Perception & Psychophysics
1976, Vol. 20(1), 66-76

Measuring the duration of perception

LEONARD MATIN and RICHARD W. BOWEN
Columbia University, New York, New York 10027

An analysis is presented of ways in which the total duration of perception of transient visual stimuli may be determined by means of psychophysical judgments of the simultaneity (or relative precedence) of two sensory events. This analysis yields a new method for measuring the duration of perception that only requires judgments of the simultaneity of the offset of one visual target with the onset of another ("offset-onset" judgments), and is thus free of differential biases between onset-onset and offset-onset judgments of simultaneity which could be involved in previous measurements. When three or more perceived durations need to be determined, the new method is more efficient than earlier methods; it requires measurement of only one PSE in order to evaluate one response duration as compared to two PSEs per response duration for previous methods. We also describe ways of determining the presence of some kinds of biases and quantitatively evaluating the magnitude of bias in the new method, as well as bias in onset-onset or offset-offset judgments of simultaneity alone; such evaluations of differential bias were not possible for the earlier methods. An experimental example of a bias analysis is described. No significant biasing effects were detected in the measures of perceived duration that were extracted as either retinal location or background luminance was changed, although background luminance itself markedly influenced the values of perceived duration.

The duration for which a transient visual stimulus remains in perception has been the subject of considerable interest in areas of sensation, perception, and cognition as diverse as the perception of flicker (cf. Pieron, 1965), perception of visual direction (cf. Matin, 1972), and memory and information processing (cf. Neisser, 1967). Attempts at inferring this duration have been made in studies of threshold flicker (Pieron, 1965), band movement (Smith, 1969), afterimages (Brown, 1965), and by means of simultaneity or temporal order judgments (Bowen, Pola, & Matin, 1974; Efron, 1970; Haber & Standing, 1970). That these approaches are not likely to be measuring the same aspect of perception is a question with which we shall deal further in this report. However, of these approaches, the use of simultaneity or order judgments appears to deal most directly with the problem of interest and obtain results most readily interpretable as values of "duration of perception." In this case, the experimenter can require a subject to report whether stimulus B began before or after stimulus A in one set of trials, and on a separate set of trials, whether B′ began before or after A terminated (Figure 1). When B and B′ are the same stimulus, the experimenter infers the duration of the perception of flash A as equal to $t_2 - t_1$ from those temporal locations of B and B′ which have been reported as simultaneous[1] with the onset and offset of A, respectively. (B and B′ need not, of course, be a visual stimulus; inputs to any other sense modality provide an appropriate "probe," although each carries with it different problems of methodology and interpretation.) Such a method cannot, of course, determine the actual time delay or latency from the onset of the physical stimulus A to the onset of its perception, or the analogous delay at the offset of A; this is a result of a similar lack of information concerning the latency to the onsets of B and B′. Since time to the onset of the perception of B is not known, any estimate of the moment when the onset of A was seen is confounded with the latency of perception of the onset of B. A true determination of the "fundamental asynchrony" of a stimulus and its perception requires identification and measurement of the neural event corresponding to the perception of the stimulus. On the other hand, the

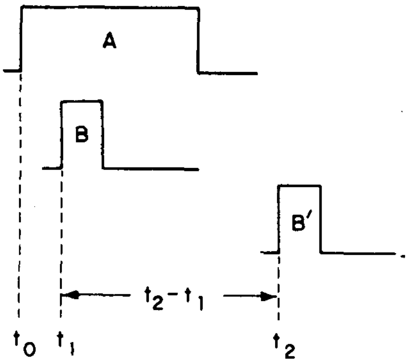

Figure 1. When the onset of B and B′ are set to appear simultaneous with the onset and offset of A, respectively, $t_2 - t_1$ has been considered as a measure of duration of perception.

This work was supported by grants from the National Eye Institute, National Institutes of Health (EY 00375), and the National Science Foundation (BMS73-01463) to Leonard Matin, and by an NIMH predoctoral fellowship to Richard Bowen.
Richard W. Bowen's present address is Department of Psychology, Loyola University of Chicago, Chicago, Illinois 60626. Requests for reprints should be addressed to Leonard Matin, Visual Science Laboratory, Department of Psychology, Columbia University, New York, New York 10027.

identification of this neural event requires prior knowledge of the fundamental asynchrony; such "bootstrapping" must leave the value of the fundamental asynchrony uncertain, although this difficulty is of the same order as exists for inferring causality in the case of any other psychophysical-neural correlation.

Nevertheless, by assuming that the fundamental asynchrony of B's onset is identical when judged in relation to the onset of A and in relation to the offset of A, the duration $t_2 - t_1$ may be interpreted as a measure of the duration of the perception of A, as indicated above. In addition, one can also determine relative variation in the onset latency of A (although not its fundamental asynchrony) with variation in the parameters of stimulation for A when B is held constant. This assumes that such variation of stimulus A does not influence the onset of latency of B. Measurements can also be made of the relative offset latency of A if it can be assumed that the onset latency of B′ is not influenced by variations in stimulus parameters of A in that situation. Several interesting results have been obtained by use of such simultaneity judgments (see Bowen, Pola, & Matin, 1974, for references to this work).

Each of the approaches to the measurement of the duration of perception has brought with it a number of difficult methodological issues. While generally free of many of the complications involved in inferring duration of perception from the other kinds of measurements, some complications do remain for the simultaneity paradigm (Figure 1):

(1) As has been indicated, it is assumed that the latency of the response to the onset of the "probe" stimulus B is unchanged under the different conditions in which it is used. Thus, for example, it is assumed that neural interactions between stimuli A and B do not differentially influence B's onset latency (and A's onset or offset latency) when B's onset is compared to A's onset or to its offset. Such an assumption is of particular concern when A and B are both visual stimuli, and of even greater concern when they are located close to each other in the visual field. Interactions within the visual system, or by way of stray light from one stimulus to the retinal region stimulated by the second stimulus, or eye movements could all serve to differentially influence measured values of the temporal characteristics of the response.

(2) It is assumed that "constant errors" associated with "onset-onset" judgments are the same as those associated with "offset-onset" judgments. This assumption is similar to stating, at a somewhat different conceptual level, that stimulus onsets and offsets are processed by the same neural center.

(3) It is assumed that duration of perception of a stimulus is not influenced by its being the first or second in a sequence of stimuli.

For many purposes, these three assumptions are reflections of a single underlying methodological problem. They are all involved with biasing of simultaneity judgments. Since duration of perception, as determined above, involves experimental determination of two quantities whose algebraic difference constitutes the measure of the duration of perception, the main concern is not simply bias, but differential bias between the two determinations. That such questions regarding bias in simultaneity judgments are not trivial is indicated, for example, by work on the "prior-entry question" in which it is reported that changed instructions which purport to shift attention from one of the two stimuli whose temporal order is being judged to the other can influence the point of subjective simultaneity for the two stimuli by as much as 70 msec or more (cf. Sternberg & Knoll, 1973; Sternberg, Knoll, & Gates, Note 1).

