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Continuous Measurement of Visible Persistence

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In the synchrony judgment paradigm, observers judge whether a click precedes or follows the onset of a light flash and, on other trials, whether or not a click precedes light termination. The interclick interval defines the duration of visible persistence. An elaboration of this method consists of two phases: In Phase 1, the luminance of a reference stimulus is psychophysically matched to the peak brightness of the test flash. Five luminance values between .1 and 1.0 of the reference stimulus are used subsequently. In Phase 2, a random one of the five reference stimuli, a test flash, and a click are presented; the observer judges whether the click occurred *before* or *after* the brightness of test flash reached the reference value (on *onset* trials) or decayed below it (on *termination* trials). This method was validated on 3 subjects with test stimuli whose luminance rises and decays slowly in time, and then was used to trace out the precise subjective rise and decay (temporal brightness response function) of brief flashes.

Visible Persistence

A brief visual stimulus presented to a subject is not perceived to end abruptly but to fade out gradually. The time difference between the physical termination of the stimulus and its perceptual termination has been investigated in a variety of paradigms. These paradigms fall into two main classes: those that infer visual storage from the accuracy of subject's reports and those that depend on subjective reports (e.g., Brindley's [1960] Class A and Class B procedures).

Typical accuracy procedures are the partial report paradigm and various picture completion paradigms. In the partial report paradigm (Sperling, 1960), the observer views a brief flash of a matrix of letters. Afterwards, a tonal cue that can be precisely located in time is used to request report of a randomly selected row of the stimulus. The decline of response accuracy with cue delay indicates the duration of short-term visual storage (iconic memory—Neisser, 1967). Picture completion paradigms require the observer to integrate information from two successive flashes in order to identify a target letter (e.g., Eriksen & Collins, 1967) or to detect a missing dot in a regular dot matrix (Hogben & DiLollo, 1974).

Subjective procedures require the observer to make a subjective judgment of perceived presence or absence of a stimulus. An example is the synchrony judgment paradigm (Sperling, 1967), in which the subject adjusts an auditory event (e.g., click) to a visual event (e.g., light termination). In synchrony judgment paradigms there are no correct or incorrect reports—the report is simply taken as its face value as an indication of the subject's perceptual state. In a technical sense, the synchrony judgment paradigm is a semantic exploration of how the words *visible* or *see* are applied in tachistoscopic viewing conditions.

On the whole, estimates of the duration of visible persistence obtained in the two classes of paradigms are similar, although there are some apparent discrepancies. Typical persistence times are found to be in the range of 100–300 ms (see Coltheart, 1980, and Long, 1980, for reviews). According to the *unitary persistence hypothesis,* the discrepancies in the duration of visible persistence between the two classes of paradigms are caused by different task requirements, which depend on different segments of one-and-the-same decay function. For example, Long (1980) states that a driving force for the popularity of the visible persistence paradigm is the assumption that the decay functions for iconic memory (accuracy

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procedures) and visible persistence are the same. However, no one has come up yet with a measure for those decay functions.

The studies concerning visible persistence fall into two groups: (a) Studies concerned with the time difference between stimulus termination and perceptual termination (Adelson, 1978; Appelman, 1980; Bertelson & Tisseyre, 1969; Bowen, Pola, & Matin, 1974; Sakitt, 1976a, 1976b) and (b) studies concerned with the total phenomenal duration of the stimulus that require reliable judgments of both onset and termination, the estimated stimulus duration being the time difference between judged onset and termination (Efron, 1970a, 1970b, 1970c; Haber & Standing, 1969, 1970; Sperling, 1967). There are no statements concerning the actual form of the rise and decay curves or of the complete representation of the stimulus as a function of time in the subject's visual system.

Clearly, a method to measure the entire moment-to-moment time course of visible persistence is needed. Because the term *visible persistence* already has several meanings (e.g., it is used to describe the time difference between physical stimulus termination and perceptual stimulus termination), the entire function will be called *temporal brightness response* (TBR). The TBR describes how the perceived brightness of a brief visual stimulus changes as a function of time. The purpose of this article is to prove the feasibility of measuring the TBR and to measure TBRs to brief flashes for 3 observers.

Elaborated Synchrony Judgment Paradigm

In an elaboration of Sperling's (1967) method, the following intermodal synchrony judgment paradigm was developed. An observer views two adjacent stimuli: a *reference stimulus*, which is presented at the beginning of the trial and remains on with constant luminance during the trial, and a *test stimulus* of varying luminance, which is presented and terminated sometime during the middle of the trial. Luminances are are adjusted so that from the observer's point of view the test stimulus initially appears dimmer than the steady-state reference stimulus but increases in intensity until eventually it becomes as bright or brighter (Figure 1).

At some instant, the brightnesses of the test and reference stimuli appear to match; that is the *match time*. The aim of the method is to discover precisely *when* the match time occurs. In a time interval around match time, the subject is presented with a click.

If the subject perceives the click to have occurred *before* match time, he or she presses a left-hand response key; if the click occurs *after* match time, a right-hand response is made.

Alternatively, the task of the subject can be construed as pressing the right key if, *at the instant the click occurred, the test was brighter than the reference stimulus*, and otherwise to press the left key. On termination judgment trials, the keys are reversed.

Repeated judgments result in a psychometric function, the probability of a *right* response as a function of time. The point of subjective equality (pse) is the 50% point of the psychometric function; it corresponds to the time at which the brightness of the reference matches that of the test. A psychometric function obtained with a particular luminance of the reference stimulus determines only one match time. The entire TBR function is obtained by obtaining match times for a full range of luminances of the reference stimulus, and by determining match times near the onset and also near the termination of the test stimulus.

Verification Procedure

Our primary interest is in the TBR function of a very brief stimulus. However, it is important to first demonstrate that a subject can make reasonable match time judgments with a slowly varying stimulus for which the TBR can be assumed to approximately track the temporal luminance function of the physical stimulus. An example of such a physical stimulus is the gradual fading out of a light bulb turned off with a dimmer. Therefore, we first determine TBRs for a control condition in which test field luminance increases linearly during a 600-ms period, stays at its maximum for 300 ms, and then turns off linearly during another 600-ms period. The data from this control condition with real "physical persistence" can be used to evaluate the method. For example, when the rising part of the test stimulus is under investigation (onset trials), we expect the match times to increase with increasing luminance of the reference stimulus, and when the decaying part of the test stimulus is under investigation (termination trials), we expect the match times to increase with decreasing luminance of the reference stimulus. After Experiment 1 (with ramped onsets and terminations) we proceed to Experiment 2, which determines TBRs for brief stimuli.

