DESCRIBING THE INFORMATION FOR ACTION

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Errata

Two lines of text were omitted from the printed version:

The top 2 lines of page 3 should be replaced with:

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The last 5 lines lines of page 8 should be replaced with:

bottomed box which allowed them ample space. This "tilting room' was supported on pivots whose axis passed roughly through the subject's ankle during support. For one set of experiments the axis lay in the sagittal plane and so tilting the room produced the optical change that would normally follow from a change in the subject's roll angle; for another set the axis lay in the frontal plane and so the optical effect was like a change in pitch. For the roll experiments the movements of a number of landmarks on the

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The control of action can be understood at different levels, where level is meant in the sense introduced by Marr. It is argued that it is important to maintain the logical distinctions between the levels, and that action theories must be seen as descriptions of information transformations at Marr's computational level. The control of balance during running is taken as an illustrative example.

1. Introduction

In order to control their actions, people and animals require information about spatio-temporal relationships between themselves and surfaces in their environments; their actions produce changes in those same relationships. A goal of action research must therefore be to produce good descriptions of the physical relationships which drive and are driven by an animal's perceptuo-motor system. Only on the basis of such descriptions will theories of motor control be able to go on to specify the processes that link the information driving an action to the effects of that action. This paper is intended to illustrate a methodology for achieving this goal of action research, which I shall approach through my view of the motor-action divide, and a possible resolution of it.

Action research takes no explicit account of neural mechanisms. I shall argue that an investigation which uses no information about the internal functioning of the nervous system cannot go beyond specifying the perception-action cycle in terms of transformations of information. That is, if the nervous system is treated as a black box, any model drawn to represent its operation must be regarded as describing an information transformation, and not as describing the nervous system's actual mode of operation. Some cognitive approaches fail to make this distinction explicit, and tend to regard such models as operational analogues rather than as functional descriptions. It is this which lays these approaches open to charges of unjustified reification (Turvey & Carello, 1981; Turvey, Shaw, Reed & Mace, 1981; Reed, 1981; Reed, 1984). However plausible it may be to propose particular memory or control structures to explain the results of action experiments, action experiments alone cannot provide evidence for the reality of such structures. An example to demonstrate this

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point will be provided shortly, but it has been made before (e.g. by Anderson, 1978; but see also Pylyshyn, 1980).

So under what circumstances can we talk about the internal mechanisms of the nervous system? To do so requires information or assumptions about the properties of neural information processing which go beyond the observation of behaviour. (I use the term information processing in its general sense, without any restrictive connotations.) A significant problem is that such assumptions tend to enter discussion of motor skills through the implicit adoption of an analogy, such as feedback control from engineering or model-based programming from computer science, instead of being precisely identified. That a particular model can predict the behaviour of an animal, however detailed and specific that prediction is, does not alone mean that the internal mechanisms of the animal correspond to the mechanisms of the model, but rather that they both lie in the class of mechanisms capable of realising the particular information transformation that has been observed. For all but trivial tasks this class is very large.

The set of contending mechanisms may only be narrowed using information concerning the limitations or structure of the physical substrate of the information processing system. Studies based on response times, for instance, only provide information about mechanisms if there is some underlying assumption that operations of comparable complexity require comparable amounts of time (for discussion of this see Posner, 1978, and Pylyshyn, 1980). Reasonable as that assumption may be, it is nonetheless dependent on some model for information processing. The model is rarely stated as precisely as it should be for a proper evaluation of the hypothetical mechanisms. Similarly, studies claiming to indicate modes of information storage (for example whether a lever movement is stored as an absolute end-point or as a relative adjustment) adopt the seductive assumption that if action outcomes can be mapped in a particularly straightforward way to some representation, then that representation is likely to be used by the biological system concerned. This is only true if the system does adopt representations which are parsimonious with respect to movement outcomes, by some engineering standards; of course this may well be the case, but again the basic assumption is rarely spelled out sufficiently plainly.

This argument suggests that the information transformation effected by an animal in acting should be analysed, and can be understood, separately from the strategies used to put it into effect. The distinction is very similar to that made by Marr (1982). The level concerning the information used by and the effects produced by an animal is that called by Marr the *computational* level: it is the level of analysis at which the goals of a problem, and the essential characteristics of solutions to it, are specified. The computational level is distinct from the *algorithmic* and *implementational* levels at which the processes by which the solution is put into effect are described. I suggest that description at the latter two levels requires a model of neural structures; such a model ultimately derives from anatomy and physiology, or from analogy with known information processing devices such as computers. An understanding of motor control requires an understanding of all three levels.

