Vision and the optic flow field

from J.R. Lishman

ATTEMPTS to understand how animals see have largely been made by the study of the perception of stationary forms even though it is probably true that the greater part of our, or any other animals, use of the visual sense is in the control of movement. When we are walking, running, driving or catching a ball the visual stimuli we are receiving are constantly changing. There is perhaps a tendency to believe that we can comprehend such changing stimuli only by performing a sort of 'frame-by-frame' analysis which reduces the dynamic input to a series of static pictures and that an understanding of perception during motion will come only after we have understood picture perception.

A different research strategy is to look for relationships in the dynamic pattern of visual stimulation — the optic flow field — that might be used directly to control behaviour. An example of this approach is seen on page 293 of this issue of *Nature*. It is shown that the time at which a diving seabird closes its wings before hitting the surface of the water appears to be controlled by a visual variable τ (tau) which gives, at constant velocity, the time-to-contact with the surface of the water and which the bird could measure from the optic flow field without knowledge of either distance to the water or velocity. The simple derivation of this tau variable from the changing visual stimulation at the retina is explained in the box alongside.

The time-to-contact at constant velocity given by the tau variable and the rate of change in the time-to-contact during acceleration and deceleration given by the time derivative of the tau variable may be exploited to control behaviour in a variety of tasks. One that has been recently examined is the control of braking by car drivers[1].

Consider someone driving along a straight stretch of road with another car ahead. If the lead vehicle is travelling at the same or a faster speed than the following vehicle then its retinal image size will be constant or contracting and if it is stopped or is travelling at a slower speed its image will be dilating. The change in the optic image of the lead vehicle tells the driver whether he is closing on the vehicle ahead. If he is closing on the vehicle then he has to begin braking early enough and control his deceleration appropriately to avoid an accident. At first sight it may seem that to do so the driver must know his velocity, the deceleration produced by his braking and his distance from the obstacle ahead. He can, however, control his braking force (and thus the rate of change of his own velocity) much more simply and directly through monitoring the rate of change of the time-to-contact with the lead vehicle (the time derivative of the tau variable).

As can be seen in the box below his current deceleration is adequate if and only if $d\tau/dt > -0.5$.

There is evidence that a driver does, in fact, control his braking by attempting to maintain a safe margin value of $d\tau/dt$. Spurr[2] found that deceleration curves of test drivers stopping at a fixed point tended to conform to the pattern of an initial steep linear increase in deceleration followed by a gradual decrease. If for an individual driver the deceleration curve for different speeds is plotted in a dimensionless form (that is, the deceleration as a fraction of the average deceleration throughout the stop against time as a fraction of the total stopping time) the curve is that expected if the driver had maintained a safe value of $d\tau/dt$ close to the critical value.

The agreement between curve and data is very close except for the initial build up of

The data are for a driver stopping at a nominated point from various speeds up to 100 km h^{-1}. The curve is what would have obtained if the driver controlled his braking by maintaining a safe value of $d\tau/dt$.
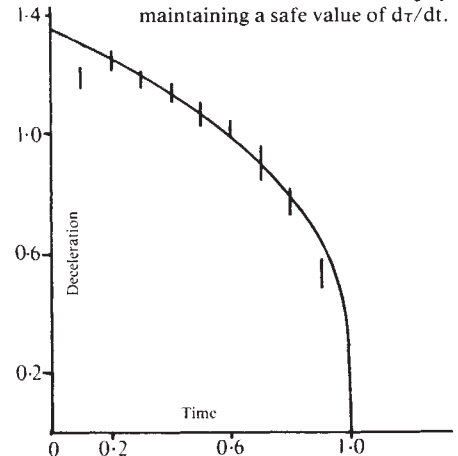
WHEN an animal is moving through the enviroment the optic array at the eye is constantly changing and gives rise to an *optic flow field* on the retina. Image elements flow out from the point towards which the animal is moving. A rigorous description of the optic flow field shows that it contains a great deal of information which could be used for controlling behaviour.

