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COMMENTS

A Signal-to-Noise Theory of the Effects of Luminance on Picture Memory: Comment on Loftus

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In studies of picture memory, subjects typically view a sequence of pictures. Their memory is tested either after each picture is presented (short-term recall) or at the end of the sequence (long-term recall). The increase in performance as a function of picture viewing time defines "the rate of information acquisition." Loftus (1985) found that reducing the luminance of a picture reduces the rate at which information is acquired (for both short-term and long-term tests) and, for long viewing times, reduces the total amount of recall. The theory proposed here assumes that both of these effects are consequences of intrinsic noise in the visual system that becomes relatively more prominent as signal (picture luminance or contrast) is reduced. Noise shares a limited capacity channel with signal, and thus noise reduces the rate of information acquisition; noise, as well as signal, occupies space in memory, and thus noise reduces recall performance.

Memory for pictures is conveniently studied in two ways: Long-term recall is measured by a *recognition* test in which previously viewed pictures are interspersed with new pictures and the subject must say "old" or "new" to each picture presentation. Short-term recall is measured by the number of picture details the subject can report immediately following picture presentation. Loftus (1985) used both procedures to measure picture memory as a function of two variables: the viewing time (exposure duration, D) of a picture before onset of a noise postexposure masking field and the luminance of the picture (bright or dim). For performance with short exposure durations ($D < 200$ ms), he found that a reduction in luminance could be perfectly compensated by a proportional increase in D but, for long exposure durations, short- and long-term performance suffered where pictures were too dim.

That reducing picture luminance ultimately impairs recall and recognition is obvious, but it is noteworthy that serious memory losses occur even when the visibility (in extended views) of picture details is not seriously impaired. That performance for briefly exposed low luminance pictures is precisely compensated by a proportional increase α in exposure duration (where α depends on luminance but not on exposure duration) is remarkable. Here, a signal-to-noise (S/N) theory is proposed to derive both effects from the same basic mechanism.

The S/N theory is a computational mechanism for calculating the effects of visual noise on visual memory derived from processing functions that typically are assumed for the visual system. The S/N theory is illustrated in Figure 1. Let $s(x, y, t)$ be the stimulus input as a function of time. (Whatever is presented to the visual system is called input.) Some of the input may be signal, and some may be noise. In Loftus's experiments, the input was entirely signal although, at very low luminances, quantum noise in the stimulus would become significant. Input occurs in parallel at all locations x, y in space. The input $s(x, y, t)$ is transduced by a sensory transducer that has two critical aspects for the present purposes. The first is that it adds independent random noise $n(x, y, t)$ to the input $s(x, y, t)$. The second is that the output of the sensory transducer represents pictorial features or informational elements in the picture. Whereas it is not necessary to spell out all this sensory processing in detail for the kind of predictions that are derived here, it is important to keep in mind that ultimately memory limitations are best expressed in terms of features or other informational units, not in terms of x, y, t intensity distributions.

Let the noisy output of the transducer be y_1. Signal and noise must be kept separate in subsequent computations, and we will be concerned only with the total amount of signal and noise over the whole picture area. Therefore, it is convenient to regard $y_1(t) = [S(t), N(t)]$ as a two-component, time-varying vector with S and N as orthogonal vector components representing total number of features determined, respectively, by signal and by noise at time t.

It is useful to consider the parallel case of external physical noise added directly to the stimulus with respect to any theory about internal noise. Adding external noise to the stimulus means directly superimposing a noise field on the stimulus. When the value of external noise is large compared to internal noise (which it is at moderate-to-high picture luminances and contrasts), then the signal and noise quantities of the theory become directly observable quantities.

Let $S(t)$ and $N(t)$ be the root mean square (RMS) values of input stimulus and input noise. In the case either of external or

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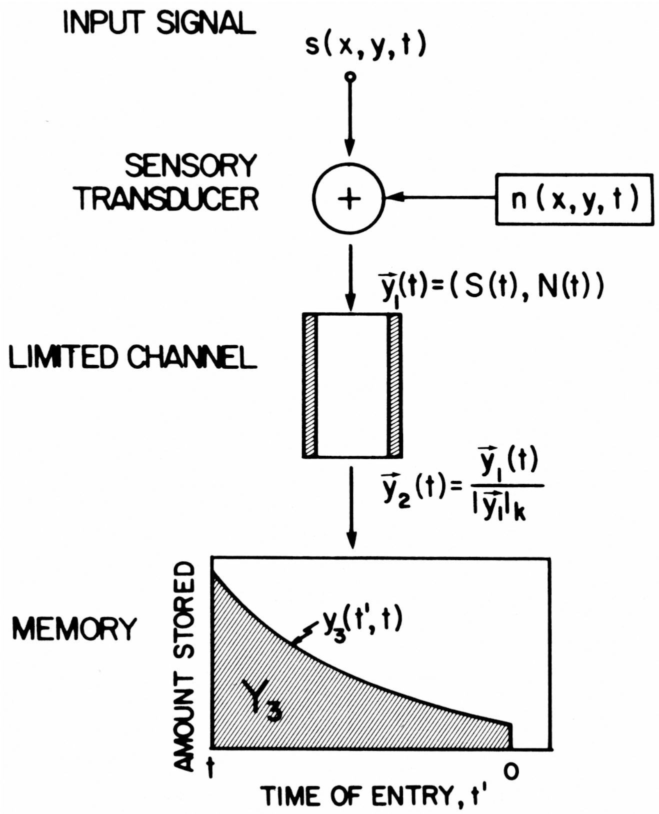

