Stroboscopic motion: Effects of duration and interval¹

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The quality of stroboscopic motion induced by the successive presentation of two illuminated squares obeys two rules. For all stimulus durations shorter than 100 msec, optimal motion occurs when the stimulus onsets differ by about 120 msec. For stimulus durations longer than 100 msec, optimal motion occurs when the second stimulus begins at the termination of the first stimulus. The two rules relating quality of motion to duration suggest a single principle, namely, that the quality depends only on the interval between the visual responses to the two stimuli. The interresponse interval at which motion is optimal is independent of stimulus duration.

This paper elaborates a treatment of apparent motion that was presented earlier to account for the effects of temporal factors on stroboscopic motion (Kahneman, 1967). We deal with the case in which apparent motion is produced by the successive presentation, in two locations, of stimuli that are identical in shape, intensity, and duration of exposure.

Wertheimer (1912) concluded that optimal motion was perceived at an interstimulus interval (ISI) of 60 msec between the termination of the first stimulus and the onset of the second. This view is no longer held. Korte (1915) stated, in his fourth law of motion, that the optimal ISI for motion decreases when the duration of the stimulus, t , is increased. Neuhaus (1930) and Kolers (1964) both confirmed Korte's fourth law, but they disagreed on the shape of the function that relates the optimal ISI for motion to t .

The results of a recent experiment (Kahneman, 1967) conformed to a particularly strict version of Korte's fourth law for durations ranging from 25 to 125 msec. Apparent motion was always best when the sum of the duration t and the interval ISI was about 100-120 msec. The sum of duration and ISI defines the interval between the onsets of the two stimuli (stimulus-onset asynchrony, SOA). Thus, an onset-onset law was found to apply to the quality of apparent motion over a range of brief durations.

The onset-onset law is an empirical generalization, not a theoretical statement. A theoretical account of that law should meet two requirements: (1) Whereas the onset-onset law deals with the temporal

characteristics of stimuli, the theory must deal with the temporal characteristics of interacting visual responses. (2) A parsimonious theory of apparent motion should apply to longer durations of exposure, to which the onset-onset law does not apply.

A formulation that appears to meet these requirements was suggested in the earlier study. It attributes the quality of stroboscopic motion to the interval between the termination of the response to the first stimulus and the onset of the response to the second, at some intermediate level of visual analysis. This interval is called the interresponse interval, IRI. Further, the theory suggests that optimal motion is seen when the responses to the two stimuli are concurrent for a critical period of time (negative IRI). The underlying rule for apparent motion may be summarized by the following statement of an IRI law: "The quality of stroboscopic motion depends only on IRI, for a given spatial display. The optimal IRI for motion is negative, and constant for all values of duration of the two stimuli."

The IRI law is not testable without further assumptions, since the duration of the effective visual responses that interact to produce motion are not observable. Consequently, any test of the IRI law must rely on an explicit statement of the rules that relate the duration T of the effective visual response to the duration t of the stimulus. Our hypotheses concerning these rules are the following (see Fig. 1):

(1) For brief stimuli: The duration of the response to all brief stimuli ($t \leq t_a$) is constant, and its value is T_a . Because of visual persistence, $T_a > t_a$.

(2) For longer stimuli: The duration T of the response is given by $T = t + (T_a - t_a)$. The value in parentheses defines visual persistence, which is assumed to be constant for all prolonged stimuli.

Figure 2 illustrates the derivation of IRI from the other parameters. In general: $IRI = SOA - T_1$, where T_1 is the duration of the response to the first stimulus of the sequence.

For brief stimuli, $T_1 = T_a$; therefore,

$$IRI = SOA - T_a, \text{ for all } t \leq t_a. \quad (1)$$

Thus, the value of IRI depends only on SOA for brief stimuli. Note that IRI may be negative if $T_a > SOA$.

For longer stimuli, $T_1 = t_1 + (T_a - t_a)$; therefore,

$$IRI = SOA - t_1 - (T_a - t_a)$$

which may be rewritten (see Fig. 2):

$$IRI = ISI - (T_a - t_a). \quad (2)$$

The value of IRI depends only on ISI for long stimuli. Note that the value of ISI is negative when the two stimuli overlap.

