus manipulations of reciprocity relations to a broad response spectrum which has generated considerable research activity on the topic and makes a symposium like this possible and of interest to a number of people. However, the large variety of response measures employed has created certain methodological and conceptual problems most of which have been overlooked or ignored. The purpose of the present report is to analyze and discuss some of the characteristics of stimulus reciprocity, such as the critical duration, for suprathreshold conditions. Particular stress is to be placed upon the responses under investigation. We propose to discuss three different topics concerned with the relationship between responses, and for heuristic purposes these topics can be classed according to the degree of similarity between the responses involved:

1) Different levels of the same response; e.g., 50% discrimination compared to 75% discrimination. In psychophysics there is always a question as to the best level of discrimination to use to specify the threshold. Our stimulus reciprocity data indicate that one response level may be preferable to another in that it may display a greater consistency with the other measured characteristics of reciprocity.

2) Different responses within a single response class; e.g., different discriminative responses. Since it is known that suprathreshold stimuli contain numerous perceptual qualities such as brightness, color, perceived duration, etc., the question arises as to how these factors are related to stimulus reciprocity. Our data show that it is necessary to take into account such response complexities to adequately measure stimulus reciprocity.

3) Different response classes; e.g., accuracy of discrimination compared to speed of response. Some recently published reaction time studies of stimulus reciprocity conclude that in contrast to discriminative responses there may be little or no reciprocity effect for timed responses. Our data show some similarities between perceptual and psychomotor responses and a definite reciprocity relationship for simple reaction time over a much longer time than previously reported.
Each of these three topics is to be discussed in detail in order to illustrate the importance of response variables in stimulus reciprocity for suprathreshold conditions.

In the studies to be described we have attempted to relate the manipulations used to investigate reciprocity at absolute threshold levels to the suprathreshold case. Characteristically, studies of Bloch's law measure stimulus reciprocity by obtaining psychophysical curves which encompass a wide range of responding (say 0 to 100% detection of the stimulus) by fixing stimulus duration and varying stimulus luminance. From a family of such curves, each for a different duration, it is possible to select a single response level (this is usually 50% detection) and to determine the particular luminance and duration values associated with that response level. Thus, the typical data plot in an investigation of Bloch's law consists of the stimulus conditions which give rise to a single, predetermined level of responding. Complete reciprocity of the stimulus is inferred when a perfect trading relationship is demonstrated between the stimulus intensity and duration, so that as one is reduced (or increased) the other must be increased (or reduced) by the same amount in order to maintain a constant response. Under these circumstances the response is determined by the energy of the stimulus which is defined as the product of stimulus intensity and duration.

In our suprathreshold experiments we manipulate stimulus duration and intensity in the same manner as that described above, for absolute thresholds. Before giving the specifics of our stimulating conditions, I want to briefly describe the apparatus used for the experiments to be reported. The stimulus to be discriminated was a circular target approximately one log unit above a foveal detection threshold. The target subtended a 42 minute visual angle and was foveally fixated in binocular view. The light source was a glow modulator gas-discharge tube which produces a white-appearing light. Stimulus intensities were controlled by neutral density filters while stimulus durations were produced by a multivibrator timer.

The psychophysical method employed was a three-position temporal forced-choice procedure. As Figure 1 shows, on a single trial four light pulses were presented successively with a one-second period between each pulse. The first pulse was a preparatory light designed to ready the subject for the stimuli to be judged and to make his light-adapted state for the remaining stimuli more alike. Of the three pulses to be judged, two --- the Comparison pulses --- were identical brief pulses, while the third pulse --- the Test pulse --- was the stimulus that was varied. From trial to trial the position of the Test stimulus was changed. On trial one, for example, the Test stimulus is in the third position while on trial two it is in the second position. The subject's task from trial to trial was to say which one of the three pulses was different from the other two. He was informed after each trial of the accuracy of his choice. His ability to correctly discriminate the 'different' pulse was the dependent variable. The Comparison stimulus was four msec. in duration and was unfiltered (100% transmission). The independent variables manipulated were the duration and luminance (and therefore the energy) of the Test stimuli. The center portion of Figure 2 shows Test and Comparison stimuli with the same energy but with the Test stimulus being longer and of reduced luminance. This condition is subsequently referred to as the equal-energy condition. Notice that according to the reciprocity law, when the Test duration is shorter than the critical duration, as in Example 1 in the upper section of Figure 2, the Test and Comparison stimuli are equivalent, and therefore should not be discriminated. Discrimination
Two examples illustrating the temporal forced-choice method with each example representing a single trial. From trial to trial the position of the Test stimulus is changed randomly. There is a one second period between each of the four stimuli of a trial.

**FIG. 1. TEMPORAL FORCED-CHOICE METHOD**

Two examples of three different luminances of the Test stimulus so its energy is less than that of the Comparison stimulus (left side), equal to the Comparison stimulus (center section), or greater than the Comparison stimulus (right side). In Example 1, the Test stimulus is shorter than a hypothetical critical duration. In Example 2, it is longer and therefore some of its energy is presumed unintegrated. The Comparison stimulus is of fixed duration and luminance. The parameter of the experiment is the duration of the Test stimulus.

**FIG. 2. STIMULUS CONDITIONS FOR THE FIXED DURATION-VARIABLE LUMINANCE EXPERIMENT**
of the equal-energy condition becomes possible when, as is shown in the bottom of the Figure in the center section (Example 2), the Test duration is longer than the critical duration, since then some of the Test stimulus energy is not integrated, and therefore it would appear dimmer than the Comparison stimulus. Thus, as the duration of the Test stimulus is lengthened, it should become increasingly discriminable from the Comparison stimulus.

