The Optic Flow Field: The Foundation of Vision

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The optic flow field: the foundation of vision

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As a basis for understanding the visual system, we need to consider the functions that vision has to perform, which are pre-eminently in the service of activity, and the circumstances in which it normally operates, namely when the head is moving. The fundamental ecological stimulus for vision is not a camera-like time-frozen image but a constantly changing optic array or flow field, the description of which must be in spatio-temporal terms. A mathematical analysis of the optic flow field is presented, revealing the information that it affords for controlling activity – information both about the topography of the environment and about the movement of the organism relative to the environment. Results of human behavioural experiments are also reported. It is suggested that the optic flow field should be the starting point in attempting to discover the physiological workings of the visual system.

1. Introduction

An animal is constantly active when awake, moving around its environment, interacting with objects and other organisms, and so on. Even when simply sitting or standing still and looking at something, the body is always swaying slightly and the sway has to be actively kept in check. The result of this continual activity is that the head is always moving relative to the environment and so the animal's view of the world is constantly changing. This means that the ecological stimulus for vision is a globally changing optic array or optic flow field. In other words, the ecological stimulus is inherently spatio-temporal.

Activity is also spatio-temporal. It occurs in space-time. The guidance of activity therefore requires that spatio-temporal information be obtainable through the perceptual systems. This paper is about how the optic flow field affords information for controlling activity.

2. Perceptuo-motor coordination

Over 40 years ago, Bernstein (cited in Bernstein 1967) offered two significant insights into how body movements are coordinated and regulated. First, from his empirical studies of rhythmical movements such as walking, which revealed a high homogeneity of movement of a form that could not be attributed to simple mechanical factors, he argued that there must exist in the central nervous system exact 'formulae of movement' which contain the whole course of the movement over time. Lashley (1951) had basically the same idea, arguing that all skilled activity involves the problem of serial ordering of units of action and so there must exist internalized 'schemata' which direct the sequencing of these units.

What form do these formulae of movement take? The answer might seem obvious: specific temporal patterns of efference to the muscles. This was the classical view. However, Bernstein's second insight was that this cannot be. For since the effect of the efference will necessarily vary, e.g. with the prevailing external forces on the limbs, which are never completely predictable, there cannot exist an unequivocal relation between the efference and the form of the movement.

Also, basically the same movement can be made by using quite different muscle systems (e.g. signing one's name on paper and on a blackboard). Bernstein therefore concluded that movements must be directed in terms of an internalized motor image or program corresponding to the intended form of the movement, and that continual perceptual regulation of the program was necessary.

Bernstein, like most present researchers (see, for example, Stelmach (ed), 1976), was mainly concerned with the control of movements involving minimal interaction with the environment. Consequently, his and most current theories lack sufficient regard for the important role that must be played by the perceptual systems, particularly vision, in the control of normal everyday activities like locomotion through an obstacle-laden environment.

A comprehensive theory of perceptuo-motor coordination must address the question: What types of information are required in controlling movement relative to the environment? Gibson (1966) postulated that there are two basic types of information needed: *exterospecific* information about the layout of the surfaces in the environment and about external objects and events, and *propriospecific* information about the animal's own bodily movements. Such a binary conception, however, tends to obscure the fact that the animal is in interaction with its environment. To control this interaction, the animal needs information about the position, orientation and movement of its body as a whole or part of its body relative to the environment. Lee (1978) proposed the term *expropriospecific* in an attempt to capture the relativistic nature of the information.

How does expropriospecific information fit into the scheme of motor control? Let us consider, for example, the control of locomotion. Given that locomotor acitivity must be directed by a motor program and that the program has to be continually regulated to correct for deviations of the activity from its intended course, the question arises as to how it is regulated. Since it is only the yet-to-run sections of the motor program that can be adjusted, it seems clear that what is required is expropriospecific information that is *predictive*, in the sense that it is of such a form that it can be integrated with the current motor program to yield a prediction of the potential future course of the locomotion were the program left to run, and that it is on this basis that upcoming sections of the motor program are regulated. In the following section I shall show how such predictive information is available in the optic flow field.

