

The influence of urgency on decision time

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A fruitful quantitative approach to understanding how the brain makes decisions has been to look at the time needed to make a decision, and how it is affected by factors such as the supply of information, or an individual's expectations. This approach has led to a model of decision-making, consistent with recent neurophysiological data, that explains the observed variability of reaction times and correctly predicts the effects of altered expectations. Can it also predict what happens when the urgency of making the response changes? We asked subjects to make eye movements to low-visibility targets either as fast or as accurately as possible, and found that the model does indeed predict the timing of their responses: the degree of urgency seems to influence the criterion level at which a decision signal triggers a response.

Saccadic eye movements serve to bring the images of objects of interest on to the fovea¹. Often triggered by the sudden appearance of a stimulus in the periphery, they are very fast movements, reaching velocities of 900 degrees per second, with a notably stereotyped time course². Yet their reaction times are both surprisingly long (typically around 200 ms) and extremely variable across trials. Since presentation of visual targets can generate activity in the superior colliculus within as little as 40 ms (ref. 3), and electrical stimulation of the superior colliculus triggers saccades with a delay of just 20 ms (ref. 4), it is clear that conduction delays alone cannot account for the long latency. Instead, it seems to reflect a process of procrastination⁵: in the real world, we are typically faced with many potential, competing targets, and the extra time is needed for higher levels of the brain to decide which, if any, it is appropriate to foveate.

Quantitative analysis of this variability shows that although reaction times are unpredictable in individual trials, they obey a simple stochastic law: the reciprocal of latency follows a Gaussian distribution. Thus, plotting cumulative latency distributions on a probit scale as a function of reciprocal latency (a recipit plot) yields a straight line⁵. (Under some conditions, as here, there may in addition be a distinct population of faster responses that appear to follow a different law, but their numbers are normally small.) The law appears to apply to all reaction times: manual as well as oculomotor, and to auditory and tactile stimuli as well as visual⁶.

Is this a mere empirical description, or can it tell us something about the underlying decision process? A simple model, which readily explains the observed distribution, postulates a decision signal S associated with a particular response. When an appropriate stimulus appears, S starts to rise linearly from an initial level S_0 at a rate r ; upon reaching a pre-specified threshold S_T , the saccade is triggered⁷ (Fig. 1). If r is subject to Gaussian perturbation, it accounts for the straight line on the recipit plot, as reaction time is $(S_T - S_0)/r$. This model is known as the LATER model (linear approach to threshold with ergodic rate), a name that also recalls the procrastination it embodies.

Is this model consistent with known neurophysiology? Within the frontal eye fields of monkeys are populations of visuomotor

neurons that begin firing well in advance of saccades, their activity rising linearly upon presentation of a suitable target stimulus^{8–10}. The rate of rise varies randomly from trial to trial, and the saccade itself is initiated when this activity reaches a fixed threshold. All of this corresponds closely with what would be expected from the LATER model.

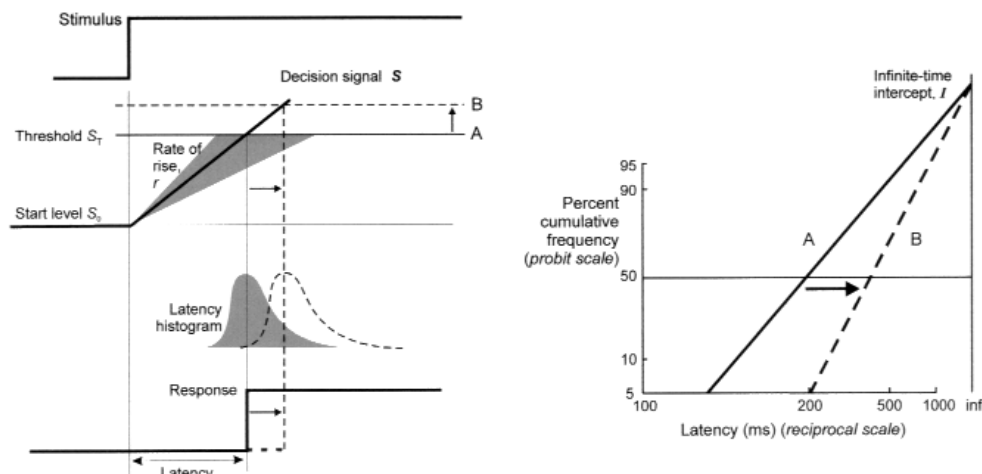
Furthermore, consideration of likelihood theory implies a clear functional interpretation of the parameters of this model. S may be taken to embody a measure of belief that a particular response to a possible stimulus is required, its mean rate of rise (μ) reflecting the rate of accumulation of information, whereas S_0 is related to the prior expectation that the response will be demanded⁷. The need for action is finally accepted when S reaches the criterion level, S_T , that corresponds to a significance level in a statistical test. Is this interpretation justified? More specifically, if we vary the amount of information supplied, the prior expectation, or the urgency, do they have the effects on reaction times that they ought to have, if the result is to alter respectively μ , S_0 or S_T ?

