

Brief communication

The two-pulse experiment and cross-correlation

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Received 30 March 2005; received in revised form 26 September 2005

Abstract

Rashbass [Rashbass, C. (1970). The visibility of transient changes of luminance. *Journal of Physiology*, 210, 165–186] presented pairs of flashes having various contrasts separated by a delay, and found that the thresholds for detecting the pairs fell on an ellipse. He fit the data using a model that computed the filtered energy of the pulses. Although this Rashbass model is phase-insensitive, many other experimental results show that humans can perform phase-sensitive detection consistent with a template-matching mechanism. We show that an observer who uses a form of template-matching produces thresholds that fall on an ellipse, just like the Rashbass model. The results from two-pulse experiments are consistent with the idea that humans cross-correlate the stimulus (signal or noise) with a filtered version of the expected signal rather than the signal itself. In symbols, we propose that observers compute $\int r(t)[s(t) * h(t)] dt$ where $r(t)$ is the received stimulus on a given trial [$s(t) + n(t)$ or $n(t)$], $s(t)$ is the signal, $h(t)$ is the visual filter, and $*$ is convolution.

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Keywords: Ideal observer; Rashbass model; Temporal summation

Rashbass, 1970 measured the temporal response of the visual system by fitting an elegant model to the results from a two-pulse experiment. The observer was presented with pairs of flashes (pulses) having various positive and negative contrasts, and the task was to detect the pair. He fit the data with a model that computed the filtered energy of the pulse pair. Although the model fit the data well, other experimental results suggest that humans use a cross-correlation or template-matching algorithm for detection (Burgess, 1990; Burgess & Ghandeharian, 1984; Levi & Klein, 2002; Simpson & Manahilov, 2001). A cross-correlator's output depends on the signal phase, whereas the Rashbass model's output is unaffected by phase. Since observers in other detection experiments behave as template-matchers, we wondered if the results of the two-pulse experiment might also be consistent with a phase-sensitive mechanism. In this note we will show that the Rashbass model mimics a nonideal observer model

where the observer cross-correlates the stimulus (which in a yes–no task is either the signal + noise or noise alone) with a filtered version of the expected signal. Thus, the results of two-pulse experiments (Cohn & Lasley, 1976; Manahilov & Simpson, 1999; Rashbass, 1970; Simpson, 1994) are consistent with the body of literature pointing to cross-correlation as the human visual detection mechanism.

In the Rashbass experiment, the observer receives a stimulus $r(t)$ that is either the signal $s(t)$ or a blank. We assume that white Gaussian noise $n(t)$ is added internally, so the received stimulus on each trial is either

$$r(t) = s(t) + n(t)$$

or noise alone

$$r(t) = n(t).$$

The signal is a pair of impulses $\delta(t)$ and $\delta(t - \tau)$ separated by a delay τ and having contrasts x and y

$$s(t) = x\delta(t) + y\delta(t - \tau).$$

In the Rashbass model, the observer bases his decision on

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$$Q = \int [r(t) * h(t)]^2 dt, \quad (1)$$

where $h(t)$ is the impulse response of the visual filter and $*$ is convolution. We can assume, as Rashbass does, that the energy of the impulse response is unity. On signal trials the expected value of Q is

$$E(Q) = \int [s(t) * h(t)]^2 dt, \quad (2)$$

$$= \int [xh(t) + yh(t - \tau)]^2 dt, \quad (3)$$

$$= x^2 + y^2 + 2xy \int h(t)h(t - \tau) dt. \quad (4)$$

In Rashbass's experiment the threshold was defined as the 50% point of the yes–no psychometric function. In the theory presented here, this threshold point corresponds to some criterion level of Q , and thus a plot of the two impulse contrasts at threshold for a given delay will be an ellipse tilted to the left or right at 45 deg (Eq. (4)). The tilt and eccentricity of the ellipse indicate the auto-correlation function of the visual filter's impulse response.

An ideal observer will cross-correlate the stimulus (signal plus noise or blank plus noise) with the expected signal. A real observer, however, cannot access the external signal $s(t)$ directly but only a representation that has been filtered by the visual system: $s(t)*h(t)$. The received stimulus on signal trials is therefore

$$r(t) = s(t) * h(t) + n(t).$$

Both the received stimulus and the template will be filtered versions of the actual signal. Then the detection decision will be based on

$$Q = \int r(t)[s(t) * h(t)] dt. \quad (5)$$

The expected value of Q on signal trials is

$$E(Q) = \int [s(t) * h(t)][s(t) * h(t)] dt, \quad (6)$$

$$= \int [s(t) * h(t)]^2 dt, \quad (7)$$

$$= x^2 + y^2 + 2xy \int h(t)h(t - \tau) dt. \quad (8)$$

Thus, a nonideal observer using a filtered template (Eq. (5)) produces exactly the same threshold ellipse as the Rashbass model (Eq. (1)). Note, however, that the two models are not identical. Suppose, for example, the observer expects the signal $s(t)$ and so has formed the template $s(t)*h(t)$. Imagine that we now surprise the observer by presenting not the signal $s(t)$ but a phase shifted version $-s(t)$. The Rashbass model will produce the same output as when $s(t)$ is presented. But for the nonideal observer the expected value of the response is now $\int [-s(t) * h(t)][s(t) * h(t)] dt$. This cross-correlation will be much smaller than when $s(t)$ is presented. Thus the nonideal observer is phase-sensitive in the same way as a real observer.

In conclusion, we have shown that the results from the Rashbass two-pulse experiment are consistent with those of the large literature pointing to inefficient cross-correlation as the mechanism underlying human visual detection.

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