General Method

Overview

For both experiments, the verification experiment and the main experiment, the same apparatus and a similar method were used. We begin with a detailed description of Experiment 1 and add the differing details of Experiment 2 later.

Apparatus and Stimuli

All experiments were completely computer controlled. The stimuli were presented on a Hewlett Packard 1310A cathode-ray tube (CRT) with a fast P4 phosphor. The CRT was driven by a Digital Equipment Corporation PDP-11/34 computer via an especially designed display interface (Kropfl, 1975) and software for real-time vision experiments (Melchner & Sperling, 1980). The equipment made it possible to control display parameters in the millisecond range. The click was presented with Sennheiser HD 414 headphones.

Spatial arrangement. The stimuli consisted of two, adjacent, square-wave gratings (10 cycles/degree), separated by a gap of 0.25° visual angle, and each subtending a visual angle of 1.6° × 1.6° (Figure 2). The two gratings were viewed binocularly from a distance of 90 cm, with a fixation dot in between. Each stimulus was composed of a 32 × 32 dot matrix, with every second horizontal line suppressed. The individual dots can be seen in Figure 2, Panel a. This grating was used because it is a spatial frequency to which the visual system is highly sensitive and because the visible presence of the grating might facilitate the observer's task in judging the persisting presence of the stimulus. It is possible, indeed probable, that visible persistence depends on the precise geometric form of the test stimulus. However, in their judgments, observers were instructed to match the overall brightness of the stimuli, and the grating structure appears to have been unimportant.

Stimulus intensity. Over trials, reference stimuli with five different luminances were used (see first column of Table 1). The intensity of the test stimulus followed a ramped square-wave function in Experiment 1 (control condition) and a brief pulse function in Experiment 2.

The display was refreshed at a rate of 67 Hz, well above the critical flicker-fusion frequency of about 45 Hz for these stimuli. The high refresh rate guaranteed that the variations in intensity were perceived to be continuous. The intensity of the test stimulus changed with every refresh, while the

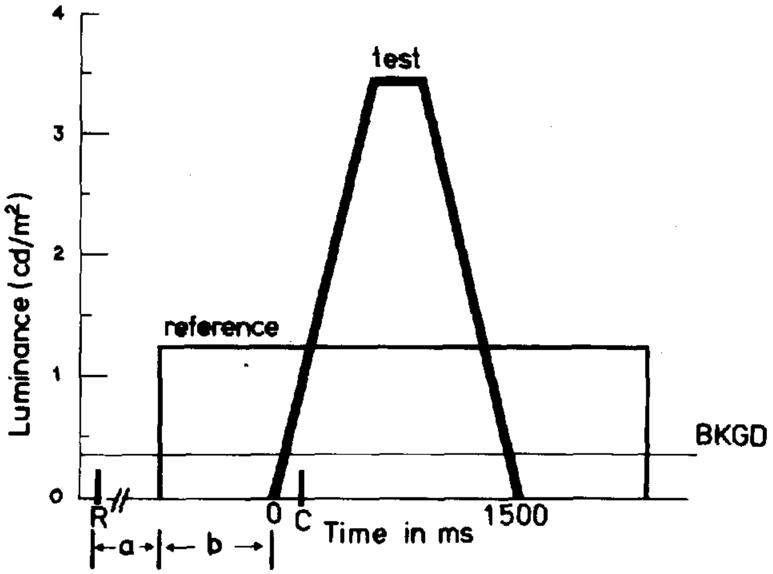

Figure 1. The elaborated synchrony judgment paradigm with the stimuli of Experiment 1. (The ordinate indicates the luminance of the stimuli; the abscissa indicates time. All times are given relative to the onset of the test stimulus, which consists of two 600-ms ramps connected by a 300-ms plateau. The events depected are the subject's response [R] on the previous trial; a random time interval of 200–2,000 ms [a] after which the reference stimulus appears; a random time interval of 450–900 ms [b] before test stimulus begins; a click at a predetermined time [c]. The subject judges whether the click occurred before or after the brightness of the test equaled the brightness of the particular reference stimulus [0.5 of maximum reference luminance is shown]. A uniform background light [BKGD] of 0.35 cd/m^2 is present continuously.)

intensity of the reference stimulus remained constant (Figure 2, Panels b and c). The luminance levels were externally checked with a United Detector Technology 40x Opto Meter. Two incandescent lamps were mounted to the left and to the right side of the display, providing a background illumination of 0.35 cd/m^2 throughout.

The click was generated with a 0.5-ms wide pulse to the headphones. A relative measure of click intensity was obtained by having subjects match the loudness of a 1000 Hz tone to the loudness of the click. The click and the tone were perceived to be equally loud when the intensity of the 1000 Hz tone was 80 dB above its own threshold (average of 3 subjects).

Procedure

Individual trials. At the beginning of a sub-block of 100 trials, the subject was shown a message indicating whether onset or termination judgments were required. After a random time interval of 200–2,000 ms (Interval a in Figure 1), the reference stimulus was turned on. After another random time interval of 450–900 ms (Interval b in Figure 1), the test stimulus began. On the first trial, the onset time of the click was randomly chosen within an interval of ± 200 ms around starting points (initial values), which were determined in preliminary experiments (see below). The reference stimulus was physically present for 3,000 ms; the test stimulus was on for 1,500 ms in Experiment 1 (Figure 1), and for 31 ms (3 refreshes) in Experiment 2; the background illumination was constant throughout.