Figure 1. Flow chart for the signal-to-noise theory of visual memory. (The input signal $s[x, y, t]$ and internal noise $n[x, y, t]$ combine in the sensory transducer [+] and pass through a limited-capacity channel to visual memory. The vector quantity y_1 represents the magnitudes of signal and of noise; y_2 represents the normalized output of the limited-capacity channel; $y_3[t', t]$ indicates the amount of memory at time t for information that entered memory during a brief interval $[t', t' + \Delta t']$, $t' \geq 0$; and the shaded area Y_3 represents the cumulative content of memory. See text for details.)

internal noise, regarding $S(t)$ and $N(t)$ as the real and imaginary components of a complex number offers a convenient mechanism for keeping track of S and N in their passage through the processing system. However, complex arithmetic is not essential for any part of the theory. And, in the case of either external or internal noise, noise is assumed to have the same dimensional units as the input; it represents random added features or pictorial elements that are unrelated to the desired performance.

At very high levels of noise relative to signal, the noise features perturb the estimated values of the signal features to such an extent that some signal information is lost and not recoverable. The present S/N theory is concerned with relatively lower levels of noise that leave the original signal completely recoverable, although the recovery takes more time. Specifically, noise interferes with performance by occupying space in a limited-capacity channel and by occupying space in a limited-capacity memory.

Figure 1 illustrates the sensory input s, the transduced input $s + n$, the limited capacity channel, and its output, which is cumulated in a short-term sensory memory. The channel/memory system has two significant properties: (a) the limited-capacity channel cannot process input at more than a fixed, maximum rate; (b) short-term memory cumulates its input imperfectly (leaky integration) as it reaches its limited memory capacity, C. So formulated, the theory can account qualitatively for the effects of luminance on picture memory. For greater specificity, a particular functional form of the theory is offered, but its quantitative predictions are not formally tested.

Limited Capacity

The limited-capacity channel is represented by a normalization process, such as Grossberg (1983) proposes for memory systems. The normalization is not perfect; when there is no stimulus input, the channel produces fractionally less (by $1/k$, $k \geq 1$) than its maximum output. Specifically, the restricted memory channel's input is $\mathbf{y}_1(t)$; its output $\mathbf{y}_2(t)$, like its input, is a two-dimensional vector,

$$\mathbf{y}_2(S(t), N(t)) = \left(\frac{S(t)}{[S(t)^2 + k^2N(t)^2]^{1/2}}, \frac{N(t)}{[S(t)^2 + k^2N(t)^2]^{1/2}}\right), \quad (1)$$

of magnitude (RMS power),

$$|\mathbf{y}_2[S(t), N(t)]| = = \left(\frac{S(t)^2 + N(t)^2}{S(t)^2 + k^2N(t)^2}\right)^{1/2}.$$

The effect of channel capacity is to restrict channel ouputs to a maximum RMS power of 1, which is approached when S/N is large. As luminance decreases, s diminishes but internal noise N does not, so that the S/N ratio of $\mathbf{y}_2(t)$ decreases. For vanishingly small values of S/N the channel output is essentially pure noise of RMS power $1/k$, $k \geq 1$. The constant k is introduced to admit the possibility of increasing total output $\mathbf{y}_2[S(t), N(t)]$ as a function increasing signal level. (For the special case of $k = 1$, the RMS power of $\mathbf{y}_2(t)$ does not vary.)