Neurophysiological experiments demonstrate the existence of saccade-related cells in prefrontal cortex whose activity depends on the amount of information provided in random-dot kinetograms¹¹ or in conjunction tasks¹², but similar experiments in humans, with analysis of the distribution of reaction times, have not yet been published. On the other hand, what has been demonstrated clearly in human subjects is that it is possible to manipulate S_0 by changing the prior expectation of a particular response. Median reaction time is then proportional to log prior probability, as predicted by likelihood theory⁷, and the effect on the distribution of latency for the main population is almost exactly as expected from the LATER model.

To test the model further, it would clearly be desirable to examine the effect of manipulating the threshold S_T in a similar way. Because this threshold reflects the confidence level required before commitment to a particular course of action, we would expect S_T to be high if a very accurate response were needed, and low if it is essential to respond quickly, and accuracy is less important. Accordingly, we presented subjects with very low-contrast

Fig. 1. The LATER model.

On presentation of a stimulus (top left), a decision signal S rises linearly from an initial level S_0 at a rate r ; when it reaches the threshold S_T , a saccade is initiated (bottom). On different trials, r varies randomly in a Gaussian manner, resulting in a skewed distribution of latencies (shaded area). If the threshold S_T increases (B, dashed lines) the latency is increased in proportion. These effects can be seen on the reciprob plot on the right, in which the cumulative distributions of saccadic latencies are plotted on a probit scale with a reciprocal time axis, longer reaction times increasing to the right up to the limit formed by the infinite-time axis. A straight line on such a plot implies a Gaussian distribution of reciprocal latency and thus of r itself. An increase in S_T will result in a swiveling of the line about the point I , its intercept with the infinite-time axis.



targets under conditions of either accuracy or urgency, instructing them to respond either with as few errors as possible, or alternatively as fast as possible. The LATER model makes a clear quantitative prediction about what should happen. If it is true that conditions of urgency, for instance, decrease S_T , the median latency will indeed be shortened; but a further and much more exacting prediction is that the reciprob plot should swivel about a fixed infinite-time intercept, I (Fig. 1). Had the change in reaction time been due to change in the mean rate of rise μ , the line on the reciprob plot would undergo a parallel shift, the slope remaining constant. What is actually observed?

RESULTS

Distribution swivels as urgency changes

Figure 2 shows reciprob plots of the saccadic latencies of four subjects made under the two conditions of accuracy and urgency. Apart from the obvious increase for most subjects in the incidence of anticipatory responses under conditions of urgency, in a very similar manner to what had previously been observed when target expectation is

increased⁷, the most striking difference between the distributions is the combination of an increased median with higher accuracy, and steeper slope. This causes the line to swivel in precisely the way the LATER model predicts if urgency does indeed reduce the threshold level, S_T . A Kolmogorov-Smirnov two-sample test (Methods) confirmed that, for every subject ($p > 10\%$), the two distributions in each case were indeed compatible with swiveling about a fixed common intercept I , and conversely that the difference was incompatible with a parallel shift, which would indicate a change in the mean rate of rise, μ .

Urgency changes match changes in expectation

A further, even more stringent, test confirms that the change in reaction time resulted from a change in S_T . In the LATER model, the latency is determined by the time taken for S to rise from S_0 to S_T . If both these levels were to change by an equal amount, then the resultant distribution of reaction times would be entirely unaffected. We know that S_0 can be manipulated by changing the

Fig. 2. Effect of urgency instructions on the distribution of saccadic latency. Reciprob plots (as in Fig. 1) are shown for four representative subjects given instructions to respond either as accurately as possible (filled circles) or as fast as possible (open circles). The actual percentages of correct responses under the two conditions are shown in the boxes. Most saccades follow a recinormal distribution, generating a linear cumulative distribution. However, particularly under the urgency condition, there is an obvious population of anticipatory responses generally lying on a different straight line (dashed) from that of the main population, with a shallower slope. The solid lines represent a best fit to the main population subject to the constraint of a common infinite-time intercept (not shown, see Fig. 1), demonstrating the expected swiveling of the distribution about a fixed intercept with the infinite-time axis.

