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P31 phosphor persistence at photopic mean luminance level

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Abstract—P31 phosphor screens are frequently used for short-term presentation of dot and grating patterns, but experimental data obtained with this technique have been criticized because of possible parasitic effects of phosphor persistence on subjects' visual performance. Recently, this issue provoked a controversial discussion in Vision Research (Groner *et al.*, 1993; Westheimer, 1993, 1994; Irwin, 1994; Di Lollo *et al.*, 1994) which was concerned with persistence effects of P31 screens for dot patterns. Supplementing this discussion, the present work deals with the effects of different types of patterns (dot pattern vs. gratings) and background mean-luminance levels (scotopic vs. phototopic) on phosphor persistence. Physical measurements of P31 persistence occurring with grating patterns of a mean luminance of 20 $cd\,m^{-2}$ (i.e. photopic range) were obtained by using an extremely linear photometer with high temporal resolution. Under this photopic condition, the measurements demonstrate a fast decay of residual grating contrast to 1.4% of its original value within 50 ms after pattern offset. This phosphor behavior must be considered when designing an experiment with a P31 screen though it certainly embodies no problems in many applications.

1. INTRODUCTION

Phosphor persistence of visual displays by definition is the light emission that continues after excitation has ceased. It occurs when any stimulus (e.g. a bright bar) is switched off. Typically, its intensity shows a rapid decay to about 10% of peak luminance followed by a slow convergence to zero (Bell, 1970; Larach and Hardy, 1973; EIA, 1989); both time constants depend on the phosphor type. This dynamic behavior must be considered when stimuli generated by phosphor tubes on a visual display unit (VDU) are changed over time either by switching them on and off or by a periodic temporal modulation such as in flicker experiments (Flynt, 1989). Here we want to emphasize that it is essential to distinguish different persistence behaviors in the two cases, namely (1) when single items are presented as bright stimuli on

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an otherwise dark screen under scotopic viewing conditions, and (2) when the stimuli are superimposed on a steady uniform background of rather high luminance, e.g. 20 cd m^{-2}, maintaining photopic vision. In the former case (e.g. when displaying a dot pattern), the long lasting tail of the decay characteristic of the phosphor has certainly to be taken into account since residual luminance of a switched-off stimulus is presumably detectable until it arrives at almost zero level. In the latter case, which frequently arises in presenting gratings (e.g. Campbell and Robson, 1968), the phosphor elements are excited with every frame, independently of whether a stimulus is present. Therefore, persistence problems are not as likely to occur, given that the frame rate is sufficiently high and the second decay phase with the large time constant can be neglected.

Phosphor persistence became an issue of increased interest in the early eighties, when Jonides *et al.* (1982) withdrew findings providing evidence for saccadic-information transfer, publishing another paper with contradicting results (Jonides *et al.*, 1983). They realized that their initial experimental results were biased by phosphor persistence which itself preserved information from the pre-saccadicly-presented pattern over the period of the saccade, thus 'enhancing' post-saccadic vision. After this experience, a general tendency to call into question experimental results acquired by use of phosphor screens for stimulus presentation arose. Recently, the discussion on phosphor persistence was revived by studies of Groner *et al.* (1993), Westheimer (1993, 1994), Di Lollo *et al.* (1994), and Irwin (1994). While Groner *et al.* (1993) claimed that P31 phosphor persistence lasts several hundred milliseconds under specific experimental conditions, Westheimer stated that residual luminance decays within 2 ms to less than 2%; this is below the visual threshold and, therefore, not visible when superimposed on a dim background illumination by ambient light. Disagreement also exists about the relevance of physical luminance measurements: whereas Westheimer (1993, 1994) concluded from his luminance data that the light residue cannot be detected because it is subthreshold according to commonly known sensitivity curves for human observers, Di Lollo *et al.* (1994) and Irwin (1994) opposed that the physical readings cannot substitute a specific psychophysical visibility test of the persistence (e.g. by use of a shutter).