Changes in discriminability also can be produced by reducing the luminance of the Test stimulus so it actually contains less energy than the Comparison stimulus, as is shown by the examples on the left side of Figure 2. It is possible to obtain a monotonic curve showing increased accuracy of discrimination as a function of a decrease in the luminance of the Test stimulus. A similar monotonic curve of increased accuracy can be obtained by increasing the energy of Test stimulus beyond the energy level of the Comparison stimulus, as in the condition on the right side of Figure 2. Combining these two operations, we can produce U-shaped functions of accuracy of discrimination with the left limb of the curve for the condition where the Test energy is less than the Comparison energy and the right limb of the curve for the condition with the Test energy greater than the Comparison energy.

We have described the usual condition for studying reciprocity at threshold, fixing duration and varying luminance. However, Bloch's law implies that the opposite set of stimulus manipulations should give the same results, i.e., by fixing stimulus luminance and varying stimulus duration it should be possible to obtain U-shaped functions similar to those obtained for the luminance-varied case. We have tested the fixed-luminance, varying duration condition and compared the results with the results obtained by the fixed duration and varying luminance condition. Figure 3 shows the results of two subjects with both sets of stimulus conditions where all stimulus durations were presumed to be shorter than the critical duration. The energy of the Test stimulus was increased and decreased by the same amount for both the luminance-varied and the duration-varied conditions. The boxed-in data points represent the equal-energy conditions. Thus, as we anticipated, the two U-shaped response curves for each subject are very similar, especially for subject DL.

The use of a temporal forced-choice method with instructions to the subject to select the 'different' stimulus in no way elucidates the basis of his judgments and his accuracy of discrimination. Therefore, the subject is asked to report after selecting the 'different' stimulus on what characteristics or attributes he judged it as different. Our highly experienced subjects report similar cues or attributes for similar stimulating conditions. Figure 4 shows the cue reports and the accuracy data of one of the two subjects whose accuracy of discrimination data were just shown. Inspection of these data show that the same cues were reported for both the duration and the luminance manipulations. Notice on the right side of each U-shaped function the cue of 'brighter' is predominant (this is when the Test stimulus has more energy than the Comparison stimulus) and on the left side the cue of 'dimmer' is predominant (when the Test stimulus has less energy than the Comparison stimulus). The frequency of report of these cues also is highly associated with the accuracy of discrimination. These cue reports corroborate the obvious: namely that energy increments and decrements are associated with changes in apparent brightness.

Although a single U-shaped curve illustrates what happens when the
Percentage of correct discriminations for two subjects of a Test stimulus varied in energy by changing either its duration or luminance from a 4-msec. Comparison stimulus. Boxed points are the equal-energy condition. Each point for subject DJ is based upon 45 trials; for subject DL upon 105 trials.

**FIG. 3. ACCURACY OF DISCRIMINATION FOR THE LUMINANCE AND DURATION VARIED EXPERIMENTS**

**FIG. 4. CUE REPORTS OF ONE SUBJECT FOR THE LUMINANCE AND DURATION VARIED EXPERIMENTS**

Distribution of cue reports of subject DJ for the conditions depicted in Fig. 3. The accuracy of discriminating the Test stimulus from the 4-msec. Comparison stimulus is shown by the algebraic sum of the different cues for each energy difference between the Test and Comparison stimuli.
Test stimulus has greater, equal, or less energy than the Comparison stimulus, it does not provide much information about the reciprocity relationship. What is needed is a family of such curves, obtained either with duration as the parameter and luminance varied or with luminance fixed and duration varied. We have obtained a family of curves for both sets of manipulations. Figure 5 shows a family of curves obtained by fixing Test luminance and varying the Test duration around the different fixed luminances. Note that stimulus luminance is decreasing (the parameter) while the duration of the stimulus (the abscissa) is increasing. All of the functions obtained are U-shaped similar to those seen in Figure 4. The boxed-in points are the equal-energy conditions. Figure 6 shows a similar family of U-shaped curves which were generated for a different subject using the reverse set of operations—fixing Test duration and varying Test luminance. Again, as duration increases (this time as the parameter) luminance decreases (on the abscissa). Notice also the dotted line drawn through the adjusted 50% correct level. This line intersects two points on each U-shaped curve, one on the left limb which is the condition where there is more energy in the Test stimulus than the Comparison stimulus and one on the right limb where the Test stimulus has less energy than the Comparison stimulus.

From these systematic results obtained by different but comparable manipulations it is apparent that operations used to measure stimulus reciprocity at threshold can also be employed for suprathreshold experiments. However, in suprathreshold studies of stimulus reciprocity it is fruitful to analyze in detail the nature of the responses under investigation. First, let us consider the problem of choosing between different levels of the same response. In psychophysics there always has been a question as to the best level of discrimination to use to specify a threshold. Our data indicate that one response level may be preferable to another because it shows consistency with other measured characteristics of reciprocity. Let us illustrate by comparing reciprocity data measured at two response levels, 0% and 50% correct. Notice the adjusted 50% correct discrimination level shown on Figure 6. Figure 7 shows the 50% points obtained from these and the previously shown set of U-shaped curves (Figure 5) for the two different subjects. Each U-shaped curve contributes two points. The curves on the left show the points of the subject in the fixed duration-variable luminance experiment (Figure 5). The dashed line running between the two curves is the equal-energy line and indicates the slope which would be obtained if there were complete stimulus reciprocity for the conditions tested; the two curves obtained by connecting the data points parallel the equal-energy line out to the longest duration tested which is 35 msec.; obviously, the critical duration for these conditions is greater than 35 msec. The fact that the two curves do not overlap the equal-energy line is exactly what was expected since some energy difference is needed for the stimuli to be discriminated; the curve with the circular points is from the right limb of the U-shaped function where the Test stimulus had less energy than the Comparison stimulus (that is why all the circular points are below the line) while the curve with the triangular points is from the left limb of these functions where the Test stimulus had more energy than the Comparison stimulus. The functions on the right side of Figure 7 shows exactly the same results for the other subject for whom duration instead of luminance was varied (Figure 5). Again, the two curves obtained by connecting the data points fall on the expected side of the equal-energy line; also, the curves remain parallel to the line and therefore there is no evidence of a critical duration out to 32 msec. Based on an analysis of the 50% accuracy response level, we would conclude that for both subjects these very orderly-appearing data show complete stimulus reciprocity for all conditions tested.
Percentage of correct discrimination for one subject of a Test stimulus of variable duration from a 1-msec. Comparison stimulus. The parameter is the luminance of the Test stimulus. The boxed points are when the Test and Comparison stimuli are equal in energy. Each point is based upon from 60-150 trials.

