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Quick thinking: perceiving in a tenth of a blink of an eye

Jan Drugowitsch & Alexandre Pouget

What is the minimal sensory processing time before we can make a decision about a stimulus? A study now reports that, for simple perceptual decisions, this can take as little as 30 ms.

Imagine looking for a friend in a large crowd. At each fixation of your eye, you must process the image, decide whether or not your friend is there and, if not, move your eyes to the next location. How much processing time does it take to make a decision about whether or not your friend is at the fixated location? More generally, what is the minimal sensory processing time before we can make a decision about a stimulus? This would seem to be one of the most basic questions about perception, and one for which we would already have hard numbers. Instead, the answer is unknown even for the most basic perceptual decisions, such as deciding whether a stimulus is green or red.

To measure this, one might think that we only need to present a stimulus and measure the time it takes for the subject to respond correctly. There are, however, several problems with this. First, we must define what we mean by correctly. If we require 100% accuracy, the subject may wait far longer than required before committing to a decision, just to be sure of making absolutely no mistakes. Second, the reaction time includes other components besides the sensory processing, such as access to short-term memory, motor planning and so on, whose influence may not be easy to estimate. Getting to the heart of the issue requires a careful experimental design, which is what Stanford *et al.*[1] describe on page 379 of this issue. They report that, for a very simple perceptual decision ('Is this red or green?'), it

takes as little as 30 ms to make a decision that is correct 75% of the time.

Stanford *et al.*[1] trained monkeys in a task in which every trial started with the appearance of a fixation point of a specific color, plus two colored targets (**Fig. 1a**). When the fixation point disappeared, the monkeys were trained to make a saccade to the target whose color matched the color of the (now no longer visible) fixation point. So far, this is a fairly standard task, but Stanford *et al.*[1] added a crucial twist: at the time of the disappearance of the fixation point, the targets were neither red nor green; both were yellow. Because the monkeys were trained to initiate a saccade as soon as the fixation point disappeared, they had to pick a target randomly and prepare a saccade without knowing whether that target was the correct one. However, after a random delay, varying from 50 ms to 250 ms after the disappearance of the fixation point, one of the targets turned green and the other red. Thus, if the delay is short enough so that no saccade has been performed yet, the monkey can pick the target that matches the color of the fixation point. If, however, the delay is too long, the saccade will be initiated before the subject can take into account the color of the target, resulting in a random choice.

How does this experiment reveal the time it takes to process a stimulus with an accuracy of 75%? The logic is as follows. On every trial, the reaction time (the time from the disappearance of the fixation point to the onset of the saccade) contains two main periods: the 50–250 ms random delay period imposed by the experimenter and the time taken to actually perceive the stimulus, the sensory processing time (**Fig. 1a**). Technically, there are also the sensory latency and motor

time, but these should be the same across all trials, and can therefore be ignored in this experiment. Because we can measure the reaction time on every trial, and we know what the delay was on these trials, we can compute the sensory processing time by subtracting the delay time from the reaction time. Next, we can bin trials with similar sensory processing times and plot the percentage of correct responses as a function of this time. For short sensory processing times, performance should be close to chance (50%), whereas for long sensory processing times, it should saturate at 100% correct (**Fig. 1b**). We can then look at this curve and simply read out the sensory processing time—that is, the time it takes performance to go from 50% to 75%. This is precisely what Stanford *et al.*[1] did, and they report that this number is remarkably short: between 30 and 50 ms, depending on the subject.

In addition to the experiment, the authors also propose a model of perceptual decision making for this type of task. The model has two variables, racing against each other to a threshold, at which a saccade is initiated. Each variable represents the motor plan to perform a saccade to one of the two targets, and so the variable that crosses the threshold first determines the target of the saccade. The race starts with the disappearance of the fixation point, at which point the two variables are randomly assigned speeds. After the delay period, when the targets change colors, the variable corresponding to the correct target accelerates and the one corresponding to the incorrect target decelerates (**Fig. 1c**). If the threshold for saccade initiation is reached within the delay period, the decisions are purely random because the target has not been revealed yet. This corresponds to what

The authors are in the Department of Brain and Cognitive Science, University of Rochester, Rochester, New York, USA.
e-mail: alex@cvs.rochester.edu

was observed in the monkeys' behavior. Immediately after the delay period, mistakes are still possible because the inertia of the racing variables causes their speeds to change slowly. Well after the delay period, however, the variables have had time to change course, and so mistakes are rare (**Fig. 1c**).

Despite its simplicity, the model performs surprisingly well. It captures not only the dependence of the decision accuracy on the effective sensory processing time, but also the full response time distributions for the different delay periods. This is not a given, particularly in the light of a distinct, and usually hard-to-model, bimodality of the response time distribution for long delay periods. In a variation of the task, Stanford et al.[1] manipulated the amount of reward associated with each of the target colors, causing a bias in the subjects' responses toward the higher-rewarding target. This reward imbalance is effectively modeled by a bias in the initial race speeds, again resulting in a remarkably good fit of the model to the observed behavior.

