

Visuo-Motor Coordination in Space-Time

From: Lee, D. N. (1980), In G. E. Stelmach & J. Requin (Eds.), *Tutorials in Motor Behavior* (pp. 281-295), Amsterdam: North-Holland.

Abstract Activity takes place in a space-time world. It therefore requires spatio-temporal information for its guidance. Where does this information come from? Since activity involves movement relative to the environment it generates a constantly changing optic array at the eye - a spatio-temporal optic flow field. This paper sets out to examine the cooperative relationship between vision and action - how the optic flow field yields spatio-temporal information for guiding activity and how activity makes that information available. The central thesis is that the visual system and the motor system are functionally inseparable: they are components of a unified perceptuo-motor system, which is itself a component of the organism-environment system.

INTRODUCTION

"Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality."

H. Minkowski, 1908

Though Minkowski was addressing a meeting of physicists in the early days of Relativity Theory, his words are equally germane for students of motor control. For actions are performed in a space-time world and controlling activity means directing it through "points" in space-time. Running to intercept a cross-ball at soccer or playing a tennis shot are clear examples of skills requiring getting both to the right place and at the right time. Furthermore, it makes no sense, if the player happens to miss the ball, to attempt to attribute this either to an error in spatial judgment or to a timing error, for success could have been achieved by getting either to the same place at a different time or to a different place at the same time - or, indeed, to a different place at a different time. The error is a

(opposite) **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)

At each point of observation there is a unique optic array. It is the passage of the eye through successive points of observation that gives rise to the optic flow field at the eye. A convenient way of describing the optic flow field is in terms of its interception with a projection surface. For the purpose of analysis, it is immaterial the projection surface we choose 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. For clarity of exposition, we will 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, and confine our attention to the analysis of the rectilinear optic flow field i.e., that which results when the eye is moving along a straight path through the environment. (For an analysis of the curvilinear optic flow field see, e.g., Lee & Lishman, 1977).

It is easier to explain, and equivalent geometrically, if we consider the eye stationary and the environment moving. Figure 1 shows the environment moving with velocity V towards the eye in a direction perpendicular to the projection plane (the schematic retina). P and G denote any two environmental texture elements, G being on the ground. Corresponding to P and G are the optic texture elements P' and G' . It is clear that whatever the layout of surfaces in the environment the optic flow field has the invariant property that all optic texture elements move outwards along radial flow lines emanating from the centre O of the "retina". (With backward movement of the observer, the optic flow is inwards towards O .)

It has been shown mathematically (Lee, 1974) that the existence of a rectilinear optic flow field at the eye specifies that the eye is moving along a straight path through the environment; i.e., the flow field could not have been

generated in any other way (except by artifice). In other words, there is visually available exproprioceptive information about the organism's movement relative to the environment. That this is potent information has been demonstrated experimentally. The human subjects' visible surroundings - a floorless "swinging room" suspended from a high ceiling - were moved in such a way as to produce optic flow fields at their eyes corresponding to forward and backward or sideways movement of themselves. The experiments showed that vision affords the most sensitive exproprioceptive information about body sway for controlling standing balance, both in toddlers (Lee & Aronson, 1974) and in adults (Lee & Lishman, 1975) and that when a person has conflicting visual and non-visual exproprioceptive information about the direction in which he or she is walking or being passively moved, the conflict is normally dominated by vision (Lishman & Lee, 1973).