Finally, there remains a continued mistrust by researchers in experimental work with phosphor screens, especially with P31 tubes. Moreover, several authors have reported effects of phosphor persistence on perception (Eysel and Burandt, 1984; Wilkins, 1985; Harwood and Foley, 1987) and on eye movements (Wilkins, 1986; Neary and Wilkins, 1989). Specifications of persistence for different phosphors (Bell, 1970; EIA, 1989) have been published only for conditions where a single spot on the otherwise dark screen is excited maximally, and then switched off. From these curves, however, no exact prediction of the persistence behavior and, accordingly, of the visibility of luminance residues, can be made for the specific experimental situation as put forward by Groner *et al.* (1993) and Westheimer (1993). In order to fill this gap for grating and bar patterns with photopic mean luminance levels, we performed physical measurements of P31 persistence as it occurs in this specific condition.

2. METHODS

Phosphor persistence was investigated with the X-Y-display which has been used in our previous work (Wolf *et al.*, 1978, 1980): a Hewlett–Packard 1300A with P31 phosphor, static deflection, frame rate switch-selectable between 100 s^{-1} and 1000 s^{-1}, frame size 20 cm wide and 16 cm high. Background luminance L_M was adjusted to 20 cd m^{-2}. For the persistence measurements, a vertical bar of 5 cm width, either bright ($L_B = 30$ cd m^{-2}) or dark ($L_B = 10$ cd m^{-2}), could be displayed on the screen for 200 ms. Hence, the contrast of the bar was $C = 0.5$ according to $C = (\Delta L/L_M)$ with $\Delta L = |L_B - L_M|$. The bandwidth of the z-amplifier was from DC to 20 MHz. A pin photodiode (UDT PIN 10) with a sensitive square area of 1 cm^2 was mounted on the rear of a black tube of 3 cm diameter and 5 cm length. (For test measurements, the sensitive area of the photodiode could be artificially reduced to a vertical slit of 0.5 mm width by a black, nontranslucent film stuck to the screen surface in front of this black tube. This provided a better spatiotemporal resolution of the measuring system at the expense of a slightly reduced signal-to-noise ratio.) The photodiode was used as a current source in conjunction with an operational amplifier OP27, together providing high sensitivity and linear behavior

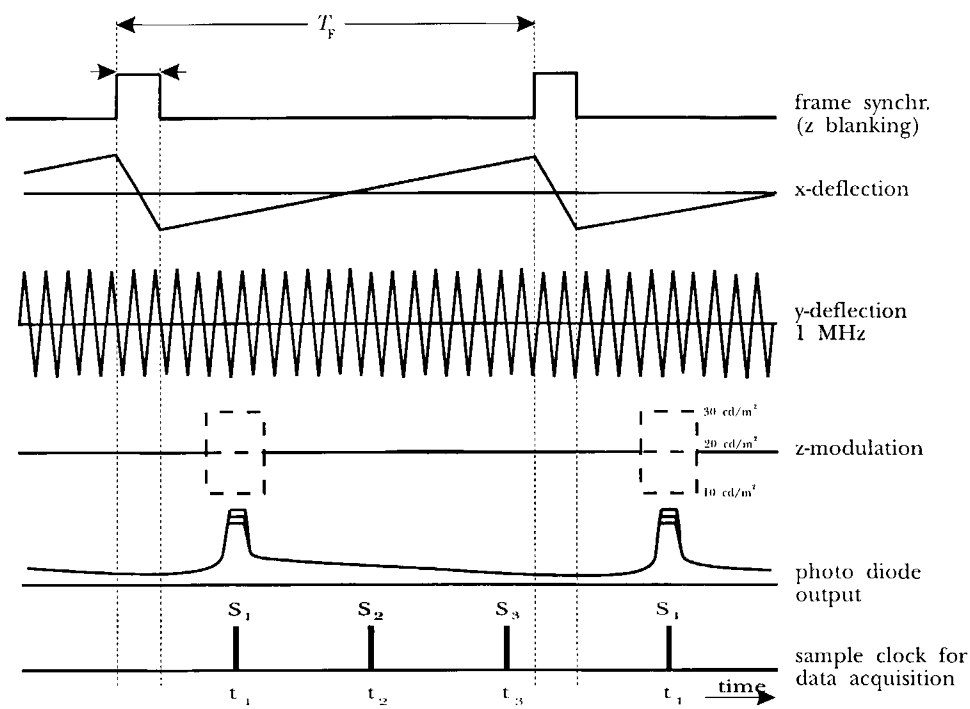

Figure 1. Timing diagram of display control and luminance measurement. The frame frequency is determined by the period T_F of the sawtooth x-deflection signal, and the frame synchronization signal is used for triggering the z-modulation generator and the A-D converter sample clock. The y-deflection follows a triangular waveform of 1 MHz (the real frequency cannot be shown in the diagram). The amplified output signal of the photodiode, which is fixed on the screen over the area of rectangular z-modulation (bar pattern), is sampled at times t_1, t_2 and t_3 of every frame.

