Vision Res. Vol. 33, No. 7, pp. 913–917, 1993
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0042-6989/93 $6.00 + 0.00

On the Confounding Effects of Phosphor Persistence in Oscilloscopic Displays

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Received 23 July 1992; in revised form 16 October 1992

Phosphor persistence has been a source of confounding in studies of temporal integration in vision. We examined the confounding by assessing the effects of the persistence of two commonly-used phosphors (P15 and P31) on performance of a temporal-integration task. In one experiment we eliminated the visibility of phosphor persistence by closing two mechanical shutters upon display termination. In a second experiment we estimated the duration of phosphor persistence by displaying the image behind closed shutters which opened upon display termination. No detectable persistence was every produced by P15 phosphor. By contrast, P31 phosphor produced persistence that lasted several hundred milliseconds even when a veiling light was projected on the screen. We ascribe the earlier instances of confounding to inadequate interpretation of the technical data on phosphor decay.

Phosphor persistence   Visible persistence   Temporal integration   Phosphor decay

Temporal integration of stimuli displayed sequentially on an oscilloscope can occur in at least two ways: within the visual system, as the outcome of sensory processing activities, or on the oscilloscope's screen because of phosphor persistence. The two sources of integration have been confounded in a number of earlier studies. Because of this confounding, temporal integration that was, in fact, due to phosphor persistence was ascribed instead to visual processes. Irwin, amongst others, has identified and corrected a number of these misattributions (e.g. Irwin, Brown & Sun, 1988; Irwin, Yantis & Jonides, 1983; Irwin, Zacks & Brown, 1990; Jonides, Irwin & Yantis, 1983).

Lest this confounding occur again in the future, it seems pertinent to ask why it has occurred so frequently in the past. We suggest that one likely reason may have been the ready—albeit unwarranted—acceptance of widely-available technical information on the temporal decay of phosphor persistence in cathode-ray tubes (Bell, 1970). In itself, the technical information is probably correct. However, as discussed later in this paper, that information can be misleading if used as an index of stimulus visibility in psychophysical experiments. For example, that information indicates that P31 phosphor decays to 0.4% of maximum brightness in 0.5 msec. On this basis, Jonides, Irwin and Yantis (1982) ascribed the temporal integration obtained in their studies to visual processes. However, the same researchers, as well as others, later realized that the integration was due entirely to phosphor persistence.

In some instances, a veiling light has been used to obviate the unwanted effect (e.g. Baker & Braddick, 1985; Farrell, Pavel & Sperling, 1990). However, no information is available as to the level of veiling light required to achieve the desired result. In any case, this solution is less than optimal because it rules out investigations under scotopic viewing conditions. An alternative solution has been to use a different phosphor, P15, which is believed to decay much more rapidly (e.g. Di Lollo, 1977; Morgan & Watt, 1983; Uttal, 1969). However, this belief is based largely on the same technical information that had proved inadequate in the case of P31.

Two issues must be addressed if the problem of phosphor persistence in temporal-integration experiments is to be resolved. First, we need to know why the commonly-used source of information on phosphor persistence (Bell, 1970) has proved inadequate as an index of stimulus visibility. Some reasons for this failure are advanced later in this paper. Second, and more important, we need an empirical assessment of the course of decay of phosphor persistence under conditions that are directly applicable to temporal-integration performance in psychophysical experiments. It is worth noting that cross-phosphor comparisons (revealing substantial differences among phosphors) have been carried out in flicker fusion experiments (Turnage, 1966). However, in temporal integration and visible persistence experiments, where phosphor effects are potentially just as detrimental, comparative tests of phosphor persistence have not been done.

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Some such tests were carried out in the present work. First, we checked whether the persistence of P15 phosphor influenced performance in a temporal integration task. Having found that it did not, we compared the persistence of P15 and P31 phosphors at several levels of trace intensity, with and without a veiling light. We found that P15 phosphor never produced any detectable persistence even under extreme conditions. However, this was not true for P31 phosphor.

EXPERIMENT 1

Data were collected from two paid observers; both had normal vision with corrective lenses. Two Tektronix 608 oscilloscopes equipped with P15 phosphor were arranged at right angles to each other as illustrated in Fig. 1. Observers viewed the two display surfaces through a beam splitter (a 12.8 × 17.9 cm pellicle, ST-SQ-NP 40 by National Photocolor Corp.). Interposed between each oscilloscope and the pellicle was a mechanical shutter [Gerbrand Model G1166 (D)/(S)] that changed between open and closed states in 2 msec. The experiments were done in a dark room where observers sat for at least 20 min before an experimental session. Observers viewed the displays monocularly with the preferred eye from a distance of 35 cm (the length of the optical path) set by a chin-rest.