Let us now turn to a more detailed analysis of the optic flow field to determine the information it contains about the layout of the surfaces in the environment and about the moving organism's dynamic relationship to those surfaces. Returning to Figure 1, the position of an environmental texture element P relative to the eye may be defined by the distance coordinates $Z(t)$ and R 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

$$Z(t)/R = 1/r(t) \quad (1)$$

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, or else that depth perception requires binocular vision. However, if we examine the spatio-temporal structure of the optic flow field we find that the depth dimension is not in fact missing. Differentiating equation (1) with respect to time we obtain

$$R/V = r(t)^2 / v(t) \quad (2)$$

where $V = -dZ(t)/dt$ is the velocity of the eye relative to the environment and $v(t) = dr(t)/dt$ is the velocity of the optic texture element P . Eliminating R between equations (1) and (2)

$$Z(t)/V = r(t)/v(t) \quad (3)$$

These equations (2) and (3) mean that the distance coordinates ($R, Z(t)$) of all visible environmental texture elements are optically specified in terms of the organism's velocity.

Equation (3) is particularly informative. It states that the time remaining before the eye will be level with the texture element P (assuming the current velocity V were maintained) is directly specified by the value of the optic variable $r(t)/v(t)$. In particular, if there is a frontal plane surface ahead, then the value of the optic variable specifies the *time-to-contact* with the surface; in this case the value of the optic variable will be the same for all points on the surface and equal to the inverse of the rate of dilation of the optic image of the surface (Lee, 1976). In the following sections we will examine how the optic variable specifying time-to-contact under constant approach velocity affords information for controlling various activities, including those where the approach velocity is not in fact constant. Since the optic variable appears to be a particularly informative one we will give it its own symbol $\tau(t)$.

CATCHING AND HITTING

Catching a ball requires not only getting the hand to a place where the ball will be and appropriately orienting it but also starting to close the fingers *before* the ball reaches the hand. Alderson et al. (1974) in a high speed cine analysis of one-handed catching of tennis balls projected from about 6m found that the fine orientation of the hand started about 150-200ms before the ball contacted the

palm and the grasp started 32-50ms before and ended about 10ms after contact. Taking into account the time taken for the ball to pass from the outstretched finger tips to the palm (ca 16ms) and the velocity with which the ball would rebound from the palm of the hand (ca 2.5ms) they calculated that the error margin for the timing of the grasp was from about 16ms before to less than 30ms after the optimum time. In successful catches their subjects initiated their grasps within about ± 14 ms of the optimum time.

Such precise timing of the grasp must be based on equally precise predictive visual information about the time of arrival of the ball at the hand. It seems likely that the catcher uses the directly available visual information about time-to-contact discussed above. This information would have to be available an adequate time before contact so that the preparatory orienting of the hand leading on to the start of the grasp can be accurately timed. Sharp and Whiting's (1974, 1975) experiments indicate that the critical time for the information to be available to the eye is when the time-to-contact is about 300ms. The subjects' view of the tennis ball, projected from about 7m, was limited by turning on and off the room lights. In their 1974 study where they used exposure periods of 20-160ms, one-handed catching performance was best (about 50%) when the ball was visible for at least 40ms when about 300ms from contact with the hand. Longer exposure periods up to 160ms spanning the 300ms time-to-contact point had no significant effect on performance. In their 1975 study they found that catching performance increased to about 85% when the ball was visible for 240ms up to the 300ms time-to-contact point. This longer exposure would allow time for the subject to foveate the ball, thus making available more precise visual information about time-to-contact.

Why should there apparently be an optimum time-to-contact of about 300ms when the catcher needs to see the ball? It is reasonable to suppose that the decrement in performance when the ball is only seen when less than 300ms away is due to there being inadequate time to properly program and execute the reaching and catching movement. But why should earlier (i.e., longer) time-to-contact information be not so effective? Consider again the catching task. The performer has to reach out, orient the hand and start the grasping action, this whole movement having to be accurately timed to occupy the time-to-contact interval. In principle, there are two temporal degrees of freedom which the performer has to control: when to initiate the movement and its duration. An efficient solution to the visuo-motor problem would be, with practice, to

standardise the duration of the movement thereby reducing the problem to that of initiating the movement at a specific time-to-contact. In a study of a similar skill involving moving a slider in a frontal plane to hit a target directly approaching at a constant speed, Schmidt (1969) found that subjects tended to keep their movement durations constant, achieving a mean absolute timing error of 20-30ms (about the same as found by Alderson et al. (1974) in ball catching). In a later related study, Schmidt and MacCabe (1976) found that movement time became more consistent with practice.