FIG. 5. FAMILY OF U-SHAPED CURVES: FIXED LUMINANCE-VARIABLE DURATION EXPERIMENT

FIG. 6. FAMILY OF U-SHAPED CURVES: FIXED DURATION-VARIABLE LUMINANCE EXPERIMENT
The log intensity and duration of the Test stimulus necessary for its 50% correct discrimination from the 1-msec. Comparison stimulus. Data from Fig. 6 are on the left (the fixed duration-variable luminance experiment) and data from Fig. 5 are on the right (the fixed luminance-variable duration experiment). The diagonal dashed lines of both graphs show the energy of the Comparison stimulus distributed in different luminance-duration packages. Curves above this equal-energy line (the triangles) are when the energy of the Test stimulus is greater than that of the Comparison stimulus (are from the "brighter" limb of the U-shaped functions) and curves below the equal energy lines (the circles) are when the energy of the Test stimulus is less than the Comparison stimulus energy (are from the "dimmer" limb of the U-shaped functions).

Percentage of correct discrimination of a 1-msec. Comparison stimulus from an equal-energy Test stimulus as a function of the increased duration and reduced luminance of the Test stimulus. Each point is based upon 505 trials.
We can analyze these same data using another and, what can be shown to be, more sensitive response measure of reciprocity. Critical duration in this analysis is defined as the duration at which accuracy of discrimination is greater than chance. To clarify our analysis look at the lower half of Figure 2 which shows the stimulus conditions for this experiment. In Example 2, where the Test stimulus is longer than the critical duration and therefore some of its energy is not integrated, we would expect the Comparison and Test stimuli to be discriminated. Since we are using a forced-choice technique with an accuracy indicator and therefore are not limited by subject variability to provide a response measure, we can define discriminable at any accuracy level; it is not necessary to use a 50% accuracy level of discrimination if there is evidence that discrimination is occurring systematically for lower levels. Look again at the U-shaped curves of Figure 5, especially at the boxed equal-energy points. Notice that for the short stimulus durations the equal-energy points are all at chance levels of discrimination, but as the stimulus durations increase discrimination of the equal-energy points gradually increases also. The change from chance to above-chance accuracy provides the estimate of the critical duration; in this case it is somewhere between 22 and 25 msec. Notice that all the equal-energy points in Figure 5 are below the 50% response level which explains why when using the 50% response level to estimate critical duration we concluded that the critical duration was greater than 35 msec. By using a high response level one obtains a correspondingly longer estimate of critical duration. An inspection of Figure 6 shows for the other subject a similar, systematic increase in the discrimination of the equal-energy pulses as duration increases, with these points also being below the 50% level of discrimination. By defining critical duration as the transition from chance to above-chance discrimination for this subject, the best estimate of critical duration would be between 10 and 22 msec., much shorter than the previous estimate with the 50% response level.

The use of the transition to above-chance discrimination to define critical duration can be challenged since all of the equal-energy points gave relatively low levels of discrimination, and it may be that chance factors produced the discriminations. To demonstrate that the equal-energy pulses were, in fact being discriminated, we did a supplementary experiment using this same subject. The experiment was the same as before except the subject was given only the equal-energy Test stimulus to discriminate from the Comparison stimulus, and longer Test stimulus durations out to 38 msec. were included. Figure 3 shows that discrimination of the equal-energy Test stimuli of different durations is a monotonically increasing curve reaching almost 80% accuracy for the 38 msec. Test stimulus. From these data, obtained a considerable time after the U-shaped curves, the best estimate of critical duration for subject DL would be between 10 and 22 msec., quite close to the estimates obtained from the U-shaped functions when analyzed at the same response level but much briefer than when analyzed at the 50% response level.

Our data supports in still another way the contention that the change from chance to above-chance discrimination is a more sensitive and meaningful response level than some higher, arbitrary value. If, as we contend, discrimination between the Test and Comparison stimuli is due to some of the Test stimulus energy not being integrated, then by increasing the physical energy of that stimulus (either by increasing its luminance or duration) it should be possible to reduce discrimination between those stimuli before a further increment in physical energy produces the other limb of the U-shaped function for which the Test stimulus would appear as brighter. There are numerous examples in these data of the accuracy of discrimination being reduced by increasing the Test.
stimulus energy to more than that of the 4-nsec. fully-integrated Comparison stimulus. In Figure 5 the three longest Test stimuli all show a decrease in discrimination as the luminance is increased beyond the equal-energy condition. In Figure 5 a similar effect is obtained for the three lowest fixed luminance curves by increasing duration. While none of the reductions in accuracy of discrimination are very large, the fact that all six of the most extreme conditions show the effect supports the interpretation that some of the Test energy is not being integrated. The result is an interesting apparent paradox where the introduction of physical differences between the two stimuli produces less rather than more discrimination.