3. THE OPTIC FLOW FIELD

What information is available in the light at the eye for controlling activity? Gibson (1950, 1958, 1966) was the first to tackle this problem and the following analysis owes much to his insights. Only an outline of the analysis will be given; for more details see Lee (1974, 1976) and Lee & Lishman (1977).

The environment consists of material substances bounded by surfaces. It is by means of the light reflected from the surfaces that visual perception is possible. Now a surface does not reflect light uniformly, unless it is mirror-like. It contains facets, patches of differing pigmentation and so on. In short, a surface may be considered to be densely covered with *texture elements* which reflect light differently from their neighbours. Thus the light reflected from the surfaces in the environment forms a densely structured optic array at a point of observation. The optic array may be thought of as a bundle of narrow cones of light with their apices at the point of observation; each cone has as its base a distinct environmental texture element and is thus optically

differentiable from its neighbours in terms of the intensity and/or spectral composition of the light it contains.

At each point of observation there is a unique optic array. Consequently, when the head is moving relative to the environment, as it normally is, the optic array at the eye is never the same from one moment to the next. The array changes continuously over time, giving rise to an *optic flow field*. A convenient way of describing the optic flow field is in terms of the changing pattern of light incident on a projection surface that intercepts the time-varying optic array. Since the description of the optic flow field in terms of its projection on one surface can be uniquely transformed into a description for any other surface, the choice of a projection surface is simply a matter of convenience. For clarity of exposition, we shall here consider the projection of the optic flow field onto a plane surface behind the point of observation, like the image plane of a camera.
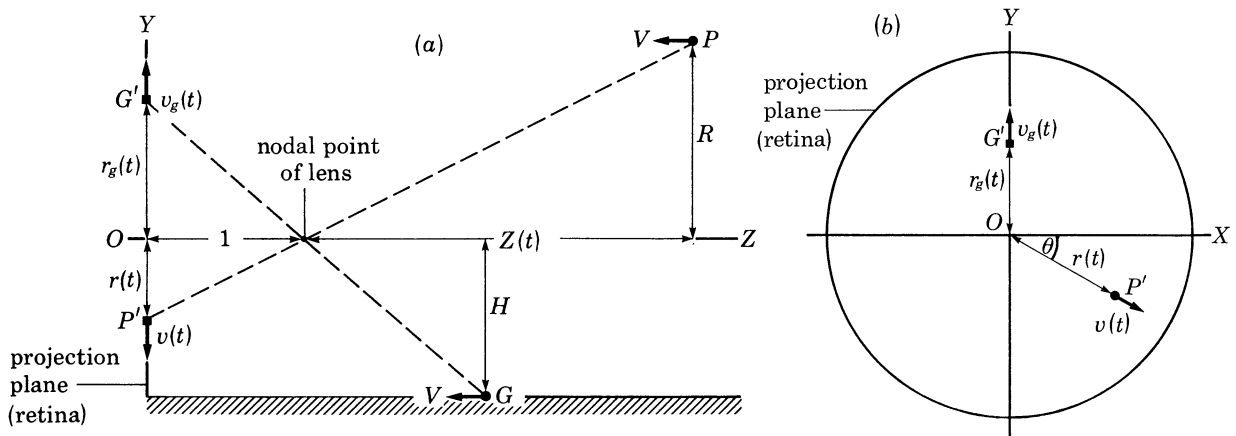

FIGURE 1. Showing how rectilinear movement of the point of observation relative to the environment generates an optic flow field. The schematic eye is considered to be stationary and the environment moving towards it with velocity V in the direction Z to O. P and G denote texture elements on surfaces in the environment, G being on the ground surface. Light reflected from the moving environmental texture elements passes through the nodal point of the lens giving rise to the moving optic texture elements P' and G' on the 'retina'. The densely textured environment gives rise to a densely textured optic flow field wherein all optic texture elements move outwards along radial flow lines emanating from O. How the optic flow field affords information about the environment and about an animal's movement relative to it is explained in the text. (Modified from Lee (1974).)