The action approach seeks then, in my view, to deal with the computational level. As Schmidt (1982) comments, each approach has its own taken as a whole. The motor approach takes a finer grained level of analysis, with functional subunits within the animal as its black boxes; descriptions in motor theoretic terms seem closest to the algorithmic level of analysis. A full account of motor skill will require analysis at the algorithmic and implementational levels to be integrated with analysis at the computational level, but this must be done explicitly. A description of operation at the computational level should logically precede the elaboration of theories based on assumptions such as modularity of functional organisation or concordance of representation with outcome. At the level at which a whole animal is taken as the object of investigation. I propose that a description of behaviour is best given in terms of the the information used by it and the information needed to state the outcome of its actions. Both sets of information concern the physical spatio-temporal relationship of the animal to things in its environment. Such a description defines a class of mechanisms which could realise the information transformation, but is neutral with respect to particular mechanisms within this class.

How should a description of an information transformation be formulated? An obvious way is to use an algorithmic level description of one way of performing the transformation. The problem is that this looks like a model, and so can be presented as if it were a model of the system rather than a way of specifying the information transformation. The blurring of this distinction contributes to the motor-action controversy. It seems better, therefore, to attempt to specify information transformations in more abstract terms.

To illustrate these ideas, this paper will first elaborate the point that even in a very simple case, many internal mechanisms can correspond to a particular computational strategy for solving a visuo-motor problem, then will consider how the results of particular experiments can be described in terms of the information used by a subject.

2. Balance control in a machine: an example

The main experimental investigation presented later in this paper is concerned with the maintenance of balance during human running. In this section, a closely related but rather simpler problem is discussed in order to clarify the means by which balance may be controlled, and to reinforce the point that there is a variety of ways of implementing any particular observable balance control strategy.

The problem considered here is that of balancing a rod on a moving support (for instance a blackboard pointer on one's hand). It is easy to establish that a simple feedback control system can carry out this task. Suppose that a machine were available for investigation that could do a restricted version of the task, that is a version where the rod was resting against **a** smooth wall and so could only fall in one rather than in two dimensions. If the machine in actual fact worked according to the scheme shown in Figs, la and lb, what could be found out about it given the opportunity to experiment with it but no knowledge of its internal mechanisms? By jiggling the rod to produce perturbations and by