In a number of other suprathreshold experiments involving extensive testing of two dozen subjects, at low mesopic luminance levels, we have used the 0% response criteria to obtain estimates of critical duration ranging from 8-25 nsec. (Kietzman, 1966; Kietzman & Sutton, 1968). We wonder to what extent the reports by other investigators of much longer critical durations can be attributed to their use of higher response levels.

The second response topic to be discussed concerns the role of different discriminative responses in stimulus reciprocity. Suprathreshold stimuli produce a number of perceptual cues which may enter into the discriminative process. In the simplest case, manipulation of the intensity and duration of the stimulus gives rise to changes in brightness and perceived duration (protensity). With more complex stimuli a large number of additional cues may be introduced. Therefore, for suprathreshold studies it is necessary to consider how such multiple cues relate to stimulus reciprocity. The early studies of reciprocity were concerned primarily with sensitivity or brightness, as in the absence or presence of a stimulus or as in brightness differences. Therefore, we might expect other measures of brightness to display stimulus reciprocity similar to that of the absolute and differential threshold work. The relationship between stimulus reciprocity and judgments of stimulus duration is less clear since relevant studies do not seem to have been reported, perhaps because of the earlier emphasis upon brightness. However, our research has shown that the duration variable may influence measures of reciprocity and therefore must be measured or controlled.

In the preceding discussion about the U-shaped function of Figure 6, we noted that the equal-energy Test stimuli gradually become discriminable from the shorter Comparison stimulus, and we attributed that increase in discrimination to the failure of some of the energy in the Test stimulus to be integrated because it was of a duration longer than the critical duration. Notice that for these equal-energy points the duration difference between the Test and Comparison stimuli is increasing as the duration of the Test stimulus increases. Consequently, it is possible that both factors, the duration difference and an integrated-energy difference, may have produced the increasing discrimination. However, if the difference in integrated energy between the Test and Comparison stimuli were the sole determiner of discrimination, then by increasing the energy of the Test stimulus in small steps it should be possible to equate its integrated energy with that of the Comparison stimulus and reduce discrimination to chance. We mentioned before that increasing energy beyond the equal-energy point by luminance or duration manipulations did reduce discrimination. However, these operations did not reduce the level of discrimination completely to chance, although for one curve it came very close. This was true despite the fact that in some cases stimulus duration manipulations of the order of
700 microseconds enabled a very fine titration-like procedure. Therefore, it must be concluded that factors other than the differences in integrated energy were contributing to maintaining some above-chance discrimination. Our cue reports suggested that the duration difference was one such factor since our subjects sometimes reported the longer duration Test stimuli as appearing "longer" or "slower" than the 4-msec. Comparison stimulus. To be sure that such small duration differences are perceptible we have done other studies to directly test this question and find that with our forced-choice methodology such stimulus differences are discriminable (Kietzman & Sutton, 1968).

The implication of our failure to bring the minima of our U-shaped curves down to a chance level of discrimination is that the differences in stimulus duration may be contributing to discrimination and thereby modifying estimates of the characteristics of stimulus reciprocity, even when a change in stimulus luminance (and therefore brightness) is the major variable. If this is the case, then what procedures are available to control, measure or reduce the duration factor? This is not a new problem; all previous studies of reciprocity necessarily involve stimulus duration differences. The usual approach has been to rely upon the ability of trained subjects to follow instructions, but in the research just described the subjects were instructed only to pick the "different" stimulus, with no attempt made to limit the choice to brightness. Would our conclusions about suprathreshold stimulus reciprocity be much different if, under similar stimulus conditions, the subjects were instructed to make their discriminations on the basis of a brightness difference? Another related question is, Can subjects follow instructions to respond to brightness thus ignoring duration? It apparently has been assumed that they can, but the assumption does not seem to have been tested. If subjects differ in their ability to follow such instructions, then one might expect different estimates of 'reciprocity' for what are clearly non-sensory reasons.

To answer some of these questions we designed an experiment using a forced-choice method as before (but without feedback) in which the subject was instructed to say which of three successively presented stimuli was the brightest. Two of the stimuli, the Comparison pulses, were identical and of fixed duration and luminance. The third stimulus, the Test pulse, was briefer than the Comparison pulses and its duration was varied so that it contained more, less, or the same energy as the Comparison stimulus. The parameter of the experiment was the duration and luminance of the equal-energy Comparison stimuli. Figure 9 shows a Comparison stimulus of a duration shorter than a hypothetical critical duration. In this case the Test and Comparison stimuli would appear equally as bright since they contain the same physical energy (center section of the figure), and therefore the Test stimulus would be chosen as brighter 33% of the time which is the chance frequency. As the Test stimulus energy is increased by increasing its duration (as the 4.8 msec. pulse on the left) it would appear brighter than the Comparison stimulus and therefore would be chosen more frequently than chance. When the Test stimulus has less energy than the Comparison stimulus (e.g., the 3.6 msec. pulse on the right) it would be chosen less often as the brighter stimulus. Figure 10 shows a Comparison stimulus which has the same physical energy as before but with a duration that is greater than a hypothetical critical duration. In this example some of the energy of the Comparison stimulus is not integrated and therefore the 4.0 msec. Test stimulus, which contains the same physical energy as the Comparison stimulus, would be reported as brighter more frequently than chance. However, as the energy of the Test stimulus is reduced by shortening its duration to less than 4.0 msec. its frequency of report as brighter would be reduced to the chance level. By manipulating the duration (and therefore the
Three Test stimuli containing either more energy (4.8-msec. Test), equal-energy (4.0-msec. Test), or less energy (3.6-msec. Test) than a 10.5-msec. Comparison stimulus. The luminance of all Test stimuli is equal and constant, and the energy of all Comparison stimuli is the same. In this example, the duration of the Comparison stimulus is shorter than a hypothetical critical duration and therefore all of its energy presumably is being integrated.