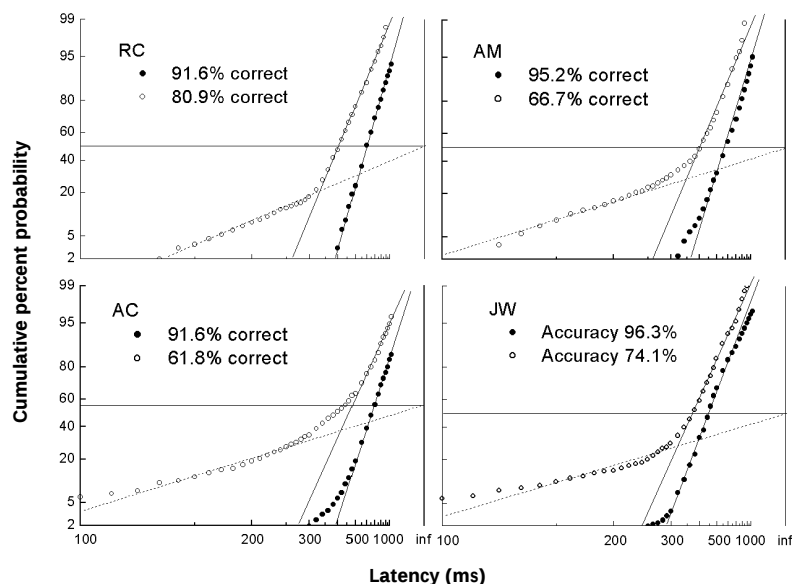
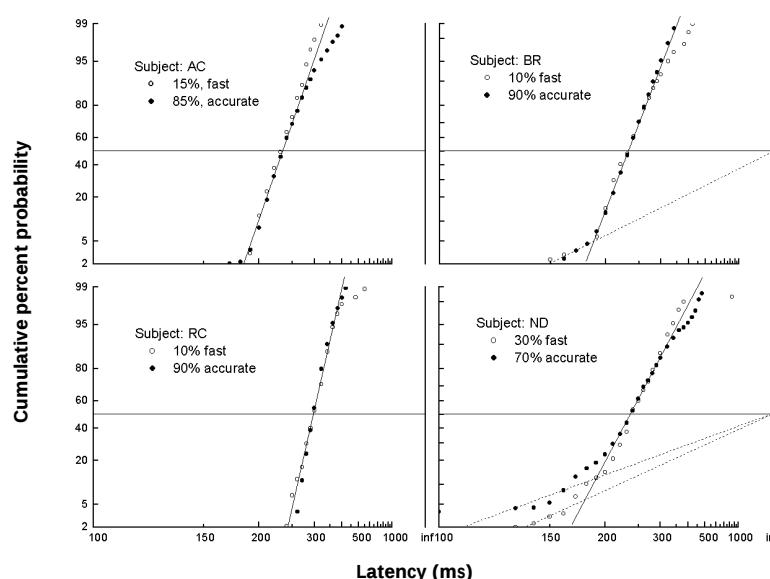


Fig. 3. Equivalence of changes in urgency and changes in expectation. Subjects performed saccades under conditions of either accuracy or urgency, to targets of two different probabilities, as shown in the labels. The resultant distributions are shown as reciprob plots, as in Fig. 2. Filled circles show accurate responses to high-probability targets; open circles show urgent responses to low-probability targets. The apparent identity of the distributions in the two cases was confirmed by the Kolmogorov-Smirnov test.



prior probability⁷; so for any particular degree of urgency, it should be possible to find a prior probability such that the resultant change in S_0 is identical to the change in S_T due to the urgency instructions. Since the distance that the signal S has to rise is then the same in both cases, the distribution of urgent responses to the low-probability target should be identical to that of non-urgent responses to the high-probability target. This would be powerful evidence for the idea that control over urgency is exerted by changes in S_T .

Reciprob plots for four representative subjects (Fig. 3) demonstrate the predicted cancellation of the effects of changes in urgency by appropriate changes in expectation. A Kolmogorov-Smirnov test in each case showed that the pairs of distributions (urgent, unexpected and accurate, expected) were indeed statistically indistinguishable ($p > 10\%$).

DISCUSSION

The two experiments in this study therefore suggest rather strongly that instructing subjects to respond either more carefully or more hastily is equivalent to altering the threshold in the LATER model at which a response is initiated. Urgency is translated into a change in the pre-determined 'significance' level, and in general it seems to be indistinguishable in its behavioral effects from a change in prior expectation. All this in turn suggests a natural scale for representing degrees of urgency: like expectation, it is appropriately represented on a logarithmic probability scale, and experiments like ours show how it can be quantitatively measured.

METHODS

Eight subjects (MA, age 22; RC, 53; ND, 21; OM, 21; BR, 21; JW, 20, all male, and AC, 20, and AM, 20, female) performed, with informed consent, a visually guided saccade task while their eye movements were recorded. The general procedures used had been given local ethical committee approval.