Let us start by determining the general structure of the rectilinear optic flow field that results when the point of observation is moving along a straight path through a rigid environment. It is equivalent geometrically to consider the point of observation to be stationary and the environment moving relative to it. In figure 1 the environment is moving with velocity V towards the point of observation in a direction perpendicular to the projection plane. P and G denote environmental texture elements; P' and G' denote the corresponding optic texture elements. It is clear that whatever the layout of the surfaces in the environment the optic flow field has the following invariant property: all optic texture elements move outwards along radial flow lines emanating from O, the centre of the projection plane (see figure 1, also figure 3 *a, b*).

There is a second important invariant property of the optic flow field relating to the fact that during movement of the point of observation surfaces go out of view and come into view as they are progressively occluded and disoccluded by nearer surfaces. The reflexion of this fact in the optic flow field is that when an optic texture element moving along a radial flow line catches

up with a slower moving element, it 'occludes' or replaces it. This is because the faster moving optic element corresponds to a nearer environmental texture element (see equation (2), §3c).

It has been shown that the above two invariant properties of the optic flow field geometrically specify that the point of observation is moving rectilinearly relative to a rigid environment (Lee 1974). In other words, there is available in the optic flow field information about the physical state of affairs. To test whether this information is actually picked up by the visual system, and, if so, how potent the information is, human subjects were given visual information about how they were moving relative to the environment which conflicted with the information available through their other senses. This was done by moving their visible surroundings – a floorless 4m × 2m × 2m suspended 'room' – in such a way as to produce optic flow fields at their eyes that corresponded to forward and backward movement of themselves.
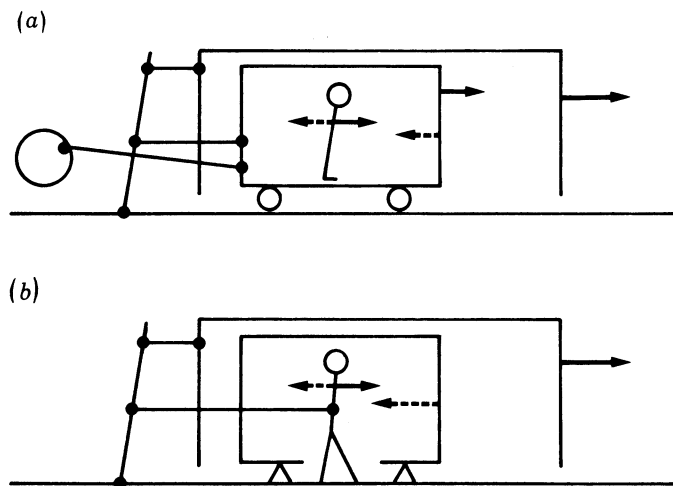

FIGURE 2. Experiments on visual perception of ego movement. (a) Passive movement: crank moves subject on trolley and surrounding 'room' (at twice the speed) forwards and backwards. (b) Active movement: with trolley floor removed, subject steps forward and back on laboratory floor moving the 'room' with him at twice his speed. Only one direction of movement is illustrated. Solid arrows indicate the movement relative to the laboratory floor. Broken arrows indicate the visually specified movement – the movement relative to the 'room'. The lengths of the arrows are proportional to speed. In each experiment, 13 out of 16 subjects reported that they and the trolley were moving in the visually specified way shown; they perceived the 'room' to be stationary. The remaining subjects' reports were confused: none apprehended what was actually happening. (Modified from Lishman & Lee (1973).)

