MAPS, PROGRAMS AND THE VISUAL CONTROL OF LOCOMOTION

by

James Alick Thomson

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This thesis is dedicated to my grandmother, Mary Clayton. Gun till mi mas maireann mi.

ABSTRACT

This thesis attempts to outline a solution to the general problem of how organisms control their behaviour relative to the environment. The principal concern is with how such guidance is achieved on the basis of visual information. The main argument is that behaviour is controlled on the basis not of current information but of previously acquired information. Experiments are reported which show that even complex locomotor acts can be accurately executed when all visual information is excluded during the act. The research suggests two ways by which motor activity is controlled. Firstly, visual information can be used directly to formulate programs for action. These programs contain precise prescriptions of the motor actions necessary for controlling the behaviour, and are executed with minimal reliance on information available during the act. It seems that programs can be formulated for distances up to about five metres. Secondly, a map or internal representation of the external environment can be formed which can be used in place of direct vision to formulate programs and control behaviour. Such maps allow behaviour to be controlled over distances up to 21 metres at least, though they are an effective substitute for vision for not more than about eight seconds. Programs seem to have a longer duration. The findings are taken to imply that vision is used to a far lesser degree in on-going control than is commonly supposed. Two basic reasons are proposed for this. Firstly, it is argued that only a map/program strategy of this kind can allow the complexity typically seen in visually-guided behaviour. Secondly, vision must frequently be free to perform its many other functions. Only by devolving its work-load can it achieve this necessary freedom.

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When I go toward the exit to a room,

I am already there.

M. Heidegger

"Bauen, wohnen, denken"

Vorträge und Aufsätze II, 1954

PART I

A FORMULATION OF THE PROBLEM

INTRODUCTION

The world in which animals live and with which they must interact is a highly complex one. It is not an open world, with the ground surface extending unbroken to the horizon: such cases are limited to sandy deserts or the open sea. The surrounding environment is usually a highly cluttered one. It is littered with boulders and rocks, with broken branches and fallen trees. It abounds with protrusions like exposed roots and overhanging limbs. It is pock-marked with gaping holes, ditches and streams. And it is peopled with plants, bushes and forests of trees. These things constitute the furniture of the earth and give it its distinctive character. For the animals which inhabit the world, they can afford many things; from food or shelter, tools or missiles of war. There is one thing which is afforded by almost all of the earth's furnishings, however: they afford impedance to an animal's free movement. No comprehensive list of the preventers of locomotion exists, but Gibson (1976) has proposed the following as generalised categories. The preventers of locomotion consist of obstacles like rocks or trees; of barriers like cliff faces; of water margins like the banks of a river; and of brinks, like the edge of a cliff. Any animal wishing to move around in the world can do so only by overcoming such impedances with which it is confronted. For this reason, we may conceive of much of the behaviour of animals as being directed towards the solving of what may be termed motor problems posed by the external environment. Understanding how such motor problems are solved represents a fundamental problem over a wide area of Psychology. It is also the problem to which this thesis is addressed.

To solve this very broad problem, there are two fundamental subquestions which may be asked:

(1) What information does an organism have about the external environment and how does it become available?

(2) How is that information, however acquired, actually <u>used</u> by an organism faced with the practical problem of interacting with the external world?

In the past, perceptual theorists have concerned themselves almost exclusively with the first of these questions. Consequently, while there are theories of perception purporting to explain every facet of our perceptual awareness, when it comes to explaining how such information is used to accomplish even apparently simple acts like lifting objects or walking through doorways, theoretical arguments are conspicuous by their absence. For this reason, the majority of models of perceptuo-motor control to be found in the literature are essentially trivial when compared to the complexity of behaviour which they are meant to accommodate. It is true that most writers have recognised the severe limitations of their models; yet, remarkably little progress has been made towards the development of a convincing model of perceptuo-motor control since the early days of the cybernetic revolution. The classical contribution made 30 years ago by Wiener (1948) has not been substantially developed since, and was indeed itself in many ways eclipsed by a statement of the problem published some 20 years before that (Bernstein, 1935). The work reported in this thesis constitutes just such an attempt to go beyond these elementary outlines to the development of a model capable of accommodating at least some of the fundamental abilities underlying the perceptuo-motor control to be found in the behaviour of animals and man.

A fundamental factor underlying the research reported here has been the conviction that only by considering problems of the kind actually experienced by living organisms in their natural environments, can we succeed in building up a meaningful and non-trivial model of motor control. In this, the present writer differs from most other workers in this area, who are prone to examine behaviours of very limited extent, more often than not in entirely artificial situations. Such studies are generally founded on the assumption that the essence of real life skills is most clearly to be seen in highly simplified versions of the natural event. Other reasons frequently cited in defence of the artificial experimental situation are the increased ease with which it is said that subjects' performance can be measured; the greater control which the experimenter can exercise over the stimulus situation; and the possibilities which can be created for separating the different mechanisms which are normally simultaneously mobilised in skilled performance. This approach was rejected throughout the present series of investigations on a number of grounds. Firstly, it was considered that it is, in fact, perfectly possible to investigate the mechanisms of skilled performance without resorting to the drastically simplified experimental situation with its accompanying dangers: the dangers in particular of trivialising the essential problem through an accumulative neglect of the basic issues, and of forcing a mechanism designed to function in one way to function in another. Secondly, it was felt that, while such approaches are not valueless, the number of insights into the nature of motor control which they have generated has not been particularly encouraging, and it is still difficult to feel that any real progress towards an understanding of the essential features of motor control has been made. It was felt at an early stage that many fundamental issues were not being considered from within the existing paradigms and that this neglect was essentially due to the parad~~yms~~igms themselves which had become self-perpetuating. Finally, it was felt to be not through mere coincidence that some of the best experiments to be done in the area of motor behaviour, some of them at a very early stage indeed, had retained as straightforward and natural a situation as possible (e.g. Woodworth, 1899; Bryan and Harter, 1899). For these reasons, the experiments reported below have attempted to keep the experimental situation in just this natural vein insofar as this was possible, while at the same time ensuring the strict control of all relevant variables. The reader may judge for himself the success of this approach in generating ideas and evidence on the nature of perceptuo-motor control.

It must be said that the perceptuo-motor system investigated in this thesis belongs to a terrestrial animal which is rather unusual (bipedal) in its mode of locomotion. Some points must be made about this. Firstly, whilst the subjects of the experiments used one form of locomotion among many to be found amongst terrestrial animals, it was felt that the principle is equally applicable to them all. Indeed, the generation of the theoretical position involved, ~~and~~ was in some ways dependent on, arguments based on the diversity of locomotor styles to be found amongst terrestrial animals. Secondly, although we have concentrated on the problems faced by terrestrial animals, it is argued that these problems are shared at least to some extent by organisms using other forms of locomotion (cf. birds and fish). Nevertheless, it is admitted that the problems encountered by these animals are likely to be sufficiently different for a model of control formulated with respect to one class not to be fully generalisable to the others. It is hoped, however, that some principles will be adduced which are shared by all of these rather different species.

It must also be emphasised that it is locomotion and not any other form of motor behaviour, which is considered here. This, too, differs from most research on motor skills, which generally involves reaching or manipulating with the hands. Once again, it is not necessarily the case that a model which fits one form of motor behaviour will necessarily fit them all. This is perhaps particularly so in view of the great differences which superficially at least, exist between locomoting on the one hand and manipulating with the fingers on the other. For this reason, most of the conclusions are restricted to locomotion, though discussion of other behaviours is included where appropriate.

