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COMMENTS

Information-Acquisition Rate, Short-Term Memory, and Cognitive Equivalence: Reply to Sperling

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The effect of stimulus luminance on visual information acquisition depends on the duration for which the stimulus is displayed. In this reply, three duration regions are described, and the accounts of luminance effects provided by Loftus (1985d) and Sperling (1986) are compared for each region. Of particular interest is why different combinations of duration and luminance produce equal performance levels. Two possibilities are considered: first, equal performance may be a logical consequence of equivalent cognitive states and second, equal performance may be a coincidental consequence of different cognitive states. I suggest that equal performance following relatively short durations results from equivalent cognitive states, whereas equal performance following longer durations results from different cognitive states.

Notation and Overview

The time course of visual information acquisition may be represented by a *performance curve* that shows memory performance for some visual stimulus as a function of the duration for which the stimulus had been exposed. Figure 1, an idealized representation of the Loftus (1985d) data, shows performance curves for low-luminance and high-luminance (hereinafter, dim and bright) pictures.

Sperling (1986) and I both wish to explain the effect of luminance on visual information acquisition under different circumstances. Directly relevant to our explanations is the confirmation or failure of *horizontal parallelism* of dim and bright performance curves (cf. Loftus, 1985d p. 346). As indicated in Figure 1, parallelism is confirmed in short-duration (low-performance) regions, but fails in long-duration (high-performance) regions.

Characterization of Regions

At a purely notational level, different performance curve regions can be characterized in terms of either performance regions or duration regions. I have chosen to characterize regions in terms of duration, because duration units, in contrast to performance units, are independent of the particular dependent variable that is reported.

The data-analysis technique used by Loftus (1985d) involved determining how much exposure duration was necessary to achieve a given performance level under different luminance levels (see Loftus, 1985a, 1985b, 1985c; Loftus, Johnson, & Shimamura, 1985; Loftus, Truax, & Nelson, in press, for similar techniques). For any given performance level, there are two relevant durations: bright-picture duration and dim-picture duration. For ease of discourse, the term *duration* will, unless otherwise specified, refer (arbitrarily) to bright-picture duration.

As Figure 1 shows, there are three duration regions, each of which produces a different joint duration/luminance effect on performance. In the *short-duration* region, dim-picture performance equals bright-picture performance when dim-picture duration exceeds bright-picture duration by some ratio (2.00 in this example) that is constant over duration. In the *intermediate-duration* region, the ratio of dim-picture duration to bright-picture duration that produces equal performance is not constant, but increases over duration. In the *long-duration* region, dim-picture performance is asymptotic; thus dim- and bright-picture performance cannot be equal at all.

Sperling (1986) suggests a model to explain these phenomena. In this reply, I summarize the similarities and differences between Sperling's and my views and then discuss the effects produced in the different duration regions within a somewhat broader context.

Relation Between the Two Views

Short-Duration Stimuli: Confirmation of Horizontal Parallelism

In the short-duration region, there is a multiplicative tradeoff between picture duration and picture luminance: The deleterious effect of lowering luminance is compensated for if and only if duration is multiplied by some constant factor, k (which ranged, across experiments, from 1.4 to 2.0 to compensate for a 99% luminance reduction). It is this tradeoff that produces the horizontally parallel performance curves shown in Figure 1 (note that because duration is on a log axis, equal ratios imply equal horizontal distances).

Loftus (1985d) noted that a luminance/duration tradeoff of this sort is consistent with a simple general model: the same task-relevant information is acquired from dim and bright pic-

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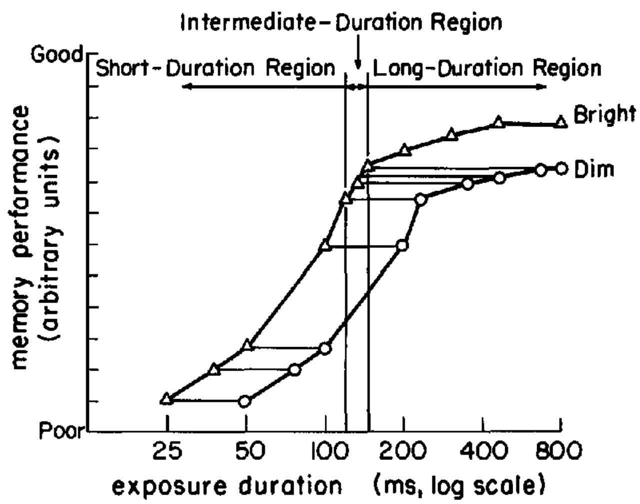

Figure 1. Generic data from Loftus (1985d): Memory performance as functions of duration for dim and bright pictures. Horizontal lines between the curves connect short bright conditions with longer dim conditions that produce equal performance.

tures, via the same perceptual processes, but at a rate that is lower by a factor of k (the same k as in the preceeding paragraph) for the dim pictures. Sperling (1986) provides a specific version of this model in which task-relevant features (signal) from the picture compete with task-irrelevant features (noise) for transmission space on a limited-capacity serial channel. Lowering picture luminance is, in Sperling's model, assumed to increase the amount of noise; hence with dim pictures, the same signal is transmitted, but at a slower rate. Thus, with respect to the short-duration region, Sperling (1986) and Loftus (1985d) are in agreement; Sperling's explanation is simply more specific than mine.