It is worth noting that the methods with which we are concerned do not purport to measure the apparent duration of a perception but rather to determine, by psychophysical means, the physical duration of a perception. Thus, the perception whose duration was measured as $t_2 - t_1$ (Figure 1) may appear longer or shorter under different conditions or bodily states without influencing the value $t_2 - t_1$ obtained. The methods themselves yield measurements of simultaneity, and values of duration of perception are derived from such measures. Subjective or apparent duration of a perception may or may not be simply related to such values. But judgments of apparent duration are not values derived from simultaneity judgments, and how they relate to the psychophysically determined physical duration of perception is a separate problem.

The present article develops a general framework for dealing with the duration of perception in the context of simultaneity judgments, develops some new ways of using simultaneity judgments to measure the duration of perception, and provides a theoretical basis for some experimental tests of the underlying assumptions, particularly those regarding certain possible biases. We also present some data from an experiment which employed the new method in order to demonstrate by example how a test for bias may be evaluated.

THE GENERAL MEASUREMENT MODEL

The method of obtaining total response duration that was described above depends on taking a difference between two measurements, one of which is determined by onset-onset judgments, the other by offset-onset judgments. As we have indicated, the result will be biased by any difference in the way in which these two sorts of judgmental situations are themselves differentially biased. As an outcome of the attempt to obtain measurements that are free of this difficulty, we have developed a method for measuring total response duration that is based on offset-onset judgments only. The method also has built into its basic apparatus the possibility of quantitatively evaluating the effects of some of the biases mentioned above.

Figure 2 depicts a stimulus array we used with the method to be described below. It contains a fixation target and three circular 1° diam, steady adapting fields (L) upon which additional 18′ flashed targets (ΔL) were superimposed. On any given trial, two of the three targets were flashed and the subject reported whether the onset of the second target occurred before or after the offset of the first target. As we have developed the method, the locations of the two stimuli to be flashed were known to the subject beforehand, although he did not know the temporal order of the offset of the first stimulus and onset of the second, or the interval between the offset of the first stimulus and onset of the second; the latter was varied from trial to trial.

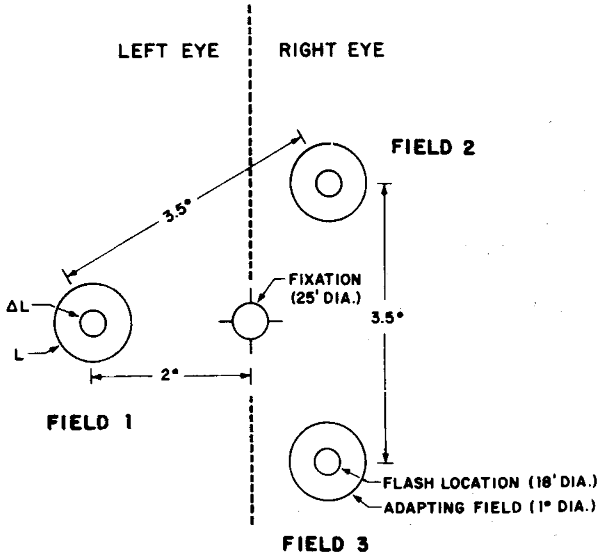

Figure 2. Stimulus dimensions of view as seen by subject in making offset-onset simultaneity judgments required for determining perceived durations of test flashes ΔL. Each background L was separately illuminated: luminances of ΔL and L were separately adjustable and were set so that ΔL/L was maintained at 1 log unit. All stimuli were presented in Maxwellian view.

Fundamental Relations

Figure 3 shows the temporal relation between physical flashes and visual responses 1 and 2 when their presentation has been adjusted so that the offset of flash 1 appears to have occurred simultaneously with the onset of flash 2; this simultaneity is represented in Figure 3 by lining up the offset of the visual response[2] to flash 1 with the onset of the visual response to flash 2. Consider flash 1:

$$L_1 + R_1 = d_1 + \bar{L}_1, \tag{1}$$

where L_1 and $\bar{L}_1$ represent onset and offset latency, respectively, and R_1 is the total duration of the visual response to the stimulus of duration d_1. Thus, by rearranging Equation 1, we note that the total visual response to flash 1 may be represented as

$$R_1 = d_1 + \bar{L}_1 - L_1 = d_1 + \ell_1, \tag{2}$$

where $\ell_1 \equiv \bar{L}_1 - L_1$. P_{12} is the temporal interval between the offset of the first flash and onset of the second flash when the flashes have been temporally adjusted for the appearance of offset-onset simultaneity. Here (from Figure 3)

$$P_{12} + d_1 = L_1 + R_1 - L_2, \tag{3}$$

and substituting for R_1 from Equation 2, we have

$$P_{12} = \bar{L}_1 - L_2, \tag{4}$$

a result that can also be read directly from Figure 3. Thus, Equation 4 states that the point of subjective simultaneity of the offset of flash 1 and the onset of flash 2 (P_{12}) is equal to the difference between the offset latency of the first flash and the onset latency of the second flash.[3]

Among the three flashed stimuli in Figure 2, we have six ordered pairs of stimuli. We may determine a point of subjective simultaneity for each pair in the fashion depicted in Figure 3, and thus we may write:

$$\left.\begin{aligned} P_{12} &= \bar{L}_1 - L_2 \\ P_{21} &= \bar{L}_2 - L_1 \\ P_{13} &= \bar{L}_1 - L_3 \\ P_{31} &= \bar{L}_3 - L_1 \\ P_{23} &= \bar{L}_2 - L_3 \\ P_{32} &= \bar{L}_3 - L_2. \end{aligned}\right\} \tag{5}$$

These equations, which involve both empirically determined terms (P_{12}, P_{21} ...) and theoretical quantities (L_1, $\bar{L}_1$ ...), may be combined in groups of three to obtain another set of equations, each of which is written in terms of the difference of offset and onset latency for a particular stimulus. Two such

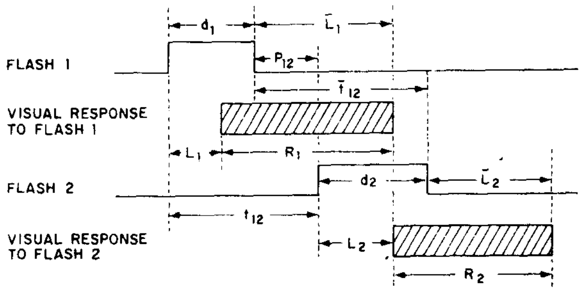

Figure 3. Component analysis of durations associated with offset-onset simultaneity judgments. The representation here is for a case in which the offset of flash 1 is seen as simultaneous with the onset of flash 2; perceived simultaneity is shown by the vertical alignment of the end of the visual response to flash 1 with the beginning of the visual response to flash 2. d_1 and d_2 are stimulus durations, R_1 and R_2 are perceived durations, L_1 and L_2 are onset latencies, $\bar{L}_1$ and $\bar{L}_2$ are offset latencies, P_{12} is PSE for offset-onset simultaneity, and t_{12} and $\bar{t}_{12}$ are differences in stimulus onset times and in stimulus offset times, respectively.