Hitting a ball similarly involves precise timing, and again there is evidence that performers tend with practice to develop a standard movement duration. Tyldesley and Whiting (1975) found that for expert and intermediate table-tennis players the durations of their forehand drive shots were consistent to within about ± 4 ms, whereas novices showed no such consistency. In a film analysis of baseball batters, Hubbard and Seng (1954; see also an analysis by Fitch & Turvey, 1977) found that the batters tended to synchronize the start of their step forward with the release of the ball from the pitcher's hand, adjusted the duration of the step to the speed of the ball and kept the duration of their swings constant. The timing of the initiation of the swing appears to be based on time-to-contact information picked up during the 500ms or so that the ball is in flight.

The visuo-motor skill of intercepting a moving object appears to start developing at an early age. Hofsten and Lindhagen (1979) found, for example, that 18 week old infants could reach out and catch an object moving across in front of them at 0.3ms^{-1} . Their results indicated that by the time infants have mastered reaching for stationary objects they can also catch moving ones, suggesting that there is a basic human capacity to coordinate behaviour with external events.

PLUNGE DIVING

The prey-catching behaviour of the gannet (*Sula bassana*) is a beautiful example of finely timed activity. This large seabird (length about 0.9m wing-span 1.70m) hovers over the water at heights up to about 30m. When it sights its prey it plunges down with wings half open, presumably to give it some steerage, and then just before hitting the water it starts to fold its wings so that its body is streamlined for entering the water. Given that from a height of 30m it

will hit the water at about 25ms^{-1} or 55 miles h^{-1} , it clearly has to time the folding of its wings very precisely to avoid possible fatal injury. It normally catches its fish on its way back up to the surface.

How does the gannet time the folding of its wings preparatory to entering the water? A recent film analysis of ten plunge dives indicated that the birds do not allow themselves much of a safety margin. The mean time before hitting the water when they started to fold their wings was about 310ms (S.D. 90ms, range 200-440ms) and the mean time taken to fold their wings was about 400ms (S.D. 80ms, range 240-520ms). Only two of the birds had their wings completely folded when they hit the water, but they all had before they were submerged. Given the range of heights from which the birds were diving (about 4 - 12m) and hence the range of falling times (about 900-1550ms) it is infeasible that the dive is simply a stereotyped act with the wings being programmed to fold an invariant time after the start of the dive.

The timing of the wing folding clearly appears to be under visual guidance. What type of visual information might the birds be using? While it is theoretically conceivable that the bird might visually determine its hovering height, from this compute how long it will take to reach the water and then pre-program the timing of its wing folding, this does not seem very likely if only because the vicissitudes of the wind could easily set its predictions much awry. It seems most probable that the bird determines when to fold its wings on the basis of visual information picked up during its dive.

The film analysis indicated that the birds based their judgments on information about their *time* away from the water rather than their distance away, which makes sense in view of their varying speeds of contact with the water. For example, in a 12m dive the bird started to fold its wings when it was about 5.5m above the water whereas in a 4m dive the wing folding started at a height of about 2.3m, but the times away from the water when wing folding started were quite similar (400ms and 320ms respectively). It is interesting to note, however, that the wing folding started earlier with the higher dive. This general tendency shown in the film data suggests the type of temporal information the birds might be using.

For the bird to compute its actual time-to-contact with the water when diving would be a complex task requiring information about its current speed and distance away from the water and its acceleration. There is, however, a simple heuristic that the bird could use, which is to initiate its wing folding when the

optic variable τ (the inverse of the rate of dilation of the image of the water) reaches a certain margin value τ_m . As was shown in Section 2, the value of τ specifies the time-to-contact with the water if the current speed were to be maintained. It does not therefore specify the gannet's actual time-to-contact with the water, since the bird is accelerating. However, as we will show, it does constitute adequate information for timing wing folding. Furthermore, using this information would result in wing folding starting sooner before hitting the water the higher the dive, which is what the film data indicated.