Lastly, although reference has been made on several occasions to perceptuo-motor control, we are here concerned principally with <u>visuo-motor</u> control. No other source of information is discussed in detail. The use which animals might make of other sources is left mainly to the discussion of perceptuo-motor control in general at the end of the thesis.

STATEMENT OF THE PROBLEM

The present discussion takes for its starting-point the proposition that the behaviour of animals constitutes attempts to solve motor problems posed by the external environment. These problems normally arise in the course of achieving certain higher-order goals. For example, the desire to reach some fresh grazing on the far side of a stream involves a set of locomotor problems which have to be solved before the higher-order goal can be realised (for example, the stream has to be crossed). It is now necessary to attempt an analysis of the mechanisms underlying these motor resolutions. The following is the outline ~~to~~ of a potential model; detailed consideration will be given to the various sections when this is necessary.

Receptor System

The first requirement of any system designed to interact with the environment is, of course, that it be capable of picking up information about the layout of that environment. Hence the system must be provided with a receptor of set of receptors. The amount of information which the receptors are capable of picking up may vary according to the nature and complexity of the behaviour to be performed, but there must always be sufficient information to enable the organism to perform its life-activities.

Absolute Distance Perception

If an animal is to control its behaviour in relation to the objects and surfaces in the world, however, it is not sufficient for it to know only the relative layout of the surrounding environment. In order to perform tasks like circumventing obstacles in the path of locomotion or stopping short at the brink of a cliff, it must obtain sufficiently precise information about its own subjective relation to these obstacles before reaching them, in order that it can take appropriate action. The problem of how this information is derived has traditionally been called the problem of absolute distance perception. This term is usually taken to refer to our ability to apprehend, in one way or another, the actual physical distance of objects. It is normally set against relative distance perception, which enables us to say whether one object is nearer to us or farther away from us than another, but does not allow us to say what the distances involved actually are. Only absolute distance perception can allow us to do this. Much research effort has been devoted to trying to understand how these latter judgments are possible.

The classical explanation of the visual ability to "measure" distances in this way draws on a system of "cues" of which the main ones are said to be accommodation of the lens, convergence of the eyes, disparity between the images in the two eyes and motion parallax. The essential proposition was that proprioceptive information derived from the various eye and (in the case of motion parallax) neck muscles, combines with that provided by vision to bring about a solution. In the case of motion parallax, for example, proprioceptive information from the neck and eye muscles together with transformations of the optic array at the eye are said to provide sufficient information for a "trigonometrical" solution to the problem to be possible (Johansson, 1973).

However, there are numerous difficulties with these explanations. In the first place, with few exceptions, the experiments (of which there have been many) have come out with negative results; though there has always remained an element of doubt due to methodological problems. Of the cues of accommodation and convergence, Woodworth (1938) wrote;

> 'From all these experiments so far ... we can surely conclude that the tactile-kinesthetic sensations of accommodation and convergence contribute very little to the accurate perception of distance. Even at distances as small as 6 to 12 inches convergence and accommodation alone seem to have little effect on perception of depth ...'
>
> 1938, p. 652.

The same conclusion is reached by Linschoten (1956) after his long review. The cues of motion parallax and binocular disparity invoked as powerful informants about distance since Helmholtz's (1867) work, are subject to the same criticisms. Although it has long been clear that they provide information about the relative layout of objects in space (Helmholtz, 1867; Bourdon, 1902), their role as a cue to absolute distance has been unclear (Eriksson, 1972; Gogel, 1972). Even in the most favourable studies (for example Johannson, 1973) it is not clear that the degree of veridicality achieved is sufficient to be "usable" and to allow the kind of accuracy that we characteristically find in the visually-guided behaviour of animals. Certainly, there is no evidence that these cues can provide even the most approximate information about the absolute distance of objects when these are outwith the near-space (generally defined as around 2 metres). Yet it seems certain that the absolute position of objects can be apprehended at distances which are far greater than this. The evidence derives first of all from the fact that we seldom find when we have walked up to an object that its position is different from that which we thought it to be in the first place, even when this distance is great (the occasions on which this does happen are most noticeable). In the second place, for reasons which will be elaborated on below, it would seem to be impossible for behaviour of the complexity typically seen in animals and man to be found if they are only able to relate themselves to objects and surfaces at less than 2 metres distance. Briefly, there is a finite time below which corrective actions cannot be made due to limited processing times in the nervous system. The minimum time during which a correction can be made seems to be approximately .5 to 1 sec. However, an animal running at, say 15 m.p.h. will cover approximately 7 metres in 1 sec. This means that if evasive action is to be taken, it would have to be planned at a distance of 7 metres at least. For these reasons it would seem that animals must be able to accurately apprehend distances of far more than 2 metres. The question then arises as to why studies of absolute distance perception have so uniformly failed to evidence it.

The most common method of measuring a subject's perception of the absolute distance of an object has been simply to ask him to estimate, in inches, feet or metres, how far away the object lies. This method of investigation makes the assumption that if the subject can make a reasonably accurate estimation of the target distance in these terms, then he can "see" where it lies in space and could orient to it appropriately if asked to do so. Conversely, if he cannot make such an estimation then he cannot "see" its spatial location and could not lift or touch it if this was required of him.

This method of examining the perceptual processes is a highly artificial one. It seems to be underlain by three fundamental errors. Firstly, it makes the implicit (though not necessarily explicit) assumption that the metric system is a basic and absolute framework for the measurement of distances in Euclidean space. It further assumes that the perceptual system resonates to this framework in a sufficiently direct way for the estimations to represent a close reflection of phenomenological experience. Essentially then, this standpoint takes the traditional ontological position whereby only the basic variables of physics are given primary reality status. Clearly, however, this position is quite unjustified. Metric systems of measurement are structures arbitrarily imposed on the world by those with the practical aim of describing its topographical organisation and structure. Metrics are mere inventions to ease this process; they have no independent reality, and there is therefore no reason to suppose that the perceptual system apprehends distance in terms of them. The arbitrariness is clearly seen in the use of two different systems, the imperial and the metric, to describe the perceptions. If we accept that the use of such techniques is occasioned merely by convenience, we are confronted with an even more daunting problem, however. We have no reason to suppose that an inability to give a numerical tag to perceived distance is a genuine reflection of the subject's phenomenological experience. A number of studies show that the ability to estimate distance in these terms varies widely. Gibson and Bergman (1954), for example, have found that training to estimate distances in feet and inches improves markedly after training, and improves also over a control group who have as much experience, but no training. Gibson, Bergman and Purdy (1955) showed that the effect could be generalised to a number of different terrains, and that the effect was not produced by familiarity with one particular layout. Clearly, therefore, an inability to give good estimates is no evidence that absolute distance is not perceived. The same argument applies in reverse, because a subject giving a good estimate of distance does not guarantee that the phenomenal experience corresponds. The problem is that reported distance contains both a perceptual and a cognitive component. Gilinsky (1951) describes the problem as follows:

> 'When a subject says that a distant object appears to be one mile away, he means that it appears as far away as an object known to be a mile away. That is an absolute judgement (based on past experience) and not a measure of perceived distance ... Accordingly, the perceived distance of an object 100 yards away may be only 30 or 40 yards, although we may have learned, by training or experience, to judge it as 100 yards away. Similarly, the perceived distance to the horizon or the moon may be only 50 yards by this definition.'
>
> 1951, pp. 464-465.