experimentally independent specifications may be obtained for each stimulus, each equal to the difference between an offset and an onset latency to a given stimulus, that is to a value of ℓ_1. Thus:

$$\left.\begin{aligned} P_{21} - P_{23} + P_{13} &= P_{31} - P_{32} + P_{12} = \ell_1 \\ P_{32} - P_{31} + P_{21} &= P_{12} - P_{13} + P_{23} = \ell_2 \\ P_{13} - P_{12} + P_{32} &= P_{23} - P_{21} + P_{31} = \ell_3. \end{aligned}\right\} \quad (6)$$

We now write equations of the form of Equation 2 to yield values for total duration of the visual response to each of the three stimuli:

$$\left.\begin{aligned} R_1 &= d_1 + \ell_1 \\ R_2 &= d_2 + \ell_2 \\ R_3 &= d_3 + \ell_3. \end{aligned}\right\} \quad (7)$$

Since two experimentally independent determinations of each value of ℓ_i may be obtained, two solutions for each R_i are also obtained. These are:

$$\begin{aligned} R_i &= P_{ij} + P_{ki} - P_{kj} + d_i \\ &= P_{ji} + P_{ik} - P_{jk} + d_i; \\ i, j, k &= 1, 2, 3; i \neq j \neq k. \end{aligned} \quad (8)$$

Each of these two solutions is thus based on a different trio of measurements. Where one solution involves P_{12}, the second solution involves P_{21}, etc. The two independent solutions may be compared quantitatively to determine the presence or absence of bias, as we shall indicate below.

For some purposes, it is useful to express response duration in terms of stimulus onset differences (as $\bar{t}_{12}$ in Figure 3). Such expressions are readily derived. From Figure 3, we have:

$$\left.\begin{aligned} t_{12} + L_2 &= L_1 + R_1 \\ \text{or} \quad t_{12} &= P_{12} + d_1. \end{aligned}\right\} \quad (9)$$

Thus, by substituting Equation 9 in Equations 5-8, we have response duration expressed in terms of either of two trios of stimulus onset differences:

$$\begin{aligned} R_i &= t_{ij} + t_{ki} - t_{kj} \\ &= t_{ji} + t_{ik} - t_{jk}; \\ i, j, k &= 1, 2, 3; i \neq j \neq k. \end{aligned} \quad (10)$$

Also, since we have from Figure 3

$$\left.\begin{aligned} t_{12} + d_2 &= \bar{t}_{12} + d_1, \\ \text{or, in general} \quad t_{ij} + d_j &= \bar{t}_{ij} + d_i, \end{aligned}\right\} \quad (11)$$

we obtain an entirely equivalent series of solutions in terms of stimulus offset differences:

$$\begin{aligned} R_i &= \bar{t}_{ij} + \bar{t}_{ki} - \bar{t}_{kj} \\ &= \bar{t}_{ji} + \bar{t}_{ik} - \bar{t}_{jk}; \\ i, j, k &= 1, 2, 3; i \neq j \neq k. \end{aligned} \quad (12)$$

Of course, this implies that

$$t_{ij} + t_{ki} - t_{kj} = \bar{t}_{ij} + \bar{t}_{ki} - \bar{t}_{kj}, \quad (13)$$

a result that may also be obtained more directly. An additional useful expression is

$$t_{ij} + t_{ki} - t_{kj} = P_{ij} + P_{ki} - P_{kj} + d_i. \quad (14)$$

The response durations in Equations 10 and 12 are for the first stimulus of a pair in a trial, as represented in Figure 3. Solutions for the same stimulus when it is the second stimulus of a pair in a trial may also be obtained. In order to allow for the possibility that the duration of perception does depend on whether a stimulus is first or second within a trial, we allow unprimed values in Equations 15-19 below to refer to the first flash and primed values to the second flash (although up to now we have not distinguished between these and have used unprimed terms for both). Thus, if we rewrite the general case of Equation 9 as

$$t_{ij} + L'_j = L_i + R_i, \quad (15)$$

we are led to

$$R_i = t_{ij} + t_{ki} - t_{kj} + L'_i - L_i \qquad (16)$$

in place of Equation 10, and by making use of Equation 11, we also have

$$R_i = \bar{t}_{ij} + \bar{t}_{ki} - \bar{t}_{kj} + L'_i - L_i \qquad (17)$$

in place of Equation 12. Since we also have, from Figure 3,

$$\bar{t}_{ij} + \bar{L}'_j = \bar{L}_i + R'_j, \qquad (18)$$

we are similarly led to

$$R'_i = t_{ij} + t_{ki} - t_{kj} + \bar{L}'_i - \bar{L}_i$$

and

$$R'_i = \bar{t}_{ij} + \bar{t}_{ki} - \bar{t}_{kj} + \bar{L}'_i - \bar{L}_i. \qquad (19)$$

Thus

$$R_i - R'_i = (L'_i - L_i) - (\bar{L}'_i - \bar{L}_i), \qquad (20)$$

and only if the difference between onset latencies for a given stimulus in the two positions in a trial equals the difference between the two offset latencies will the response durations of the stimulus be equal in the two positions. (A special case of this condition is that response durations for a given stimulus will be equal in the two positions within a trial if neither onset latency nor offset latency depends on whether the stimulus is first or second.) Thus, only when $R_i - R'_i = 0$ is the total duration of response truly equal to the simple linear combination of a trio of onset or offset differences as in Equations 10 and 12.[4]

Prediction of Onset-Onset and Offset-Offset PSEs from Offset-Onset PSEs

Although the method we present employs only offset-onset determinations of simultaneity, it does predict values of onset-onset and offset-offset PSEs that can be compared to values obtained using onset-onset measurements or offset-offset measurements. These predictions can be derived as follows. If the onsets of flash 1 and flash 2 in Figure 3 were set to appear simultaneous, then the onset-onset PSE would be equal to $L_1 - L_2$ as in Figure 4. But from Equation 3,

$$Q_{12} = L_1 - L_2 = P_{12} + d_1 - R_1$$

or in general

$$Q_{ij} = L_i - L_j = P_{ij} + d_i - R_i, \qquad (21)$$

where Q_{ij} is the onset-onset PSE predicted from offset-onset measurements alone. This result may be written wholly in terms of offset-onset PSEs by