Suppose the gannet starts diving from a height h_0 at time $t = 0$. Then at time t later its velocity v and its height h above the water will be

$$v = gt$$

$$h = h_0 - 0.5gt^2$$

where g is the gravitational acceleration. Thus the optic variable will attain the margin value τ_m at time t_m where

$$\tau_m = h/v = (h_0 - 0.5gt_m^2)/gt_m$$

i.e.

$$t_m = \sqrt{\tau_m^2 + 2h_0/g} - \tau_m \quad (4)$$

Now the bird's total falling time will be $\sqrt{2h_0/g}$ and so at time t_m , when $\tau = \tau_m$, its actual time-to-contact t_c with the water will be, from Equation (4)

$$\begin{aligned} t_c &= \sqrt{2h_0/g} - t_m \\ &= \tau_m + \sqrt{2h_0/g} - \sqrt{\tau_m^2 + 2h_0/g} \end{aligned} \quad (5)$$

A graphical representation of this equation is given in Figure 2. The curves show how following the simple heuristic strategy of initiating wing folding when the value of the optic variable τ reaches a margin value τ_m would result in the wing folding starting at a longer time t_c before contact the higher the height h_0 of the dive, thus allowing a higher margin for error the greater the risk of injury. It would, of course, take the bird a certain response time to register that the margin value had been reached and to start the act of folding its wings. To allow for this, the values of t_c shown in Figure 2 would need to be lowered by this response time. Thus, for example, with a response time of 150ms and using

a margin value τ_m of 750ms, the time-to-contact where the wings would start to fold would be 300ms from a dive height of 3m and 480ms from 30m.

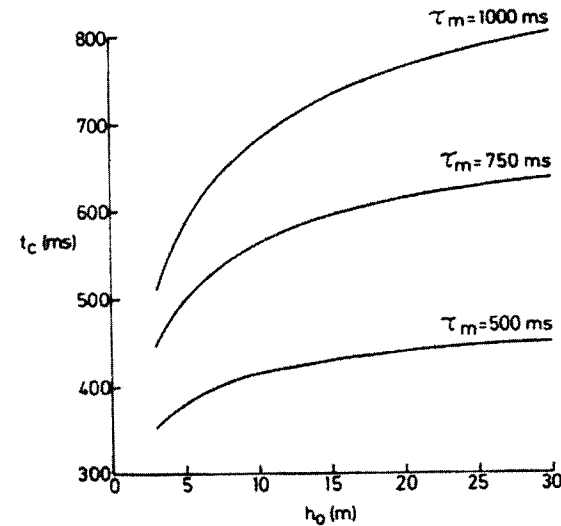


Figure 2. A graphical representation of equation 5.

RUNNING AND JUMPING

The importance of vision for movement control is particularly evident when one is walking or running through the normal cluttered environment. The motor program generating the coordinated pattern of locomotor movements has to be continually adjusted on the basis of visual and other sensory information in order to meet the demands of the terrain - adjusting to varying compliance of the ground, negotiating steps, securing adequate footing, leaping over obstacles and so on.

Consider a person running over a level stretch of ground. As Bernstein (1967) has shown, the coordinated pattern of limb movements is normally cyclicly very regular. In particular, the swing-through phase of each leg is accurately timed so that the foot strikes the ground in the right way, normally just in front of the hips. Now there are three components to the swing-through time: the first flight time (between the foot leaving the ground and the other foot striking it), the ground-contact time of the other foot and the second flight time.