The IRI law states that optimal motion is always obtained at the same value of IRI, regardless of stimulus duration. By (1), this entails the prediction that optimal motion will be obtained at the same value of SOA over the range of brief exposures, up to a

Fig. 1. Hypothetical function relating the duration of visual response to the duration of the stimulus.

Fig. 2. Responses (R_1 and R_2) to two successive stimuli (S_1 and S_2). The delay of the responses is not represented. See text for explanation of the parameters.

Fig. 3. (a) Mean ratings of perceived motion as a function of stimulus-onset asynchrony, for four short durations of exposure (40-100 msec). (b) Mean ratings of motion as a function of interstimulus interval, for four long durations (240-800 msec). Each point is the average of 24 ratings, 3 each for eight Ss.

critical value, t_a . For exposure durations that exceed t_a , the IRI law entails, with (2), that motion be optimal at a constant value of ISI. As mentioned above, the SOA law was experimentally confirmed (Kahneman, 1967) for both apparent motion and metacontrast suppression. The objectives of the present experiment were to replicate that study, to test the ISI law for a range of longer durations, to find the transitional value t_a , and to determine whether the transition from one law to the other was abrupt or gradual.

METHOD

Eight paid volunteers, two males, served for three 1-h sessions on consecutive days. The Ss were students at Harvard and Radcliffe, naive to the purpose of the experiment.

The S was seated at a distance of 2.7 m from a translucent screen on which the stimuli were projected from an adjoining room. A dimly illuminated fixation cross, 12.5 mm in size, was constantly in view. The stimuli were two illuminated squares, 24 mm large, subtending 31 min at the viewing distance. The centers of the squares were 29 mm below the fixation point and 19 mm to the left and right, respectively. The squares were presented at a luminance of approximately 10 mL. A Gerbrands timer (Model 150) controlled

the movement of shutters attached to pen motors (Model Schwartzer 265a), which were placed at focal points of two separate projection systems. With this method of exposure, rise time and fall time were approximately 1 msec.

The following instructions were read to the S on each day of the experiment:

"Our experiment is concerned with an effect in perception called apparent motion. When an object is shown, first in one place then in another, it is often seen as moving smoothly and continuously from the first position to the second. Movies and television operate on this principle. We are investigating the conditions under which motion is seen, and those under which it is not.

"I shall be showing you two squares on this screen, first one, then the other. Perfect apparent motion will be the case when you have the impression of a single square that moves smoothly from one position to the other, without disappearing or changing in brightness along the way. Partial motion is the case when the starting and arrival positions can be seen as two separate squares, but there is a feeling of motion between them.

"Your task is to rate each display according to how well what you see corresponds to this description of apparent motion. Use numbers for your ratings, as

follows: The number 5 indicates that you saw perfect apparent motion. The number 3 indicates that motion is only partial but still quite marked. The number 0 indicates that what you saw bears no resemblance at all to apparent motion. Use intermediate numbers to indicate various degrees of correspondence between the description and what you see. Note that the squares occasionally remain stationary for some time. You should not be concerned with this in your judgements of motion, as it is the moment of transition that you are to rate."

Thirteen durations of exposure were studied: 40-200 msec in steps of 20 msec, and 240, 280, 400, and 800 msec. The duration of exposure was the same for the first and for the second stimulus in the sequence. For the durations 40-200 msec, the S rated apparent motion at 19 values of stimulus-onset asynchrony (SOA): 0, 20, 40, ... 360 msec. For durations of 240 msec and beyond, he was exposed to 19 values of ISI ranging from -180 msec (180 msec overlap between the two squares) to +180 msec (180-msec blank interval), again in steps of 20 msec. A single series of measurements was obtained at each duration on each day. During such a series, S was exposed to each value of SOA or ISI in random order. The order of durations within each session was also random. Altogether, there were 247 different conditions of exposure, and S rated each condition three times, once each day.