(a) Visual perception of ego movement

In one set of experiments (Lishman & Lee 1973), the subject was in a trolley inside the experimental room. Several combinations of room and trolley movement were used in two subsets of experiments. In the passive movement experiments, the subject stood on the trolley floor while the room and trolley were moved by the experimenter. In the active movement experiments, the subject himself moved the trolley and room by holding a bar connected to a lever system and walking back and forth either on the trolley floor or, with that removed, on the real floor beneath the trolley. Figure 2 shows two of the twelve experimental conflict situations. In the great majority of cases, vision dominated the conflict. The movement of the self experienced was not the movement relative to the Earth but the visually specified movement relative to the experimental room, which was perceived to be stationary. This might seem particularly

strange in the active movement cases (see, for example, figure 2b). Surely the subjects knew when they were stepping forward and when they were stepping back. The experiments, in fact, bring to light the distinction between propriospecific and expropriospecific information, between sensing one's bodily actions and sensing how one is moving relative to the environment as a result of those actions. Swimming in a current illustrates this point well; without vision, the swimmer cannot tell how he is moving relative to the shore. For further evidence on the power of vision in specifying movement relative to the environment see Johansson (1977), Turvey & Remez (1978), Warren (1976) and Wehrhahn & Reichardt (1975).

(b) The role of vision in balance control

Maintaining stance is a fundamental motor skill. It requires exapropriospecific information about the orientation and sway of the body relative to the environment. The classical view, still current in many textbooks, was that the information is obtained primarily through the vestibular system and the mechano-receptors in the feet and ankles. The experiments described in § 3a, however, lead to the suspicion that vision plays a major role in balance control.

In a series of experiments with the use of the moveable room to simulate the visual effects of body-sway, this suspicion was confirmed (Lee & Aronson 1974; Lee & Lishman 1975). The main conclusion drawn from the experiments was that vision generally affords the most sensitive and reliable information for balance and is an integral component of the control system. For example, oscillating the experimental room through as little as 6 mm caused adult subjects to sway approximately in phase with this movement. The subjects were like puppets visually hooked to their surroundings and were unaware of the real cause of their disturbance. Vision was found to be especially important, often crucial for balance control (a) when the support surface is compliant, unsteady or narrow, which renders unreliable the information obtainable through the feet, and (b) when learning a new stance, which requires attunement to unfamiliar afference from the feet and ankles. Toddlers and adults in unpractised stances could readily be knocked off balance by movement of the experimental room. However, while balance is often impossible without vision when first learning a new stance, with practice vision often becomes non-critical, suggesting that visually guided practice facilitates attunement to information available through the feet. This is supported by experiments with blind people who were found to sway twice as much as sighted people with their eyes closed (Edwards 1946). Recent neurophysiological work by Glickstein & Gibson (1976) and Thoden et al. (1977) has suggested possible anatomical mechanisms whereby visual information is incorporated into balance control.

(c) Visual information about the relative layout of the environment

Let us now examine in more detail the structure of the rectilinear optic flow field to determine what other information it contains for controlling activity. What we are seeking are properties of the optic flow field that afford information about the geometrical layout of the surfaces in the environment and about the animal's movement relative to its environment.

The position of an environmental texture element P relative to the eye may conveniently be defined by the distance coordinates $Z(t)$ and R shown in figure 1, together with the angle between the OZP and OZX planes. This angle is specified in the optic flow field by the angular coordinate θ of the optic texture element P'. But are the distance coordinates $Z(t)$ and R optically specified? From similar triangles,

$$Z(t)/R = 1/r(t). \tag{1}$$

This equation is an expression of the well known problem of the missing depth dimension which arises when the visual stimulus is treated as an image, a time-independent spatial structure. The problem is that the *position* of an optic texture element specifies only the direction in which an environmental texture element lies, not its distance away. This problem of the missing depth dimension has puzzled theorists for a century or more and has led to the view that there must be embodied in the visual system quite detailed 'assumptions' about what is being viewed for three-dimensional perception to be possible. However, if we examine the spatio-temporal structure of the visual stimulus, we find that the depth dimension is not in fact missing.

Differentiating equation (1) with respect to time we obtain

$$R/V = r(t)^2/v(t), \tag{2}$$

where $V = -\mathrm{d}Z(t)/\mathrm{d}t$ is the velocity of the environmental texture element P and $v(t) = \mathrm{d}r(t)/\mathrm{d}t$ is the velocity of the corresponding optic texture element P' (see figure 1). Eliminating R between (1) and (2),

$$Z(t)/\dot{V} = r(t)/v(t). \tag{3}$$

These equations, (2) and (3), mean that the distance coordinates $(R, Z(t))$ of all visible texture elements are optically specified to within a scale factor of V. In other words, there is information available in the optic flow field about the relative distances, sizes and orientations of surfaces and objects in the environment (see also Koenderink & van Doorn 1977; Nakayama & Loomis 1974).