Intermediate- and Long-Duration Stimuli: Failure of Horizontal Parallelism

In the intermediate- and long-duration regions, Loftus (1985d) found that the ratio of dim-picture duration to bright-picture duration that produced equal dim- and bright-picture performance increased with duration, eventually reaching infinity. Loftus suggested (and presented indirect evidence for the idea) that this breakdown of a strict multiplicative tradeoff is attributable to a change in the eye-fixation pattern in dim relative to bright pictures. Within Sperling's (1986) model, the breakdown is attributable to a difference in the signal capacity of short-term memory for dim relative to bright pictures. These two explanations, although different, are not mutually exclusive.

On the Possible Bases of Equal Performance for Dim and Bright Pictures

As noted earlier, Loftus (1985d) was concerned with the rules governing when short-duration bright pictures and longer duration dim pictures lead to equal performance. Such equal-performance condition pairs are connected with horizontal lines in Figure 1. Note that, by definition, equality of dim-picture and bright-picture performance is achieved only in the short- and intermediate-duration regions. How is such equality to be explained?

Cognitive Equivalence

In general, two different combinations of variables (e.g., two different combinations of duration and luminance) can produce equal performance for one of two reasons. First, the two combinations may produce equivalent states of whatever part of the cognitive system determines task performance (a situation hereinafter called *cognitive equivalence.*) Second, the two combinations may produce cognitive states that are qualitatively different, but coincidentally produce equal performance.

A demonstration of cognitive equivalence suggests, and sometimes even implies, a mechanism by which the cognitive system reduces the large number of informational structures presented by the physical world into a smaller number of informational structures represented in memory.[1] Thus, it is important to determine whether performance equality in a given situation is or is not attributable to cognitive equivalence. There are various ways of making such a determination (see Bamber, 1979, and Palmer, 1984, for excellent discussions of the issue). In what follows, I suggest one such way.

Simple Laws Suggest Cognitive Equivalence: Complex Laws Do Not

In some circumstances, a simple law can be found that relates the durations required for equal performance under different levels of some independent variable. The Loftus (1985d) short-duration data could be described by the simple function,

$$PH(t) = PL(kt), \quad (1)$$

where PH (x) and PL (x) are performance for bright and dim pictures displayed for a duration of x, and k is a finite constant, $k > 1.0$. Such a finding suggests that equal performance is a consequence of cognitive equivalence, because such a regular pattern of results would have a very low a priori probability of being a consequence of a set of qualitatively different cognitive states. In Sperling's (1986) model, task performance is determined by amount of signal stored in short-term memory. In the short-duration region, according to the model, certain combinations of short, bright stimuli and longer, dim stimuli produce the same amount of signal in short-term memory, as will be illustrated in detail later.

In other circumstances, no simple law can be found relating the durations required for equal performance under two levels

[1] A classic example of equivalence is found in the study of color vision wherein two entirely different physical stimuli (e.g., a monochromatic yellow light on the one hand and a mixture of red and green lights on the other hand) appear to be identical. The reason for this equivalence is well understood: the two different physical stimuli produce equal quantum catch distributions in the three cone classes; thus equivalent effects of the two stimuli must occur at all stages of the cognitive system beyond the level of the photoreceptors.

of a focal variable. The Loftus (1985d) intermediate-duration data could only be described by the not-so-simple function,

$$PH(t) = PL\{[k + m(t)]t\} \quad (2)$$

where PH, PL and k are as in Equation 1, and m is a monotonic function with a range from 0 to infinity. Such a finding mitigates against cognitive equivalence; it suggests that equal performance is a coincidental consequence of different cognitive states.

Performance Equality without Cognitive Equivalence: Qualitative Differences

Loftus's (1985d) explanation for the intermediate-duration data includes the assumption that equal dim-picture and bright-picture performance stems from qualitatively different cognitive states. The different eye-fixation patterns suggested by Loftus imply that different areas of a picture are encoded for dim and bright versions of a picture, and the memory representations for intermediate- and long-duration dim and bright pictures are therefore qualitatively different.