Unknown to S, the first series of trials on each day, conducted at a duration of 50 msec, was considered practice. By the time data collection began, S was dark-adapted for at least 10 min. S communicated his ratings by intercom. E did not speak during the session except to announce short breaks between blocks and

Fig. 4. Mean ratings of motion for five intermediate durations of exposure (120-200 msec) are plotted, respectively, (a) against stimulus-onset asynchrony, together with a composite curve for short durations derived from Fig. 3a; and (b) against interstimulus interval, together with a composite curve for long durations derived from Fig. 3b.

to answer direct questions, which were rare. The questions were answered by repeating or paraphrasing relevant parts of the instructions. Ten Ss began the experiment; however, two of them announced a sudden and extreme change of criterion on their second session and were discontinued.

RESULTS

The results of the experiment are summarized in Figs. 3 and 4. Figure 3a includes mean ratings of apparent motion for the four shortest durations (40, 60, 80, and 100 msec), plotted against stimulus-onset asynchrony (SOA). The support for an onset-onset law is good, as the four curves overlap closely. For brief durations, the quality of motion depends on SOA alone, and not on either t or ISI, in accord with the results of an earlier experiment (Kahneman, 1967), which was conducted with a different display.

Figure 3b includes mean ratings of motion for the four longest durations studied (240, 280, 400, and 800 msec), plotted against ISI. According to the ISI law, the four curves should overlap. Although the agreement among the functions is poorer than in Fig. 3a, none of the differences among the curves in Fig. 3b approaches statistical significance. Because of their high variability, the data in Fig. 3b cannot be considered conclusive with respect to the proposed ISI law. As we shall see, however, the evidence derived from ratings of intermediate durations lends additional support to the validity of that law.

The ratings for the five intermediate durations (120, 140, 160, 180, and 200 msec) are presented twice in Fig. 4. In Fig. 4a, they are plotted as a function of SOA, together with a composite curve derived by averaging the ratings given at the four shortest durations (40-100 msec). The ratings for $t > 120$ msec differ in two ways from those for shorter durations. First, the peak ratings of motion are lower when durations are longer. The peak ratings of motion at each intermediate duration are significantly lower (by t test) than the mean of the highest ratings at the four shorter durations. Second, the peak of the function tends to occur at a longer SOA, as t increases. Thus, there are two indications that t_a , the longest duration that may still be considered brief, lies between 100 and 120 msec, under the conditions of this experiment.

The poorer motion that is reported for durations longer than 100 msec is probably associated with a qualitative change in experience. When t is short, one sees an object in continuous motion from one location to another. When t is long, one

Fig. 5. Composite curves for intermediate durations (120-200 msec) and for long exposure durations (240-800 msec) as a function of interstimulus interval, from ISI = -80 to ISI = 160 msec.

sees an object that is stationary for a while, then moves to a new position. Ss' comments indicated that a target that never appears to pause gives the most satisfactory impression of movement. Thus, it is likely that $t \cong 100$ msec represents a threshold for the perception of the stationary phase.

The ratings for intermediate durations are plotted against ISI in Fig. 4b, which also includes a composite curve derived from the four longest durations. The correspondence between Figs. 4a and 4b is illustrated in the following examples: for $t = 120$ msec and for $t = 160$ msec, respectively, an SOA of 20 msec corresponds to ISIs of -100 and -140 msec. If an ISI law applies to durations that exceed t_a , the curves of Fig. 4b should overlap. The ISI law is violated for negative ISIs, but the deviations are simply explained: When the two stimuli begin together (SOA = 0) they are perceived as simultaneous, and motion is never seen.

Figure 4b includes so many curves that a slight systematic trend could perhaps be obscured. An average curve for the five intermediate durations was therefore computed, which is shown in Fig. 5 together with the composite curve for the four longest durations, over the range of ISIs between -80 msec and +160 msec. A monotonic drift of the ISI required for peak motion would be clearly revealed in this comparison. However, the close agreement of the two curves supports the conclusion that the ISI law is valid for durations between 120 and 800 msec. Motion is most often optimal at an ISI of 0, when the second stimulus is presented just as the first is removed. A similar result was reported for $t = 800$ msec in a previous study (Kahneman, 1967).