From reference 6.
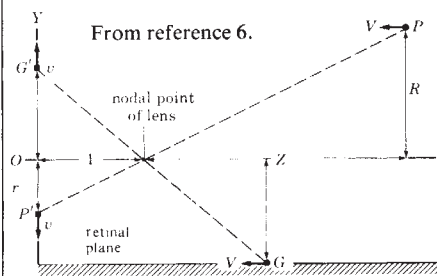
For convenience let us consider the point of observation to be stationary and the environment to be moving towards it at velocity V in the direction K to O (see figure). The image of the environment falls on the retinal projection plane. Two texture elements, P and G, in the environment will give rise to two images P' and G' on the retina which move out along radial flow lines emanating from O. From similar triangles:

$$\frac{Z}{R} = \frac{1}{r} \qquad (1)$$

(Z and r are dependent on time t) and if we differentiate with respect to time we obtain

$$\frac{R}{V} = \frac{r^2}{v} \qquad (2)$$

where V is the velocity of the texture element P and v the velocity of its corresponding retinal image P . Eliminating R between (1) and (2)

$$\frac{Z}{V} = \frac{r}{v} \qquad (3)$$

Equations (2) and (3) mean that the distance coordinates of all visible texture elements are specified within a scale factor V — the optic flow field thus gives information about the relative distances, sizes and orientations of surfaces and objects in the environment.

Time-to-contact

Of great interest is equation (3) which gives the time-to-contact with the texture elements Z/V. This is equal to the optic variable r/v, tau (τ) which is essentially the distance apart of image elements on a surface divided by their rate of separation and gives us the sensation of an object 'looming up'. It gives us a *direct* measure of the time-to-contact with the surface at constant velocity.

$$\frac{Z}{V} = \frac{r}{v} = \tau \qquad (4)$$

Control of deceleration

As described in the text the time-to-contact and its rate of change can be used by a car driver to control deceleration to avoid collision with an obstacle ahead. A driver travelling with velocity V and stopping with a deceleration D will come to a complete halt in the distance

$$\frac{V^2}{2D}$$

The driver will avoid a collision if this distance is less than that to the obstacle Z. Thus the deceleration is adequate if

$$\frac{V^2}{2D} \leqslant Z \qquad (5)$$

or

$$\frac{ZD}{V^2} \geqslant 0.5 \qquad (6)$$

Now from (4)

$$\frac{Z}{V} = \tau$$

Differentiating with respect to time t

$$\frac{ZD}{V^2} = 1 + \frac{d\tau}{dt} \qquad (7)$$

Combining (6) and (7) we see that

$$\frac{d\tau}{dt} \geqslant -0.5$$

that is, if the rate of change of the tau variable is -0.5 then the driver is decelerating rapidly enough to avoid a collision.

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deceleration — this is to be expected as the theory simply assumes the driver instantaneuosly reaches a particular decelation while a real driver does not 'slam on the brakes'.

The above argument is not restricted to the control of man-made machines: exactly the same kind of visual information could be used to control landing whether of a bird on a branch or a bee on a flower and there are numerous other skills which require accurate visual monitoring of time-to-contact.

Analysis of the optic flow field may enable us to explain how athletes get the kind of precise visual information they need to control their footing. One task that has been looked at from this viewpoint is the long jump[3]. A long jumper sprints some 40 metres and then leaps off a 20 centimetre wide take-off board. To achieve a successful jump the athlete must leap from as close as possible to the front edge of the board without overstepping it.

Film analysis of jumps made by three international standard athletes shows that the run up can be divided into two phases. In the 'run up' the athletes, although trying to use a stereotyped approach, inevitably build up positional errors as they sprint down the track. Three or four strides from the take-off they average standard errors in footfall position of more than 30 cm. They then 'zero in' and use visual information to adjust the final strides so that they hit the board with a standard error of less than ten cms (at a speed of around 22mph).