(linearity error: $\pm 2\%$ over 6 decades). The tube with the photodiode was fixed directly on the screen over the area where the bar appeared. The purpose of the tube was to provide a certain distance between the screen surface and the photodiode in order to avoid electromagnetic disturbances on the semiconductor layer of the diode caused by the electrons striking the phosphor layer. The spectral sensitivity of the Schottky barrier-type photodiode that was used, used ranges from about 450 nm up to 1000 nm; this matches well the phosphor color centered at 520 nm which is the same for the fluorescent as well as for the phosphorescent emission of P31. The temporal resolution of the photo detector system was determined by measuring the response to a light impulse of 30 $cd\,m^{-2}$, produced by a light-emitting diode with rise and fall time less than 1 μs. The evoked output signal shows a rise and fall time of about 20 μs which is more than the needs of this work.

The luminance of the area covered by the tube was measured three times every frame (t_1, t_2, t_3) as shown in Fig. 1. Since the measurement device was fixed, its output signal sampled at these times roughly gives the time course of the luminance of the selected area within one frame period, while the sequence of the output values sampled at times t_1 of consecutive frames characterizes the persistence that is investigated here. The sample clock sequence (S_1, S_2, S_3) of the A-D Converter was triggered by the frame-synchronization signal. Data acquisition was done by a PC system running the 'Turbolab' software from Stemmer Inc. in combination with the A-D Converter DT2128F from Data Translation Inc.

3. RESULTS

Figure 2 shows the temporal luminance profile of the P31 phosphor for two different frame rates but the same mean luminance $L_M = 20\ cd\,m^{-2}$ (upper trace: $T_F = 1$ ms, i.e. frame rate 1000 s^{-1}; lower trace: $T_F = 10$ ms, i.e. frame rate 100 s^{-1}). The responses shown can be characterized by a sharp impulse followed by a long tail converging against zero. The perceived luminance is determined by the average of this luminance signal within the frame period T_F (Westheimer, 1993), i.e. the temporal integral of this response over T_F (in case of zero z-modulation, this is the mean luminance L_M). Strictly speaking, we have to analyze the decay of this average to determine phosphor persistence. But since the main light energy is concentrated in the sharp peak, which becomes obvious when comparing the upper trace captured at $T_F = 1$ ms (frame rate 1000 s^{-1}, $L_M = 20\ cd\,m^{-2}$) and the lower trace for $T_F = 10$ ms (frame rate 100 s^{-1}, $L_M = 20\ cd\,m^{-2}$) of Fig. 2, the peak amplitude of the response at t_1 can be taken as a convenient approximation of the average luminance, which simplifies measurement and computation demands.

Figures 3(a)–(c) show the time course of the z-modulation (upper traces) and of the corresponding luminance peak amplitudes (lower traces). Since only the transient parts of the responses are of interest here, a relative scaling of luminance is used. Figure 3(a), (b) depicts the data for a frame frequency of 1000 s^{-1}, and Fig. 3(c) those for the 100 s^{-1} condition. It can be seen from the luminance trace in Fig. 3(a) that a smooth but fast transient occurs at both the temporal onset and offset of the