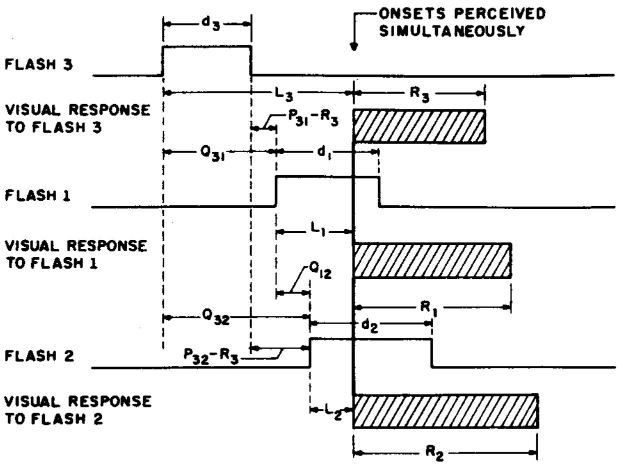

Figure 4. Component analysis of durations associated with onset-onset simultaneity judgments. The representation here is for the case in which the onsets of flash 3 and flash 1 are perceived as simultaneous in one set of trials and the onsets of flash 3 and flash 2 are perceived as simultaneous in another set of trials. As before, d_1, d_2, and d_3 are stimulus durations, R_1, R_2, and R_3 are perceived durations, and L_1, L_2, and L_3 are onset latencies. Q_{31}, Q_{32}, and Q_{12} are onset-onset PSEs. The relation of this figure to Equation 22—which predicts the onset-onset PSE from offset-onset PSEs—may be seen by setting $i = 1$, $j = 2$, and $k = 3$, and noting from the figure that $Q_{12} = (P_{32} - R_3) - (P_{31} - R_3)$, where, as before, P_{32} and P_{31} are offset-onset PSEs. (That the distance between the offset of flash 3 and onset of flash 1 is actually equal to $P_{31} - R_3$ can be seen by noting that if d_1 and R_1 were moved as a unit to the right so that the offset of R_3 was vertically aligned with the onset of R_1, the time difference between the offset of flash 3 and onset of flash 1 would be equal to P_{31}; but such a movement to the right is by the duration R_3 which would be added to $P_{31} - R_3$. A similar visualization may be carried out for $P_{32} - R_3$.)

substituting either of the two solutions for R_i from Equation 8. Thus:

$$Q_{ij} = P_{kj} - P_{ki} \qquad (22)$$

and

$$Q_{ij} = P_{ij} + P_{jk} - P_{ji} - P_{ik}. \qquad (23)$$

Some of these relations are schematically represented in Figure 4 among three stimuli which have been set to onset-onset simultaneity in pairs.

Similarly, if the offsets of flash 1 and flash 2 in Figure 3 were set to appear simultaneous (Figure 5), then the offset-offset PSE would be equal to $\bar{L}_1 - \bar{L}_2$. But from Figure 3, $P_{12} + d_2 = \bar{L}_1 + \bar{R}_2 - \bar{L}_2$, and so

$$\bar{Q}_{12} = \bar{L}_1 - \bar{L}_2 = P_{12} + d_2 - R_2$$

and in general

$$\bar{Q}_{ij} = \bar{L}_i - \bar{L}_j = P_{ij} + d_j - R_j, \qquad (24)$$

where $\bar{Q}_{ij}$ is the offset-offset PSE predicted from

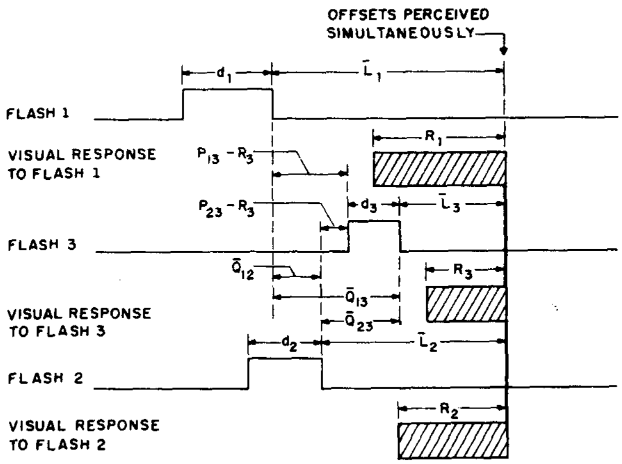

Figure 5. Component analysis of durations associated with offset-offset simultaneity judgments. The representation here is for the case in which the offsets of flash 1 and flash 3 are perceived as simultaneous in one set of trials and the offsets of flash 2 and flash 3 are perceived as simultaneous in another set of trials. As before, d_1, d_2, and d_3 are stimulus durations, R_1, R_2, and R_3 are perceived durations, and $\bar{L}_1$, $\bar{L}_2$, and $\bar{L}_3$ are offset latencies. $\bar{Q}_{12}$, $\bar{Q}_{21}$, and $\bar{Q}_{23}$ are offset-offset PSEs. The relation of this figure to Equation 25—which predicts the offset-offset PSE from offset-onset PSEs—may be seen by setting $i = 1$, $j = 2$, and $k = 3$, and noting from the figure that $\bar{Q}_{12} = (P_{13} - R_3) - (P_{23} - R_3)$, where, as before, P_{13} and P_{23} are offset-onset PSEs. (That the distance between the offset of flash 1 and onset of flash 3 is actually equal to $P_{13} - R_3$ may be seen by noting that if d_3 and R_3 were moved as a unit to the right so that the offset of R_1 was vertically aligned with the offset of R_3, the time difference between the offset of flash 1 and onset of flash 3 would be equal to P_{13}; but such a movement to the right is by duration R_3 which would be added to $P_{13} - R_3$. A similar visualization may be carried out for $P_{23} - R_3$.)

offset-onset measurements alone. This result may be written as either of two solutions wholly in terms of offset-onset PSEs. Thus:

$$\bar{Q}_{ij} = P_{ik} - P_{jk} \tag{25}$$

and

$$\bar{Q}_{ij} = P_{ij} + P_{ki} - P_{kj} - P_{ji}. \tag{26}$$

It is important to recall that the general method we are describing involves measurements of offset-onset PSEs only. All of the above onset-onset and offset-offset PSEs are predicted values. It is these predicted values, Q_{ij} and $\bar{Q}_{ij}$ (in Equations 21-26), that may themselves be compared with direct measurements of onset-onset and offset-offset judgments, respectively. It is worth noting that neither onset-onset PSE measurements alone nor offset-offset PSE measurements alone are sufficient to predict either the set of offset-onset PSEs or the durations of perception of the three stimuli R_i, R_j, R_k. The reasons for this asymmetry follow immediately when we note that $Q_{ij} \equiv -Q_{ji}$ and $\bar{Q}_{ij} \equiv -\bar{Q}_{ji}$, but that $P_{ij} \not\equiv -P_{ji}$.