Leaky Short-Term Memory

It is assumed that the short-term memory $\mathbf{y}_3(t, t_o)$ at time t for an event that occurred at time t_o is reduced by retroactive interference. Retroactive interference at time t for an event that occurred at time t_O is assumed to be an increasing function of the signal plus noise that arrived in the interval $[t_o, t]$ that is, $Y_2(t_o, t) = \int_{t_o}^{t} |\mathbf{y}_2(t)|dt$. For specificity, this retroactive interference is formulated as an exponential decay, so that the amount of memory $\mathbf{y}_3$ at time t for events that occurred during the interval $[t_o, t_o + \Delta t]$, where Δt is small, is

$$\mathbf{y}_3(t_o, t)\Delta t \approx [e^{-Y_2(t_o,t)/C}S(t_o), e^{-Y_2(t_o,t)/C}N(t_o)]\Delta t. \quad (2)$$

For $k \approx 1$, the magnitude of $\mathbf{y}_2$ is approximately constant so Equation 2 becomes

$$\mathbf{y}_3(t_o, t)\Delta t \approx e^{-(t-t_o)/C}\Delta t[S(t_o), N(t_o)]. \quad (3)$$

Short-term memory $\mathbf{y}_3(t_o, t)\Delta t$ for both the signal and noise components $[S(t_o), N(t_o)]$ is proportional to the learning time Δt, for small Δt, and decays exponentially with the retention interval $(t - t_o)$.

Limited Short-Term Memory Capacity, C

The memory capacity C is defined by Equation 2, above. The larger C, the more of the S and N components of y_3 is retained in memory. The total amount of y_3 ultimately stored in long-term memory is assumed to be monotonically related to the amount in short-term memory, but no assumption is made about the specific form of this relationship.

Retroactive Interference Versus Time Decay

Under the conditions of Loftus's experiments, it is assumed that signals and noise start at time 0, and that observed performance at time t depends monotonically on the cumulated amount of signal stored in memory, the real component of Y_3,

$$\mathrm{Re}[Y_3(0, t)] = \int_0^t \mathrm{Re}y_3(0, t')dt'$$

$$= \int_0^t e^{-Y_2(0,t')/C} S(t')dt'. \quad (4)$$

For $k \approx 1$, $Y_2(0, t')$ in Equation 4 is replaced simply by t'. Internal noise affects memory by occupying memory space (Y_2 includes both signal and noise) that otherwise might have been occupied by signal.

There are several assumptions that are implicit in this exposition. For example, the amount of interference that is caused by the flow of time as opposed to that which is produced by new stimuli is determined by the parameter k. When $k \gg 1$, and $S \gg kN$, only new stimuli matter. This occurs because $Y_2 \approx 0$ when $S = 0$ (no stimuli being presented). Only when new stimuli are being presented ($S \gg kN$), is there an accumulation of Y_2 to diminish memory for earlier stimuli (Equation 2). When $k = 1$, the flow of input Y_2 to memory is independent of S/N; that is, is constant in time, representing purely temporal decay. In other words, when $k = 1$, the internal noise in absence of stimuli takes precisely as much space in memory as stimuli would have.

Specific predictions of performance require relating the quantity and quality of information in memory to the task requirement. Absolute performance predictions are inherently complex; the approach here is the prediction of relative performance as a function of some parameter, such as picture luminance or contrast.

Predictions of Performance

Time-Scaling

Reducing the luminance of a picture is represented in the theory as a reduction in the signal-to-noise ratio of the input. The rate of signal acquisition by short-term memory as a function of exposure duration is slowed in reduced-luminance pictures because noise shares the limited-capacity channel with signal. This is a pure time-scaling effect, precisely as described by Loftus's Equation 1 [PH(t) = PL(Kt)], which relates performance with high luminance pictures (PH) to performance with low luminance pictures (PL). (Note that Loftus's constant K, $K \geq 1$, is monotonically related to the k in Equation 1 above.)

In the S/N theory, performance depends ultimately not on the limited-capacity channel but on the amount of signal in memory. Thus, empirical time scaling can hold only when memory capacity is not taxed. As memory load increases, there is an additional loss with low luminance pictures, above and beyond what is predicted by pure time scaling, because memory for low luminance pictures is not as good as for high luminance pictures. Loftus consistently reports this as an increase in the "constant" K for long exposure durations. Because it is predicted and observed that memory performance for low luminance pictures ultimately asymptotes at a lower value than for high luminance pictures, K must approach infinity for some value of t and, for still larger values of t, Loftus's Equation 1 must fail completely. Empirically, time scaling as described by Loftus's Equation 1 fails. Theoretically, in the S/N theory, there is perfect time scaling because of the limited-capacity channel. Time scaling appears to fail empirically because of noise-limited memory.

Total Amount Recognized or Recalled

Asymptotic performance as exposure duration of pictures is increased in short-term and long-term memory tests is correspondingly reduced because of the memory space that is wasted by the stored-noise elements. This is the explanation of the asymptotic differences observed by Loftus between low and high luminance pictures in his Experiments 1 (recognition) and 2 (recall).