We employed an experimental task that has been used extensively to study temporal integration in vision (Di Lollo, 1977; Shioiri & Cavanagh, 1992). The display comprised 24 of the 25 elements of a 5 × 5 square matrix. Each element was composed of four tightly-packed dots, and was seen as a small square dot. The separation between adjacent matrix elements was 0.65°. The observer's task was to identify the matrix location of the missing element. On any given trial, the 24 elements were shown in two successive frames (F1 and F2) of 12 elements each, chosen randomly on each trial. The two frames were displayed for 10 msec each, and were separated by a variable inter-stimulus interval (ISI) during which the screens remained blank. Success at this task depends critically on the simultaneous visibility of all 24 elements. But, when the two frames are separated by an ISI, simultaneous visibility can occur only if F1 generates sufficient persistence to bridge the temporal gap. The longest ISI at which the task can still be performed to a specified criterion is an index of the duration of visible persistence.

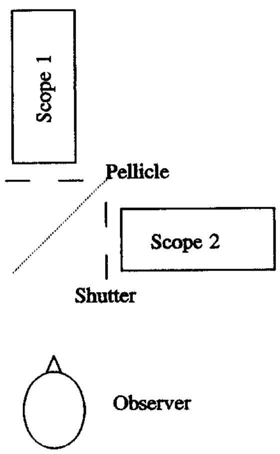

FIGURE 1. Physical arrangement of the display equipment in Expt 1.

To separate phosphor persistence from visible persistence, we employed two conditions. In the first ("two-scopes") condition, F1 and F2 were displayed on separate oscilloscopes. The sequence of events was as follows: at the beginning of a trial both shutters were open and four fixation dots marked the corners of a square area slightly larger than the matrix. Upon a button-press by the observer, F1 was displayed on one oscilloscope. Upon stimulus termination, the shutter positioned in front of that oscilloscope was closed and remained closed to the end of the trial. This prevented the observer from seeing any phosphor persistence that might have lingered on the screen after stimulus termination. After the appropriate ISI had elapsed, F2 was displayed on the other oscilloscope, and the second shutter was closed upon stimulus termination. Finally, having identified—or guessed—the matrix coordinates of the missing element, the observer entered them in a response box.

In the second ("one-scope") condition, F1 and F2 were displayed on the same oscilloscope. The shutter remained open throughout the display sequence—notably during the ISI—and was closed upon termination of F2. In this condition, any phosphor persistence that might have been produced by F1 remained visible throughout the ISI and the duration of F2. Comparison between the one-scope and two-scope conditions provides an index of phosphor persistence as follows: performance in the one-scope condition should remain accurate over longer ISIs to the extent that phosphor persistence (invisible in the two-scope condition) remains high throughout the ISI and into the period of F2.

In the present work, intensity of the displays is expressed in candelas microsecond (cd μsec). These are units of luminous directional energy per point (LDE) and provide an appropriate description of the luminous intensity of oscilloscopic displays (Sperling, 1971). Each of the two conditions was run at two levels of intensity: high (0.0816 cd μsec) and low (0.0027 cd μsec). To a dark-adapted observer, the high-intensity stimuli appeared very bright and almost flaring on the display surface; the low-intensity stimuli were barely visible. Stimuli were displayed by a fast plotting buffer at a rate of 1 dot/μsec (Finley, 1985). Luminance of the displays was measured with a Minolta LS-100 luminance meter following the method described by Sperling (1971).