Readers familiar with models of decision making may have noticed an unusual feature of this model: all the stochasticity in the subject's responses is attributed to the random choice of the initial race speeds (as in ref. 2). No extra noise is added at a later time, even after the delay period, when the color of the targets is revealed. As a result, incorrect choices occur only because of the inertia of the racing variables. This is quite different from standard models of decision making, such as drift diffusion models[3–5] and race models[6], which assume that the strategy of the decision maker is optimal, and that incorrect decisions and varying response times are due to sensory noise and uncertainty in the stimulus itself. Here, though, the authors assume that sensory information is perfectly informative, and that mistakes arise owing to inertia in the racing variables.

It would be interesting to see whether an optimal model based on the accumulation of noisy sensory evidence, such as the drift diffusion model[3–5] and its neural counterparts[7,8], could fit the data of these experiments as well as the deterministic race model proposed here did. In this case, incorrect choices could well be interpreted as resulting from uncertain, noisy sensory information, rather than the inertia of competing motor plans. This would also help to establish a link between this work and probabilistic models of decision making and neural computation[8].

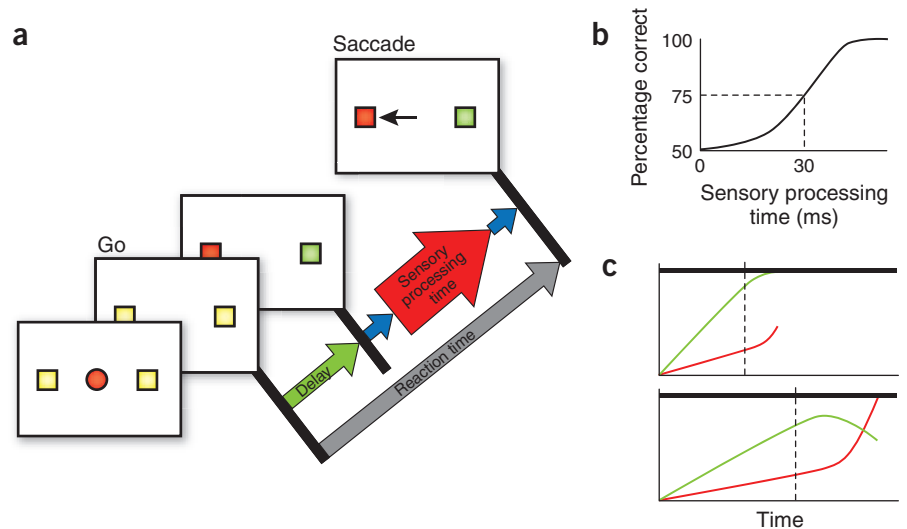To validate their model, the authors also report the response of neurons in the

Figure 1 The experimental design used by Stanford et al.[1]. (**a**) The task requires making a saccade to the target (squares) that has the same color as the fixation point (circle). The saccade must be initiated when the fixation point disappears (the 'Go' signal), but the color of the targets is revealed only after a random delay (green arrow) after the Go signal. The reaction time is equal to the sum of the delay and sensory processing times (red arrow), as well as the efferent and afferent delays (blue arrows). Because the delay is known and the reaction time is measured, one can recover the sensory processing time on each trial (assuming constant afferent and efferent delays). (**b**) The tachometric curve shows the percentage of correct responses as a function of the sensory processing time. For some subjects, performance goes from 50% to 75% correct within 30 ms. (**c**) Race model. Two variables race to a threshold (thick upper lines) with speeds randomly drawn at the beginning of the trials. These two variables correspond to the two possible saccades. When the colors of the targets are revealed (dashed lines), the speed of the race increases for the variable corresponding to the correct target and decreases for the other variable. Here we illustrate two trials in which the fixation point is red but the model initially favors the target that will eventually become green. When the colors are revealed, the green race slows down while the red one accelerates. The change of speed, however, is subject to inertia. As a result, if the green variable is close to threshold when the colors are revealed, the green variable still hits the bound owing to inertia, resulting in a mistake (top panel). If, on the other hand, the green variable is still some distance from the threshold at the end of the delay period, the model has time to 'change its mind' and makes the correct decision (bottom panel).

frontal eye field (an area that is known to be involved in the initiation of eye movements) during the period after the disappearance of the fixation point. As predicted by the race model, the firing rates increase at a constant rate until the end of the delay period. As soon as sensory evidence becomes available, the increase becomes steeper if the evidence supports the corresponding motor plan, and less steep or even negative otherwise (**Fig. 1c**). Interestingly, however, the neural traces do not seem to show any inertia; the firing rate shows an almost instantaneous transition in response to the sensory evidence (Fig. 6e in Stanford et al.[1]). It is probably premature to draw any strong conclusions from the limited neural data presented here but, one hopes, future data may be able to address the issue of whether inertia in competing motor plans is the culprit in erroneous decisions, or whether accumulation of noisy sensory evidence is in fact to blame.

Ultimately, even if the inertia idea is not confirmed, this would not diminish the authors' accomplishments. We finally have an answer to a longstanding question in perception: what is the minimum sensory processing time? Apparently, not much: a tenth of the average blink of an eye.

COMPETING INTERESTS STATEMENT
The authors declare no competing financial interests.

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