Visual stimuli. Three rectangular yellow diffuse light-emitting diodes (LEDs) subtending 14×23 min arc were presented by a beam splitter against a color-matched background of uniform luminance 1.4 cd/m^2 . An appearance task was used¹³, in which two target lights were presented at 90° on either side of a central fixation light of 100% contrast, which remained on throughout the experiment, thus preventing its offset from providing a cue. To make the task sufficiently demanding for a significant number of mistakes to occur, we presented the two targets at a contrast chosen to be approximately 1% above threshold. An independent computer controlled the LED illumination levels by pulse-width modulation at a frequency well above flicker fusion frequency, while the experimental computer controlled their sequence and timing.

Data collection. Eye movements were measured using an infrared oculometer¹⁴ with a range of $\pm 30^\circ$, which was symmetrically linear to 1% over a range of about $\pm 10^\circ$. Output was sampled at 10-ms intervals by

the PC-based saccadic analysis system SPIC¹⁵, which displayed and stored the eye movement data received by the transducer as well as controlling the stimuli and detecting saccades in real time by an algorithm using acceleration, speed and position. Saccadic latencies of less than 50 ms were ignored by the computer. The traces were inspected following each experimental session, and records with errors caused by blinks, head movements or other artifacts were eliminated from further analysis.

Tasks. We used two behavioral protocols. In each, subjects pressed a button to initiate a block of 100 trials. A trial began with a tone, warning the subject to fixate the central light, followed after a random interval, distributed uniformly in the range 0.5–1 s, by illumination of one of the peripheral targets randomly on the left or the right. The probability of appearance on either side was an experimental variable.

In the first task, the target was equally likely to appear on the left or the right. There were two conditions, one encouraging accurate responding and the other encouraging urgency: before each block, subjects were instructed either to move at a comfortable pace and to be as accurate in their responses as possible ('accuracy' condition), or to respond as rapidly as possible, worrying less about making mistakes ('urgency' condition). A thousand trials were collected under each condition for each subject. The results for any one subject were collected during one session to reduce the effect of long term variation in latency, with a suitable number of breaks to minimize the effects of fatigue.

The second task consisted of the same two conditions as the first, but in this case the frequency of presentation to each side was not equal, resulting in the development of a difference in median latency of response in each direction. Various probabilities were tested for each subject until a ratio was found that generated the same median latency toward the unexpected side in the 'urgency' condition and the expected side in the 'accuracy' condition. For each new probability, a considerable training period was required, as it takes at least 500 trials for the latency differences to become fully apparent. Having established the correct probability ratio to be used, we collected data under each condition for four subjects (AC, RC, ND and BR).

The number of trials performed by each subject was dictated by the need to obtain enough saccades in the low prior-probability direction to permit adequate statistical testing. For instance in the case of subject RC, 2000 trials were performed to obtain 184 saccades to the less likely side. Again, data were collected during a single session, with several breaks to avoid undue fatigue.

Statistical analysis. Subsets of the data in one direction, or under a particular condition, can be individually selected within SPIC, statistically analyzed, and displayed as a reciprob plot. The population of

anticipatory responses then shows up clearly as a subpopulation lying on a different line from the main population¹⁶: the latency corresponding to the intersection of the two lines was used as a criterion point to exclude this fast population from further analysis. A Kolmogorov-Smirnov one-sample test¹⁷ was performed on each dataset to confirm the agreement between the observed cumulative scores and the theoretical distribution expected from the LATER model. A Kolmogorov-Smirnov criterion was used to calculate a line of best fit to the main part of the distribution, ignoring the fast population, and from this the median latency, the slope and the intercept with the infinite-time axis I were estimated.

Blocks of data were only merged in all protocols if the Kolmogorov-Smirnov value exceeded a significance level of 10%, ensuring that aberrant data sets were excluded. In the second task, to test that two data sets were indistinguishable, the two-sample Kolmogorov-Smirnov test was used to test the hypothesis that they could have come from the same distribution.

In task 1, to ascertain if a pair of reciprobability distributions could be related by a parallel shift (corresponding to a change in the mean rate of rise, μ), we determined whether each could be fitted by lines differing only in median and not in slope, using the Kolmogorov-Smirnov criterion at 10%. Likewise, to determine whether the difference between the curves could be attributed to swiveling about the infinite time intercept, a value of the intercept I was sought that was compatible with both distributions (Kolmogorov-Smirnov, $p > 10\%$).

In task 2, the distribution of urgent responses made to infrequently presented targets was compared with that of accurate responses made to frequently presented targets. The Kolmogorov-Smirnov two-sample test was used to estimate the likelihood that the two samples could have been drawn from the same distribution ($p > 10\%$), and were therefore consistent with the prediction that the threshold and prior probability effects are equivalent.

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