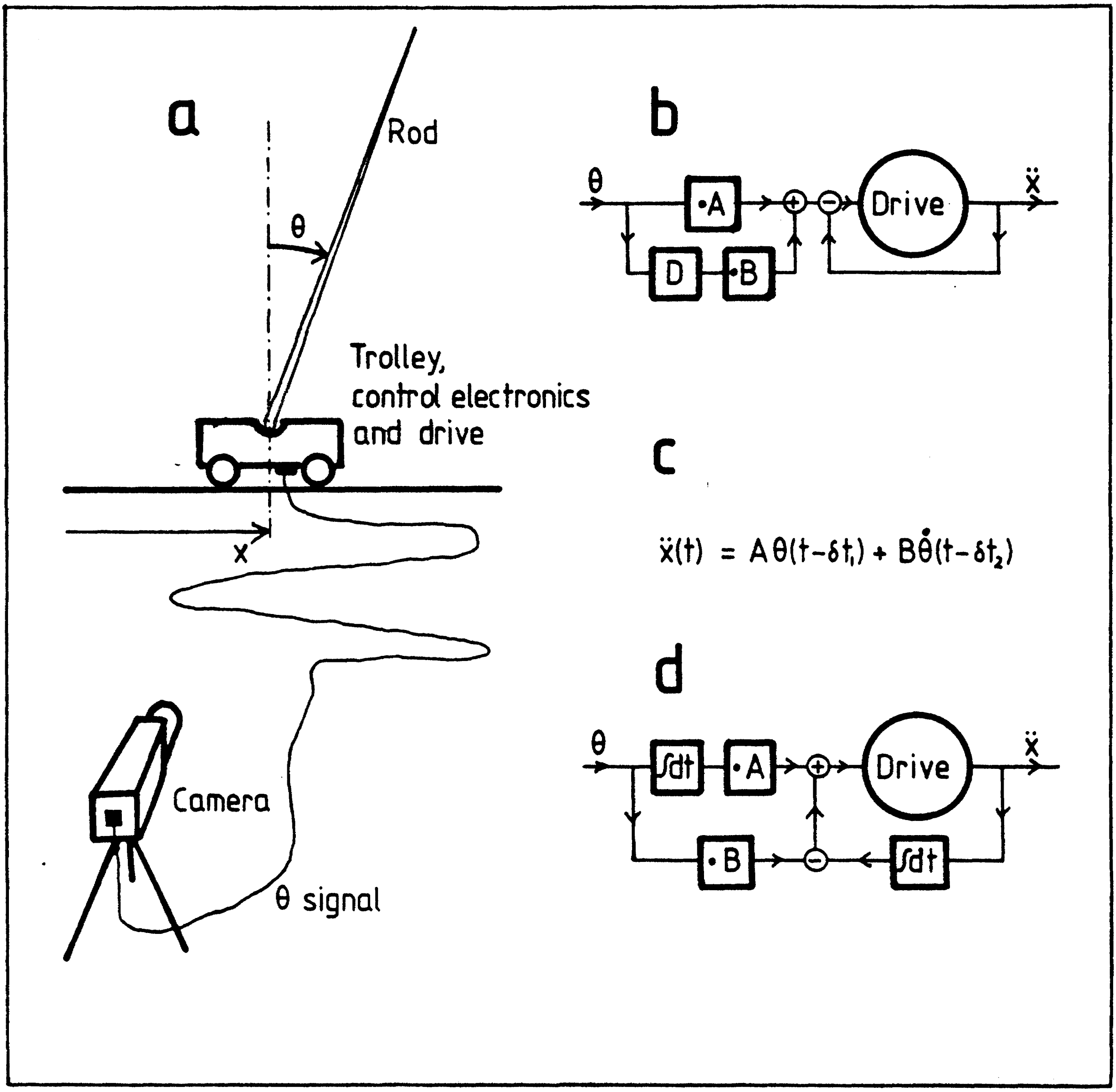

FIGURE 1

a. Machine to do rod-balancing task. The rod-angle with the vertical, θ, is measured by a camera which signals it to the information processor and drive mechanism for the trolley, which in turn changes x, the coordinate of the point of support of the rod, so as to balance the rod.

b. Simplified outline of one mechanism for the balancing machine. A and B are constants that multiply the signal, and D represents the operation of obtaining the rate of change of the signal. With an appropriate choice of A and B, the rod will balance (though extra feedback would need to be added if the trolley is not to accelerate off to the left or right). It is assumed that the mechanism has access to a sensor to measure $\ddot{x}$, the trolley acceleration.

c. The observable relationship between the variables. δt_1 and δt_2 are time delays. A dot above a variable denotes differentiation with respect to time. This assumes that the drive acts as a powerful amplifier so that the signal at its input is kept small.

d. An alternative scheme for realising the relationship given in *c*. $\int dt$ means that the signal is integrated with respect to time. The subtractive node feeds $B\theta\text{-}\dot{x}$ to the additive node, which therefore passes the sum $A\int\theta dt+B\theta\text{-}\dot{x}$ to the drive. Again if the drive acts as a powerful amplifier, and if the time-constants associated with it are small, it will change $\ddot{x}$ so as to make $\dot{x}$ equal to $A\int\theta dt+B\theta$. This is simply an integrated form of the equation in *c*. (Time dependence and time delays are understood in these formulae.)

measuring the behaviour of the device, standard methods would allow its response to be characterised (D'Azzo & Houpis, 1981). Firstly, it would be possible to establish that the controlled variable was the horizontal coordinate of the support, rather than, say, some combination of this with the vertical coordinate. Second, it would be possible to establish that the acceleration of the horizontal coordinate was linked to a linear combination of the rod angle and the rate of change of this angle. The nature of the linkage would in this case be fully specified by the the time delays between the angle, the rate of change of the angle, and the acceleration of the support reaching corresponding values, as shown in Fig. 1c. All this would amount to a complete description of the information transformation instantiated by the machine. It says nothing about how the machine achieves that transformation. As Fig. 1d shows, it is simple to invent another mechanism that is equivalent to the first but is fundamentally different in its operation at the algorithmic and implementational levels. The example is in fact rather oversimplified, but this does not affect the main point that the mapping from mechanisms to information transformations is many to one.

A more radical example would be to replace the rod by another mechanism which sensed how the trolley was moving, and which used a motor to drive a light pointer to simulate the rod's movement. Such a mechanism might use a microprocessor to process information about trolley acceleration to yield the correct angle for the pointer. The rod itself is, of course, the simplest way to do this particular information transformation, and in this sense the rod can be seen as a simple information processor.

What sort of information about the machine would enable us to suggest which sort of algorithm was used? Two kinds of knowledge could be relevant. The most obvious is specific knowledge about the inside of the device. If it could be dismantled and measurements made of the signals at different points in it, then in a case as simple as this it would not be difficult to establish how it worked. Alternatively, if it was known to use, say, electronic components from the laboratory stores, then the general properties and limitations of these components would provide strong indications of the class of algorithms that might have been instantiated using them: for instance the quality of the capacitors would provide limits on the time constants available to the system, the signal-to-noise ratio of the transistors would limit the degree of resolution of signals and so forth. Together with the assumption that the device was built in a reasonably economic manner, this implementation-level information would enable one to distinguish less likely from more likely algorithmic descriptions.