The results are shown in Figs 2 and 3 for the high- and the low-intensity stimuli, respectively. Each point in Figs 2 and 3 represents the mean of 100 observations. Clearly, no consistent differences in temporal integration performance were obtained between the one-scope and two-scope conditions at either level of intensity. It must be concluded that, within the ambit of this experiment, P15 phosphor did not produce any detectable persistence on the display surface. Further aspects of the results are

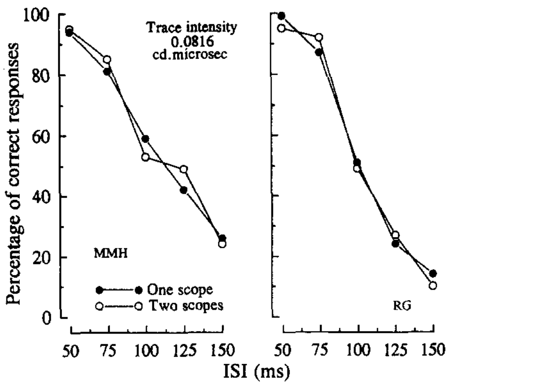

FIGURE 2. Performance in identifying the missing element in a 5 × 5-element matrix displayed in two separate frames of 12 elements each. The oscilloscopes were equipped with P15 phosphor. In the "one-scope" condition the two frames were displayed on the same oscilloscope; in the "two-scope" condition they were displayed on separate oscilloscopes. Observers viewed the displays through a beam splitter and a mechanical shutter placed in front of each oscilloscope. In the two-scope condition, any phosphor persistence was rendered invisible by closing the appropriate shutter upon display termination.

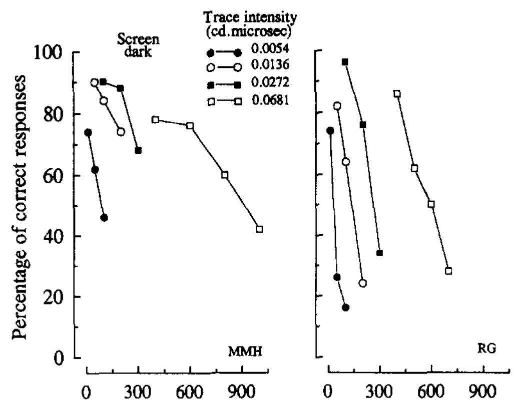

FIGURE 4. Performance in identifying the missing element in a 5 × 5-element matrix. All 24 elements were displayed simultaneously behind closed shutters on an oscilloscope equipped with P31 phosphor. The blank period indicates elapsed time from display termination to shutter opening.

discussed below. Now we turn to Expt 2, in which a direct comparison between P15 and P31 phosphors had been planned.

EXPERIMENT 2

In Expt 2 it had been our intent to compare P15 and P31 phosphors directly. However, we discovered that P15 phosphor never produced any detectable persistence on the screen even under the most extreme conditions (very intense stimuli and dark-adapted observers). Nevertheless, the results obtained with P31 phosphor are worth reporting in that they reveal the inappropriateness of P31 phosphor for investigating temporal integration in vision.

Data were collected from the same two observers. Only one oscilloscope was used in any given condition: either a Tektronix 608 equipped with P15 phosphor or a Kikusui COS1711 equipped with P31 phosphor. The pellicle was removed from the equipment stand, and the display was viewed binocularly through the two shutters placed in front of the observer's eyes. On any given trial, the sequence of events was as follows: the trial began with open shutters to display the fixation points. Upon a button-press by the observer, the fixation points were turned off and both shutters were closed. After an interval of 100 msec, all 24 dots of the incomplete matrix were displayed for 10 msec behind closed shutters. A variable blank interval was allowed to elapse between the termination of the display and the opening of both shutters. The observer then attempted to identify the location of the missing element from the phosphor persistence remaining on the screen.

To examine the effect of a veiling light on the visibility of phosphor persistence, observations were made under two conditions: in the "dark" condition, the screen and the room were completely dark and the observer was dark-adapted as in Expt 1. The intensity of the stimuli was varied between 0.0054 and 0.0681 cd μsec, and the duration of the blank period was varied between 10 and 1000 msec. In the "light" condition, a fixed level of background luminance was provided by front-illuminating the screen with light from a Kodak carousel projector attenuated to 3.0 cd/m^2 by neutral-density filters. The intensity of the dots (exclusive of background luminance) was varied between 0.0681 and 0.8168 cd μsec, and the

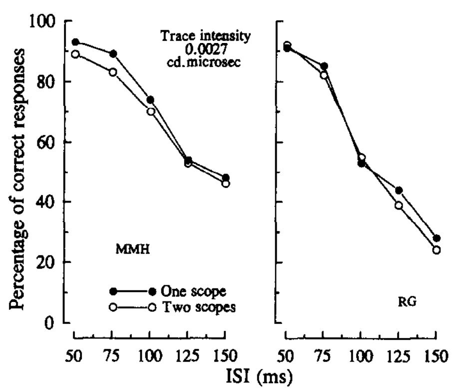

FIGURE 3. Same as Fig. 2, with dimmer stimuli.