DISCUSSION

The theory from which these predictions were derived includes rules that relate the duration of the visual response to that of the stimulus. Specifically, all brief stimuli are treated as if they lasted about 100 msec, and the responses to longer stimuli, $t > 100$ msec, reflect the stimulus duration. The theory proposes that the SOA law and the ISI law of motion express a single underlying rule, that the quality of motion depends solely on IRI: the interval—or overlap—between the responses to the two stimuli at an unspecified level of visual analysis.

The study provides no new answers to two crucial questions: (1) What is the IRI at which the best motion is seen? (2) By what mechanism is the temporal separation—or overlap—of two responses coded into a percept of motion?

Under the conditions of this experiment, the best motion is obtained with long stimuli when the first stimulus is removed just as the second appears (ISI = 0). At that ISI, the responses overlap in time to the extent of visual persistence ($T_a - t_a$, in (2) above). In these data, $t_a \cong 100$ msec, but T_a , the duration of the corresponding response, is unknown; consequently, the optimal value of IRI cannot be estimated. It is most likely, however, that there is some visual persistence ($T_a > t_a$) (Haber & Standing, 1968; Hochberg, 1968; Parks, 1964). If so, optimal motion is obtained when the responses to the two stimuli overlap in time. In fact, good motion is often seen even when the stimuli themselves overlap (ISI < 0). The perception of the phase of overlap is then suppressed. Evidence for the prevalence of backward suppression in the motion paradigm has been reviewed elsewhere (Kahneman, 1967). The more general point has been made (Kahneman, 1968; Weisstein, 1968) that apparently retroactive effects can only occur when the responses to the interacting stimuli overlap in time.

Optimal motion is certainly a retroactive effect. The percept that the first stimulus would elicit by itself is altered and is integrated into the percept of a single moving object. However, there are experiences of motion that lack this retroactive character. Motion may be attributed mainly to the second stimulus or to the intervening space, as in pure phi. Related distinctions between types of motion were drawn by Wertheimer (1912) and by Korte (1915). It may be possible to formalize the subtle phenomenal distinction between retroactive and proactive motion effects by the method of the present study, in which naive observers compare their experiences to a standard

description of a perceptual effect. Under different instructions, the very slow decrement of ratings with ISI that we obtained could probably be sharpened. The distinction between proactive and retroactive effects may be especially relevant to the interpretation of Korte's first law, that the optimal ISI for motion increases with interstimulus distance in space. Informal observations suggest that retroactive effects are virtually absent when distance is large, although an experience of motion is still obtained. Korte's first law must be studied to assess the generality of the finding reported here, that motion is best when $ISI = 0$.

Another parameter that was identified in the present study may be of general significance. That is the transitional duration of exposure, $t_a \cong 100$ msec, which separates brief from long exposures. There are several indications that the perception of a stimulus that is presented for more than 100 msec becomes immune to fundamental alterations by subsequent stimulation. We reported suggestive evidence that the first stimulus of the motion sequence is seen as stationary before it moves, when $t > 100$ msec. It was noted earlier that complete suppression by

metacounter does not occur when the first stimulus is exposed for more than 100 msec (Kahneman, 1967). Similar observations have been reported in a comprehensive description of sequential blanking effects (Mayzner, Tresselt, & Helfer, 1967). Michotte (1963) reports major perceptual changes at that duration, in a very different context: (1) Causality is not experienced in the launching paradigm when the two objects are stationary side by side for more than 100 msec; (2) the motion of a single object loses all unitary character when it is interrupted for more than 100 msec. This convergence of observations may eventually suggest a new approach in the search for that elusive prize, a fundamental unit of psychological time.

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NOTES

1. Address: Department of Psychology, Hebrew University, Jerusalem, Israel.
2. The study was supported by Grant P 01-MH-12623 from the National Institute of Mental Health to Harvard University, Center for Cognitive Studies.

(Accepted for publication November 15, 1969.)