To sum up, the observations of the device as a black box, interpreted properly, allow it to be described at the computational level. This description defines the class of algorithms that could be implemented by the machine. (Here algorithm is used in a very general sense to mean any definite method for producing some behaviour.) Knowledge at the implementation level, either specific or general, can reduce the size of the class of admissible algorithms. A description of the information transformation effected by the machine is complete at the computational level; I do not regard it as globally complete, but, with Marr, suggest that understanding the full story requires descriptions at the algorithmic and implementational levels too.

3. Running balance control in humans

3.1. The control of running balance

Balance control is one of the central components of much human action. It provides a good illustration for the ideas of the introduction, in that the possible sources of information for balance and the possible ways of using the information are very varied. Furthermore, better understanding of the ways in which humans control balance would be of great value in rehabilitation and the training of many skills. First, the mechanics: how, in principle, can control of balance be exerted?

Unlike a blackboard pointer, a person is a jointed and flexible structure, and so there is a second way of controlling balance in addition to moving the centre of support, which was the only means of balancing the rigid rod. Specifically, transferring angular momentum between body segments (for example by swinging the arms) can shift the centre of mass so that the gravitational torque may be controlled. A full discussion of this would take a good deal of space and as it is not central to the discussion of the information used, will not be given. However it may be worth noting that in running, control through centre of support position largely consists of adjusting footfall position at foot strike, whereas angular momentum transfer can only operate to shift the centre of mass when the foot is in contact with the ground. Thus to a certain extent the two modes of control must alternate. It would be interesting to investigate the relative importance of these two modes in human running, but for the time being it will be assumed only that some combination is effective, and attention will be confined to the question of the information used.

Balance in running requires control of orientation both in the sagittal plane and in the frontal plane, that is control of pitch and roll respectively. The discussion so far applies equally to both of these aspects of balance. However, each interacts with other goals in running, and these need to be taken into account: pitch interacts with control of speed and roll interacts with control of course. To speed up, for instance, the force from the ground needs to be directed forwards, and if this is not to produce a torque which would rotate the runner backwards, then the centre of mass must be ahead of the average centre of support. Similarly, a turn to the left would cause a runner to fall to the right unless the centre of mass were made to lie to the left of the centre of support. This is not to say that balance control must be subordinate to speed and course control, but rather that it is not separable from them. Raibert (1986) has shown how in a working running machine, course and speed control can both be simply effected by perturbing the fundamental balance control mechanism. An increase in speed, for instance, can be produced by initiating a fall forward and allowing the balance control mechanism to compensate for it. Similarly changing course to the left entails initiating a fall to the left, and indeed the problem is the same as that of steering a bicycle, which is a machine designed so as to produce the condition that a tilt to the left causes a shift in centre of support to the left. (It should be pointed out here that changing course means changing the direction of travel, and that this is not the same thing as changing the direction in which one is facing, which is a problem not considered here. Bicycles automatically face the direction of travel; people have little difficulty in doing so; one legged balancing machines may find it rather hard.)

Can the control of pitch and the control of roll be investigated separately? The answer depends on whether or not the information needed for one is independent of the information needed for the other, and whether the control variables for one are independent of the control variables for the other. Raibert's machine (Raibert, 1986) shows that a strategy based on this independence can work. His free hopping machine has control structures for pitch and roll, each of which is essentially similar to the one used for a constrained hopping machine which could only fall in a plane. Intuitively it is plausible that the same would apply to human locomotion, in that changing speed and changing course seem independent goals, and there is no obvious biomechanical reason why the two should interact. Ultimately the question must be answered empirically, but for the time being it will be assumed that regarding the two degrees of freedom as separable is a valid procedure.

3.2. Information for running balance

In the example of rod-balancing, the angle of the rod to the vertical, and the rate of change of this angle were the only variables needed for control. In running balance the line joining the centre of support during stance to the centre of mass plays the role of the axis of the rod, and there are two angles that describe its orientation. These are the angles made with the vertical by the projection of the line into the frontal plane (the roll angle) and by its projection into the sagittal plane (the pitch angle). These angles and their rates of change specify part of the state of the body at any moment in time. Many other variables are needed to specify the full dynamic state of the body, which includes information about the position and motion of all the body segments. However, the pitch and roll angles play a key role, because together with the height of the centre of mass they determine the net gravitational torque, and this alone is what produces changes in the runner's total angular momentum. Since changes in the height of the centre of mass are generally quite small compared with the mean height, whereas changes in the two angles are much larger than their means (the latter must be close to zero), changes in the angles are a good deal more important than than changes in the height of the centre of mass. Thus this simple analysis of the mechanics indicates that picking up information related to the pitch and roll angles and their rates of change will be an important part of balancing. In addition the system will need much other information: both propriospecific information about the disposition of the body segments relative to one another, and expropriospecific information about, for example, the timing of the next heel strike. For the time being though, I will develop the question of what information about the pitch and roll angles and their time derivatives is