The flight times will be determined by the vertical component of the launch velocity, which in turn will be determined by the strength of the thrust force applied to the ground and the compliance of the ground. For example, the same thrust applied to more compliant ground will result in a shorter flight time and hence require a shorter swing-through time. Thus in running over ground of irregular compliance, the temporal patterns of muscular forces controlling the swing-through and the thrusts on the ground have to be finely coordinated and adjusted to the terrain. The same is true when running over undulating ground. Here the flight times will vary with the undulations; stepping into a dip, for instance, will result in a larger flight time, requiring lengthening the swing-through time.

These examples illustrate some of the subtleties of locomotor control in which everyday experience suggests that vision plays a major regulatory role. For instance, running over undulating ground in the dark is a jarring experience, whereas in the light it is normally quite smooth. Another example is stepping off a kerb that one has not noticed. This brings us to another aspect of locomotor control, namely the shock-absorber action of the leg muscles. When the foot strikes the ground there is a sudden passive stretching force applied to the muscles which has to be adequately resisted to avoid jarring the skeletal structure. Melvill Jones and Watt (1971) have shown that this is achieved, at least in part, by tensioning the gastrocnemius muscle some 140ms *before* contacting the ground. That vision is essential for the programming of such preparatory activity is indicated by the study of Freedman, Wannstedt, and Herman (1976) on stepping down (e.m.g. recording from the triceps surae) and that of Dietz and Noth (1978) on falling on one's hands against an inclined board (e.m.g. recording from the triceps brachii). In both studies, preparatory muscular activity timed to cushion the landing occurred only when the subjects were allowed normal vision.

In running over uneven ground the timing of the swing-through and the preparatory shock-absorber action of the leg could be based on the visual information about time-to-contact discussed above. To be sure, a runner is in a different situation to a diving gannet; the runner needs information about time-to-contact of the foot with the ground whereas for the bird it is time-to-contact of the head with the water that matters. However, it can be shown that the type of heuristic strategy proposed above for the gannet would also work in timing landing on the feet. It will be remembered that following the strategy would

result in preparatory activity being initiated sooner before contact the higher the fall. This was observed in the film data on the gannet and is also evidenced in Greenwood and Hopkin's (1976, Fig. 5) data on the preparatory tensioning of the soleus muscle of a person's leg during sudden drops from different heights.

Let us now consider another locomotor control problem, that of securing adequate footing. Running over stepping stones is a good example. The person not only has to appropriately adjust the lengths of his strides but also has to land on each successive stone in just the right way else he will not be able to propel himself to the next stone. For example, if he is running down a straight line of stones and then has to veer to the right down another line, he has to land on the corner stone with his centre of gravity to the right of his foot. If the stones afford only narrow footing, this means that he has to prepare for the veer by launching himself off in the right direction from the stone before the corner one. In other words he has to plan at least two strides ahead. In a recent study involving such a set-up (small blocks of wood screwed to the laboratory floor), it was found that subjects often started preparing their veers by shifting their centres of gravity when they were about two strides from the corner stone, and that if they were prevented from seeing which way they had to veer until after they were about 150ms away from landing on the stone before the corner one then they could not veer successfully.

Running over stepping stones brings to light the problem of distance and size perception which so far we have discussed rather little. In Section 2 it was shown that there is available in the optic flow field at the eye information about the *relative* sizes and distances of surfaces in the environment, scaled in terms of the animal's velocity. However, what an animal 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, it needs *body-scaled* spatial information about its environment. Let us consider 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 yard-stick it could use is the height H of its eye above the ground, which will be more or less constant. Referring to Figure 1, H is the R -coordinate of any texture element on the ground over which the animal's eye will pass. Therefore, applying Equation (2), Section 2, to the ground texture element G depicted in Figure 1

$$H/V = r_g(t)^2 / v_g(t) \quad (6)$$

and eliminating V between Equations (2), (3) and (6)

$$R/H = r(t)^2 v_g(t) / r_g(t)^2 v(t) \quad (7)$$

$$Z(t)/H = r(t) v_g(t) / r_g(t)^2 v(t) \quad (8)$$

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 current distances away and the sizes of surfaces and objects in the environment in units of the animal's eye height.