ANALYSIS OF BIAS BY MEANS OF THE MEASUREMENT MODEL

The method for measuring total response duration that we described in the previous section is based on measurements made by means of offset-onset simultaneity judgments only. Values of total response duration obtained by this method are thus totally free of differences in bias between onset-onset and offset-onset judgments. Since previous use of simultaneity judgments for measuring total response duration has required both onset-onset and offset-onset judgments, freedom from such bias has not been possible before.[5] (Whether such differences in bias are nonzero in other methods where nonzero values are possible remains to be determined, and can be determined by the methods we outline.) However, there is no gilt-edged protection against the undesirable intrusion of bias into an experiment in general. No method is immune from poor controls and failure to randomize appropriately against uncontrolled sources of variations. Any attempt on our part to carry out general tests for methodological bias would yield no guarantee that the method would yield similar biases or freedom from bias under other conditions or in another laboratory. Biases are easy to generate. For example, if two stimuli whose perceived durations were of interest were placed close enough together so that retinal interactions between them occurred, the perceived duration of each would depend on whether it was presented first or second on a trial. Such biasing might be of interest as a subject of study in itself.

Bias Introduced by Onset-Onset and by Offset-Offset Judgments of Simultaneity

Although we have not yet done so, the development of the new method also allows an exact measurement of the magnitude of bias introduced by onset-onset judgments. This can be done by comparing values of total response duration obtained by the old and by the new methods under identical conditions. The conclusion that such a comparison does yield an overall measure of bias (or constant error) due to onset-onset judgments is derived as follows:

Suppose that each offset-onset PSE contains a bias component α, and that each onset-onset PSE contains a bias component β. A value of response duration as measured by the new method involves the sum of three offset-onset PSEs (see Equations 6 and 7); each PSE brings a value α to the sum, but two of these are positive and one is negative. Hence, each value of response duration in Equation 7 is inflated by α. Response duration determined by the earlier method outlined in Figure 1 contains an onset-onset PSE inflated by β and an offset-onset PSE inflated by α; since response duration from this method involves the difference of these two PSEs, the net bias is equal to $\alpha - \beta$. The difference between net bias from the two methods is thus equal to β and is thus equal to the bias due to onset-onset judgments alone.[6]

A variant of earlier methods for obtaining values of total response duration involves the joint use of offset-onset and offset-offset judgments. It is also possible to extract the bias introduced by offset-offset judgments by an analogous approach.

The approach taken here assumes that the magnitude of α and β will be independent of the particular pair of stimuli being compared. This analysis can be carried further by removing this assumption and determining separate values of bias for each comparison.

Bias Introduced by Offset-Onset Judgments of Simultaneity

Theoretical treatment. Although bias due to the use of onset-onset judgments and bias due to the use of offset-offset judgments can thus be extracted as lumped values, an analogous lumped value of bias due to offset-onset judgments cannot. Nevertheless, the method we have described yields two experimentally independent solutions for response duration (see Equations 6 and 7), and each contains a different set of component sources from which bias could originate. However, from the single assumption made in the next paragraph, a prediction of zero difference between the lumped contributions to bias in the two solutions follows, and this is readily subject to experimental test. We carry out one such test below. Further dissection is also feasible, but we shall not do so here, although lines for further analysis will be indicated.

Our ability to write $R_i = d_i + \ell_i$ in Equation 7 depended on assuming that response latency (either offset or onset) of any specific stimulus did not depend on which stimulus it was being compared with. This assumption also was made in setting the two solutions for each ℓ_i equal to each other in Equation 6. Failure of this assumption will lead to differences in the two solutions for each ℓ_i and hence in the two solutions for each R_i. The details of the relation between the kind of failure and the resulting difference in the two solutions are not simple. Nevertheless, the most straightforward overall test for the validity of the assumption remains the test for equality of the two solutions in Equation 8.

To clarify these statements, we will use the notation ${}_1\bar{L}_2$ and ${}_3\bar{L}_2$ to indicate that the offset latency to stimulus 2 was derived from simultaneity judgments with stimulus 1 and with stimulus 3, respectively; a similar use of subscripts is employed for other latencies. Thus, for example, from Equation 5, the two solutions for ℓ_1 may be written as

$$\left.\begin{aligned} &P_{21} - P_{23} + P_{13} \\ &\quad = ({}_3\bar{L}_1 - {}_2L_1) + ({}_1\bar{L}_2 - {}_3\bar{L}_2) + ({}_2L_3 - {}_1L_3) \\ &P_{31} - P_{32} + P_{12} \\ &\quad = ({}_2\bar{L}_1 - {}_3L_1) + ({}_3L_2 - {}_1L_2) + ({}_1\bar{L}_3 - {}_2\bar{L}_3). \end{aligned}\right\} \quad (27)$$

The assumption that a particular latency is independent of the stimulus with which it is compared means that:

$$\left.\begin{aligned} {}_j\bar{L}_i &= {}_k\bar{L}_i = \bar{L}_i \qquad i, j, k = 1, 2, 3 \\ {}_jL_i &= {}_kL_i = L_i \qquad i \neq j \neq k \end{aligned}\right\} \quad (28)$$

and the solutions reduce to those in Equation 6. Clearly, numerous other more complicated assumptions about distributions of bias would also yield equality of the two solutions for ℓ_i [e.g., jointly assume: $({}_1\bar{L}_2 - {}_3\bar{L}_2)$, $({}_2L_3 - {}_1L_3) = ({}_3L_2 - {}_1L_2) = ({}_1\bar{L}_3 - {}_2\bar{L}_3)$, $({}_3L_1 = {}_2\bar{L}_1)$, and $({}_2\bar{L}_1 = {}_2\bar{L}_1)$]. Thus, while validity of the independence assumption is a sufficient condition for equality of the two solutions for R_i, it is not necessary.

Further, it is possible for other sets of biases to selectively perturb other subsets of latencies, influencing one or more of the three values of R_i, but such a perturbation may remain totally unnoticed, since the equation between the two solutions for each R_i would continue to hold (e.g., if γ were added to ${}_3L_2$ and to ${}_1\bar{L}_2$, R_1 would be increased by γ and R_3 would be decreased by γ, while R_2 would be unaffected; but the two solutions for R_1 would remain equal to each other, as would the two for R_2, and the two for R_3). This kind of influence thus would not be directly detectable by our present methods; its possibility indicates that our conclusions regarding bias will be relativistic at best rather than absolute.

However, for two reasons, the limitations on our ability to detect the bias we have described in the two previous paragraphs are actually very much less restricted than first appearance would suggest: (1) For each subset containing equal biases that would not influence the equation of the two solutions for each R_i, there is another subset that will influence each of the three equations and by the same amount (e.g., while addition of γ to ${}_3L_2$ and to ${}_1\bar{L}_2$ leaves the three equations unperturbed, addition of γ to ${}_3L_2$ and ${}_2\bar{L}_1$ produces an inequality equal to 2γ in each equation). The likelihood is small—if not negligible—that a substantial series of different experimental tests searching for bias would all belong to the set that leaves the equation undisturbed if any substantial bias is present. (2) Unequal biases among different latencies would result in an inequality between the two solutions for each R_i even when the unequal biases are between those latencies for which bias equality produces no disturbance in any equation. This should be readily detectable. For example, if the bias added to ${}_3L_2$ exceeded the bias added to ${}_1\bar{L}_2$ by δ, the pair of solutions for R_1 would differ by δ (see Equation 27); equal biases added to ${}_3L_2$ and to ${}_1\bar{L}_2$ would leave the two solutions to R_1 equal to each other and the bias would be undetectable.