The pitch and roll angles were defined above relative to the vertical. That is, they were defined in a frame of reference fixed with respect to the direction of gravity. This will be called the *mechanical frame of reference.* Alternatively, the orientation of the centre of mass/centre of support line could be measured relative to the line where two walls of the laboratory meet. This would amount to the same thing if, as in a normal room, this intersection was always vertical. However, in the experiments to be described, the walls of the room surrounding the subject were moved, and so orientations measured with respect to them were not the same as orientations in the mechanical frame of reference. The walls of the room had no mechanical link to the runner, and so their only effects were through the optic array they establish (Gibson, 1966; Lee, 1980). The frame of reference fixed relative to the walls of a rigid room will therefore be called the *optical frame of reference.* Under normal circumstances, the mechanical and optical frames are fixed relative to one another, and so orientation information specified in either is equally useful for balance control. If the room moves, information in the optical frame of reference will no longer specify the pitch and roll angles, or their rates of change. By moving the room and so decoupling the frames, the information used for balance can be identified. (Note that in referring to room movements I assume the mechanical frame.)

Information about body orientation is available in both frames of reference. For instance, the torques at a runner's ankles, accessible to mechanoreceptors, depend on orientation in the mechanical frame, and the vestibular system can pick up information about head orientation in the same frame. On the other hand the visual system picks up information in the optical frame. Finding out what information - mechanical frame or optical frame orientation - is being used can thus help show how it is being picked up. Knowledge about the properties of the receptive systems (that is knowledge at the implementation level) may subsequently help in understanding why the runner's actions are controlled by that particular information.

33. An experimental inTestigation of human running balance

Human running balance was investigated in a series of experiments in which David Lee, William Warren, Michael Anderson, Martin McCrindle and I collaborated. Using the Selspot movement monitoring system (Woltring, 1977) and a modification of the 'swinging room* (Lishman & Lee, 1973; Lee & Lishman, 1975), the experiments produced a large amount of data concerned with runners* movements during normal treadmill running and during perturbation of the optical frame of reference.

Method. The arrangement was as shown in Fig. 2 (full details will be published elsewhere). Each subject ran on a powered treadmill at about 2.6 metres/sec, inside an open-bottomed box which allowed them ample space. This the subject's ankle during support. For one set of experiments the axis lay in the sagittal plane and so tilting the room produced the optical change that would normally follow from a change in the subject's roll angle; for another set the axis lay in the frontal plane and so the optical effect was like a change in pitch. For the roll experiments the movements of a number of landmarks on the