In § 3e we shall examine how this spatial information might be body-scaled for use in controlling activity, but first let us consider another important type of information given in the optic flow field, namely temporal information.

(d) Visual information about time-to-contact

In (3), $Z(t)/V$ is the time that will elapse before the point of observation is level with the surface texture element P. The equation states that the time is optically specified by the value of $r(t)/v(t)$. This higher-order optic variable $r(t)/v(t)$ – which gives rise to the experience of an obstacle 'looming up' – is an important one, for it affords information for timing actions relative to the environment. For example, if the texture element P lies on a surface directly ahead, the optic variable specifies the time-to-contact with that surface. This is the type of information that a bird, for instance, needs in preparing to land.

In the following sections it will be shown how the optic variable $r(t)/v(t)$ affords information for controlling various types of locomotor activity. The variable appears to be a particularly informative one. I shall designate it by the symbol $\tau(t)$, thus

$$\tau(t) = r(t)/v(t), \tag{4}$$

and treat $\tau(t)$ as the basic variable associated with an optic texture element rather than its velocity $v(t)$. Thus, by using (4), (2) and (3) may be written as

$$R/V = r(t)\,\tau(t) \tag{5}$$

and

$$Z(t)/V = \tau(t). \tag{6}$$

(e) Visual body-scaled information

In §3c we showed that there is available in the optic flow field information about the relative sizes and distances of objects and surfaces in the environment. This purely exterospecific information is, however, of little functional value to an animal. What it basically needs is information that is relevant to controlling its activity, e.g. that a hurdle is a certain fraction of its own height, so many strides away and so on. That is, an animal needs body-scaled information about its environment. The following are two ways that body-scaled information might be obtained from the optic flow field.

Consider an animal running straight over a level stretch of ground. Suppose at a particular time t its speed is V. One bodily yardstick it could use is the height H of its eye above the ground, which will be more or less constant. Since H is the R-coordinate of any texture element on the ground over which the animal's eye will pass, applying (5) to the ground texture element G depicted in figure 1,

$$H/V = r_g(t)\, \tau_g(t),\tag{7}$$

and eliminating V between (5), (6) and (7),

$$R/H = r(t)\, \tau(t)/(r_g(t)\, \tau_g(t))\tag{8}$$

and

$$Z(t)/H = \tau(t)/(r_g(t)\, \tau_g(t)).\tag{9}$$

In other words, there is a particular relation between the optic flow from the line of ground ahead and the optic flow from other environmental texture elements which specifies the distances and sizes of surfaces and objects in the environment in units of the animal's eye height. A horse, for instance, presumably needs such information when preparing to leap a fence.

Another bodily yardstick is stride length or stride duration. Consider a long jumper approaching the take-off board. The athlete not only has to strike the board but has to do so in the right posture for take-off. The last few strides to the board are critical in setting up the right posture. Now a skilled athlete can, after sprinting 40 m, strike the take-off board with a standard error of about 10 cm. How is such accuracy achieved? Since no adjustments to the stride pattern are normally apparent, many coaches and athletes believe that it is all a matter of developing a standard run-up. However, a recent film analysis of athletes showed that their run-ups were nowhere near as standard as they thought (Lee *et al.* 1977). The standard errors of their footfall positions increased considerably down the track, reaching a peak of 35 cm for one Olympic athlete. Over the last three strides, however, the standard error decreased dramatically to about 8 cm at the take-off board, the length of each stride being highly correlated with the athlete's distance from the board.