We may thus conclude that the possibility is negligible that any substantial systematic bias selectively affecting one subset of PSEs or latencies could escape detection in a test for equality between the two solutions each for R_1, R_2, and R_3. We now report such a set of experimental measurements. It should be noted that any difference that is found between the two solutions for R_1 will be identical to the difference between the two solutions for R_2 and to the difference between the two solutions for R_3. This identity may be seen more clearly by noting that the difference between any pair of solutions in Equation 6 or Equation 8 may be written as:

$$I = (P_{12} - P_{21}) + (P_{23} - P_{32}) + (P_{31} - P_{13}). \quad (29)$$

We shall refer to I as interaction and use it in our analysis below. Thus, I equal to zero will result only when the two solutions for each R_i are equal.

Some experimental measurements concerned with bias. In this section, we present an experimental example of the application of our method for measuring perceived duration. We analyze a set of data in the interest of demonstrating how a test for bias might be carried out. The stimulus variables we examine for influence as biasing agents are retinal location and stimulus luminance. The experimental effects evident in the data have implications for visual processes, but we reserve these for treatment elsewhere and restrict our attention here to questions regarding bias.

The particular data we report are four conditions from a broader experiment (Bowen, 1975, Note 2) which employed the stimulus array of Figure 2. Stimuli 2 and 3 were both 70-msec incremental flashes of 2.0 log trolands superimposed on backgrounds of 1 log troland each. Stimulus 1 was a 30-msec incremental flash of fixed contrast ($\Delta L/L = 1$ log unit) presented against each of four values of background luminance, L = 0, 1, 2, 3, and 3 log trolands. Four replications were carried out under each of the four background luminances for stimulus 1. Each replication involved measuring four PSEs (P_{12}, P_{21}, P_{13}, and P_{31}). P_{23} and P_{32} were measured only once for each condition; the same values of P_{23} and P_{32} were thus utilized in calculating response durations from the four replications of a given condition. The measurement of each PSE involved 120 trials, 24 at each of 5 intervals between the two flashes. The 120 trials were actually carried out in 24 randomized blocks (interflash duration in the range of uncertainty—established from pilot work—was the random variable), with a group of 12 blocks presented sequentially in one session and the two groups of 12 such blocks for a given luminance being randomly ordered within sessions along with groups from other luminances. Each of the 72 PSEs for each of the two subjects was calculated by a least squares fit to the distribution of binary reports by the subject reporting whether or not the offset of the first stimulus preceded the onset of the second stimulus.

Figure 6 and Table 1 show the mean values (averaged over the four replications) of the solutions for total duration of responses R_1, R_2, and R_3 at each of the four values of luminance employed for the background to stimulus 1. This is presented for each of the two subjects. Some idea of the stability inherent in the method is provided by the small values of standard deviation[7] (SD) of these means, which are also given in Table 1, and by the high degree of stability obtained in the solutions for R_2 and R_3, while the solution for R_1 changes by a large amount as a result of the variation in the luminances of stimulus 1 and its background. Such independence between the solutions for the three response durations is essential for the method to be useful.

As described above, the interaction I (Equation 29) is equal to the difference between the two independent solutions for each of the three values of R_i—R_1, R_2, and R_3. These values of interaction are shown in Table 1. In no case do the interactions for the four replications appear similar. The case most suggestive of systematic bias occurs for R.B. at a background luminance of 2 log trolands where all four interactions are positive and the largest deviation of the mean value of I from zero occurs, reaching almost two SD units. In all of the other cases but one, the mean deviation from zero of I is less than 1 SD unit. The solutions for response duration thus show no systematic bias across replications at any luminance or at any change in bias with luminance.

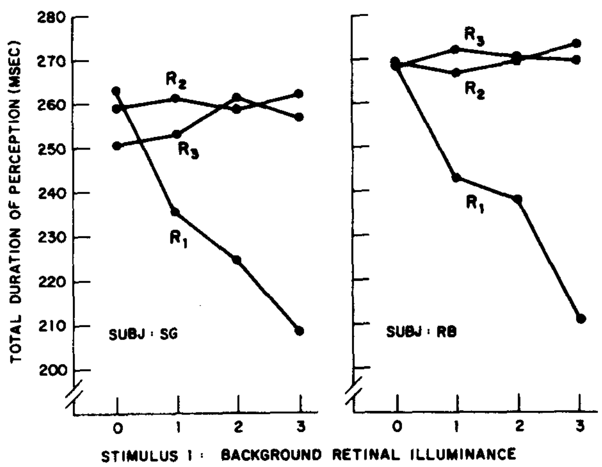

Figure 6. Mean durations of perception for two subjects (S.G. and R.B.) plotted as a function of background luminance for each of the three incremental flash stimuli in the stimulus configuration of Figure 2.

Table 1
Results of an Experiment in Which Response Durations Were Measured for Visual Stimuli Presented With the Apparatus Shown in Figure 2

Stimulus 1:		Subject S.G.				Subject R.B.			
Background Illum. Log L	Replication	Response Duration R_1	Response Duration R_2	Response Duration R_3	Interaction I	Response Duration R_1	Response Duration R_2	Response Duration R_3	Interaction I
0	1	259.1	269.7	248.6	−.7	267.3	265.8	271.5	−3.4
	2	259.9	260.7	248.6	3.6	261.4	271.5	265.8	.6
	3	268.6	260.3	248.9	5.9	268.7	272.3	265.1	16.1
	4	263.5	253.6	255.6	.8	279.1	267.1	270.3	−2.4
	Mean	262.8	258.8	250.4	2.4	269.1	269.2	268.2	2.7
	SD	4.3	3.5	3.5	2.9	7.4	3.2	3.2	9.1
1	1	233.2	257.7	257.0	−12.0	246.1	268.0	271.2	13.7
	2	241.0	258.6	256.1	7.3	240.4	273.6	265.6	13.1
	3	229.5	263.3	251.4	−8.1	254.0	259.7	279.5	−1.5
	4	236.2	264.7	250.1	2.8	231.6	267.2	272.0	8.5
	Mean	235.0	261.1	253.6	−2.5	243.0	267.1	272.1	8.5
	SD	4.9	3.5	3.5	9.1	9.4	5.7	5.7	7.0
2	1	226.9	255.6	264.8	4.3	240.2	267.6	272.2	13.8
	2	230.4	257.6	262.7	−7.6	225.2	270.1	269.7	4.1
	3	219.9	260.0	260.3	−6.1	244.4	276.2	263.5	5.3
	4	219.8	261.3	259.1	4.6	241.2	264.3	275.5	13.5
	Mean	224.2	258.6	261.7	−1.2	237.8	269.6	270.2	9.2
	SD	5.3	2.5	2.5	6.6	8.6	5.0	5.0	5.2
3	1	206.3	261.9	256.9	1.0	220.3	277.5	265.1	−12.3
	2	213.3	264.3	254.6	9.1	203.5	276.0	266.5	4.2
	3	213.4	259.6	259.2	−4.8	206.9	268.9	273.7	−19.4
	4	198.9	259.2	259.7	4.0	223.6	271.4	271.1	−4.7
	Mean	207.0	261.3	257.6	2.3	213.6	273.5	269.1	1.6
	SD	6.9	2.4	2.4	5.8	9.9	4.0	4.0	13.6