As in Fig. 9, three Test stimuli containing either more energy, equal-energy or less energy than a 16.0-msec. Comparison stimulus. The energy of this Comparison stimulus equals that of the 10.5-msec. Comparison stimulus in Fig. 9. In this example, the duration of the Comparison stimulus is longer than a hypothetical critical duration and therefore some of its energy presumably is not being integrated.
energy) of a Test stimulus to be discriminated from the various Comparison stimuli so that it sometimes appeared brighter and sometimes dimmer than the Comparison stimuli; a brightness function is obtained for each Comparison stimulus in which the frequency of discrimination is a function of the duration of the Test stimulus. From these functions it is possible to determine a point of subjective brightness equality between the Test and Comparison stimuli which is defined as the duration of the Test stimulus at which it is judged brighter than the Comparison stimulus 50% of the time. If the Comparison stimulus is within critical duration, then the point of subjective equality would occur with the 4.0 msec. Test stimulus, i.e., at the point at which the two pulses are of equal energy. For partially integrated Comparison stimuli, a shorter Test stimulus would yield the point of subjective equality and the 4.0 msec. pulse would appear brighter than the Comparison pulse. The amount of energy by which the Test stimulus is reduced to obtain the point of subjective equality provides an estimate of how much energy of the Comparison stimulus is not integrated.

Figure 11 shows nine such brightness functions obtained from one subject for Comparison stimuli ranging from 5.16 msec. to 40.2 msec.; each point on these curves are based on 90-180 trials. On the left side of the figure are values in which the Test stimulus is greater than 4.0 msec. and therefore contains more energy than the Comparison stimulus; while the right side shows Test stimuli shorter than 4.0 msec. and therefore have less energy than the Comparison stimulus. In the center of the figure the Test and Comparison stimuli contain the same energy.

Figure 12 shows the lines of best fit obtained by the least squares method for the data shown in Figure 11. Notice the monotonic decrement in the frequency which the Test stimulus was judged as brighter as a function of decreasing its duration. Notice also that as the duration of the Comparison stimulus was lengthened for any Test duration, (the parameter of the figure running from left to right), the frequency of any Test stimulus being judged as brighter increased. This result is consistent with the interpretation that the longer the duration of the Comparison stimulus, the less its energy is being integrated. However, even for the longest Comparison stimulus, discrimination of the Test stimulus as brighter was brought to a chance level by shortening its duration.

Of primary interest in Figure 12 is the determination of the energy levels of the Test stimulus at which the brightness functions cross the chance level of discrimination. These cross-over points represent points of subjective brightness equality. Determining the Test energy levels at these points allows an estimate of critical duration and provides a quantitative measure of the magnitude of partial integration (stimulus reciprocity beyond critical duration). With regards to critical duration, all Comparison stimuli which were not discriminated from the 4.0 msec. Test stimulus, i.e., the two stimuli were subjectively equal in brightness, were within critical duration. Comparison stimuli longer than critical duration were discriminated at an above chance level from the 4.0 msec. equal-energy Test stimulus.

In Figure 13, the duration of the Test stimulus necessary to bring the brightness functions for the different Comparison stimuli to the point of subjective brightness equality is shown for three subjects, the subject BP whose data were shown in Figure 11 and 12 and two other subjects whose data were similarly fitted by the method of least squares. All three subjects show the same general trend: for short duration Comparison stimuli the Test stimulus which produced the brightness match was 4.0 msec. i.e., there is complete reciprocity and no energy loss for these Comparison stimuli. However, as the dura-
FIG. 11. PER CENT DISCRIMINATION OF THE TEST STIMULUS

Frequency of discriminating the Test stimulus as brighter than the Comparison stimulus as a function of the Test stimulus duration. The parameter is the duration of the Comparison stimuli which all contain the same energy; the energy of the 4-msec. Test stimulus is also the same. The point of subjective equality is when the Test stimulus is discriminated by a chance (33%) frequency.

FIG. 12. FITTED LINES FOR THE DATA OF FIG. 11

Lines of best fit obtained by the method of least squares applied to the discrimination data of Figure 11.
FIG. 13. ENERGY LOSS AS A FUNCTION OF COMPARISON STIMULUS DURATION (LOG-LOG COORDINATES)

Data of three subjects showing the reduction in the duration of the Test stimulus (left ordinate) necessary to produce chance discrimination from the equal-energy Comparison stimuli of varying durations (abscissa). This point of subjective brightness equality provides an estimate of the magnitude of energy loss of the Comparison stimuli (right ordinate).

FIG. 11. PER CENT DISCRIMINATION: BRIGHTER VS. SHORTEST INSTRUCTIONS

Frequency of discriminating the Test stimulus from the Comparison stimulus as a function of the duration of the Test stimulus under two sets of instructions: (1) "pick the brightest stimulus;" (2) "pick the fastest or shortest stimulus." Only one brightness function is shown here (the 11.7-msec, Comparison stimulus) but the other brightness functions for this subject are shown in Figs. 11 & 12.
tion of the Comparison stimuli was increased the duration of the Test stimulus had to be reduced to obtain the brightness match, i.e., these Comparison stimuli had exceeded the critical duration and some of their energy was not integrated. The magnitude of this energy loss is directly related to the duration increases of the Comparison stimulus.

Specific critical durations displayed by the individual subjects differ slightly; subject BP showed a critical duration between 5.26 and 8.1 msecs; the most variable subject, LG, showed a critical duration between 3.1 and 15.1 msecs; subject PN, who in the two previous experiments was reported to have a critical duration between about 10-22 msecs, showed a critical duration in this experiment between 8.1 and 21.7 msecs.