The athletes were clearly visually adjusting the lengths of their last three strides to zero-in on the take-off board. Furthermore, since the total duration of these three strides was only about 0.7 s, it is likely that they were programming these strides as a unit. What visual information could the athletes have been using? One possibility is information about time to reach the board (specified by the value of the optic variable $\tau(t)$ corresponding to the board), for the task of zeroing-in on the board may be conceived of as programming the durations of the forthcoming strides to just fill the time remaining to reach the board. This temporal conception of the task is probably more appropriate than a spatial one (i.e. programming stride lengths), since the athlete has direct control over the duration of his strides by how hard he thrusts on the ground, whereas the length of his strides are a function also of his speed of travel.

(f) Visual information for controlling braking

Consider a driver approaching an obstacle in the road. How does he manage to stop safely? He not only has to start braking early enough but he also has to adjust his deceleration to an adequate level during the stop (if, for instance, he brakes too lightly to begin with he will run out of braking power). In other words, a driver can get himself into a 'crash state' (i.e. when his current speed is too high in relation to his distance from the obstacle) well before he actually hits the obstacle.

How does a driver avoid getting into a 'crash state' while he is braking? He clearly needs visual expropriospecific information about how he is closing on the obstacle so that he can appropriately adjust his braking. It might seem that he needs to obtain information about his distance from the obstacle, his closing velocity and deceleration, and then perform complicated mental calculations. However, this is not necessary: the value of the time derivative of the optic variable $\tau(t)$ corresponding to the obstacle affords him sufficient information.

Suppose that at a time t the driver is a distance $Z(t)$ from the obstacle, his instantaneous velocity is $V(t)$ and he is braking with a deceleration D. Then his deceleration D is adequate if and only if the distance that it will take him to stop with that deceleration is less than or equal to his current distance from the obstacle, i.e. if and only if

$$V(t)^2/2D \leqslant Z(t),$$

or

$$Z(t)\,D/V(t)^2 \geqslant 0.5. \tag{10}$$

Now $Z(t)/V(t)$ is specified by the value of the optic variable $\tau(t)$ for the obstacle (see equation (6)), i.e.

$$Z(t)/V(t) = \tau(t); \tag{11}$$

differentiating this equation with respect to time we obtain

$$Z(t)\,D/V(t)^2 = 1 + \mathrm{d}\tau(t)/\mathrm{d}t. \tag{12}$$

Hence, from (10) and (12), the value of the time derivative of the optic variable $\tau(t)$ specifies whether the driver's current deceleration is adequate or not. It is adequate if and only if

$$\mathrm{d}\tau(t)/\mathrm{d}t \geqslant -0.5. \tag{13}$$

In other words, the driver has available visual exropriospecific information about his potential future course were he to maintain his current braking level. A safe braking strategy would consist in the driver adjusting his braking so that $\mathrm{d}\tau(t)/\mathrm{d}t$ remained as a safe value. The deceleration profiles produced by this hypothetical braking strategy (Lee 1976) in fact matched quite closely those of test drivers recorded by Spurr (1969), the only data on visually controlled braking found in the literature.

(g) Visual information for controlling steering

How does a driver control his steering? As with braking, the driver can get himself into a 'crash state' well before he actually runs off the road. This can occur not only if he takes a bend too fast but also if he does not adjust his steering early enough on a bend and so gets into the situation where he needs to steer an impossibly tight curve. What the driver needs is visual exropriospecific information not so much about his current position on the road but about his