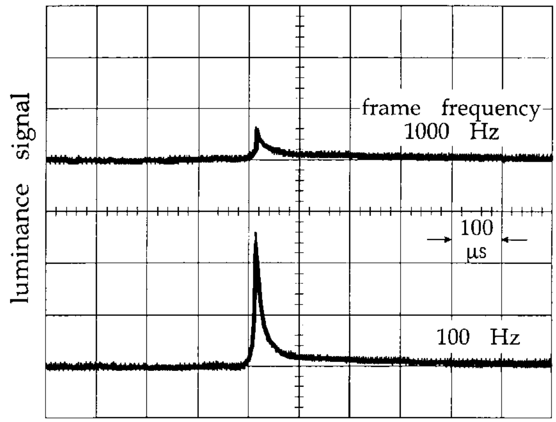

Figure 2. Oscillogram of the local phosphor luminance for two frame frequencies (upper trace 1000 s^{-1}, lower trace 100 s^{-1}) without any z-modulation. In both cases, mean luminance of the screen was 20 $cd\,m^{-2}$, and x-deflection of the scope was 100 μs/div. The peak luminance is considerably higher with the lower frame frequency. The effective luminance is determined by the integral of the luminance signal over one frame period, but the peak amplitude of the response can be taken as a convenient approximation for this, simplifying the measurements. (Notes: (1) The upper trace comprises the total frame period of 1 ms, whereas the lower trace shows only 1/10 of the frame period of 10 ms. (2) For these measurements, the sensitive area of the photodiode in x-direction was reduced to a width of 0.5 mm, as described in the Section 2. (3) The onset of the luminance signal shows the maximum slope of the measurement system; thus optical radiation onset may be faster.)

bright bar. The offset behavior is magnified in Fig. 4, showing that within 50 ms the residue of the bar luminance decays to 1.4 percent of its original value which is equivalent to an absolute contrast of $C_r = 0.0035$.

Figure 3(b) shows the time course of luminance but now for the case of switching off the *dark bar* modulation, i.e. the behavior of a dark modulated screen area returning to mean luminance. When Figs 3(a) and 3(b) are compared, it becomes obvious that the decay characteristic for both the bright- and dark-bar modulation are very similar. Detailed analysis reveals a slightly faster transient from high luminance values to the mean level than from low luminance values to mean level, but this small difference can be neglected for the purposes of this study. We will use the term 'phosphor persistence' to characterize this onset and offset behavior of the luminance, but it should be noted that this is not completely compatible with the definition of 'phosphor persistence' given by the first sentence of the Introduction; excitation will certainly cease after the impulse-like driving of the local phosphor particles but is repeated during every frame. Maybe, the term 'phosphor inertia' should therefore be introduced.

Figure 3(c) again shows the luminance for bright bar modulation as in Fig. 3(a) but now for the lower frame frequency of 100 s^{-1}. Here, the return to mean level occurs faster than for the higher frame rate of 1000 s^{-1}, and luminance already reaches the mean level after 20 ms (or 2 frames). Note that the sampling raster (once every frame) is now 10 ms instead of 1 ms as before. The faster decay is plausible since the relaxation process of the phosphor particles, which is restarted every frame, can proceed further in this case owing to the longer frame period.