In Loftus's Experiment 4, the rate of acquisition of pictures of digits was slowed in low luminance presentations, but asymptotic performance as t increased did not depend on luminance level. The inference from the S/N theory would be that digits are stored in memory in a noise-free form—either in a nonvisual memory or in a visual memory in which the amount of stored noise is so small that it does not interfere with digit retrieval. These aspects of memory structure can be investigated experimentally. For example, recall for visually presented noisy digits may be compared with recall for noisy pictures to determine whether the physical noise mimics the assumed effects of internal noise in both sets of materials. Alternatively, visual memory for actual, physical noise perturbations may be tested in digit recognition tasks (or in picture memory tasks), to determine whether noise indeed is stored in memory.

Predictions Summary

The S/N theory accounts qualitatively for the significant aspects of Loftus's recall and retrieval data with pictures. Because internal noise shares the limited input channel with input stimuli, the rate of information acquisition is slowed in dim versus bright pictures. Pure interval time scaling in the limited channel produces time scaling of observable performance, although observable time scaling fails as memory capacity is approached. Because internal noise is stored along with the representations of input stimuli in memory, memory capacity is reduced for dim versus bright pictures. With digit stimuli, noise slows the rate of information acquisition as it does for pictures. The number of digits retrieved from memory is independent of the S/N ratio either because the representation of digits in memory has been noise stripped or because it is noise resistant—processes that can be described within but are not specifically predicted by the S/N picture theory.

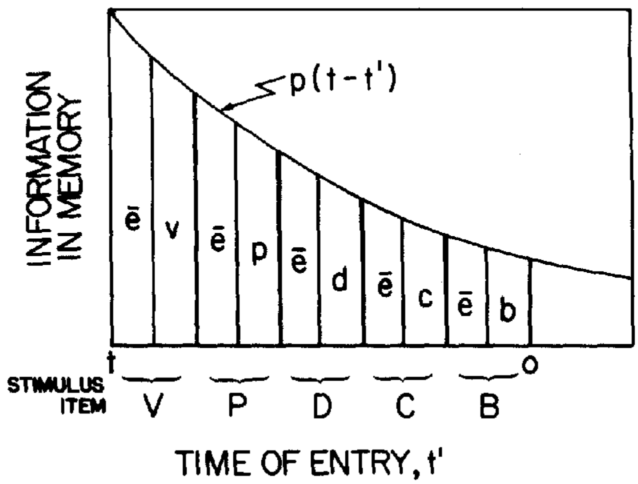

Figure 2. A limited-capacity short-term memory for letters. (Constituent phonemes of letters enter memory at time t'. At retrieval time t, the i-th phoneme is remembered and forgotten independently with the probability $P(i, t) = \int_{t_i}^{t_{i+1}} p(t - t')dt'$, a monotonically decreasing function of its residence time $t - t'$ [equivalent here to the number of subsequent phonemes] in memory. The contents of memory illustrated represent the phonemes in the stimulus sequence B, C, D, P, V. The probability of correctly recalling a letter is derived from the probabilities of correctly reconstructing the letter given retrieval of zero, one, or both of its constituent phonemes.)

Relation to Auditory Memory

A similar S/N theory was used by Sperling (1968) and Sperling and Speelman (1970) to quantitatively predict the performance loss in short-term memory for auditory stimuli due to acoustic confusability of stimulus items. In their theory, phonemes are remembered and forgotten independently in memory. Lists of confusable items (such as *B, C, D, G, P, T, V*, etc.) are not well remembered because the phoneme *e* occupies space in memory but is not useful for distinguishing between stimulus items. In auditory memory, the phoneme *e* functions like noise in picture memory. A single memory with a fixed phoneme capacity (Figure 2) precisely predicted performance in a variety of different recall tasks with two stimulus sets (confusable, nonconfusable). Predicted differences between lists composed of confusable and nonconfusable items with two stimulus sets (confusable, nonconfusable) were based entirely on a priori considerations of the phonemic efficiency of the stimulus sets and did not require estimating any parameters from the data.

The advantage of a S/N formulation is that it can make precise predictions in various new situations. In the present context, it implies that there is physical noise (equivalent to the transducer noise) that could be physically added to the high-luminance pictures so that their performance would equal that of the low luminance pictures in all significant aspects. Further, if the spatial frequency bandwidth of the added noise could be manipulated to reproduce the types of errors observed with memory failures, the external noise would have an equivalent spectrum to visual system's internal noise. By determining memory loss as a function of the intensity of physical stimulus noise, the equivalent transducer noise could be determined by methods similar to the determination of the equivalent noise of physical detectors (i.e., from the intercept of the low and high noise-intensity asymptotes on a performance versus noise-intensity graph, Pelli, 1981). The analysis further suggests that it would be useful to discriminate between transducer noise and memory noise, although the present experiments do not require this elaboration.

Conclusion

The use of noise as in the study of sensory systems is a powerful tool that is applicable to the study of memory systems. Low luminance exposes internal noise indirectly. In combination with the introduction of physical noise, luminance manipulations may yield important insights into the nature of visual memory.

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