Another potential bodily yard-stick is stride length. Suppose that at time t an animal's stride length is L and the duration of its strides is t_s . Then for any environmental texture element P (see Fig. 1) we have

$$Z(t - t_s) - Z(t) = L \quad (9)$$

Thus from Equation (3), and noting that $r(t)/v(t) = \tau(t)$, viz. the "time-to-contact" optic variable,

$$[Z(t - t_s) - Z(t)]/V = L/V = \tau(t - t_s) - \tau(t) \quad (10)$$

and so eliminating V between Equations (2), (3) and (10)

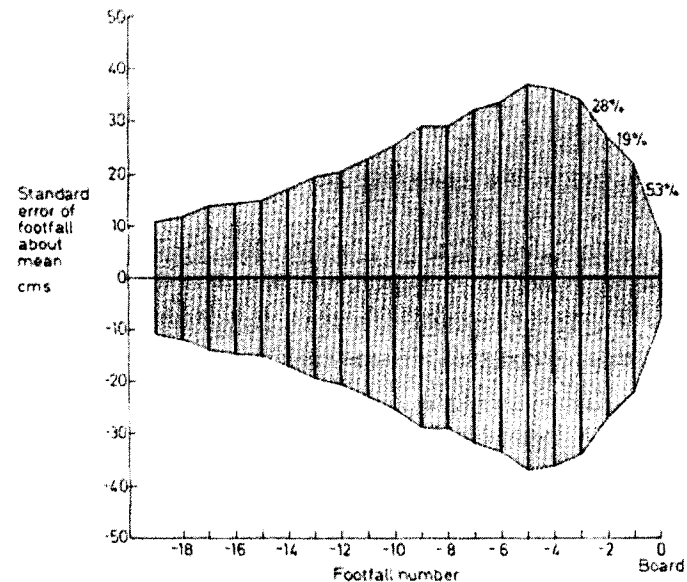
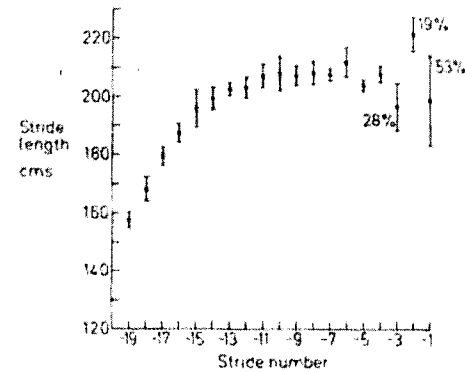
$$R/L = r(t) \tau(t) / [\tau(t - t_s) - \tau(t)] = r(t) \tau(t) / t_s \quad (11)$$

$$Z(t)/L = \tau(t) / [\tau(t - t_s) - \tau(t)] = \tau(t) / t_s \quad (12)$$

i.e., the current distances away and the sizes of surfaces and objects in the environment are optically specified in units of the animal's stride length.

As an example of the combined use of visual body-scaled spatial and temporal information, consider a horse jumping a fence. The horse needs body-scaled information about the height of the fence in order to determine how hard to thrust from the ground and time-to-contact information to determine when to

jump. (It may be said that it has to judge where to leap from, but the proper place depends on its speed whereas the proper time does not.) For the horse to achieve an optimally efficient jump where at its zenith it is just above the top of the fence, the energy that it needs to put into its leg thrust is essentially proportional to the height h that it has to raise its centre of gravity and the time-to-contact when it should start its jump is proportional to \sqrt{h} .