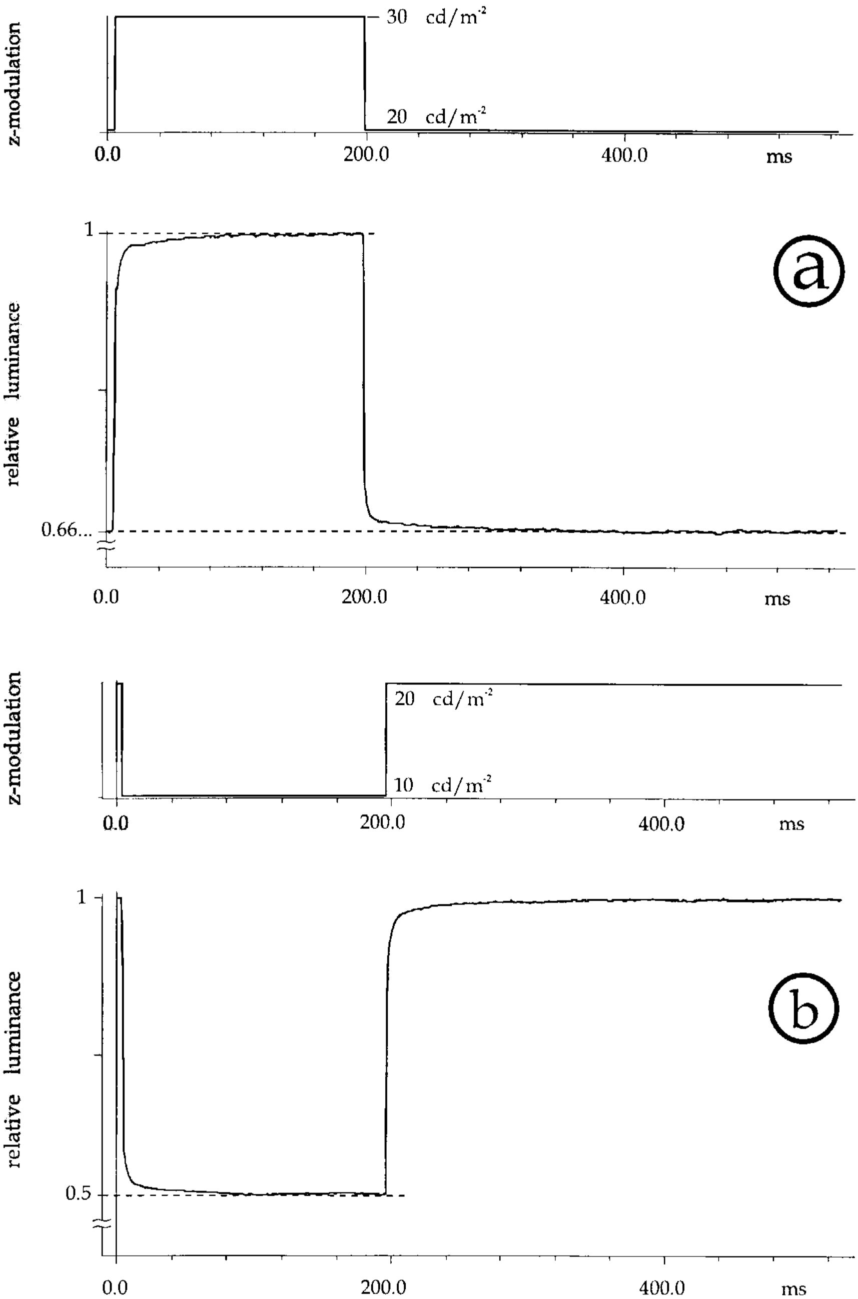

Figure 3. Time course of peak luminance with bar modulation as indicated in the upper traces. The lower traces show the amplitudes of the S_1 samples (see Fig. 1) in arbitrary units (normalized to bar luminance of 30 cd m^{-2}) as a function of time, demonstrating an exponential transient at the beginning and the end of bar modulation. Data are obtained by averaging recordings from 50 sweeps in order to reduce noise components: (a) bright bar, frame frequency 1000 s^{-1}; (b) dark bar, frame frequency 1000 s^{-1}; (c) bright bar, frame frequency 100 s^{-1}.

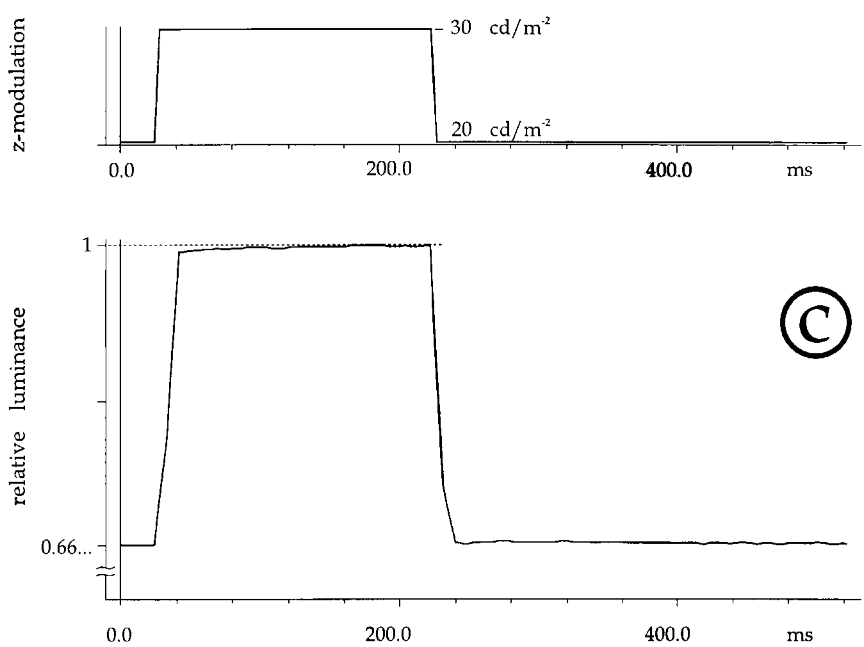

Figure 3 (Continued).