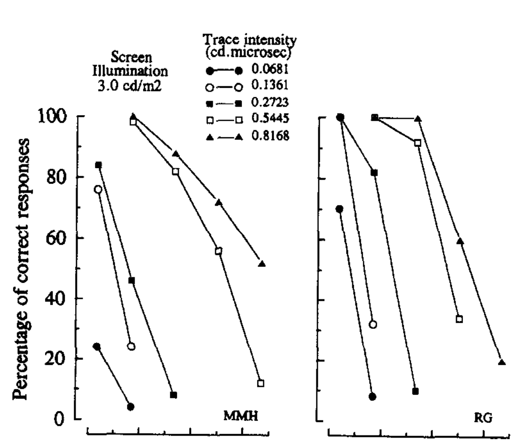

FIGURE 5. Same as Fig. 4, with more intense stimuli and with the screen illuminated with a 3-cd/m^2 veiling light.

duration of the blank period was varied between 10 and 200 msec.

The results are illustrated in Figs 4 and 5, where each point represents the mean of 100 observations. As might be expected, the visibility of phosphor persistence was longer in the dark (Fig. 4). The actual duration of persistence was remarkably long: performance was still quite accurate up to 1000 msec after the stimuli had disappeared from the screen. It should be stressed that, because of the high spatial requirements of the experimental task, these estimates of phosphor persistence must be regarded as conservative. Diffuse luminescence of the display area remained visible over much longer periods. What is even more remarkable, when P15 phosphor was used under these conditions, not even a diffuse luminescence was ever detectable on the screen. This was true even when the duration of the blank interval was reduced to 1 msec and the intensity of the stimuli was increased to a level at which the matrix elements were surrounded by large flares on the display surface. The absence of any phosphorescence was so compelling that, on his first trial with P15 phosphor, one of the observers believed that, through an equipment malfunction, the shutters had remained closed.

Results with a veiling light are shown in Fig. 5. Even with a level of veiling luminance well into the mesopic range, the persistence of P31 phosphor was sufficient to maintain a good level of performance in this spatially demanding task after very long blank periods and at relatively low levels of stimulus intensity. Bearing in mind that veiling lights of rather less than 1 cd/m^2 are often used (e.g. Farrell *et al.*, 1990), the evidence in Fig. 5 is particularly noteworthy.

DISCUSSION

The evidence is unambiguous: P15 phosphor never produced any noticeable persistence even under the most demanding conditions; we conclude that it can be used with confidence in experiments in which absence of phosphor persistence is a crucial requirement. By contrast, P31 phosphor produced persistence of such magnitude as to make it unsuitable for that class of experiments. This conclusion is especially important in view of the widespread use of P31 phosphor for experimental displays. We did not have at our disposal a suitable oscilloscope equipped with P4, another commonly-used phosphor. However, from casual observations of raster-scan monitors equipped with P4 phosphor, we suspect that it may not differ significantly from P31.

Clearly, P15 must be regarded as the phosphor of choice if screen persistence is to be avoided. If other phosphors must be used, it might be desirable to employ an arrangement of appropriately-timed shutters, as used by Irwin (e.g. Irwin *et al.*, 1990) or in the present Expt 1. However, this solution has the obvious drawback that as many separate display channels are required as there are stimuli in the display sequence. At the very least, preliminary trials should be run—perhaps in the manner of the present Expt 2—to check whether phosphor persistence is likely to affect the experimental outcome.

Ubiquity of the confounding effects

It must be stressed that the confounding effects of phosphor persistence are not limited to experiments designed to study temporal integration or visible persistence. For example, it has been shown that the persistence of P31 (but not P15) phosphor can reduce the perceived duration of motion aftereffect by compounding the contours of successively-plotted images during the adaptation phase of the experiment (Di Lollo & Bischof, 1991).