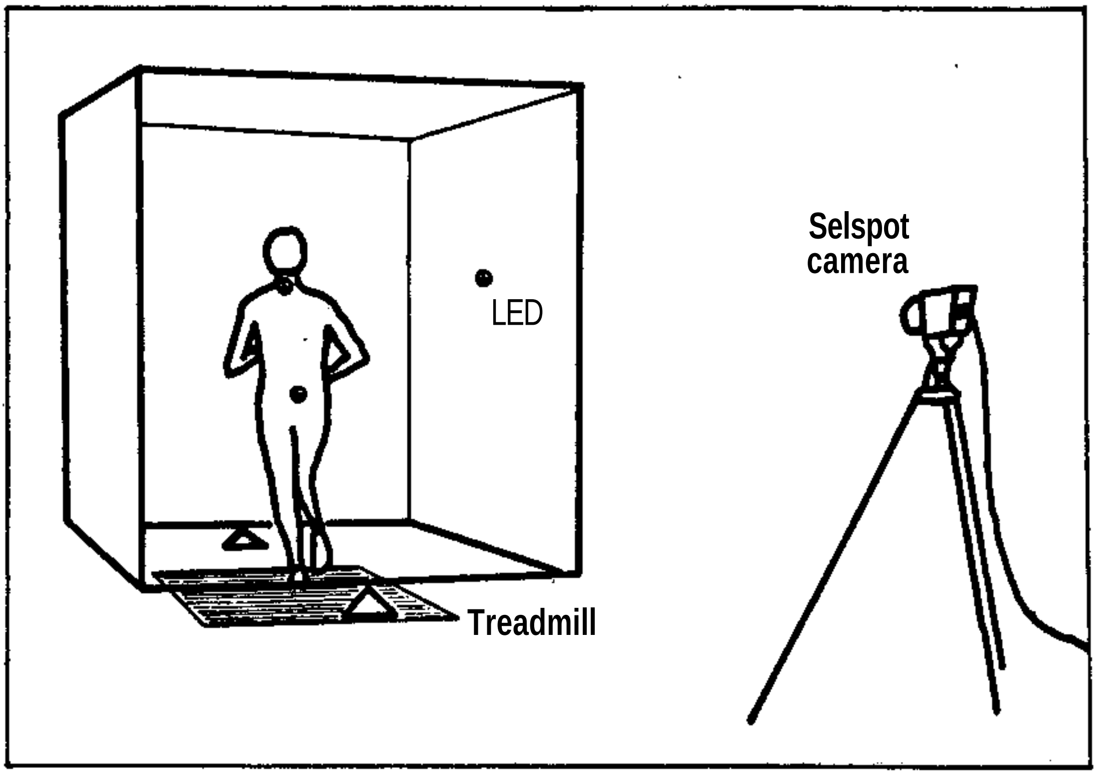

FIGURE 2
Experimental arrangement for the roll experiments in the "tilting room". The Selspot camera signals the positions of the three infra-red light emitting diodes (LEDs) to a computer about 300 times a second. The arrangement for the pitch experiments was similar, but with the room, fulcrums and camera rotated so that the room could tilt forwards and backwards instead of left and right.

subject's body were recorded from behind using a Selspot opto-electronic measuring system; for the pitch experiments the action was recorded from the side. (This meant that in the pitch experiments the tilting room had an open side to the subject's left. The inside of the tilting room was brightly lit while the surrounding room was kept gloomy, and the subjects' reports and the experimental results suggest that the tilting room rather than the external surroundings supplied the optical frame of reference. It will be assumed that this was the case.) Selspot also recorded the room movement.

After the subject had been running for a while, movement recordings of 10 sec were made, and 7 sec into each recording the room was abruptly tilted through about 3 degrees in one of the two possible directions (left or right in one set of experiments, forward or backward in the other), chosen at random. The subject knew that the room could tilt, and knew whether the movement would be pitching or rolling, but he had no warning of the moment at which each lurch of the room was started, nor in which direction it would be. For safety, the subject always wore a safety harness which would have prevented injury in the event of his falling.

Results and Discussion. For the analysis, an estimate of the subject's response to the room movement was needed. Initially, the estimate was obtained from the orientation of a line joining a landmark on the nape of his neck to one over his coccyx. Although this line has only a loose relation to the centre of mass/centre of support line so central to the analysis above, it was used as a quick way of estimating the orientation of the subject's most massive body segment, which would inevitably reflect the way his overall response was being organised. That he was responding to information in the optical frame of reference was in fact obvious from watching his response to the room's lurches. However, to make a conclusive demonstration of this it was shown that the recorded information about the orientation of this line was sufficient to tell whether the room had been rolled to the right or to the left in the roll experiments. The subject's body orientation was displayed by playing back the movement recordings onto a computer display screen, with only the line joining the coccyx and nape markers shown. A fresh subject watched ten playbacks from each of two runners and in every case correctly identified whether the room had rolled left or right.

Thus one question can be answered immediately: information specified to the runner in the optical frame of reference was involved in maintaining balance. The next question to ask is whether this was all the information used, or whether other frames of reference were involved and if so how the information was combined.

To show more exactly how the runners responded, Fig. 3 shows example plots of the roll and pitch angles for the nape–coccyx line, along with the roll and pitch of the room. These plots have had the cyclical component of the motion removed so that the transient response to the room movement may be more clearly seen. (The cyclical component was obtained as follows. The pitch or roll angle curve for a period of unperturbed running on the treadmill was divided up into strides, and an average curve for a stride obtained by summing corresponding points in each of these separate stride curves. Now the curve that the pitch or roll angle would have followed had the room not moved was estimated by repeating this average curve over and over. This cyclical curve was then subtracted from the observed curve in order to give the plots shown.)

As Fig. 3 shows, when the room was rolled, the runner responded by initially rotating with it: the body tilt tracked the room tilt. Subsequently, when the room stopped moving, the runner recovered, and the body returned to the upright. On the other hand, when the room pitched, the runner briefly tilted back before recovering, regardless of whether the room had pitched forwards or backwards.

It is not possible here to indulge in a description of how to fit a quantitative model to these data, but a qualitative analysis will be sufficient for my argument. (An example of a quantitative analysis applied to a very closely related task is given by Hubbard, 1980.) First, it is clear that the optical frame of reference was not the only one involved. For if it had been, then since this frame's orientation remained inclined after the room was shifted, the runner would likewise have tried to remain angled afterwards, instead of