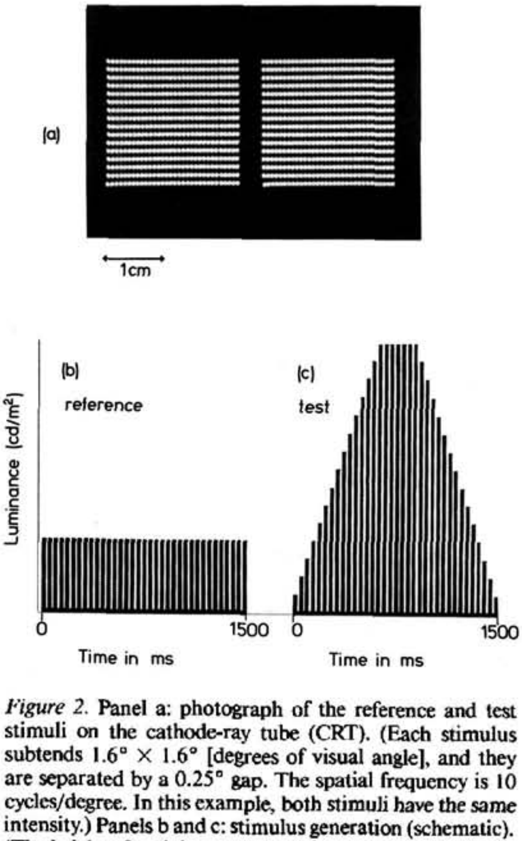

Figure 2. Panel a: photograph of the reference and test stimuli on the cathode-ray tube (CRT). (Each stimulus subtends 1.6° × 1.6° [degrees of visual angle], and they are separated by a 0.25° gap. The spatial frequency is 10 cycles/degree. In this example, both stimuli have the same intensity.) Panels b and c: stimulus generation (schematic). (The height of each bar represents *luminous energy* [Sperling, 1971] on the CRT. The distance between bar onsets represents the time between refreshes [15 ms]. [b] Reference stimulus: 1,500 ms of the 3,000-ms long reference stimulus are shown; [c] Test stimulus, Experiment 1. Because of limitations in print quality, only 1/3 of the actual flashes are shown.)

The subject's task was to decide whether the click had occurred before or after the instant of perceived brightness match between the two stimuli, and, accordingly, to press one of two response keys. This is a forced-choice task with two-alternatives, "click before" and "click after." The subject had unlimited time to arrive at a decision but typically responded within 2 s. The response automatically initiated the next trial.

Blocks of trials. The subjects were run in two blocks of 400 trials, each block being subdivided in four 100-trial sequences of onset or termination judgments, respectively. The points of subjective equality (i.e., the match times when the brightnesses of test stimulus and reference stimulus appear to match) were determined by a transformed up–down procedure (see below). There was a total of 20 conditions per experiment: reference stimuli of five luminances, test stimulus to the left or to the right side of fixation, and onset or termination judgment (5 × 2 × 2). Blocks of 400 trials lasted about 45 min, separated by a break.

Staircase procedure. To find the match times most efficiently, a transformed up–down procedure described by Levitt (1971) was used. Two interleaved staircases to estimate the $X_{.29}$ and $X_{.71}$ points on the psychometric function were run; from these, both the $X_{.5}$ point (pse) and the variance of the underlying distribution are computable. In addition to the well known advantages of staircase methods, the interleaved estimation of two (or more) points eliminates sequential stimulus dependencies and therefore ensures that the subject cannot anticipate stimuli and adjust responses accordingly.

The first click in any one of the 20 conditions was randomly placed around an initial value found in preliminary experiments. The following clicks were determined according to Levitt's transformed up–down procedure. In Staircase 1, which estimates $X_{.29}$, the click time is decreased by a fixed time interval (*step size*), when the subject responds "Click time occurred *after* match time," and increased by step size, when the subject responds *two* consecutive times "Click time occurred *before* match time." In Staircase 2, which estimates $X_{.71}$, the converse applied.

As determined by preliminary experiments, a step size of 100 ms was chosen for the first five trials, and a step size of 20 ms afterwards. This step size coincides with reports on the resolving power for temporal order judgments, which was found to be 15–44 ms. (Exner, 1875; Hirsh & Sherrick, 1961; Rutschmann, 1966). Per 400 trials, 20 staircases were run simultaneously (and interleaved), one for each combination of reference stimulus (5), visual field (2), and point on the psychometric function (2). The Subjects BW and SW did not know about this procedure.

Each staircase consisted of 20 trials (stopping rule). The .50 point on the psychometric function (match time) was estimated by computing, separately for each condition, the average of the click times for each staircase ($\bar{X}_{.29}$, $\bar{X}_{.71}$) from the first reversal on, and then by computing the arith-

Table 1
Match Times and Other Data From Experiment 1

	Subject								
	BW			EW			SW		
Reference cd/m²	MT	*SE*	DIF	MT	*SE*	DIF	MT	*SE*	DIF
Onset									
0.31	186	28	225	36	23	130	70	15	75
0.67	240	27	196	69	23	194	136	18	73
1.23	328	33	269	113	32	136	235	11	100
1.95	463	31	289	170	26	130	342	30	170
2.57	703	60	258	400	25	256	452	43	182
Peak alone	703	10		563	4		686	13	317
Offset									
2.57	712	56	297	705	18	395	940	39	349
1.95	1,014	40	360	1,108	21	304	1,212	18	168
1.23	1,242	26	242	1,336	33	145	1,331	31	161
0.67	1,389	22	370	1,403	36	102	1,420	21	154
0.31	1,467	23	170	1,485	31	145	1,466	17	86

Note. MT is mean match time, *SE* is standard error of the mean, and DIF is difference between 0.3 and 0.7 estimates of the match-time psychometric function (equal to 1.09 × Standard Deviation of the Match-Time Density Function assuming Normality). All data are in millseconds. Each MT is based on 240 observations, except the MTs for the absolute brightness peak of the test stimulus ("peak alone"), which were determined independently with 400 observations per subject. DIF could not be computed for BW's and EW's peak alone judgments. The stimulus was a ramped square-wave function.

metic mean of both averages: match time = 0.5 ($\bar{X}_{.29}$ + $\bar{X}_{.71}$). Assuming that the psychometric functions are symmetric in their midrange (not necessarily normal), this method is known to give bias-free estimation of $X_{.50}$, the match time. (The symmetry of the psychometric functions was not tested formally because graphs of the psychometric functions derived from the judgments did not show any obvious asymmetries.)

Subjects

Three male graduate students (BW, EW, and SW) participated in the two main experiments. All subjects had normal or corrected-to-normal vision. Two of the subjects (BW and SW) were paid $4.00 per hour. Subject EW had taken part in exploratory experiments; Subjects BW and SW were initially naive subjects. There were only a few practice trials for Subjects BW and SW.

Experiment 1

Experiment 1 consisted of two phases. In Phase 1, stimulus parameters for Phase 2 were empirically determined. In Phase 2, the TBR for a ramped test stimulus was measured using the parameters from Phase 1.

Method

Procedure

Phase 1. The experiments in Phase 1 determined (a) the luminances of the reference stimulus that matches peak test brightness and, hence, the choice of appropriate luminances for the reference stimuli, and (b) the time of occurrence of a click that co-occurs with the test peak and, hence, the choice of appropriate initial click values. The peak luminance of the test stimulus itself was arbitrarily chosen at a low value (3.43 cd/m²) to aviod obvious retinal afterimages while still being a moderately bright flash.