Sperling's (1986) model is not explicit about how dim-picture performance could ever equal bright-picture performance in the intermediate-duration region. To explain the intermediate-duration data, however, the model must incorporate the idea that individual information-acquisition rates vary in some way—for example, over pictures, subjects, or trials. Figure 2 provides one very simplified illustration of Sperling's model that accounts for equal dim and bright picture performance at intermediate durations. This model includes the assumption that individual pictures vary in the rates at which information can be extracted from them. The four solid curves show number of features in short-term memory as a function of time since

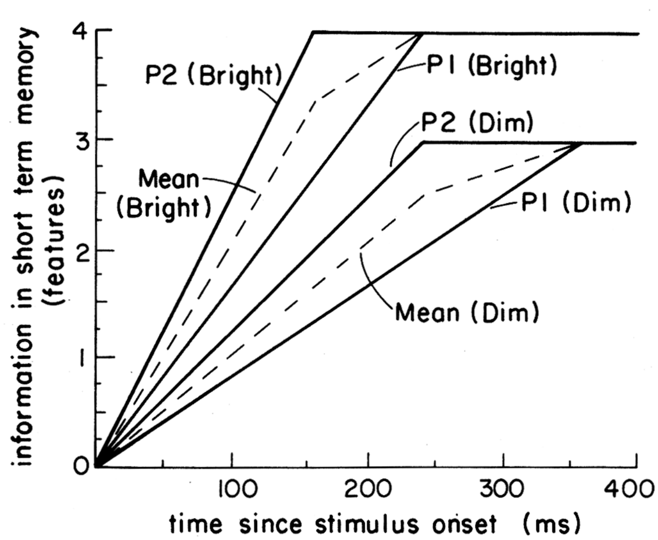

Figure 2. A very simplified version of Sperling's model. Solid lines represent features acquired in short-term memory as functions of time since stimulus onset for two pictures (P1 and P2) in two luminance conditions (dim and bright). Dashed lines represent mean features for each luminance condition.

Table 1
Durations (in Milliseconds) Necessary to Achieve Varying Numbers of Features in Short-Term Memory for Bright and Dim Pictures

Features in short-term memory	Bright pictures	Dim pictures	Ratio
0.5	24.0	48.0	2.00
1.0	48.0	96.0	2.00
1.5	72.0	144.0	2.00
2.0	96.0	192.0	2.00
2.5	120.0	240.0	2.00
2.6	124.8	264.0	2.12
2.7	129.6	288.0	2.22
2.8	134.4	312.0	2.32
2.9	139.2	336.0	2.41
3.0	144.0	360.0	2.50
3.5	180.0	U	U
4.0	240.0	U	U

Note. U = undefined. The right-hand column shows the ratio of dim to bright duration for each feature level.

stimulus onset for two pictures, P1 (from which information is acquired relatively slowly) and P2 (from which information is acquired relatively quickly). The upper two curves represent the two pictures in the bright condition and the lower two curves represent the two pictures in the dim condition. As per Sperling's model, the dim and bright curves differ in two ways. First, the feature-acquisition rate (represented by the slope of a given curve) is lower (by a factor of 2.00 for both P1 and P2) in the dim relative to the bright condition. Second, the capacity of short-term memory (represented by the curve asymptotes) is lower (by 1.00 feature) in the dim relative to the bright condition. The two dashed lines show mean (over P1 and P2) acquired features for the two luminance conditions. (For simplicity, I also assume that performance is linearly related to number of features in short-term memory. This assumption is not central to the major point.)

Table 1 shows the durations required to reach increasing levels of mean features for both luminance conditions, along with the ratio of dim to bright durations. These predicted data are in accord with the data shown in Figure 1. At short durations (0–120 ms), this ratio is constant at 2.00, reflecting the feature acquisition rate ratio in the bright relative to the dim condition. At intermediate durations (120–144 ms), the ratio increases from 2.00 to 2.50. At a long duration infinitesimally greater than 144 ms, the ratio is infinity, and at long durations beyond that, the ratio is undefined because there is no dim-picture performance that is equal to bright-picture performance. Returning to the issue of cognitive equivalence (or lack of it), note that, at short durations, equal dim and bright performance levels are based on identical states. For instance, a mean of 2.0 features stems from 1.6 P1 features and 2.4 P2 features in both bright and dim conditions. However, at intermediate durations, equal dim and bright performance levels are based on different states. For instance, a mean of 3.0 features stems from 2.6 P1 features and 3.4 P2 features in the bright condition, but 3.0 features from both P1 and P2 in the dim condition.

Conclusions

It is likely that equal dim and bright picture performance for short-duration stimuli in the Loftus (1985d) experiments results from cognitive equivalence; and, indeed, cognitive equivalence is assumed at these durations in both the general explanation proposed by Loftus and in the more specific explanation proposed by Sperling. It is unlikely that equal dim- and bright-picture performance for intermediate-duration stimuli results from cognitive equivalence; and indeed, qualitative differences in dim and bright equal-performance conditions are assumed both by Loftus and by Sperling. By definition, no equivalence of any sort applies to the long-duration data.

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