It is clear, then, that such results offer no real evidence concerning the subjects' perceptual abilities. Conclusions about this can only be left to the reader's subjective discretion.

A second important point concerns the evaluation of published data as evidence of distance perception, even if it is, in fact, accepted as a genuine reflection of the subject's experience. Normally, means and standard deviations of subjects' judgments are presented, and it is left to the reader to decide if they are sufficiently close to the actual position of the object to represent accurate distance perception. The implication in published work is, of course that they do. Yet this methodology provides no satisfactory way of deciding whether or not a judgment does represent such a case of absolute distance perception. Considering the fundamental importance hinging on inaccurate estimations in the real world, this lack of interest in attempting to specify the "practical" border between absolute and non-absolute judgments is remarkable. After all, an only approximate judgment can mean death to an animal with a predator in pursuit, and the distance judgments animals are forced to make must frequently be considerably more accurate than those cases which are sometimes taken as examples of veridical perception in the laboratory. The fact that no attempt has ever been made to arrive at a definition of adequacy in evaluating the judgments made in this area, presumably belies the fact that the problem has not been seen in this way, but merely as another "phenomenal" event to be explained. The fact that writers frequently refer to "approximately veridical" perceptions reinforces this point.

Finally, we are left with the problem that if absolute distance perception does not express itself in the kind of terms that have been employed to examine it, then it must do so in some other way. In what terms is distance perceived? How can we really judge whether a report is accurate or not? The traditional outlines offer us no insight into these problems.

A potential, purely visual source of information about an animal's absolute distance from objects, formulated within the context of ecological optics (Gibson 1963) has been described by Purdy (1958) and Lee (1974). These authors have suggested that there exists "body-scaled spatial information" about the layout of the environment which is optically specified in units of the animal's height above the ground.

In this way, height from the ground could be used as a constant - a kind of metre-stick - in terms of which distances could be measured. The problem for the system would be simply to pick up this source of information. Although such a system is very plausible, the body-scaled information does not, of course, have to consist of height-units. One alternative to be developed here is that distances are apprehended in terms of what we will call the animal's natural action units - or more specifically, in terms of the results of such actions. In the case of terrestrial animals, such action units would be steps or derivatives of steps, like leaps, hops or crawls. Such action units are always intrinsically defined and therefore do constitute accurate units of measurement. To use them as a measure of distance, the organism has only to learn what transformation of the optic array will accompany such action units or groups of action units when he moves relative to the environment.

One argument in support of this idea concerns the absolute distance perception of birds and other flying organisms, and of fish. These have no optical constant like height above the ground, and there is no other obvious, purely optical constant with the status of the height-constant which could be used. However, according to the present argument distances could be measured by such animals in terms of wing-beats in the case of birds, and tail-thrusts in fish. Wing-beats and tail-thrusts are the natural action units of these respective species and correspond to the steps of terrestrial animals. It is known, of course, that the movements of both birds and fish are at times subject to external pressures from air speed and fast currents. Terrestrial animals, too, are affected by external constrictions. This would render any simple action-unit account implausible, since a given action unit would produce different results according to the influence of these variables. For example, in terrestrial animals a standard action unit like a pace will yield a different result depending on the surface walked on (walking uphill, downhill or horizontally). However, this need not prove an insurmountable problem so long as the external forces are constant in their effect. If they are, the organism requires only a recalibration based on a number of instances of the effect, to put the system back in order. This will not be possible in violent crosswinds or squalls, or in areas of competing currents. However, in such conditions the animal's relation to the ground surface, and his ability to make corrections to it, will be greatly disturbed anyway. His perception of the distances will still be in action unit terms, even if such action units would not realise the intended results.

A second argument is based on the fact, shown by the experiments reported below, that it is possible to locomote accurately to objects at considerable distances when the eyes are closed throughout the orientation period. This finding implies that the specific motor actions necessary to achieve this result were programmed in advance. In this instance, the specific motor actions would be the number of steps necessary to reach the object. Thus, even if distances were apprehended in terms of height from the ground, this would have to be translated into action units for the above-mentioned results to be possible. We have every reason to suspect, therefore, that these action units are themselves the constants used to measure distance.

It will be seen that this account of the units for space measurement offers a potential way out of the difficulties outlined above in relation to the classical approaches to the problem of absolute distance perception or a conglomerate of perceptual and cognitive influences can be accommodated because we need accept only instances of accurate behavioural responses as examples of absolute distance perception. This approach to the problem is limiting, of course, insofar as it restricts the methods available. Nevertheless, this seems the only way out of that dilemma. The problem of defining adequacy in absolute distance perception may also be solved in this way since a behavioural response performed blind may be checked against one performed visually. If the accuracy of the non-visual response matches the accuracy of the visual one, then we can accept the non-visual response as adequate in terms of the accuracy achieved under normal visual conditions.

The proposition with which we began this discussion was that animals need more than relative distance information if they are to control their behaviour in relation to the objects and surfaces in the world. It was argued that they also need to be able to relate their own activity to distances in space, and it was argued that they do this by means of natural action units. Returning to the development of our model, this conclusion bears an important implication. It implies that the "absolute" distance of an object is not given directly in the receptor information but depends on the placement of what we call an absolute distance overlay on the "primary" information; that is, on the relative distance information directly available at the eye. This overlay allows us to see in advance of action the transformations in the optic array which would accompany a natural action unit or group of such units if we were to make them. In this way, distances in space are defined in terms of quanta of action, and the absolute distance overlay may be thought of as a kind of motor map of space existing within the nervous system and mirroring the external space on which it is calibrated. In this way, every individual within every species has its own measuring-stick for the apprehension of "absolute" distance.

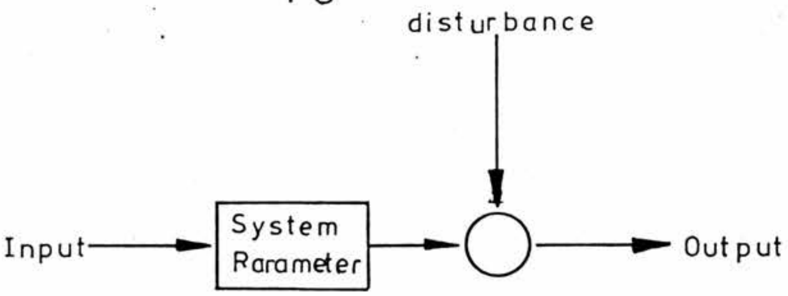
General Concepts from Control Theory

The two components of the system described above would seem to be logically essential if the organism is to be able to interact with its environment; it must have information about the layout of the world and the objects and surfaces which comprise it, and it must know its "dynamic" relation to those parts of the world with which it is to interact. The precise way in which motor problems are solved on the basis of this information is not so obviously dictated by logical necessity. Since the outline to be presented here differs in a number of important respects from existing outlines, it will be profitable to examine these alternative models first. In this way, these important aspects will be highlighted.