The elaborated synchrony judgment paradigm requires determination of the luminance of a reference stimulus whose brightness exactly matches the peak brightness of the test stimulus. Luminance matching was carried out with a symmetric up–down staircase of 30–50 presentations on which the luminance of the reference stimulus was varied, and the subject judged whether the reference was brighter or dimmer than the peak brightness of the test stimulus. The luminance of the brightness-matching reference was 0.75 of the peak luminance of the test stimulus. The results were so nearly identical for the Subjects BW, EW, and SW that for practical reasons the same reference stimulus was used for all subjects. (Individual results are given in the *Results* section below.)

In order to trace out the TBR, five reference stimuli were chosen for Experiment 1, whose values were .125, .25, .5, .75, and 1.0 of the luminance of the reference stimulus that matched the brightness peak of the test stimulus.

In a separate sequence of trials, the subjects judged the synchrony of the click and the peak of test brightness by means of same kinds of staircases as used in the main experiment. This judgment is made without regard to the reference stimulus. Together, the isolated brightness and temporal matches of Phase 1 pinpoint the brightness and time of the perceived brightness peak of the test stimulus.

Phase 2. In Phase 2 of Experiment 1, the TBR was determined for a ramped test stimulus by means of the psychophysical method described above in the *Procedure* section.

Results

The results of Phase 1 consist of the times and luminances that match the test peaks. The means are displayed as open circles at the top of the TBRs in Figure 3. Because the peak-matching luminances were quite similar, the same luminance values were used for each of the subjects in Phase 2.

The results of Phase 2 consist of the match times. Each match time is derived from 40 judgments (20 for $X_{.29}$ and 20 for $X_{.71}$ on the psychometric function) for each of the 20 stimulus conditions (onset or termination judgment, luminance of reference stimulus, visual field). This was replicated three times, yielding $3 \times 800 = 2{,}400$ observations per subject. The three replications provided an estimate of the variance of the match times.

Analysis of the match times revealed that the spatial arrangement of the test and reference stimuli (either one to the left or to the right of the fixation dot) had no significant influence on subjects' performance. Thus the match times for left and right tests were combined, providing 3×80 observations per match time.

The results of Experiment 1 are summarized in Table 1, which lists the match times of the 3 subjects, the individual standard errors of the mean for onset and termination judgments, and the results of the judged synchrony of the click with the brightness peak of the test stimulus (from Phase 1).

Figure 3 illustrates the temporal brightness response functions for the 3 subjects. The match times are plotted as open squares, and the arrows indicate the confidence interval for ± 1 standard error of the mean. The five data points on the left side of the TBR are the match times for the onset judgment, and the five data points on the right side of the TBR are the match times for the termination judgment. The open circle indicates the isolated Phase 1 judgments of the *time* of the peak test brightness (horizontal position), and the matching reference brightness (vertical position).[1]

The results are very regular. The TBRs show slopes that are comparable to the stimulus slopes. In all cases of the onset judgment, the match times were ranked in an ascending order with increasing luminance, and in all cases of the termination judgment, the match times were ranked in an descending order with decreasing luminance.

For Subject EW, the TBR has a flat plateau of 305-ms duration (compared to the 300-ms luminance plateau of the test stimulus); the other subjects' TBRs show distinct peaks, not a summit plateau, even though the physical test stimulus has a plateau. On the whole, the TBRs of all subjects track the rise and fall of the physical stimuli quite well. The half-intensity points of the physical stimuli are separated by 900 ms; the half-intensity judgments are separated by 914, 1,223, and 1,096 ms.

Discussion

In the case of the onset judgment, the match times of Subjects EW and SW occur *before* the physical luminance-match of reference and probe. This is a fairly common observation in judgments of auditory–visual order (e.g., Hirsh & Fraisse, 1964; Rutschmann & Link, 1964; Weyer, 1899). Possible interpretations are that the acoustical signal is processed more slowly than the visual signal, that the acoustical signal is "further" from an order-decision mechanism (Sternberg & Knoll, 1973), or that the temporal-order judgment is based on retrieval of stimulus events from memory and that the order of retrieving events from their modality-specific memory profoundly influences their perceived order (Reeves & Sperling, 1983).

The finding that the match times were independent of the visual field (test stimulus to the left or to the right of fixation) is a contribution to the discussion of laterality and visible persistence, which was recently reviewed by Wurst and Long (1983). Our results indicate that laterality has no influence on the TBR.

We did not observe any brightness enhancement analogous to a Broca-Sulzer effect that might make the onset of the ramped test appear to be brighter than the steady state of the reference stimulus. On the contrary, in

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[1] The match times for the brightest reference stimuli and the independent peak judgment fall on top of each other in Figure 4, Panel a. In Figure 4, Panel b, the standard error of the mean is so small that the arrows are not visible.