Note—Illuminance of the 18′ diam flash in field 1 was varied along with that of the steadily illuminated background in field 1 so that $\Delta L/L$ = 1 log unit; $\Delta L/L$ was maintained at 1 log unit for fields 2 and 3 also. At each value of background illuminance in field 1, four complete sets of determinations (replications) were made on each subject. Each value of response duration shown for each replication is the average of the two solutions for that duration calculated from Equation 8. The interaction (I) is calculated from Equation 19 and is the common difference between the two solutions each for R_1, R_2, and R_3. Mean response durations are plotted in Figure 4 also. See Ftn. 6 regarding the values of standard deviation (SD).

We may rewrite Equation 29 as

$$I = (P_{23} - P_{32}) + (P_{31} - P_{21}) + (P_{12} - P_{13}). \quad (29')$$

The invariance of I (at zero) with variation in the luminance of stimulus 1 could thus be because the difference between the two terms in each set of parentheses remained invariant with changes in luminance, or because changes did occur in each of the terms with luminance but in such a way as to balance things out. The breakdown in Table 2 shows that the former is true. While the separate PSEs each changed systematically with luminance, $(P_{12} - P_{13})$, $(P_{31} - P_{21})$, and $(P_{23} - P_{32})$ did not. (Means and SDs for P_{13} and P_{21} are not shown but were like those shown for P_{12} and P_{31}, respectively.) The invariance of $(P_{12} - P_{13})$ implies that any bias in P_{12} that changed as the luminance of stimulus 1 was changed also changed identically in P_{13}; similarly for $(P_{31} - P_{21})$, P_{31}, and P_{21}. Thus stimuli 2 and 3 were treated identically when each was compared to stimulus 1 in an offset-onset situation; this equal treatment held whether stimulus 1 came first in a trial ($P_{12} - P_{13} \cong$ constant) or second in a trial ($P_{31} - P_{21} \cong$ constant).

Stimuli 2 and 3 were identical except for retinal location. Thus, the observation that this difference did not influence bias as luminance was changed is interesting, and, particularly in view of the large literature on constant errors and position biases, not necessarily to have been expected. Overall, stimuli 2 and 3 yielded solutions for R_2 and R_3 that appeared to differ from each other only as a random variable. Some small effects are present, however, which could suggest that stimuli 2 and 3 were not processed identically. Thus the difference $P_{23} - P_{32}$ was positive in all four replications for each of the two subjects. On the other hand, the difference $(P_{31} - P_{21})$ was negative in six of eight cases. [These differences —$(P_{23} - P_{32})$ and $(P_{31} - P_{21})$—tended toward canceling each other, and since $(P_{12} - P_{13})$ was generally near zero, so was I.] The present data are not sufficiently extensive to determine which specific latencies were involved in these differences (if the differences are robust at all), nor whether the bias was "in the visual system" or a concommitant of the judgmental process involved with relating stimuli at the two locations. Further exploration with the present techniques would allow such isolation.

Table 2
Mean PSE Values and Associated Standard Deviations (SD) from the Experiment Yielding the Response Durations Shown in Table 1

	Log of Background Retinal Illuminance for Stimulus 1	P_{12} Mean	P_{12} SD	P_{31} Mean	P_{31} SD	$P_{12} - P_{13}$ Mean	$P_{12} - P_{13}$ SD	$P_{31} - P_{21}$ Mean	$P_{31} - P_{21}$ SD	$P_{23} - P_{32}$	r
Subject S.G.	0	225.8	4.9	189.4	6.9	+2.1	4.2	−6.6	2.8	+6.6	.06
	1	199.7	4.7	189.1	5.6	+.2	6.1	−7.3	5.3	+4.6	.09
	2	189.2	3.8	192.1	5.4	−4.7	4.1	−1.8	4.1	+5.0	.20
	3	170.0	4.4	195.7	5.3	−.8	4.8	−4.4	2.2	+7.5	.14
Subject R.B.	0	248.5	3.5	187.6	6.1	−1.2	7.3	−2.2	2.9	+6.1	.17
	1	217.8	6.7	196.8	5.8	−.5	9.0	+4.5	5.1	+3.4	.13
	2	208.2	4.3	200.0	6.3	+.2	3.5	+.9	7.2	+8.1	.12
	3	183.2	4.0	200.0	8.0	+.5	4.7	−3.8	10.1	+4.9	.14

Note—Mean values of P_{13} and P_{21} are not shown, but were similar to P_{12} and P_{31}, respectively; they can be derived directly by combining the PSEs given here. Values of r are Pearson product-moment correlations between $(P_{12} + P_{21})$ and $(P_{13} + P_{31})$ (see Ftn. 6).

Again, our main concern in this section was not specifically with retinal location or luminance as possible biasing parameters, but rather with an approach to the study of bias. Of secondary concern here is the fact that changing luminance yielded a substantial change in perceived response duration that is either wholly invariant or nearly so with a change in retinal location of the comparison stimulus.

A CONCLUDING COMMENT REGARDING EFFICIENCY

In order to obtain the two solutions each for R_1, R_2, and R_3, the method we have described requires that six PSEs be obtained. However, if one wishes to explore response duration for one of these stimuli —say stimulus 1—over a range of conditions in which different parameters are varied, it would be a lengthy operation to obtain six PSEs for each condition. But only two—not six—PSEs are necessary. This reduction from six to two is a result of the following: If the experimenter considers it unnecessary to be concerned with the possibility of testing for differential bias in the two solutions for R_1, then only one solution need be obtained at each condition, requiring a total of three PSEs. But, since the conditions related to stimuli 2 and 3 are kept constant, P_{23} (or P_{32}) need be measured only once in the entire experiment; this single value may then be inserted into the solution for each of the values of R_1 as the conditions related to stimulus 1 are varied. Under each of these conditions, only two PSEs—P_{12} and P_{31} (or P_{21} and P_{13})—need then be measured.