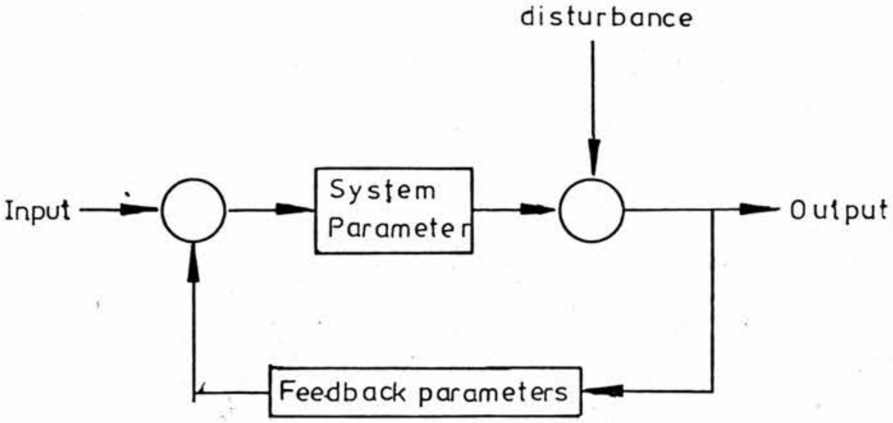
Most models of control to be found nowadays are heavily influenced by the concepts of control theory which, in turn, is heavily influenced by the concepts of cybernetics. Cybernetics, which can be defined in a general way as the "science of steermanship" (Wiener, 1948), is characterised by the fact that it is a functional science. It is concerned primarily with how things work rather than with what they are. As such, it has had wide application throughout the physical and biological sciences, drawing attention to the remarkable similarities in functioning between apparently incommensurate systems. Whether that system be electronic, mechanical, neural or economic does not seem to matter. Cybernetics can be applied with benefit to them all.

The central concept in control theory is probably that of difference or change. The task of a control system is defined as being to maintain a particular state in spite of external pressures threatening to produce change. There are three ways in which such control can be achieved. Occasionally, where external pressures are absent or exceptional, the system may operate by means of "open-loop" control. This means that once a response is initiated, no changes can be made to that response, which is executed as an independent "whole". This kind of control is said to be restricted in the main to fast movements where there exists no possibility of correction on the basis of information obtained during the act, because the speed of the movement precludes the possibility of using the information. A more common situation, however, is said to occur when independent forces attempt to create differences between the desired state and the state realised, and steps are therefore necessary to counteract these forces wherever they occur. This type of regulation is known as "closed-loop" control.

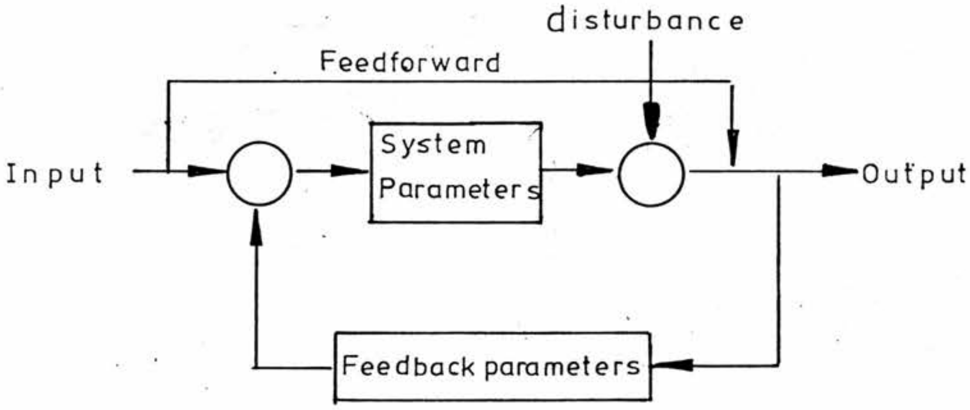
The essential mode of functioning of such a system is as follows: an input specifies a desired state that the system is to attain. A servo-mechanism controls the output with that desired state in mind. Some kind of controlling device feeds back information about the course of realisation of the state to the input element, and the input specifications to the servo are changed accordingly. In this way, the system organises itself to counteract external fluctuations. Sometimes, the nature of these disturbing factors are known or can be learned. In that case, it may be possible to predict their occurrence and set up anticipatory adjustments to them in advance. Such a mode of action is known as "feed-forward". We will have much more to say about this mode of operation presently. Simply open-loop, closed-loop, and feed-forward systems are shown in Fig. I.



open-loop control



closed-loop control



feedforward control

FIG. I. Simple open-loop closed-loop and feedforward control systems

Examples of these different modes of operation are fairly readily available in the literature. Open-loop explanations have been linked to only two cases: where it is considered that a disturbance of output during normal functioning is unlikely; or where the behaviour is to be performed at a speed which precludes correction once the act has been initiated. The most usual example of the first case concerns the control of eye movements. Since the eye is not normally a loaded organ, with little likelihood of consequent disturbance, it could be expected to differ in functioning from the limbs, for example, which are frequently subject to such disturbances. The reafference model of eye control (von Holst and Mittelstaedt, 1950), makes such a supposition. According to these writers, eye movements are controlled by means of commands from the system alone, a position which was also adopted by the outflow theory of Helmholtz (Helmholtz, 1867). There is some evidence for it, since little proprioceptive information apparently derives from the eye muscles (Merton, 1961). That vision itself might be used as the source of feedback information about eye position is sometimes vaguely mentioned, but never seriously considered. Obviously, however, commands to move must be based on information about where the eye presently is in the head. Since proprioceptive information from the muscles cannot supply this information, and since the eyes are subject to uncontrollable drift(Yarbus, 1967), and consequently command information cannot supply this information with accuracy either, the only reliable source of such information is vision itself. Such information obviously constitutes feedback. And although saccadic eye movements are themselves too quick to be guided in any continuous way, and must obviously be executed as a whole, these movements are never wholely accurate. According to

Jeannerod and Prablanc (1973), a saccadic movement takes place as a preprogrammed act, but small errors which inevitably occur are subsequently adjusted to centre the focusing. If we now consider tracking tasks - which also are executed through saccadic jumps - it will be clear that unless such small errors are taken into account after each jump (or small number of jumps), the error will increase and become significant. Jumps must be programmed taking into account the success of previous jumps and this requires feedback about the success of previous jumps. Eye movement control cannot therefore be completely open-loop. An interesting interaction of pre-programmed acts made in association with visual feedback about the success of these acts appears to take place.

The second type of open-loop control is said to occur as a result of the speed with which some actions are made. We have already seen that the eye-saccade itself constitutes such an open-loop act. Others are not difficult to find. Messenger (1968) has suggested that the cuttlefish *Sepia officinalis* captures prey by means of an open-loop attack. The animal orients to its prey and strikes with a rapid (30 m sec.) movement of the tentacles. It is assumed that no correction can take place during the execution of such an act. A similar method of attack occurs in the mantid *parastagmatoptera unipunctata* (Mittelstaedt, 1957), which captures prey with a 10-30 m sec. movement of the forelegs. In general, it is assumed that any act performed fast enough to beat the feedback loop is executed as a result of efferent commands only (McFarland, 1971).

While open-loop control may provide useful advantages of speed, such control is considered exceptional. Most systems are open to disturbances which are capable of seriously disrupting the system's performance, and some mechanism is necessary to counteract these influences. Such interfering factors occur widely in biological systems, and are compensated for by closed-loop feedback control. Among the most widely studied examples are to be found in homeostasis, for example in heat regulation where the disturbing factor will normally be excessive heat or cold or in the pupillary reflex, where it will normally be excessive or insufficient light. In all these systems, regulation is achieved by feeding back information about the current state, which is then compared to the goal state desired, and any discrepancies between the two corrected. The system is thus self-regulating.