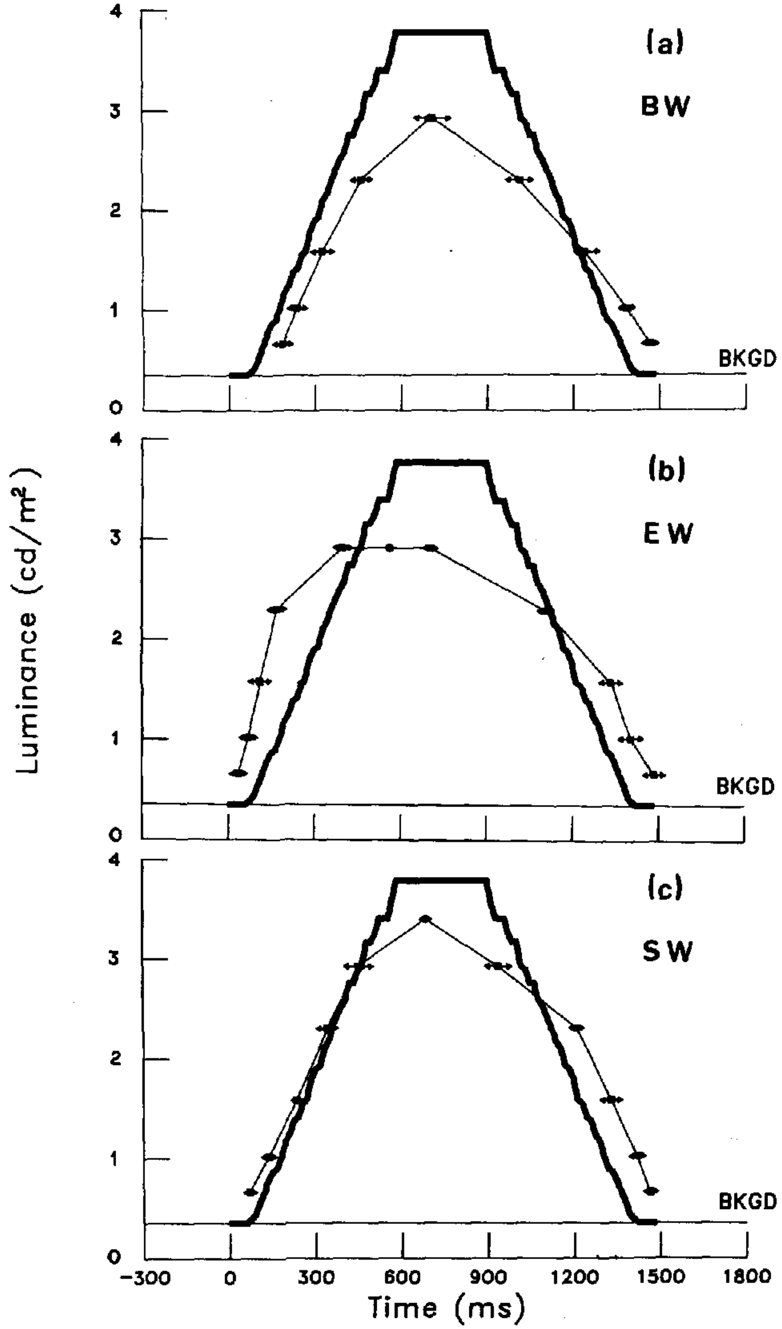

Figure 3. Temporal brightness response (TBR) functions for the ramped test stimulus of Experiment 1. (Data for 3 subjects: [a] BW, [b] EW, and [c] SW. The ordinate is the luminance of the reference stimulus; the abscissa is the match time (in milliseconds) of the test and reference stimuli as determined by the elaborated synchrony judgment method. The heavy line indicates the actual test stimulus luminance plotted to the same scale; BKGD = study background level. The thin line indicates the TBR, which connects five onset match times [open squares], the peak judgment from Phase 1 [open circles], and five termination match times [open squares]. The horizontal arrows indicate the confidence interval for ± 1 standard error of the mean. The confidence interval for peak judgments is so small that the open circle is obscured for Subjects EW and BW.)

Phase 1, we observed the opposite of a temporal brightness enhancement, with the peak brightness of the transient test stimulus being matched by a reference stimulus of 0.75 of test brightness. However, our stimulus parameters (duration of stimuli, spatial arragement) varied considerably from studies on temporal brightness enhancement; for example, Bowen and Markell (1980), and Kitterle and Corwin (1983) find that there is no temporal contrast enhancement for flashes with ramped onsets. It is noteworthy that 300 ms of steady luminance of the test flash is not long enough to make it appear equal in luminance to the much longer duration reference stimulus.

Conclusion

From the results of Experiment 1, we conclude that the elaborated synchrony judgment method yields reasonable temporal brightness response functions, and there are pronounced individual differences. We therefore proceed to Experiment 2.

Experiment 2

Experiment 1 established the feasibility of the elaborated synchrony judgment paradigm. In Experiment 2, this paradigm is applied to a 31-ms flash (three 1-ms refreshes at 15-ms intervals) to determine its TBR.

Method

Procedure

Phase 1. As in Experiment 1, it was necessary to find a reference stimulus, whose intensity matched the peak brightness of the test stimulus. This match was determined by an up–down method with several sequences of 20 presentations. It turned out that the luminance of the brightness-matching references was almost identical to the luminance of the brightest reference stimulus used in Experiment 1. Therefore, the same five reference stimuli were chosen for Experiment 2 as for Experiment 1. Also, the same synchrony judgment procedure as in Experiment 1 was used to determine the match time for a click and the peak of test brightness. (This judgment is independent of the reference stimulus.)

Phase 2. Phase 2 of Experiment 2 determined the TBR for the 31-ms pulse with the elaborated synchrony judgment paradigm. All 3 subjects who had taken part in Experiment 1 took part in Experiment 2.

Results

The results of Experiment 2 are match times. Each match time was derived from 80 judgments: 40 for $X_{.29}$ and 40 for $X_{.71}$. As in Experiment 1, the match times for left and right visual field did not differ statistically and were combined. The determination of match times was replicated four times, providing $4 \times 80 = 320$ observations per match time. The results of Experiment 2 are summarized in Table 2, which lists the match times of the 3 subjects for onset and for termination judgments, the respective standard errors of the mean, and the match times for the peak of the test stimulus (from Phase 1).

Figure 4 illustrates the temporal brightness response function for each subject. The format is similar to Figure 3; however, note the different time scale. The match times show the same monotonic behavior as the data in Experiment 1, with one statistically insignificant violation of monotonicity for Subject BW. The data are internally consistent.

For Subjects BW and SW, the peaks of the TBR for onset judgment and for termination judgment do not fall on top of each other. For Subject EW they cross slightly, although this crossing is within experimental error. Because onset and termination judgments were run in blocks (because of technical reasons), the relative horizontal placement of these segments could conceivably vary due to different "sets" of the subjects for onset and for termination judgments. Alternatively, these judgments can be taken at face value as indicating that even for a brief test flash, the TBR is rounded or even flat on top for some subjects.

Again, the individual differences between subjects are striking. Subject BW has a steep onset and steep termination in his TBR; Subject EW has a shallow onset and steep termination; Subject SW has a steep onset and shallow termination. The differences between the half-intensity onset and termination match times—which may be taken as the most reliable indicator of subjective persistence but are a slight underestimate of total persistence—are 226, 402, and 487 ms, respectively, for the 3 subjects. The stimulus duration was 31 ms.

General Discussion

Duration of Visible Persistence

Although the subjects were presented with a very brief pulse, they reported verbally and by means of their match-time judgments that

Table 2
Match Times and Other Data From Experiment 2

	Subject								
	BW			EW			SW		
Reference cd/m^2	MT	*SE*	DIF	MT	*SE*	DIF	MT	*SE*	DIF
Onset									
0.31	−71	27	118	−218	23	130	−175	32	106
0.67	−60	27	95	−156	24	146	−160	34	122
1.23	−56	19	50	−141	37	149	−152	30	102
1.95	−41	20	33	2	31	196	−103	36	202
2.57	16	23	49	124	28	178	−79	28	157
Peak alone	39	9	102	88	8	184	−20	8	149
Offset									
2.57	102	6	52	77	33	137	66	44	189
1.95	143	15	108	187	27	225	207	43	159
1.23	210	20	144	261	15	128	335	33	137
0.67	189	16	140	309	25	137	423	35	139
0.31	270	36	175	317	13	106	481	51	173

Note. MT is mean match time, *SE* is standard error of the mean, and DIF is difference between 0.3 and 0.7 estimates of the match-time psychometric function (equal to 1.09 × Standard Deviation of the Match-Time Density Function assuming Normality). All data are in milliseconds. Each MT is based on 320 observations, except the MTs for the absolute brightness peak of the test stimulus ("peak alone"), which were determined independently. The stimulus was a brief pulse function.

the test stimulus seemed to rise and fall gradually. The durations of the temporal brightness response between the onset and termination half-intensity points were 226, 402, and 487 ms for the 3 subjects. The objective duration of the test stimulus was 31 ms. Does this mean that the duration of visible persistence is the TBR duration minus 31 ms? Attempting to answer this question illustrates three fallacies in thinking of persistence as a concept that is adequately described by a single number, its duration.