A notable example of confounding due to phosphor persistence can be seen in the present results: it relates to the inverse-intensity effect in visible persistence. Visible persistence denotes the brief period during which an image remains visible after the stimulus has been turned off. The inverse-intensity effect refers to the finding that the duration of visible persistence is related *inversely* to the intensity of the inducing stimulus (Coltheart, 1980). An inverse-intensity effect can be seen in the results of Expt 1 (P15 phosphor) by comparing each observer's performance with bright stimuli (Fig. 2) and with dim stimuli (Fig. 3) at the three longest ISIs, where performance was well below ceiling. In every case, duration of visible persistence (as indexed by the percentage of correct responses) was longer with dim than with bright stimuli, thus revealing an inverse-intensity effect. By contrast, a *direct* intensity effect was obtained in Expt 2 with P31 phosphor. That is, accuracy of performance was related directly to stimulus intensity, as can be checked by noting the level of performance at any suitable ordinate in Figs 4 and 5 (e.g. Fig. 5, ISI = 50 msec). Clearly, the inverse-intensity effect that had been obtained with P15 phosphor was totally masked (indeed, it was reversed) with stimuli displayed on P31 phosphor. It is conceivable that these countervailing tendencies might have been a factor in studies that used P31 phosphor and failed to obtain an inverse-intensity effect (e.g. Farrell *et al.*, 1991).

Potentially misleading technical information

Why has a commonly-used source of technical information on phosphor decay (Bell, 1970) proved inadequate so frequently in psychophysical investigations? We suggest two major reasons.

First, decay of phosphorescence alone is an inadequate predictor of stimulus visibility because it ignores the dynamic changes in sensitivity of the visual system. Unlike a simple photomultiplier, the gain of the visual system changes considerably with adaptation. For example, the sensitivity of a given retinal location is known to increase by over 1 log unit within about 100 msec after a stimulus is turned off, and to continue increasing, albeit less rapidly, for some time thereafter (e.g. Baker, 1963). Therefore, "visibility" curves representing the decay of phosphorescence over a period of time cannot be regarded as valid for a visual system whose sensitivity changes rapidly over the same period. More specifically, stimuli believed to have decayed below visibility threshold on the basis of the photometric data, may be, in fact, still visible because of the system's increased sensitivity.

Second, the measurements were made over a very limited range of temporal intervals (3 μsec for P15, 500 μsec for P31), thus requiring a significant degree of extrapolation to the much longer temporal intervals employed in psychophysical investigations. In this respect, recent evidence by Hase, Kano, Makazawa and Yamamoto (1990) strongly suggests that phosphorescence can be expected to have an effect over much longer temporal intervals than was previously assumed. To wit, the initial decay of phosphorescence is known to follow an exponential course. Were this to remain true for the much longer intervals common in psychophysical studies, the effects on visual performance could be safely ignored. However, although there is no direct evidence on the long-term decay of P15 and P31 phosphors, studies with similar phosphors and related materials show that decay is rarely exponential. In most cases, aside from an initial exponential period, decay of phosphorescence follows the time-power law. Namely, the luminance L of any given point on the screen at time t after the beam has been extinguished is proportional to some power of t, as in equation (1):

$$L(t) \propto t^{-n} \quad (1)$$

which can be explained in terms of electron-trapping effects (Hase *et al.*, 1990; Jonscher & de Polignac, 1984). As a consequence, further decay occurs at a much slower rate (linear on a log–log scale as opposed to linear on a semi-log scale for exponential decay). Taken in conjunction with the dynamic sensitivity changes of the visual system, such prolonged phosphorescence may cause the stimuli to remain visible for much longer periods than would be expected if the decay were exponential. For many materials, the exponent n in equation (1) was found to be in the range $1 < n < 1.5$ (Jonscher & de Polignac, 1984). An analysis of the data in Figs 4 and 5 yielded a value of n of about 1.3 for P31 phosphor, consistent with the decay rate of similar materials. It goes without saying that a similar analysis could not be done with P15 phosphor because its decay was too fast to be estimated psychophysically.

For both these reasons (dynamic changes in sensitivity, and time-power, rather than exponential, long-term decay), the phosphorescence of P31 is likely to affect visual performance over much longer temporal intervals than previously assumed. This, we suggest, is the probable source of the confounding described at the beginning of this article.

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Acknowledgements—This work was supported by Grant No. OGP0006592 (to V. Di Lollo) and by Grant OGP38521 (to W. F. Bischof) from the Natural Sciences and Engineering Research Council of Canada. We thank Gary Finley for technical advice, and Gary Burchett and Lou Omerzu for technical assistance. Margolee Horn and Rob Gordon were docile observers.