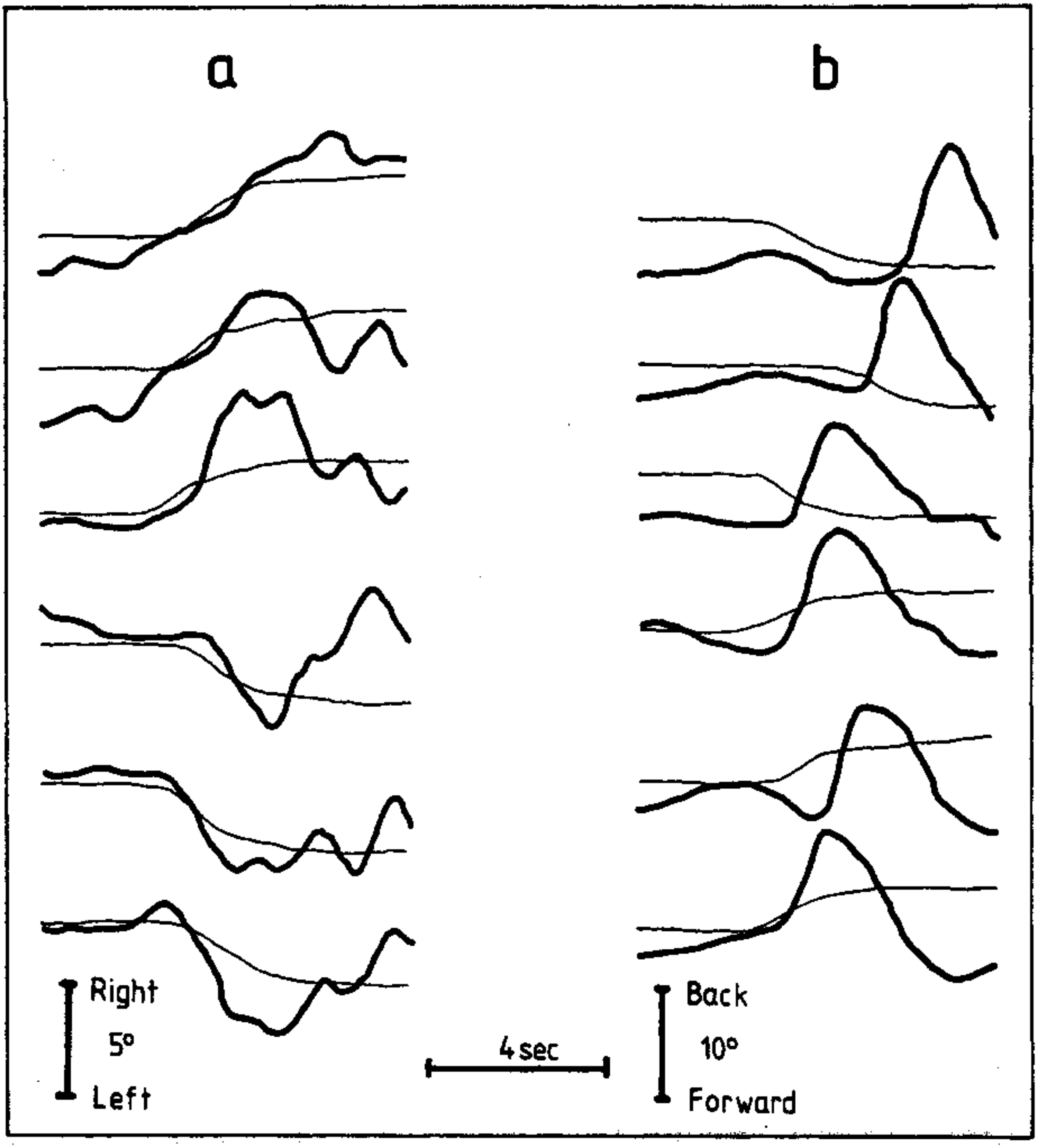

FIGURE 3
Results of the tilting room experiments, a. Roll condition. Room roll (light line) as a function of time with perturbation to subject's trunk roll (heavy line). 6. Same for pitch condition.

recovering to the vertical. This would have resulted in his ultimately falling over* which was fortunately not the outcome of the experiment* though in principle it might have happened. Therefore information from the mechanical frame was involved in the return to upright. How then was the disparate information of the mechanical and optical frames combined? Taking as an example just the control of roll, and bearing in mind that a balance mntrni cystJim rftnjiir«5 for Rtahiiity hoth th* m11 stnoi* »«H it« rat* nf rhano* *with* tii«o one description fits well. This is that to control balance the roll angle as specified in the mechanical frame was used together with the rate of change of roll angle in the optical frame.