1. It is obviously ridiculous to discriminate the first 31 ms of the TBR as being "objectively correct response" and the remainder as being "visible persistence." In fact, when the objective function is a trapezoid, as in Experiment 1, there is no uniquely defined "duration." A better approach is to choose a *measure* of the duration of the stimulus and a corresponding *measure* of the duration of the response, such as the time between half-intensity points.

2. Visible persistence cannot be measured just by the duration from the termination of the test flash to the time of a click that matches termination (not withstanding Adelson, 1978; Appelman, 1980; Bertelson & Tisseyre, 1969; Bowen, Pola, & Matin, 1974; Sakitt, 1976a, 1976b). There is an essentially arbitrary translation of the TBR on the time axis. The duration of persistence properly is indexed from an *onset judgment* to a *termination judgment* (Efron, 1970a, 1970b, 1970c; Haber & Standing, 1969, 1970; Sperling, 1967). Onset-to-termination indexing cancels any (subject dependent) constant factor that might relate judgments of simultaneity between auditory and visual events. For example, for the 3 subjects, the peak judgments (points of subjective simultaneity between the peak of the visual flash and the auditory click, peaks of TBR, Figure 4, Panels a–c) occur at −20, +39, and +88 ms after flash onset. This 108-ms variation between subjects would confound any estimate of duration based on time from objective flash termination to subjective termination. The range of the individual differences (sometimes attributed to *prior entry*) cannot be avioded by replacing the click with a light flash. Reeves and Sperling (1983) extensively explored perceived order judgments of two visual events at different spatial locations, and these are as complex as intermodal judgments. In the present context, exploratory experiments in

which the click was replaced with a light flash gave essentially equivalent results.

3. Visible persistence, or temporal brightness, responses vary greatly in shape between subjects. These very significant individual differences are not adequately characterized by

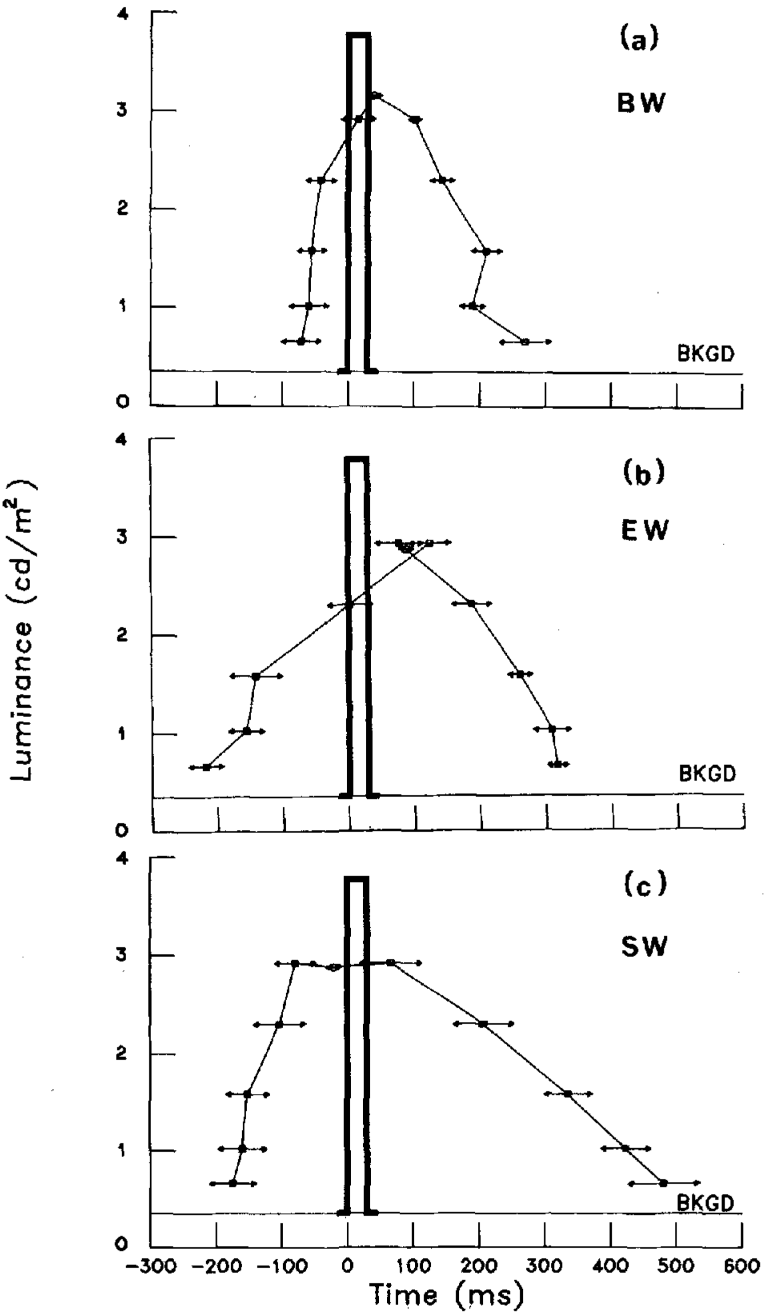

Figure 4. Temporal brightness response [TBR] functions for the pulse test stimulus of Experiment 2. (Conventions as in Figure 4.)

a single duration parameter, such as the decay constant of an exponential decay function. In fact, the TBRs do not seem to derive from any generic function. To describe visible persistence requires specification of a function, the TBR.

Further Extension of the Auditory Synchronization Method

In the introduction, it was noted that there were essentially two equivalent definitions of the subject's task: (a) a temporal judgment of whether the click occurred before or after the match time (time of equal brightness) between test and reference stimuli; (b) a brightness judgment, in which the subject judges, at the instant the click occurs, whether the test or reference stimulus is brighter. We denote these judgments as "Which is earlier?" and "Which is brighter?", respectively. Although the which-is-earlier? definition of the task best captures the intuition of the paradigm, the which-is-brighter? judgment more nearly describes the task from the subject's point of view (with a few exceptions, described below).