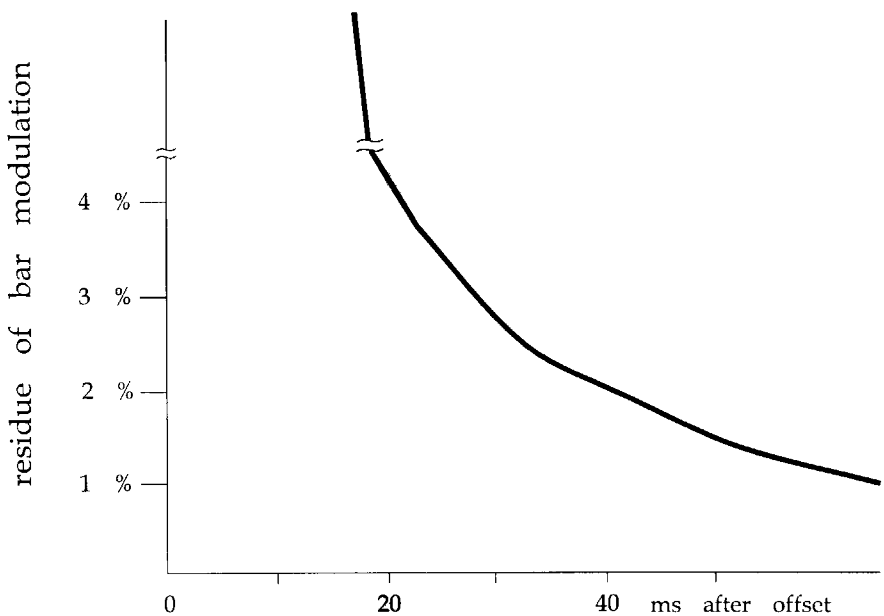

Figure 4. Time course of residual bar luminance after bar offset redrawn from Fig. 5. The diagram illustrates the fast decay within a few milliseconds followed by a slow convergence against zero (i.e. mean luminance level). Note that at 50 ms after modulation offset a residue of only 1.4% of the bar modulation is left.

4. DISCUSSION

Phosphor screens for stimulus presentation are an important tool for research in visual psychophysics, yielding the possibility of fast and exact pattern switching at reasonable expense. As already noted by Westheimer (1993), displays with P31 screens are still intensively used in vision laboratories. The physical measurements of the phosphor persistence reported here for grating stimuli supplement the data for dot patterns (Westheimer, 1993). Our data demonstrate, for the specific case of grating patterns at photopic luminance level, that the residual contrast after pattern offset amounts to less than 5% of its original value after 10 ms, less than 2.5% after 30 ms, and less than 1.4% of its original value after 50 ms. In absolute terms, this is equivalent to contrast residues of 0.01, 0.005 and 0.0028, respectively, for a grating presented with a contrast of $C = 0.2$. In many experimental conditions, such a small effect of P31 phosphor persistence should not constrain the application of this display technique in vision research.

The use of ambient light to obtain a specific background luminance as discussed by Groner *et al.* (1993) and Westheimer (1993) is quite different from the method described in this work for grating generation; since ambient light and luminance arising from phosphor persistence simply sum, phosphor persistence may still affect the experimental data. (Notice that the phosphor of a screen can be also excited by ambient light, but usually the ambient level is low and in most cases constant; thus no transient component can arise from it. This effect needs no further consideration within the scope of this paper.) On the other hand, taking advantage of periodic excitation to produce the mean background luminance as described here still has to be done with care when gratings with very low scotopic luminance levels are used. Owing to the low excitation of phosphor elements under this condition, the persistence is now dominated by the slow part of the decay characteristic rather than by the fast decay phase (as for photopic levels). A possible solution in this case is to put a neutral density filter (e.g. with 1% transmittance) in front of the screen and to increase the luminance of the pattern to compensate, so that the operational range of the phosphor is shifted to the fast decay region (Bridgeman and Mayer, 1983).