Two of the three subjects showed about the same amount of energy loss as the duration of the Comparison stimulus was increased, while subject BP showed slightly less energy loss for the longer duration stimuli. For all subjects the magnitude of this energy loss was very small, the maximum being about 15% for the 48 msec Comparison stimulus, the longest stimulus shown in Figure 13. In other experiments (data not shown) we have tested Comparison stimuli out to 81.3 msecs, and for these stimuli the energy loss never exceeded 25%. This means that in addition to demonstrating very brief critical durations our results indicate a very small energy loss up to almost 100 msecs. The implication is that investigators who do not use sensitive techniques for measurement may fail to detect the small energy loss, and may very well conclude that they have demonstrated complete reciprocity while another method could show partial reciprocity for the same duration stimuli. Such 'different' results obviously would lead to markedly different estimates of critical duration by the two techniques.

We introduced this discussion of different discriminative responses with a question as to how well our subjects, and subjects in general, are able to follow the instructions, 'Respond to the brighter stimulus.' The estimates of our subjects' critical durations are about the same with such instructions (Figure 13) and without such instructions (Figure 5, 6 & 8), suggesting either that the subjects were using only brightness cues in the non-instructed experiment or, contrary to instructions, were using all available cues in the brightness-instructed experiment. We already have described how the failure to obtain minima of the U-shaped functions at a chance level of discrimination implies that the stimulus duration differences were influencing discrimination, and how our reports supported that interpretation. The possibility remains that our trained subjects in the brightness-instructed experiment did not follow the instructions. To investigate this possibility we asked our subjects to discriminate identical stimuli under two sets of instructions: (1) which stimulus is brightest? (2) which stimulus is fastest or shortest? The stimulus conditions were exactly as before with the brief Test stimulus of different durations being discriminated from the longer Comparison stimuli.

Figure 14 shows the results for subject BP with three Comparison stimuli under the two sets of instructions. For clarity, in this figure only one brightness function is shown (the one for the 11.7 msecs. Comparison stimulus); the other brightness functions for this subject can be seen in Figures 11 and 12. The 11.7 msecs. brightness function is like the other brightness function, a monotonically increasing curve as a function of increments in the Test stimulus duration. With the same 11.7 msecs. Comparison stimulus but under the instructions to report the fastest or shortest stimulus, the subject's performance was chance for all Test stimulus durations. Under the fastest or shortest
instructions the overall level of discrimination between the Test and Comparison stimuli increased when the Comparison stimulus was 34 msec. (there was a 30 msec difference between the Test and Comparison stimuli) but the function remained essentially flat as Test duration was varied; in contrast, the brightness function decreased as the Test duration decreased. With the faster instructions the 41 msec, Comparison stimulus again produced a flat discrimination curve but at a slightly higher level of discrimination than that obtained for the 34 msec. Comparison pulse (the duration difference between Test and Comparison stimuli was 37 msec.). These results show that this subject was able to base his judgments on the brightness of the stimulus even when tested under conditions which could give rise to discrimination of differences in duration. We have obtained similar data from our other subjects.

The ability of our subjects to follow the brightness instructions is perhaps best demonstrated by noting that reducing the duration of the Test stimulus increased the duration difference between the Test and Comparison stimuli and in that way facilitated the judgment of the Test stimulus as faster or shorter. However, despite the increasing duration difference between the Test and Comparison stimuli, all brightness functions were reduced to a chance level of discrimination by reducing the Test stimulus duration. It will be recalled that a similar attempt to reduce discrimination to chance in the non-instructed experiment with the U-shaped functions was unsuccessful.

From these results we can conclude that our subjects' judgments provide an accurate estimate of the characteristics of stimulus reciprocity with regards to brightness. Still unexplained is why the two types of experiment, one with and the other without brightness instructions, gave approximately the same estimates of critical duration. The best guess is that our use of a low response level to estimate critical duration, i.e., the transition to above-chance discrimination, kept the duration differences between the Test and Comparison stimuli very small and such small differences had a minimal confounding effect upon the estimates of critical duration. However, in experiments where subjects are not instructed and trained in the use of the brightness cue (as in our experiment with the U-shaped functions) and where a high response level is employed (as the 50% response level in the earlier experiment) the comparatively large duration differences between the stimuli would increase the opportunity for confounding, especially in the measurement of partial reciprocity beyond critical duration. It was because we obtained evidence of such confounding in the U-shaped functions that we initiated the brightness-instructed experiment. The ability of our subjects to follow the brightness instruction in that experiment supports the accuracy of our obtained estimates of the magnitude of partial reciprocity.

The brief critical durations reported by us may be questioned by those who have an idea of the existence of a longer critical duration of around 100 msec, an idea propagated by several of the better known textbooks of psychology. There is increasing evidence for both absolute threshold and suprathreshold conditions that under certain conditions critical durations may be very brief and of the magnitude reported here (Albou & Stevens, 1964; Boynton, 1961, discussing Katz's data; Sperling & Joliffe, 1965, their foveal data). However, there are still some suprathreshold studies of brightness which have demonstrated critical durations of the order of 100 msec. (e.g., Kahneman & Norman, 1964). One wonders to what extent these longer estimates can be accounted for by not enough attention being given to the factors which we have found to be of importance in measuring suprathreshold stimulus reciprocity, namely: (1) use of sensitive methods; (2) concern with selecting the most
appropriate response level; (3) control of measurement of possible interactions between perceptual cues.