With the present stimuli, the which-is-earlier? and the which-is-brighter? definitions of the task are logically, if not psychologically, equivalent. However, the which-is-brighter? is the more general procedure because it can be applied to any test stimulus, even to a flickering or random temporal noise test stimulus, for which it might be impossible to label a particular match time. The question in all cases is "Which is brighter—reference or test—at the time of the click?" In the which-is-brighter? procedure, the matching luminance of the reference stimulus normally would be determined by an up–down luminance staircase, for preselected click times, instead of an up–down temporal staircase for preselected luminances in the which-is-earlier? judgments.

A particular problem occurs in the which-is-earlier? judgments, when the reference stimulus is at its highest intensity value. There is a possibility that the test flash would not reach reference's apparent brightness on some proportion of trials. Match time would be undefined. In such cases, subjects interpreted the judgment as "Did the click occur before or after the instant at which the test flash was brightest?" In the which-is-brighter? procedure, this kind of occurrence is not a problem; it simply yields a judgment of "reference flash brighter," a perfectly normal occurrence.

Relations to Other Paradigms

One other paradigm that yields an entire response function to a visual stimulus is Crawford's (1947) masking paradigm. To determine the response to a stimulus S_0 with a particular luminance waveform, S_0 is cast as a masking stimulus. The detection threshold for a brief superimposed test flash is determined when it occurs at various possible times relative to S_0. Sperling (1965) measured the masking response to brief impulse flashes, which may be compared to the brief test flashes studied here. The question may be formulated as "Do the masking and elaborated synchrony judgment paradigms yield different response functions?", or equivalently, "Is the masking power of a stimulus directly related to its brightness?" (in which case the two methods would yield equivalent response functions).

Although obtained under different conditions, the impulse masking functions (Sperling, 1965) seem to be enormously more compact in time than are the temporal-brightness-response functions. The following example further demonstrates the difference between masking response functions and brightness response functions. A very high luminance stimulus appears to be black when surrounded by an even brighter stimulus, even though it is a powerful masker, much more powerful than a brighter appearing low-luminance (white) stimulus on a dark background. Thus temporal brightness response and masking responses, which have a superficial similarity, represent at least partially different processes.

Similarly, many authors have commented on procedures that differentially affect visible persistence (as determined in the present paradigm) and informational persistence (as determined by partial reports (Sperling, 1960)). It is plausible that the temporal brightness response, which is based on subjective reports, might not relate well to response functions based on performance measures (such as detection threshold under masking or partial report accuracy). But if there is order in the mind, then brightness response functions based on direct judgments of brightness (as in the present procedure) and on indirect judgments of brightness (derived from estimates of the number of stimuli visible with stimuli in apparent motion) should coincide. Unfortunately, a strong test of this hypothesis awaits the development of motion paradigms that permit determination of a full temporal brightness response, not merely of the total duration of persistence (e.g., Efron, 1970b; Farrell, 1984; Farrell, Sperling, & Pavel, 1983). However, once one has obtained full brightness response functions, rather than merely overall durations, much more powerful analytic techniques are available to ferret out the common and differing components of the various temporal response functions, and thereby the shared and differing underlying processes in the visual memory tasks.

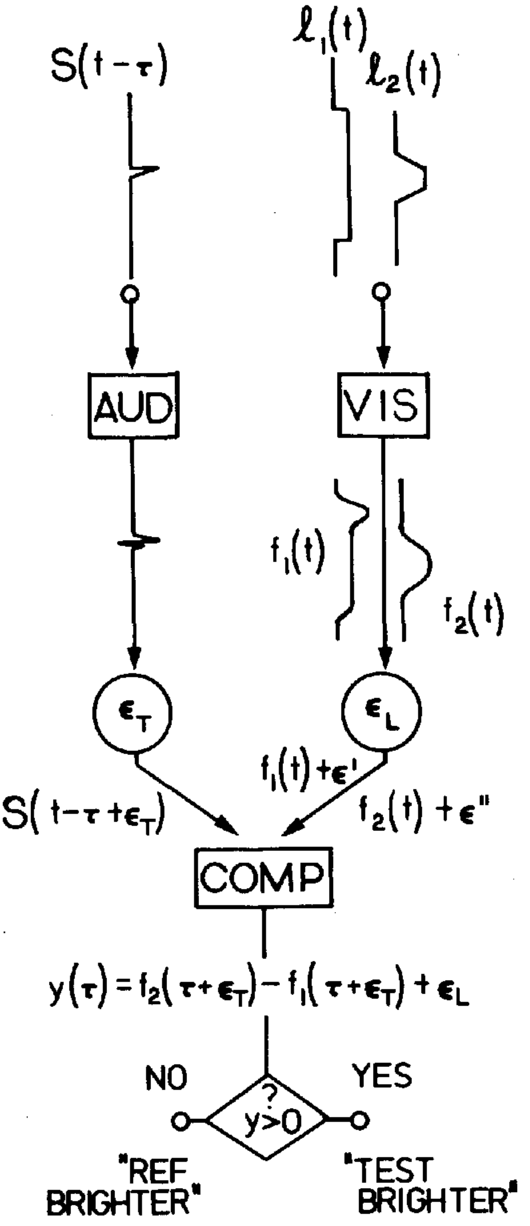

Figure 5. Sources of error in determining the observed temporal brightness response. (Visual inputs are the reference stimulus, $l_1(t)$, and a test stimulus, $l_2(t)$. The visual processor is VIS; its output in response to $l_2(t)$ is the "pure" TBR, $f_2(t)$. Luminance uncertainty is represented as an error ϵ_L that varies between trials. The auditory input is a click $\delta(t-\tau)$ at time τ. AUD is the auditory processor; ϵ_T represents the temporal uncertainty of τ. The output $y(\tau)$ of the comparator [COMP] is the perceived relative brightness of the test and reference stimuli at the perceived time $\tau + \epsilon_T$ of click occurrence. The response is "test brighter" when $y(\tau)$ is greater than zero; otherwise, "reference brighter.")