(opposite) **Figure 3.** Visual guidance in the long jump. Performance of an Olympic athlete over six jumps with a 40m, 21-stride run-up. (1) Means and standard deviations (SDs) of stride lengths for the last 19 strides to the take-off board. Note how high the SD is over the last three visually adjusted strides. (2) The SDs of successive footfall positions down the track. Note how the SB progressively increases up to a peak of 35cm and then suddenly drops to about 8cm over the last three strides. The percentages shown are estimates of the proportion of the total adjustment made on each stride, derived from linear regression analyses. (Modified from Lee, Lishman, & Thomson, 1977)

Another example is the long jump run-up. The athlete not only has to strike a narrow take-off board when running at maximum speed but also has to strike the board in the right posture for take-off, for while it is the horizontal momentum developed during the run-up that carries the athlete forward in the jump, it is the vertical take-off velocity that determines the duration of the jump and hence its length for a given run-up speed. Clearly, the last few strides to the board are critical in setting up the right posture for a powerful vertical thrust at take-off. Now a skilled athlete can, after sprinting 40m, strike the take-off board with a standard error of about 10cm. 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, Lishman, & Thomson, 1977). The standard errors of their footfall positions increased considerably down the track, reaching a peak of 35cm for one Olympic athlete (see Fig. 3).

Over the last three strides, however, the standard error decreased dramatically to about 8cm 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 their last three strides to zero-in on the take-off board. Furthermore, since the total duration of these three strides was only about 0.7s, 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 τ for the board), for the task of zeroing-in on the board may be conceived of as programming the durations of the forthcoming strides so as 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, as was pointed out above, a runner has direct control over the duration of his strides by how hard he thrusts vertically on the ground, whereas the length of his strides are a function also of his speed of travel.

DRIVING

The central theme of this paper has been that activity takes place in a space-time world, that controlling activity means directing it through "points" in space-time and that this requires perceptual spatio-temporal information. By considering a variety of skills it has been attempted to show that no matter how purely spatial a skill might appear, temporal information is always required and could indeed substitute, in part at least, for spatial information. To conclude, let us consider another common skill, stopping a vehicle at an obstacle. This skill is a particularly interesting one for it appears to require neither spatial information as such nor temporal information as such but some kind of dimensionless union of the two.

In order to stop at an obstacle a driver not only has to start braking soon enough but he also has to adjust his deceleration to an adequate level during the stop in order to avoid running out of braking power. In other words, the driver can get himself into a "crash state" (his speed too high in relation to his distance from the obstacle) well before he actually hits the obstacle. To avoid getting into a crash state while he is braking the driver clearly needs some kind of visual information about his dynamic relationship to the obstacle so that he can appropriately adjust his braking. It might seem that he needs three types of information; his distance from the obstacle, his speed and his deceleration. However it turns out that none of this information as such is necessary.

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 at a deceleration D . Then his deceleration D is adequate if and only if the distance 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

$$V(t)^2 / 2D \leq Z(t)$$

or

$$Z(t)D / V(t)^2 > 0.5 \quad (13)$$

Now $Z(t)/V(t)$ is specified by the value of the optic variable $\tau(t)$ for the obstacle (see Equation (3)), i.e.,

$$Z(t)/V(t) = \tau(t) \quad (14)$$

and differentiating this equation with respect to time we obtain

$$Z(t)D/V(t)^2 = 1 + d\tau(t)/dt \quad (15)$$

Hence, from Equations (13) and (15), 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

$$d\tau(t)/dt \geq -0.5 \quad (16)$$

A safe braking strategy would therefore consist in the driver adjusting his braking so that $d\tau(t)/dt$ remained at 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.

It will be noted that the information used in this strategy is not spatio-temporal in any conventional sense: the time derivative of the "time-to-contact" optic variable τ is a dimensionless quantity. Nonetheless this dimensionless optic variable affords information for controlling a space-time activity. Perhaps this was the kind of thing Minkowski was hinting at.