That this scheme produces the observed behaviour can be seen by considering its predictive properties. Suppose it had in fact been used. When the room was stationary, either before or after the lurch, the rate of change of body roll obtained from the optical frame was the same as the rate of change of roll in the mechanical frame. Thus combining rate of change of angle with angle predicted the future motion in the mechanical frame. When fed into a corrective control system, necessarily also operating in the mechanical frame, this prediction lead to correction of any tilt that developed, and hence to maintenance of posture before the room movement and a return to vertical from the tilted position after the room movement ceased. While the room was moving, however, the prediction was changed. Suppose the room lurched to the left and at the start of the lurch the runner was not rolling in the mechanical frame. Then his rate of roll in the optical frame became positive to the right. This predicted a future inclination to the right: the balance control mechanism inevitably compensated by generating a leftward torque. Despite the fact that in the mechanical frame of reference this immediately produced an erroneous leftwards tilt, the room motion generated a prediction, through the optical information, that this tilt was being corrected. Thus while the room tilted to the left the runner tilted with it, producing the sort of initial tracking behaviour shown. As the room stopped moving, the optical frame became positive to the left, and hence combined with the mechanical frame information generated a prediction of further leftwards tilt. From this prediction followed a corrective torque producing a smooth return to the mechanical vertical.

This explanation cannot be applied directly to the data for pitching movements, as in pitching the runner did not track the room when it moved forwards. The reason for this may be that the backward pitch produced by the runner was a general purpose emergency response designed to enhance stability by preparing for a reduction in speed. In any case, the results are still entirely consistent with the picture that the optical rate of pitch was combined with the mechanical pitch angle to yield a prediction; the difference from the roll case is how this prediction was used. It may well be that as roll control is intimately connected with control over running direction, perturbations to the roll angle occur as a matter of course in normal running, and so corrections to it can be made in a smooth compensatory way. On the other hand the pitch angle may normally only suffer substatntial perturbations when footing is disturbed, for instance by tripping over something or by striking a slippery piece of ground. Under these circumstances control might best be reestablished by leaning back and thus reducing speed. (This explanation for the difference between the pitch and roll responses is supported by the observation, not shown here, that the timing of footfalls following the lurch was rather more disrupted by room pitch than by room roll.)

This relatively simple qualitative analysis has allowed the beginnings of a rigorous description of the information used to control running balance. This description has not leant on knowledge of the properties of the visual system, of the mechanical receptors or of the capabilities of neural information processing. It would have been possible, and indeed tempting, to discuss the pickup of optical frame information in terms of properties of the changing retinal image (Lee & Young, 1985), and even in terms of the processes of the visual system that might allow these relevant properties to be extracted (Koenderink, 1985; Nakayama & Loomis, 1974). Whilst such an approach is ultimately inevitable in an investigation at the implementation level, it would have obscured the basic result of the experiments: that orientation from the mechanical frame and rate of change of orientation from the optical frame were combined to give predictive control of running balance.

4. A concluding example: interceptive action

The correct product of an experimental investigation of action control in an intact human or animal is a description of the information about spatio-temporal relationships that the organism uses. This, the main thesis of this paper, is supported by the analysis of running balance control. In conclusion I would like to offer another example of the importance of distinguishing between the computational and algorithmic levels of analysis.

Studies of the timing of interceptive actions in diving gannets (Lee & Reddish, 1981) and in humans (Lee, Young, Reddish, Lough & Clayton, 1983) have demonstrated a link between the timing of features of the motor act and predictive information about the approach of a surface. In the case of gannets diving into the sea, the moment at which the wings were folded before impact was the chosen feature, and in the case of humans punching a falling ball, it was the moment at which any given knee or elbow angle was reached in the course of building up to the punch. In both studies it was found that the timing was best described by the hypothesis that control was based on the time to contact under constant velocity (ttcv) with the ball or the sea. In the ball-punching study, for instance, the same behaviour would be generated by using the ball's current distance and speed to predict its future trajectory. It is not necessary, in fact, to know either the distance or the speed explicitly: ttcv is specified directly by the rate of expansion of the ball's image on the retina. The point I wish to make here is that although the experiment strongly supported the idea that ttcv prediction was used in controlling the leap and punch, there was no evidence whatever from the experiment itself that the rate of expansion of the retinal image was involved. To show that ttcv was the relevant control variable was to make an important statement about the nature of the spatio-temporal information used in controlling the action. To infer that ttcv is determined through the rate of expansion of the ball's retinal image, or through any other optic variable, requires more information (or more assumptions).

Further experiment could, of course, further narrow down the possible sources of ttcv information without moving to consider the algorithmic or implementational levels. Such experiment would manipulate the information available, for instance by removing the view of the ball for part of its approach, or by removing any texture from its background, and so forth. A tighter and tighter description of the information used by the puncher would ensue: a better and better understanding of the act at the computational level would follow. Similarly, tighter and tighter descriptions of the action variables at the output of the system could be developed, although this is an aspect to which I have given little attention in this paper.

In the end, however, the computational, algorithmic and implementational levels need to be linked if a full understanding of motor skill is to be obtained. I have argued that, in studying the interactions of intact organisms with their environments, we are working (in Marr's terminology) at the computational level. In order ultimately to achieve a fusion of levels, it is first necessary to avoid confusing them in interpreting the results of our experiments.

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