Finally, we must make mention of control by means of feedforward. We have already noted that feedforward may occur whenever external forces likely to disrupt attainment of the goal state are known or can be predicted. According to MacKay (1966):

> 'It is often possible to increase speed and accuracy by arranging that, in addition to the "feedback" signals ... the selector system S receives an input computed directly ... together with any other relevant advance indications obtainable via auxiliary sensors. This "feedforward" need only roughly approximate to the required form, but will leave C (i.e. the control system) free for the task of fine adjustment, on which it has the last word'.
>
> 1966, p. 427

Examples of this mode of control are to be found again in heat regulation, as when a sudden increase or decrease of temperature at the skin initiates steps determined to correct the corresponding change in the temperature of the body as a whole which will occur at a later period as a result of the temperature change being reconnoitered at present by the skin (Milhorn, 1966). Examples in motor behaviour are to be found in cases where loadings of the system have to be taken into account, for instance, in the act of lifting a ping-pong ball as opposed to a brick. Since such objects are normally picked up smoothly and easily, it seems reasonable to suggest that the system can predict the force necessary to accommodate the excess load (consider the case where errors are made, as in mistaking a box full of lead for an empty box). Furthermore, this feeding forward of predictions about the force necessary to accommodate a load is evident in early infancy, where a child can be fooled into thinking that an object is heavier (or lighter) than it really is, producing clearly identifiable excessive or insufficient effort to lift the object (Bower, 1973). The technique is used to study weight conservation in infancy. We shall have much more to say about the concepts of feedback and feedforward below.

Models of Perceptuo-motor Control

Most discussions of perceptuo-motor control draw heavily on the notion of closed-loop control. And while most writers have seen that such models are far from sufficiently sophisticated to account for the complexity of the behaviour typically seen in animals, remarkably little attempt has been made to go beyond an elementary outline. The models are thus frequently referred to as "simple" models of control (Paillard, 1960), or even as "the simplest possible" models of control (Bernstein, 1967). Adams (1961) in criticising the limited range of behaviour with which students of motor skills have concerned themselves, said of the uses of servo-mechanisms that they "have been gross or analogous and can't be taken seriously as descriptions of continuous behaviour" (p.186). In spite of these convictions that the essential features of sensory-motor control were not being elucidated, writers have continued to quote such "simple" models, and have made very little progress beyond this point (see, for example, McFarlane, 1971; Legge, 1970; Annett, 1969; Legge and Barber, 1976). Nor has this situation been caused entirely by a lack of evidence suggesting further developments, for as we shall see, such evidence is available in the literature. Its implications have not been properly appreciated, however, and the significance of the results has been overlooked. We shall be returning to this point in much greater detail below.

Since our purpose in this section is to show up the weaknesses of most current models of control, it will be profitable now to present an example of such a model which can then be examined in detail. One good outline for comparison with the one to be presented here is the system of Bernstein (1967), since this model encapsulates the essential features of most models in a lucid way.

Bernstein argues that any system for the accomplishment of motor acts must include among its minimum requirements the following: a <u>control element</u>, which conveys to the system in one way or another the nature of the task to be accomplished. The control element is thus said to specify the "sollwert" (Sw), that is, the required value of the parameter to be regulated. Bernstein is not altogether specific about the nature of the sollwert, but it seems essentially to correspond to rather broad commands such as "walk towards that tree". The sollwert thus corresponds, in this case, to the shortest possible route between the subject's present position and the target though presumably a different "route" could have been chosen. In a way, therefore, sollwert seems to apply to directional commands. We shall return to the concept of sollwert below.

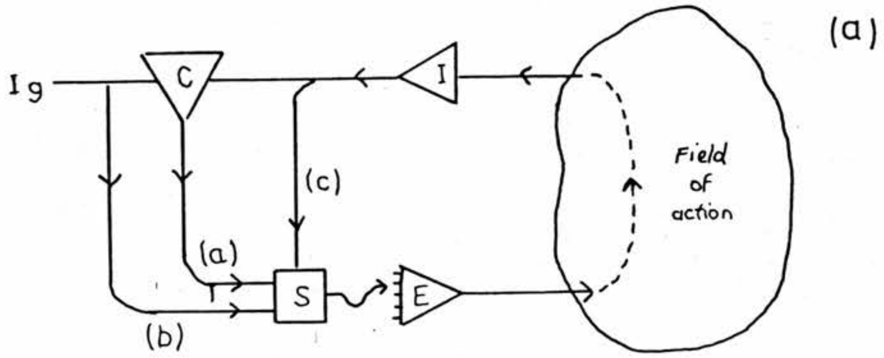
The second requirement in Bernstein's system is said to be a receptor (like the eye), which specifies the factual course which the organism is taking at any time. In this way, the receptor is said to provide information about the "istwert" (Iw), that is, the current, actual state of events. The discrepancies between Sw and Iw (Δw) is picked up by the third element in the system, the comparator. The process of accomplishing a simple act is therefore basically a process of regulating this mismatch so that Sw and Iw always correspond. As an actual example of this process, we are asked to consider the coordinational act of picking up an object from a table. Bernstein describes the process as follows:

> 'The coordinational act of seizing a visible object from a table-top may be regarded as a constant process of estimation of the rate of diminution of that section of the path over which the hand must still travel to meet the object under consideration. We have every justification to designate the position of the object Sw, the current position of the hand Iw and the regularly diminishing distance between them Δw (Iw - Sw).'
>
> 1967, p. 129.

In this way, the difference between the planned path of movement and the movement itself defines the extent of the corrections necessary during a movement. The final components of Bernstein's system are all concerned with the translating of this information into effector functions. The system therefore contains an apparatus for encoding Δw into correctional impulses which are relayed to a regulator controlling the functions of the effectors themselves. The system is shown diagrammatically in Fig. II. one Examples of a commonly cited alternative model~~s~~ ~~are~~ is presented alongside.

A number of differences between this model and the one currently being elaborated are evident immediately. In the first place, Bernstein includes in his system no linkage between the sense receptor and the command system. Such a linkage is obviously necessary, however, since otherwise the system has no information on the basis of which to specify the sollwert. Secondly, there is no component for the specification of absolute distance. This would follow from the fact that no receptor/command link is included, but it is not treated within the context of the istwert either. The fact that control is supposed to operate continuously would, of course, rule out the need for absolute distance information. On the other hand, an organism must always be able to appreciate whether an obstacle is 10 yards or 10 miles away. Some sort of absolute distance information would therefore have to be available even to a system operating by means of continuous control. We have already seen, however, that at times an animal requires very precise information about its relation to the surrounding objects and surfaces, since an animal has to know at some point in advance where an obstacle lies in relation to itself so that it can organise evasive action. At times, as when the animal is running at speed, this would have to be some distance in advance.