How do they visually regulate their final

Time — | Flight | R.Thrust | Flight |
L.SWING THROUGH
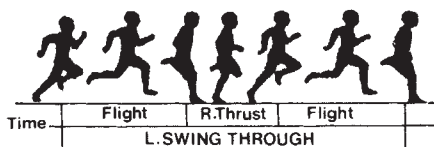
strides? As shown in the figure a stride is composed of three segments which can be varied independently: the *thrust,* from the start of the stride to the point when the foot leaves the ground, which can be increased by lowering the hips; the *flight* the airborne distance travelled which can be modulated by changing the horizontal impulse (the 'drive') which affects the velocity of the athlete or the vertical impulse (the 'lift') which affects the time for which the athlete is in the air; and the *landing length,* how far ahead the foot touches the ground, which can be increased by stretching the leg forwards.

Analysis of films of the athletes suggests that they zero in on the board by regulating only the flight segment of the stride and that they do so by modulating the "lift", which changes only the flight time, rather than the drive, which changes the velocity. The problem of striking the board may thus be usefully conceived of as one where the athlete makes a timing judgement rather than a distance judgement: the duration of the remaining strides is programmed just to fill the time remaining to reach the board — the necessary information being given in the time-to contact variable in the optic field.

The apparent simplicity with which some behaviours might be controlled by the optic flow field has lead some researchers (in particular JJ Gibson who provided much of the original inspiration in this area) to suggest that the relation between perception and the optical input to the eye is in some sense 'direct' and is characterised by an 'immediate pick up of information'. Recent controversy (see ref.4 for an attack on Gibson's theory and replies) seems to have been confounded by a lack of any clear agreement on what is meant by 'direct perception'. Some (its critics) hold that it implies the nonsensical idea that perception can take place without anything going on at all in the head. Others say that it merely implies, in contrast to the view held by many who study visual illusions, that perception does not require an animal to make 'hypotheses' about the world from inadequate visual cues.

Whether or not there is any value in the idea of 'direct perception' there is little doubt that a shift in emphasis from the analysis of static visual arrays to a consideration of what an animal actually uses visual information for (as Gibson[5] does in his 'Ecological Optics') is likely to help us to understand how animals see. □

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1. Lee, D.N. *Perception* 5, 437 (1976).
2. Spurr, R.T. *Automobile Engineer* 39, 58 (1969).
3. Lee, D.N. *et al. Athletics Coach* 11, 26 (1977).
4. Ullman, S. *Behav. Brain Sci.* 3, 373 (1980).
5. Gibson, J.J. *The ecological approach to visual perception* (Houghton-Mifflin, 1979).
6. Lee, D.N. *Phil. Trans. R. Soc.* B290, 169 (1980).

100 Years ago

The Mountain Nestor or Kea (Nestor notabilis). — Whatever may have formerly been thought to the contrary, there can be now no doubt that animals are continually changing their habits in order to suit themselves to the altered circumstances of their existence. A very familiar instance of this is that of the common swallow, which, in Europe at least, usually builds its nest in chimneys. But a much more striking and less laudable change of habit has of late years taken place in a New Zealand bird, of which we herewith give an illustration. Parrots, though varying much in the details of their diet, are generally considered to be altogether frugivorous. Fruit and seeds, and in certain special cases moss and honey, are, no doubt, their proper food. But since the introduction of the domestic sheep into New Zealand the Mountain Nestor, which was previously content with a modest repast of an entirely vegetable character, has developed a taste for mutton. Many instances have now been recorded of this bird attacking not only sick and dying sheep, but; it is alleged, even those that are strong and healthy, though we should hardly suppose that this parrot exists anywhere in sufficient numbers to be likely to do the flock-masters any serious injury.

From *Nature,* 24, 534 (1881).