REFERENCES

- Alderson, G. J. K., Sully, D. J., & Sully, H. G., (1971). An operational analysis of a one-handed catching task using high speed photography. *Journal of Motor Behavior*, 6, 217-226.
- Bernstein, N. A. (1967). *The co-ordination and regulation of movements*. Oxford: Pergamon Press.
- Dietz, V., & Noth, J. (1978). Pre-innervation and stretch responses of triceps brachii in man falling with and without visual control. *Brain Research*, 142, 576-579.
- Fitch, H. L., & Turvey, M. T. (1977). On the control of activity: some remarks from an ecological point of view. In: Landers, D. M. & Christina, R. W. (Eds), *Psychology of Motor Behavior and Sport*. Champaign, Illinois: Human Kinetics Publishers.
- Freedman, W., Wannstedt, G. & Herman, H. (1976). EMG patterns and forces developed during step-down. *American Journal of Physical Medicine*, 55 275-290.
- Gibson, J. J. (1950). *The perception of the visual world*. Boston: Houghton Mifflin.
- Gibson, J. J. (1958). Visually controlled locomotion and visual orientation in animals. *British Journal of Psychology*, 49, 182-194.
- Greenwood, H., & Hopkins, A. (1976). Muscle responses during sudden falls in man. *Journal of Physiology*, 254, 507-518.
- Hubbard, A. W., & Seng, C. N. (1954). Visual movements of batters. *Research Quarterly*, 25, 42-57.
- Lee, D. N. (1974). Visual information during locomotion. In McLeod, H. & Pick, H. (Eds), *Perception: Essays in Honor of J. J. Gibson*, Ithaca: Cornell University Press.
- Lee, D. N. (1976). A theory of visual control of braking based on information about time to collision. *Perception*, 5 (1976) 437-459.
- Lee, D. N. (1978). The functions of vision. In Pick, H. & Salzmann, E. (Eds) *Modes of Perceiving and Processing Information*. Hillsdale: Erlbaum Associates.
- Lee, D. N., & Aronson, E. (1974). Visual proprioceptive control of standing in human infants. *Perception and Psychophysics*, 15 (3) 529-532.
- Lee, D. N. & Lishman, J. R., (1975). Visual proprioceptive control of stance. *Journal of Human Movement Studies*, 1 87-95.
- Lee, D. N. & Lishman, J. H. (1977). Visual control of locomotion. *Scandinavian Journal of Psychology*, 18, 224-230.
- Lee, D. N., Lishman, J. R. & Thomson, J. (1977). Visual guidance in the long jump. *Athletics Coach*, 11 26-30 and 12, 17-23.
- Lishman, J. H. & Lee, D. N. (1973). The autonomy of visual kinaesthesia. *Perception*, 2, 287-294.
- Melville Jones, G. & Watt, D. G. D. (1971). Observations on the control of stepping and hopping movements in man. *Journal of Physiology*, 219, 709-727.
- Minkowski, H. (1908). Space and Time. Address delivered at the 80th Assembly of German Natural Scientists and Physicians, Cologne, 21 September (1908).
- Schmidt, R. A. (1969). Movement time as a determiner of timing accuracy. *Journal of Experimental Psychology*, 79, 143-147.
- Schmidt, R. A. & McCabe, J. F. (1976). Motor program utilization over extended practice. *Journal of Human Movement Studies*, 2, 239-247.
- Sharp, R. H., & Whiting, H. T. A. (1974). Exposure and occluded duration effects in a ball-catching skill. *Journal of Motor Behavior*, 6, 139-147.
- Sharp, R. H. & Whiting, H. T. A. (1975). Information-processing and eye movement behaviour in a ball-catching skill. *Journal of Human Movement Studies*, 1, 124-131.
- Spurr, R. T. (1969). Subjective aspects of braking. *Automobile Engineer* 59, 58-61.
- Tyldesley, D.A. & Whiting, H. T. A. (1975). Operational timing. *Journal of Human Movement Studies*, 1, 172-177.
- Von Hofsten, C., & Lindhagen, K. (in press). Observations on the development of reaching for moving objects. *Journal of Experimental Child Psychology*.