The central feature of Bernstein's model, however, concerns the manner of regulation of motor activity by means of sollwert, istwert and mismatch. The system implies a continuous process of information



Ig = indication of goal
C = comparator
I = indicator (receptor)
E = effectors
S = selector (of effector response)

(a) = feedback
(b) = feedforward from Ig
(c) = " from I

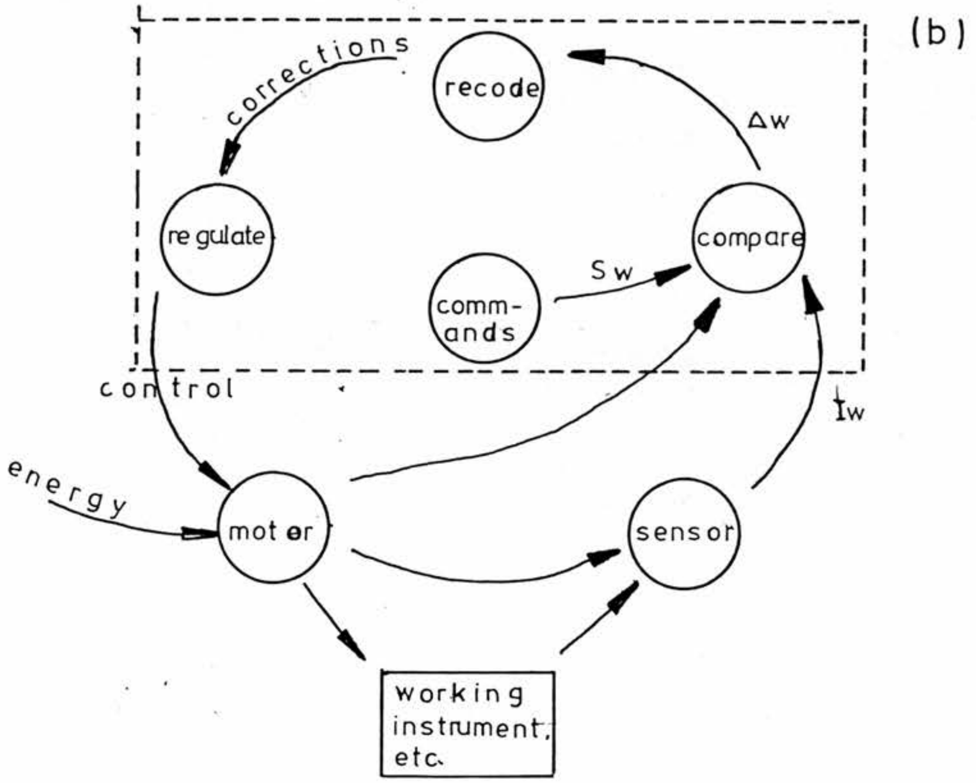


FIG. II Commonly cited models of perceptuo-motor control.

(a) from Mackay (1966)

(b) from Bernstein (1967)

pick-up together with continuous matching. On the basis of this information adjustments are continually made to keep the parameters in line. There are two reasons why it is considered necessary that guidance be continuous. Firstly, we can simply never know when a deviation from the planned path of movement will occur and it is therefore essential that the receptor system remain constantly alert for their occurrence. Secondly, it is commonly supposed that distances become increasingly hard to judge as physical distance increases. For example, Legge and Barber (1975) state '... vision cannot accurately locate objects at some considerable distance (distance becomes increasingly hard to judge as it increases)' (p.52). These statements in the textbooks are based on the results of psycho-physical studies of distance perception. For example, in Gilinsky's classical 1951 study, distances quickly become substantially underestimated as they increase. For example, at a distance of 10m, the perceived distance is rated at 7m (30% underestimation). At 20m, the perceived distance was 11m (45% underestimated). The effect was even more marked with other subjects. Studies of this kind have led to the general belief that distances outside the near-space are not perceived veridically. It is for this reason that we have seen Bernstein describe the process as 'a *constant* process of estimation ... of the path over which the hand must still travel to meet the object under consideration'. (p.129, my italics). Paillard (1960) writes of servo mechanisms in the following way:

> 'Their common feature is that they possess some kind of controlling device able to *appreciate continuously* the state of the machine realised

> at a given moment and the final aim assigned to
> it by its constructor'.
>
> 1960, p. 1700, my italics.

A little later he adds:

> 'Through a feedback circuit, the information collected from an error-detecting device is *at every moment* sent back to the servo motor controlling the output.'
>
> 1960, p. 1700, my italics.

The element concerned with the supply of this information is considered to be the eye, as we have seen, which continuously feeds back information about the current state of the ongoing act. In this way, the eye is given a remarkably limited role in the control of behaviour. It is not concerned in the *formulation* of sollwert, only in regulation of activity to realise that sollwert. It is for this reason that control models tend to omit the obviously essential link between receptor and control system (Bernstein, 1967; MacKay, 1958, 1966). This omission can only be interpreted as a theoretical muddle, occasioned by too close a reliance on the already developed cybernetic control systems (like thermostats) and not enough on the actual problem at hand. In thermostats, automatic pilots and the like, the sollwert is either permanently defined in the system, or else is under the control of a completely foreign agent, as when a housewife adjusts the temperature setting of her central heating system. In neither case is the command setting determined by the "receptor". Obviously, such systems bear only the most distant relation to the perceptuo-motor control systems found in animals and man [which] are presently being discussed. that

Programming Systems

An alternative and more economical system to the ones offered above is possible, however, if we assume that the system is capable of intermittently sampling the array and using this intermittently-acquired information to construct in advance a motor program of the precise motor actions required for behaviour within this spatio-temporal "packet". Such a system would not only be more economical but seems on various grounds to be necessary. Firstly, it is simply not possible to make motor responses "on top of" information which is just being picked up, because by the time the information had been relayed from the periphery, appropriate motor responses planned, and the corresponding coded commands relayed to the effectors, the animal would have passed the point in the world where the information would have been useful. In other words, the appropriate motor responses could not be formulated and put into effect by the time the point in the environment specified by the information had been reached and the animal would collide with the obstacle or trip over the rock. For this reason it is always necessary to plan the behaviour some finite time in advance of the point in the world where the behaviour is appropriate. If we now consider an animal running at speed it will be clear that the amount of programming will at times have to be large. This is so because the faster an animal runs, the greater the distance it covers in a given time. In this way, if speed is to be achieved or maintained, the amount of programming will have to increase monotonically with this speed. Detailed arguments about the limitations imposed by processing times and other factors will be deferred until we come to investigate the literature on motor behaviour, but at the moment we may consider the limitations imposed by a perceptuo-motor lag of 1 second which, as we shall see, is a rather liberal estimation of the time necessary to prepare a response of the complexity that is normally demanded by circumstances in the external environment. An animal running at 15 m.p.h. (a rather average speed for many animals), will cover 7.35 yards in 1 second. This means that a response to an obstacle situated at that distance, together with all responses necessary to reach that obstacle from the current position, would have to be fully formulated (and <u>accurately</u> formulated) in advance, because no further corrections can be effected after that point. The complexity of such a program is further dependent on the number of obstacles which are located within the "space-packet". Total program complexity is therefore a function of both the nature and number of impedances in the environment, and of the animal's speed of travel. Other considerations will also effect the amount of programming, but we will come to these below.

There is a second important reason why the behaviour of animals cannot be continuously guided. This is that the visual system of any locomoting animal must frequently be free to perform functions other than the simple guiding of locomotion. A predator in pursuit of prey, for example, must pay constant attention to the behaviour of the prey and must react at high speed to changes in its behaviour, since every split second lost increases the chances of the animal escaping. The predator must therefore be capable of locomoting without the eyes being constantly focused on the task of visual guidance. This point applies even more strongly to those species which hunt in groups, since only by watching the behaviour of the other members of the pack can the hunt be coordinated and have a hope of success. It is known that pack animals like lions, wolves and, of course, man use fairly extensive signalling systems to coordinate the joint activity most efficiently, and this demands that the members of the group be receptive to such signals (as well as being prepared to make them). Finally, the independence of vision is most fundamental of all to those species which form the prey of some other, for these engage in <u>continuous</u> scanning of the environment for possible attacks. Indeed, this constant scanning is particularly important when the animal is locomoting, for it is at such times that the animal will be most visible (and therefore most vulnerable (Tinbergen, 1951). It is clear, then, that independence of the receptor system from the task of straightforward guidance is fundamentally important to all species, and this demands that behaviour be capable of continuing when the eyes are turned from guidance tasks. A programming system would therefore seem to be essential for any animal which is to be capable of even moderately complex behaviour.