Pure Temporal Brightness Responses

Two processes that would distort a pure TBR to yield the observed TBRs would be *luminance uncertainty* and *time uncertainty.* The origin of these errors is illustrated in Figure 5. The inputs stimuli are $l_1(t)$ and $l_2(t)$, the luminances of the reference and test stimuli as a function of time. The output intensities of the visual processor in response to $l_1(t)$ and $l_2(t)$ are $f_1(t)$ (reference stimulus) and $f_2(t)$ (test stimulus); $f_2(t)$ is the "pure" TBR. The visual processor outputs are perturbed by added random luminance errors ϵ'_L and ϵ''_L, which represent the aggregation of quantal noise in the stimuli with internal noise in the visual system. The auditory click is processed by an auditory component and perturbed by temporal uncertainty, which is represented as a time error ϵ_T. A comparator determines whether at the perceived time of the click $\tau + \epsilon_T$ the reference or test is brighter. The combination of luminance and temporal uncertainty with $f_2(t)$ to produce the observed temporal brightness response $\mathrm{TBR}(\tau)$ is given by Equation 1:

$$\mathrm{TBR}(\tau) = l_1(\tau), \quad \text{such that} \qquad (1)$$

$$P\,[f_2(t+\epsilon_T) + \epsilon'_L > f_1(t+\epsilon_T) + \epsilon''_L] = 0.5.$$

The true TBR, $f_2(t)$, can be estimated from the data by means of Equation 1 with appropriate assumptions about $f_1(\tau)$, ϵ'_L, and ϵ''_L. The present data were not obtained in a way to yield sufficiently reliable estimates of ϵ_L and ϵ_T to warrant the "deconvolution" solution of

Equation 1, so this approach to a pure TBR, while feasible in principle, awaits further experimentation.

Criterion Effects

The model outlined in Figure 5 is especially useful for considering a question that troubles some readers when they view the 3 subjects' vastly different TBRs induced by the same brief flashes. Is it possible that intersubject TBR differences are caused by differences in criteria rather than by differences in visible persistence? Intersubject criterion differences are assumed to occur at a high level of processing; visible persistence is assumed—implicitly and probably incorrectly—to occur at a lower processing level and thus to be more stable between subjects. Resolution of this question requires quite detailed consideration of the alternatives and of the data. We consider three alternatives: (a) different temporal criteria, (b) judgments based on different aspects of the stimuli, and (c) different levels of visible persistence.

Different temporal criteria. A subject- or condition-dependent criterion would be representable as a bias component of ϵ_T (Figure 5). Thus, $\epsilon_T = b\ (C, S) + \epsilon$, where $b\ (C, S)$ is a bias constant that depends on condition C and subject S, while ϵ is randomly distributed from trial to trial with zero mean. Based on a long history of intermodal temporal order experiments (Boring, 1950), there is a reasonable expectation of bias factors in temporal judgments involving a sound and a light flash. [Logically, bias could also occur in the judgment of the equality of the two luminance functions $(f_1(t), f_2(t)$ in Figure 5). But the left–right position of test and reference is random, and the luminance judgment is symmetrical from the subject's point of view; it is hard to imagine a reasonable formulation of luminance bias.]

Specifically, we consider the at once most likely and most damaging criterion artifact: Suppose subjects had different temporal criteria for onset and offset trials. This would have the effect of introducing an arbitrary left–right shift between the onset and offset segments in Figure 4, Panels a–c, and thus of producing an arbitrary shortening or lengthening of the duration of the TBR. The data themselves are informative about such a possibility. In Figure 4, Panel a, the exact coincidence of three different kinds of judgments (onset, peak, and offset) at the peak of the Subject BW's TBR strongly speaks against a possibility of different criteria. The same coincidence, within measurement error, at the peak of Subject EW's TBR (Figure 4, Panel b) also suggests identical criteria in all conditions. Subject SW (Figure 4, Panel c) illustrates a lengthening of the TBR that might have been produced by different temporal criteria for onset and offset trials. On the other hand, Subject SW's data are completely consistent with a flat-peaked TBR, the peak judgment falling directly between the onset and offset judgments.

Three aspects of Subject SW's data further support the validity of his flat TBR peak (Figure 4, Panel c). (a) The minimum difference between the onset and offset segments is about 200 ms, whereas criterion differences in temporal order judgments seldom exceed about 100 ms. Therefore, at least 100 ms of Subject SW's 200-ms flat peak is "real." (b) The peak judgment, in which Subject SW judged the simultaneity of the peak test flash brightness and the click, was physically quite accurate. (The top center point of Figure 4, Panel c, is near the middle of the brief flash, where the brightness peak is expected to occur based on physiological and psychophysical masking data.) Subject SW's demonstrated ability to make reasonable temporal judgments of click and light in this situation makes it unlikely that the onset and offset judgments represent a quirky criterion rather than a true judgment of visible persistence. (c) No amount of lateral shift would bring the gradual offset decay of Subject SW's TBR into coincidence with the much sharper TBR decays of the other 2 subjects. Analagously, Subjects BW and SW have abrupt TBR onsets and more gradual decays; the opposite is true for Subject EW. These slope differences appear to be real aspects of visible persistence because no simple criterion variation can produce these kinds of individual differences. In summary, variations in temporal criteria can be rejected for 2 of the 3 subjects based on internal consistencies within their data. Criterion variation could not account for the main features of the TBRs nor could it substantially reduce the intersubject TBR differences.

Judgments based on different aspects of stimuli. The onset of a luminous grid on a dark background involves both low and high spatial frequencies (coarse and fine receptive fields). Is it possible that some subjects base their responses on low spatial frequencies (similarity of the test and reference in overall brightness) and others on high spatial frequencies (similarity of test and reference in the contrast of the grid lines)? Interviews with the subjects give no support for this conjecture. Brightness and contrast appeared to covary perfectly in these stimuli, and subjects focused on brightness, as instructed. The question would be better answered, however, by experiments that independently varied luminance and contrast of test stimuli and determined the persistence components due to each.

Different levels of visible persistence. In an unpublished doctoral thesis carried out under Sperling's supervision, Jane Kaufman (1977) obtained evidence for three different levels of short-term visual memory. Conceivably, the contribution of these memories to visible persistence (as measured by the elaborated synchrony judgment paradigm) varies from subject to subject. There is nothing within the elaborated synchrony judgment paradigm either to suggest or to preclude such a complication. The paradigm yields a description of the subjective phenomenon of visible persistence, whatever its origins may be. But the possibility of multiple modes of persistence (determined by different spatial frequencies) combined with multiple origins (from different levels of visual memory) does indeed caution us against overly simplistic conceptions of visible persistence.

Conclusion

The elaborated synchrony judgment paradigm utilizes a highly refined form of introspection to trace out an entire temporal brightness response function to a test stimulus. The paradigm applies to a wide variety of possible temporal waveforms. For very brief test flashes, both the onset and the termination phases of the TBR differ widely across observers, with overall durations of the TBR varying from about 200 to about 500 ms.

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