Finally, let us discuss the third topic which is the comparison of response classes as when comparing the characteristics of stimulus reciprocity for a discrimination task and a reaction time response. Such comparisons across response classes have been reported previously; for example, the measurement of reaction time for stimulus conditions capable of producing different perceptual effects, like metacognition and the Broca-Sulzer effect, to determine if there are psychomotor parallels to these perceptual phenomena (Fehrer & Biederman, 1962; Raab, Fehrer & Hershenson, 1961; Raab & Fehrer, 1962). The results of these studies show perceptual and psychomotor phenomena to be quite distinct. There have also been a few attempts to test for stimulus reciprocity by using a reaction time response to light (Grossberg, 1967; Kaswan & Young, 1965; Pease, 1964; Raab & Fehrer, 1962), although behavioral investigations of stimulus reciprocity usually have employed perceptual measures. The general conclusion of these studies is that the critical duration for reaction time is very brief, if present at all, and this conclusion has created doubt that the characteristics of stimulus reciprocity can be demonstrated for a timed response. We have collected considerable data on stimulus reciprocity and reaction time, and some of these data definitely establish the presence of some stimulus reciprocity for periods as long as 30-70 msec. after the onset of the stimulus. It is important to note that one reason why previous reaction time investigations show little evidence of stimulus reciprocity is that they were conducted at energy levels which produced comparatively fast reaction times while the most pronounced reciprocity effects occur for conditions which produce longer reaction times. Here again, the selection of a proper response level can be seen to be important; at one response level reciprocity can be demonstrated while at another response level the characteristics of reciprocity may change or reciprocity may be completely absent.

In one series of experiments done to show reciprocity effects for long periods after stimulus onset, reaction times were measured to three different types of packages of light: (1) a stimulus consisting of two, 2-msec. pulses separated by a variable interpulse interval ranging from 7.7 to 122 msec; the total duration of this double-pulse stimulus therefore ranged from 11.7 to 125 msec.; (2) a 4-msec. pulse containing the same energy as the double-pulse stimulus (this stimulus can be considered a double-pulse stimulus with a 0-msec. interpulse interval); (3) a 2-msec. pulse of the same luminance and thus half the energy of the other two stimulus packages. The perimeter of these experiments was the luminance of the three types of stimuli.

Figure 15 shows the data of one subject, MP, from three separate but related experiments in which reaction times to the three types of stimuli were obtained. In two of the experiments, pulse luminance was 0.10 NL, while in the third experiment pulse luminance was 0.37 NL. Let us consider these experiments in the chronological order in which they were conducted since slight practice effects were obtained. The higher luminance experiment was done first (the triangles in Figure 15). In this experiment the obtained reaction times were 205-218 msec., faster than all the other values measured; consequently, as it developed, this experiment was of little value in testing for reciprocity effects. The results show that the greater energy of the 4-msec. stimulus produced a faster reaction time than the 2-msec. stimulus, but when the same amount of energy was distributed over 11.7 msec. for the double-pulse
Data of one subject in three experiments showing the median reaction time as a function of the total stimulus duration. The 2- and 4-msec. pulses are single pulses of light. All other stimuli consist of two, 2-msec. pulses separated by a variable interpulse interval (IPI) such that the total stimulus is 2-msec.-IPI-2-msec. Stimulus luminance is the parameter and it is the same for both single and double pulses. Each point is based on 52-79 reaction time trials.

**FIG. 15. SIMPLE REACTION TIMES TO SINGLE- AND DOUBLE-PULSE STIMULI**

Data of one subject in three experiments showing the median reaction time as a function of the total stimulus duration. Stimulus conditions are the same as described in the caption of Fig. 15. Each point is based on 52-79 reaction time trials.

**FIG. 16. SIMPLE REACTION TIMES TO SINGLE- AND DOUBLE-PULSE STIMULI**
stimulus, there was no difference in the reaction times between the 2-msec. stimulus and the double-pulse stimulus. Furthermore, as the interpulse interval was increased beyond 7.7 msec, the reaction time remained constant and at the same level as the reaction time to the 2-msec. stimulus. This constant performance indicates that none of the energy of the second pulse of the double-pulse stimulus was integrated. From this curve one might conclude that there is no stimulus reciprocity for reaction time, but actually what has been demonstrated is that at this energy level, double the amount of energy of the 2-msec. stimulus distributed over an 11.7-msec. period does not noticeably reduce the reaction time. Under these circumstances it would be very difficult to test for reciprocity since an energy loss would not be readily detected, especially since our earlier psychophysical data (Figure 13) suggest a very small energy loss initially beyond critical duration.

In order to test this subject at an energy level where changes in energy produced larger changes in reaction time, the light pulses in the next experiment (the circles) contained approximately half the luminance of the prior experiment. This change produced slower reaction times to the double-pulse stimuli and also to the single-pulse, 2-msec. stimulus of reduced energy. An important result was the 31-msec. reaction time difference between the single-pulse stimulus and the 11.7-msec. double-pulse stimulus; here the presence of the second pulse markedly reduced the reaction time even though the second pulse occurred about 3.0 msec. after the first pulse. As this second pulse was presented at increasingly longer durations after the first pulse the reaction times became longer but they still remained shorter than those obtained to the single-pulse stimulus alone; for these long durations none of the energy of the second pulse was being integrated and was modifying the speed of response. Eventually, around 60 msec., the reaction time to the double-pulse stimulus became equal to the reaction time to the 2-msec. pulse stimulus and then remained about the same for the longest interpulse intervals. The interpretation is that until about 60 msec. none of the second pulse was integrated thereby reducing reaction times, and that at longer interpulse intervals none of the second pulse was integrated and therefore the reaction times were the same as if only the first pulse had been presented.