It should be noticed that the programming system advocated here does bear some resemblance to Bernstein's sollwert-specifying command system. A number of fundamental differences must be highlighted, however. We noted earlier a certain lack of precision as to the definition of sollwert, which was defined by Bernstein to be the actual spatial location of the object. He claims: 'we have every justification to designate the position of the object Sw ...' (p. 129). On the other hand, immediately after this, he writes: '... I shall regard ... the continuous planned path or process of movement of an organ as the variable Sw ...' (pp. 129-30). In this case, Sw seems to correspond to a sort of "invisible line" extending through the most direct route between the hand's present position and the target under consideration. Thus he writes:

> '... w will be the threshold values of deviations which are more or less accurately corrected during the course of the movement, as an example of which we may take the deviations of lines drawn by hand with a pencil or the point of a planimeter from a ruled line which a subject is set to follow'.
>
> *ibid*, p.130.

Sollwert therefore seems to be defined simply in terms of *the most direct route* to the target. On other occasions, the sollwert is actually given by the task itself. The line which the planimeter is set to follow in the above example is such a case, and many tracking tasks employ a ready-defined sollwert in the form of a "wave" which has to be followed (Poulton, 1957). On other occasions, as in 'pursuit tracking' experiments, the subject's task is to keep a pointer on a target which moves along a pre-determined path. Again, therefore, the task is to "trace" an invisible line which is defined by the path of the target though, in this case, the path has to be discovered. Only by learning this track can the subject maximise his accuracy in tracking (see Poulton, 1954, 1957; Legge and Barger, 1975). In the present context, however, such a "sollwert" becomes little more than the *reason for constructing a sollwert*. It specifies the goal which the program is designed to realise, but it is not in itself a program. In the present system, the sollwert does constitute such a program, containing within it not just a statement of the goal, with perhaps the most general guiding directives, but also a formulation of the *motor actions* necessary to attain a solution, defined so precisely that no corrections to the formulation may be necessary. In other words, the sollwert can be broken down into the exact motor components of which it is composed. Sollwert in this system is consequently a highly complex program of motor actions. In comparison to this, Bernstein's sollwert scarcely deserves the term "program".

Other Elements in the System

The program of actions worked out by the programming system on the basis of visual information requires for its fulfilment an effector system (ES) capable of executing such programs. In fact, the effectors are not controlled directly from the PPS but are regulated by a controller (C) which encodes the ~~PPS~~ specifications from the programming system into nervous impulses and relays these to the effectors.

The Role of Monitoring during Execution of a Program

It is now necessary to re-examine the notion of istwert - the element concerned with the factual state of affairs - which in Bernstein's system was supplied by the continuous pick-up of information by the receptor. This method of control was opposed in the present system, but this was not meant to imply that istwert information is unnecessary: indeed it is necessary, but its nature and supply are considerably different from in Bernstein's system, as we shall now see.

Any system of the type under discussion must receive information during the course of a movement to indicate that the program is being executed according to plan. There is a number of reasons why such information is necessary. One simple and basic reason is that some purely "technical" fault may occur which will require correction if the program is to continue. At times such a technical problem may be severe enough to necessitate a total break in the program's execution (the animal has to stop), or else a reorganisation or extension of the program if the animal is to continue. Examples of such technical faults are to be found in cases of proprioceptive loss, where control of activity may become extremely difficult. This would indicate that programs are not always executed as planned, or may on occasion not be sufficiently precise to be run off "blind". Some form of monitoring would therefore be necessary in order to evaluate whether or not the program is being executed as intended. We will return to the problem of how this monitoring is achieved below.

A second reason why it is necessary to monitor on-going activity is that some change may occur in the approaching environment which was not taken into account in the original program (as when an animal runs out into the path of locomotion). It may be necessary to have a mechanism specifically designed to contend with disruptions of this sort.

A third reason is that, as we shall see, a program cannot always take into account all of the salient features of the approaching terrain on which an ideal program would be based. There will frequently be (except in the most predictable environments) some degree of mismatch to be regulated during the execution of the program. These situations requiring changes in the plans for behaviour and for reorganisation and termination of programs probably occur much more frequently than we might at first suppose. This is probably because most of these occur without it being necessary to draw on conscious attention (though they may be revealed by an introspective attitude). In any case, it seems as if these alterations and reorganisations are fundamental to the system and depend on the detection of error during the execution of programs. We must now consider the forms of monitoring which may be operating.

It will be remembered that in Bernstein's system, information about current state was supplied in a continuous way by the receptors. However, we have already noted that the system requires a good deal of independence from such guidance constraints. In the present system, therefore, either such information must be provided by some other source, or else it must be provided by the eyes in such a way that no restrictions on the organ's other functions are applied. In fact, both these propositions seem to be true. To make this clear, we will need to examine the concept of monitoring rather closely.

The term "feedback" has so far been employed as a general concept with the broad, functional definition that it exists to provide information about the actual state of affairs at any given moment. The cybernetic models which we have so far discussed therefore refer simply to "the feedback loop". In the case of complex behaviours of the sort being discussed here, however, this is far too broad a classification. We must recognise that in perceptuo-motor control, monitoring exists on a number of levels, and is concerned with control of different parts of the total system. From the point of view of the present discussion, we may draw upon the two forms of feedback distinguished by Lee (1977). According to Lee, we require *proprioceptive* information, which is defined as "the obtaining of information about the positions and movements of the parts of the body *relative to the body*.(1977, original italics). This term is thus defined close to its original meaning (Sherrington, 1906). We further require *exproprioceptive* information, which is defined as "the obtaining of information about the position, orientation or movement of the body as a whole, or of parts of the body, *relative to the environment* (1977, original italics). Lee claims that all "feedback" information can be classified as of these two sorts.

If we now return to the notion of feedback employed by Bernstein, it will be clear that he was referring principally to exproprioceptive feedback. His concern was with the eye as an indicator of where the limb, or body as a whole, now stood in relation to the goal at any given moment. We have argued, however, that this kind of feedback is frequently unnecessary, as it is possible to formulate programs which are sufficiently precise to rule out the need for it. However, this does not rule out the need for <u>proprioceptive</u> feedback during the course of an act even when the act, in exproprioceptive terms, is unmonitored. We have already noted the possibility, in principle at least, that some "technical" fault might appear in the execution of the program which would need correcting. Since the program would now be formulated in motor terms, it would not be necessary to obtain further exproprioceptive information in order to account for such errors, but merely to monitor <u>the execution of the program</u>. This can be done by means of the proprioceptive system alone. It would appear that efferent commands alone are not sufficently precise to enable animals to perform acts in the absence of this type of internal monitoring, for in such cases, the act becomes ataxic. We shall be reviewing the evidence on proprioceptive loss below. At this point we may merely note that while the system is frequently freed from the necessity of obtaining exproprioceptive information, some form of proprioceptive monitoring continues to be necessary. The sampling of proprioceptive information may, of course, itself be intermittent. But its continued supply during the course of program seems to be essential.