Hence, if R_1 is to be explored over a range of conditions, the present method requires only that one more PSE be obtained in the entire experiment than would be necessary with the older method in which both onset-onset and offset-onset PSEs are employed (Figure 1). In each method, two PSEs are required for each condition in which a value of R_1 is desired. But, in the present method, all PSEs are offset-onset PSEs, a feature that is likely to result in some increase in criterion stability and freedom from differential biases. In addition, should the experimenter have some concern about the intrusion of response bias, a variety of checks—such as we have carried out above—are possible with the present method, whereas the opportunity for any checking at all is minimal with the older method.

Finally, as a further potential advantage of the present method, it should be noted that if one can assume that biases are negligible or of no concern, it is possible to conduct experiments by systematically varying all three stimuli simultaneously. This yields results in which R_1, R_2, and R_3 are each studied over a range of conditions. Since each trio of PSEs yields one value each of R_1, R_2, and R_3, such experiments require only one PSE per R_i, a saving by a factor of two over the older method.

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NOTES

1. By "perceived simultaneity," we shall mean an outcome of some psychophysical procedure. For example, if the method of constant stimuli is employed, the temporal interval between the onset of B and the onset of A that is reported as "B leads A" 50% of the time would be the point of subjective equality (PSE) and would be treated as the interval at which the onsets of B and A were perceived simultaneously.

2. The term "visual response" is used here to denote the percept or sensory event due to a flash of light. We do not assume that this response is of any particular shape or form, but only that the relative precedence of the temporal onset and offset of the response may each be discriminated in a report of temporal order (we really need assume only that these are "reliably" dealt with). Undoubtedly, the waveforms of the neural response underlying the psychophysical report of simultaneity will not be as simple as we have depicted in Figure 3. They will be more complex, temporally extended, and may be multimodal. Further, experimental manipulations may produce changes in the shape of the waveform and in the observer's criterion; such changes may also be the outcome of stochastic variability. However, we make no assumptions at this level. Presumably the nature of the "underlying neural response" is something to be discovered with the assistance of data from simultaneity judgments, not something to be assumed beforehand; the utilization of reports of simultaneity in obtaining measures of the total duration of a perception assumes no more than is normally done in working with psychophysical data.

3. The offset-onset PSE has itself been utilized as a measure of "visual persistence," persistence being conceptually equivalent to offset latency (Bowen, Pola, & Matin, 1974). In that case, the offset-onset PSE represents relative offset latency or persistence. Obtained measures are "relative" in the sense that offset latency (for example $\overline{L_1}$ above) is known to within an additive constant equal to the unknown onset latency of the second flash (for example, L_2 above).

4. The analysis and method we describe in this section appears capable of generality beyond problems involving the duration of perception, and to be potentially applicable to problems involving the psychophysical measurement of extent in either time or space. For example, in principle, it could be applied to the measurement of perceived length. But it does not appear directly generalizable to the study of either intensive dimensions (e.g., brightness) or "qualitative dimensions" (e.g., color). Further development into applications on intensive dimensions appear to be possible by making use of psychophysical methodologies that treat these intensive dimensions as if they were extensive. As a guide into such further development, we note that while it is not sensible to consider equating the "top" of one brightness to the "bottom" of another, (as in an offset-onset temporal judgment), it is possible to set the "midpoint" between two brightnesses equal to the "top" of a second.

5. We shall make no attempt here at segregating various sources of bias in terms of different theoretical loci (e.g., separating "criterion bias" from "attentional bias") in either the subject or behavior. Our concern here is with demonstrating that the present methodology provides means of discovering differential biases between offset-onset, onset-onset, and offset-offset judgments if such differential biases do exist.

6. It is equally feasible to analyze onset-onset and offset-onset biases in each of these methods into components expressible in terms of bias added to specific onset and offset latencies. Such a derivation is accomplished directly by using the relations between latencies and PSEs given above. This analysis may be more desirable for certain purposes.

7. It should be noted that in Table 1, for each subject at each background illuminance, the standard deviations (SD) for R_2 and R_3 are identical but different from the SD for R_1. The result is not a necessary one and depends on the following special constraint involved in the method of the experiment reported in Table 1: P_{23} and P_{32} were each determined only once at each level of background illuminance employed for stimulus 1, and these single values were used in calculating all values of R_1, R_2, and R_3 across the four replications; on the other hand, P_{12}, P_{21}, P_{13}, and P_{31} were each redetermined for each replication. If we write ΔP_{12}, ΔP_{21}, ΔP_{13}, and ΔP_{31} as the differences between any two replications in the empirically determined PSEs, P_{12}, P_{21}, P_{13}, and P_{31}, respectively, then the difference in the average value of R_2 between the two replications is $[(\Delta P_{12} + \Delta P_{21}) - (\Delta P_{13} + \Delta P_{31})]/2$. But this is the negative of the difference in the average value of R_3 between the same two replications. Variation in values of R_2 among replications must thus be exactly equal to variation in R_3 for this case, as is, in fact, shown in the identity of SD values for R_2 and R_3. The difference in the average value of R_1 between the same two replications is equal to $[(\Delta P_{12} + \Delta P_{21}) + (\Delta P_{13} + \Delta P_{31})]/2$; since this is different from the comparable values for R_2 and R_3, the SD for R_1 is different from the SD for R_2 and R_3.

The fact that the SDs for R_1 are uniformly larger than the comparable SDs for R_2 and R_3 is the result of a related fact: the terms $(P_{12} + P_{21})$ and $(P_{13} + P_{31})$ were positively correlated (see Table 2). This is derived as follows: The variable component in the average value of the two solutions for R_1 is $v_{1j} \equiv P_{12} + P_{21} + P_{13} + P_{31}$; the comparable value for R_2 or R_3 is $v_{2j} = v_{3j} \equiv P_{12} + P_{21} - P_{13} - P_{31}$, where subscript j refers to replication. Since all of the values of the measured offset-onset PSEs involved in Table 1 were positive (implying that the offset latency of the first stimulus in a trial was always longer than the onset latency of the second stimulus), $v_{1j} > v_{2j} = v_{3j}$ for each j. The variance of response duration R_i is equal to

$$V_i = \frac{1}{16}\left[3 \sum_{j=1}^{4} v_{ij}^2 - \sum_{j=1}^{4} \sum_{k=1}^{4} v_{ij} v_{ik}\right]$$

with $j \neq k$. V_1 will then be greater than $V_2 = V_3$ when $(P_{12} + P_{21})$ and $(P_{13} + P_{31})$ are positively correlated, but $V_2 = V_3$ will be greater when the correlation is negative. In fact, the difference $V_1 - V_2$ is exactly equal to the covariance term in the product-moment correlation between $(P_{12} + P_{21})$ and $(P_{13} + P_{31})$.

(Received for publication September 8, 1975; revision accepted March 7, 1976.)