The third experiment shown in Figure 15 explores further the results for longer durations (and therefore the longer interpulse intervals) of the double-pulse stimulus (the hexagons). The subject was more highly practiced for this experiment which may explain his faster reaction times for conditions comparable to those in the last experiment. The important results are that this curve was essentially flat for all the longer double-pulse stimuli from 63.3 to 124 msec. and that these reaction times were at the same approximate level as those to the single-pulse stimulus; in this range of durations, the second pulse of the double-pulse package did not modify the reaction time; none of its luminance was integrated, a result similar to that seen in the second experiment for the longer stimuli but over a wider range of stimulus durations.

In Figure 16 similar data are shown for a different subject (FW) but here three rather than two luminance levels are displayed. Again, the three experiments are described according to the chronological order in which they were done. Data from the highest luminance condition (M=0.37; the triangles) show slightly faster reaction times to the 4-msec. pulse than to the 2-msec. pulse, but when that energy was distributed over 11.7 msec. the reaction time was about the same as to the half-energy, 2-msec. pulse; when the double-pulse stimulus was increased to about 22 msec. the reaction time to it was indistinguishable from that obtained by the 2-msec. stimulus. Presumably by that
duration the energy of the second pulse of the double-pulse stimulus was no longer able to influence the speed of response. Data from the intermediate luminance level (M=0.18; the hexagons) show similar trends. The reaction time to the 4-msec. pulse was shorter than to the 2-msec. pulse but most of that difference was eliminated when the energy was distributed in a double-pulse package of a total duration somewhere between 24 to 37 msec. There is a suggestion that integration of the second pulse may be slightly longer for the intermediate luminance level than for the highest luminance condition. This trend is clearly supported by data from the lowest luminance condition (0.15 mL; the squares) which show integration of the second pulse for the longest period after stimulus onset of all the luminances tested. In these data there is a marked reaction time difference of 40 msec between the 2- and 4-msec. pulses.

For the shorter double-pulse stimuli at this lowest luminance value, the reaction times were slightly faster than to the intermediate luminance pulses and this may have been due to the subject's greater practice by the time he participated in this, the last, experiment. (The luminance differences between these two conditions was very slight and could have been outweighed by a practice effect.) The important result of this experiment was that as the interpulse interval increased, the reaction time also increased but still remained faster than the reaction time to the 2-msec. pulse, out to at least 63.6 msec. The second pulse was capable of reducing the reaction time when presented that long after the onset of the first pulse. For longer interpulse intervals of the double-pulse stimulus the reaction time stayed approximately equal to that obtained to the 2-msec. stimulus.

Based upon our data and upon prior investigations, what conclusions can be made about the comparison of the characteristics of stimulus reciprocity for discriminative and psychomotor responses? Our results show some reciprocity effect for simple reaction time over a much longer duration after the stimulus onset than reported by other studies. There are at least two reasons for this apparent discrepancy: First, most of the earlier studies used higher energy levels and therefore measured shorter reaction times than those we have found to be associated with reciprocity. In our experiments, reaction times of 220 msec. or less were found to be associated with very short periods of reciprocity and this result is consistent with the conclusions of previous investigators. Second, some reaction time studies of reciprocity used low energy levels to obtain long reaction times and still failed to find reciprocity effects because they concentrated their analysis on complete reciprocity and its termination, i.e., critical duration. Our experiments suggest that in the measurement of simple, visual reaction time the more demonstrable effects are for partial rather than for complete reciprocity. This seems to be true because the critical duration for reaction time is very brief, especially at higher energy levels. However, our psychophysical experiments using sensitive techniques also demonstrated very brief critical durations of the order of 10-20 msec., and these estimates are not much different than those reported in the earlier reaction time study for low luminance levels. The similarity of the estimates of critical duration for reaction time and suprathreshold discrimination suggests that reaction time may be a sensitive technique for measuring the characteristics of reciprocity.
FOOTNOTES

1. In this report the term stimulus reciprocity is preferred to the more usual terms temporal integration or temporal summation because it emphasizes that we are concerned with psychophysical rather than physiological measurement. It should be stressed that the term temporal integration as used in this report does not refer to physiological processing but to the integration of stimulus luminance over time, and therefore to a stimulus characteristic. Some investigators have used the term to refer to physiological processes. It is, of course, hoped that the results from studies such as are reported here can assist in the investigation of the physiological mechanisms underlying stimulus reciprocity.

2. The "adjusted per cent correct" shown in the figures refers to a correction for chance or guessing applied to the accuracy of discrimination. The formula used was: \( P_{adj} = P_0 - P_C \times \frac{1}{1 - P_C} \); where \( P_0 \) = proportion of accurate discriminations actually obtained; \( P_C \) = proportion of discriminations expected by chance; and \( P_{adj} \) = accuracy of discrimination, adjusted for chance. The use of the Preparatory stimulus does not modify the proportion of responses obtained by chance alone since this is determined by the number of observation periods in which the Test stimulus may be presented. In the experiments reported here it was 0.33 since the Test stimulus was presented only in the second, third or fourth observation periods.

3. It is well documented that the reaction time as a function of either luminance or duration is a negatively decelerating function with very long reaction times for near-threshold energy levels. The large reaction time difference between the single-and double-pulse stimuli in this instance, as compared to the slight difference in the last experiment, can be explained by the fact that in this experiment the energy level of the stimuli is half of what it was before. Thus, since the stimulus is closer to the absolute threshold the reaction times to the 2-msec. stimulus fall on the rapidly changing portion of the curve. As might be expected, variability of reaction time for the near-threshold response also increases, sometimes by as much as a factor of five or even more. In our experiments the variability of reaction time to the 2-msec. pulse increased but never by more than a factor of two. This indicates that even for our lowest energy level we were not at the level of a detection threshold. Our greatest variability occurred for the long interpulse intervals of some of the double-pulse stimuli and this increase was about three times as great as the variability of reaction times to the more intense stimuli.
REFERENCES