potential future course were he to maintain his current steering angle. This is, in fact, specified in the optic flow field at his eye (see figure 3). McLean & Hoffmann's (1973) investigations of straight-lane driving indicated that drivers do use such visual information. They found that steering adjustments were made primarily on the basis of heading angle (corresponding to potential future course) rather than current lateral position on the road.
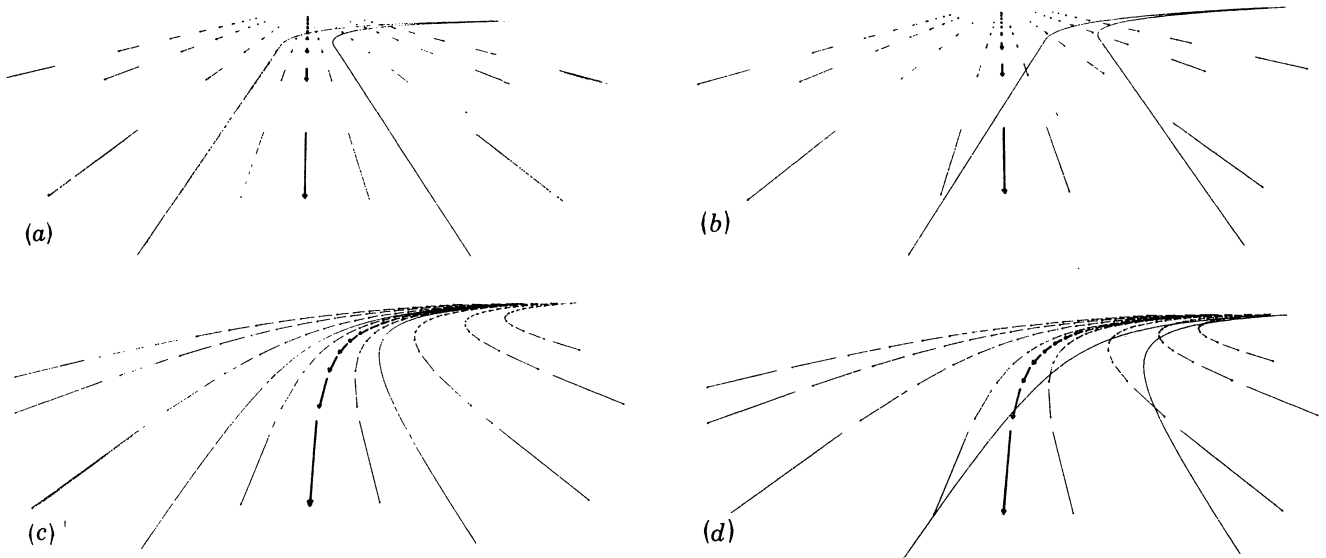

FIGURE 3. The optic flow field, projected onto a plane as in figure 1, when driving down a road. The solid lines represent the edges of the road, the broken ones the optic flow lines. The central heavily drawn flow line is the 'locomotor flow line': it specifies the potential future course of the vehicle were the current steering angle to be maintained. (a) Steering straight towards a bend on course. (b) Steering straight but off course. (c) Steering a bend of uniform curvature on course. (d) The same but off course. To see how the optic flow fields are generated, consider the vehicle to be stationary and the ground moving under it. In (a) and (b), points on the ground are moving along parallel straight paths: the radiating optic flow lines are the projections of these paths. In (c) and (d), points on the ground are moving along concentric circular paths, the centre corresponding to the centre of curvature of the vehicle's path: the hyperbolic optic flow lines are the projections of these paths. (Modified from Lee & Lishman (1977).)

4. CONCLUDING REMARKS

As Neisser (1977) has pointed out, any account of visual perception must entail as a logical primitive an adequate description of what is available to the eye. Equally importantly, a theory of visual perception must take into account the functions performed by vision. In this paper we have been concerned with the fundamental function of vision which, it is argued, is the obtaining of information in the service of activity, and with formulating a description of the input to the eye that takes cognisance of the fact that the input is constantly varying over time. It is suggested that it is with this type of analysis that one needs to start in seeking to discover the actual mechanisms of vision.

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Discussion

H. Kalmus (*Galton Laboratory, University College, Gower Street, London, WC1, U.K.*). Some of Dr Lee's ideas concerning the optical flow field can be expanded and synthesized into a mathematical theory by considering results from work on optomotor reactions of insects, performed long ago (Kalmus 1948).

Insects, for instance flies, are more suitable than man for studying visual movement in large areas, because they have a wider visual field, lack a vestibular system and possess a smaller array of possible reactions.

Developing Dr Lee's remarks that visual perception and locomotion form one system which performs 'sensory motor skills', it can be stated that just as any movement or dislocation of a rigid body can be described as a sum of translation and rotation, so a class of coherent contour movements in the environment can – in insects at least – be partitioned into a translational and a rotational component, which correspond to the momentum and angular momentum in