Another aspect of our findings concerns the smooth rise of modulation which reduces effective modulation with extremely short exposure durations of 10 ms or less, sometimes used in psychophysical measurements (e.g. Arend, 1976; Ejima and Ohtani, 1987). Our findings indicate that the thresholds reported in such investigations may be overestimated by about 5% owing to the phosphor behavior. Also, this behavior reduces the contrast of flickering patterns with increasing flicker rate, as already reported by Flynt (1989).

According to Groner *et al.* (1993) and Irwin (1994), technical literature (e.g. EIA, 1989) reports a decay to 10% within 38 μs and to 1% within 250 μs for the P31 phosphor. But these values are obtained for measurement conditions related to the commercial use of those displays. In psychophysical experiments, however, displays with static deflection (like the HP1300A) are often operated at their upper luminance limit. This is because a large stimulus size is required in order to overcome the spatial resolution limit given by phosphor dot size, and to avoid masking problems by border effects; further, a high frame rate is needed to achieve high temporal resolution and a moderate mean luminance to maintain photopic vision—all these factors promote and influence phosphor persistence problems individually. Therefore, it is not surprising that our persistence data, with a decay to 2.5% within 30 ms when doing flat-spread screen excitation for grating generation, differ severely from those of Westheimer (1993) who reported a decay to 2% after 2 ms measured in a single-light-spot situation. Moreover, Flynt (1989) showed that the persistence strongly depends on the duration of excitation which also varies between the different techniques of pattern generation. These observations demonstrate that the technical P31 specifications provide only a rough characterization of phosphor behavior (Groner *et al.*, 1993). Another aspect is that the specification of the phosphor type provides typical information only; the variation of parameters between different CRT samples shows some tolerance especially when they are made by different manufactures. (It is beyond the scope of this paper to investigate these tolerances of P31 and other phosphors.) Consequently, as proposed by Groner *et al.* (1993), persistence must be verified for every specific experimental setup and situation.

Taken together, two basic approaches can be used to determine the effects of phosphor persistence in specific psychophysical investigation. The first approach consists in a subjective test by a visual detection task (Sun and Irwin, 1987; Groner *et al.*, 1993) using a shutter in front of the display that only opens after a specific delay (e.g. 2 ms) to pattern offset. In one half of the trials, patterns are displayed (group I) and in the other half they are not (group II). Subjects have to indicate detection of (a residual trace of) the pattern; if responses are arbitrary with respect to group I and II, the visual residue of the pattern due to persistence can be assumed to be subthreshold. Psychophysical tests of this kind were performed with a P31 screen by Sun and Irwin (1987), who reported that, in their paradigm, no residue of the pattern can be visually detected 2 ms after pattern offset. The second possibility is to measure the persisting luminance objectively with a high-performance photometer and to compare this value with the known threshold value of the visual system (e.g. Westheimer, 1993). Of course, this threshold value and its expected inter-individual and intra-individual variance must be known for the used stimulus situation. Thus, this approach provides quantitative information about the visibility of the residue including subthreshold levels.

The question arises as to the pros and cons of both approaches just described, and arrived at in the literature. Using the subjective method, no information is obtained on whether the pattern residue is just at or far below threshold, and one must be aware that even subthreshold components can influence visual performance (this has been utilized in subthreshold summation techniques, e.g. Kulikowski and King-Smith, 1972; Hauske, 1981). Further, increasing the pattern luminance for the test to ensure the residue being subthreshold (Sun and Irwin, 1987) is only a qualitative approach, since changing the stimulus parameter again results in a different persistence behavior of the phosphor as mentioned previously. Further problems arise with the hardware required to perform this psychophysical visibility test of phosphor persistence when using sinewave gratings at photopic vision, since an arrangement with two displays (as shown in Fig. 1 of Groner *et al.*, 1993) must be used to provide a continuous mean-luminance background. (Ambient light is not appropriate because an additive grating produced by the phosphor changes overall mean luminance.) Finally, the shutters in front of the screens must be adjusted precisely to avoid sharp transients in luminance when switching the observer's view from one screen to the other. Fast and accurate shutters are expensive, and require time-consuming adjustment. The physical measurement of phosphor persistence (in the specific experimental situation) as proposed by Westheimer (1993) and done in this paper can, however, be performed with standard laboratory equipment and, therefore, offers another possibility of dealing with the problem of phosphor persistence.

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