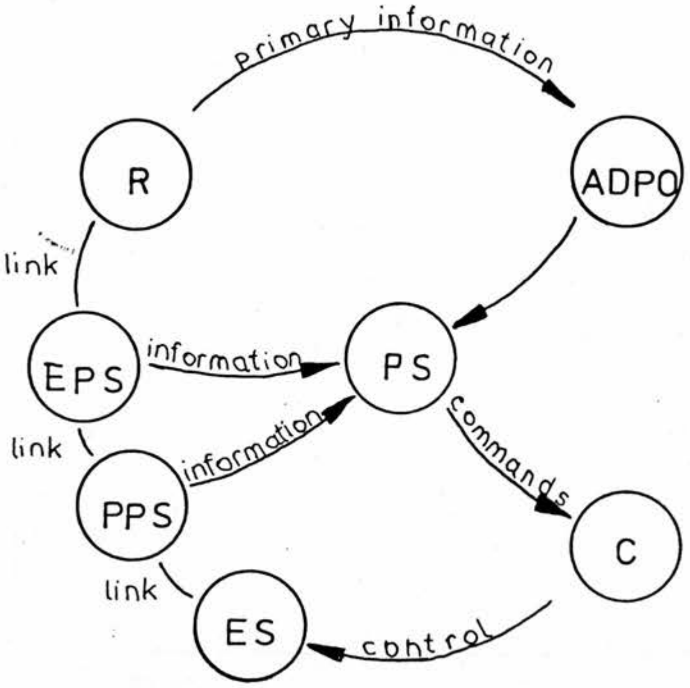
There is a further point which should be made at this juncture concerning the concept of feedback in general. As we have seen, monitoring of the kind being discussed is normally referred to as feedback. However, it is not at all clear how this concept should be defined, because it is in many ways indistinguishable from the concept of feed<u>forward</u>. For instance, in the example of heat regulation of the body which was given earlier, a change of heat at the skin is used to initiate steps to create a corresponding change in the temperature of the body as a whole. The detection of temperature at the skin may be described as feedback about the current state of affairs. This information, however, is then used as feedforward to initiate changes in the program controlling temperature of the body as a whole. Even if the concept of program is replaced with the vaguer and more general concept of "goal state", information indicating deviation from this goal state is picked up and used to correct the current state. The distinction between feedback and feedforward becomes meaningless in this situation, however, because both concepts refer to the same information. In view of this kind of confusion, it may be best to abandon these terms altogether and speak instead only of the information which is picked up during execution and which can be used to initiate changes in the program if desired. This is the practice advocated here, though for the purpose of discussing the existing literature the terms will still be occasionally used at the present time.

We gave two other reasons why some form of monitoring during the course of a program was necessary which did concern the expproprioceptive system, however. These reasons were that a change may occur in the environment and that a program cannot take into account all of the salient features on which an ideal program would be based. Since these problems are concerned with the environment or with changes occurring within the environment, it is clear that they concern the exproprioceptive system rather than the proprioceptive system. The information necessary to correct such problems can therefore only be supplied by expropriception. The problem of intruders getting in the way is not something which occurs with any regularity under normal circumstances, though most people have experienced it. In some species, the information for intrusion may be picked up by a different perceptual modality. However, it seems that the visual system can be used to detect this information without this interfering with the eyes' other functions. Trevarthen (1968) has drawn a detailed distinction within the visual system between "ambient" vision and "focal" vision. The distinction is made on anatomical, physiological and behavioural grounds which we need not go into here. The former system is said to be capable of responding to information about spatial location and movement in a "direct" way, without picking up information about form or any other exteroceptive properties at the same time. That system thus seems geared to respond, among other things, to obtrusions emerging into the visual field while the eyes are in fact essentially focused on quite different tasks. As evidence we may mention the fact that in every species examined, stimulation of the tectum in the free-moving animal results in "visually elicited orienting movements" which appear to be indistinguishable from natural orienting behaviour (Ingle, 1970). The head is sharply turned to that region corresponding to the locus of retinal input, or rather where a retinal input would have occurred if the situation had been a natural one. It would appear that in these cases the animals are responding, not to an identifiable object, but rather to an unexpected intrusion to the visual field represented by the electrical stimulation. It would appear then, that the visual system does have the capacity to pick up intrusion information without this being any burden to the eyes other functions. If the head/eye system is directed in such a way that the intruder is outwith the visual field, then a collision may occur. A collision could then only be avoided if the animal has an alternative system capable of securing the information (auditory system, vibration-sensitive system, etc.).

The final reason why expproprioceptive information may be necessary during the execution of a program is that a program is normally somewhat limited: it cannot take into account all of the salient features of the environment on which an ideal program would be based. The problem is that in running over uneven ground, for example, it is not possible to formulate a program which tells the organism exactly where its feet should be placed in relation to all the dips and protuberances on the surface. The significance of this is two-fold. First of all, and probably of greatest importance, the posture of the animal, which is obviously critical for the execution of the program, would be upset: indeed, the animal might easily fall. Secondly, the variations in surface level would tend to make the animal deviate from its directional course. Both of these problems therefore need correction during the execution of the program, and this correction must be substantially visual in nature. It seems clear now that the control of balance in situations like that pointed out above is dependent on vision (Lee and Lishman, 1975). This information is available no matter what direction the head is oriented in relative to the environment (Lee, 1974). Once again, then, the detection of information for the control of posture need not inhibit the other functions of the eyes.

It will be evident, then, that the concept of monitoring being employed here is a concept defined on more than one level. Information about the ongoing control of a program is relayed by the proprioceptive system (PS). Information for the control of posture during the execution of a program and for the pick-up of intrusions is supplied by the expropriceptive system of ambient vision (EPS). The information thus acquired is used for whatever adjustments are necessary to the program under consideration; to initiate minor corrections; to extend programs; to reorganise them; and in some cases to terminate them and construct a new one. In this way, the organism is capable of controlling its activity relative to the goals it sets itself, or has set for it, in the external world. The complete system is shown diagrammatically in Fig.III.

One or two final points about the model must be made. Firstly, it will be seen that no link has been made between the absolute distance perception overlay and the control system. Although it might be thought that such a link is necessary for those occasions when continuous control is needed, the argument being presented here is that control is <u>never</u> genuinely continuous, though it may frequently appear to be. Programming appears to operate at many levels, not necessarily simultaneously. For example, in pilot studies on which the experiments reported below were based, subjects were asked to walk up to objects which had been placed at varying distances from the subjects and pick them up. The task had to be performed with the eyes shut during the orientation period. It was found that the locomotor



R = receptor

ES = effector system

ADPO = absolute distance perception overlay

PS = programming system

C = controller

PPS = proprioceptive system

EPS = exproprioceptive system

FIG. III A model of perceptuo-motor control.

section of the act brought the subjects within the same vicinity to the object as it did when the eyes were open, but that error accumulated during the reaching phase. This was demonstrated by the fact that the error obtained was the same whether the subject had to walk 2 or 10 metres to get within reaching distance of the object. This finding might have led us to conclude that the first section of the act (the locomotor section) is programmable, but that the second section (the reaching section) requires continuous, closed-loop guidance. However, Woodworth (1889) found that whensubjects were asked to join points 2 feet apart with a pencil line, the longest part of the act was pre-programmed as evidenced by the fact that the lines were almost identical whether the eyes were open or shut. Only the last inch or two benefited from further visual guidance. These reaching acts therefore seem to have been subject to the same type of control as the locomotor act above. When subjects were asked to join lines which were separated by little more than this terminal phase, the accuracy was now higher still. This suggests that no area of motor behaviour is subject to guidance by means of continuous control but that programming is to be seen at all levels of motor behaviour. The problem seems rather to be that not all sections of a complex motor act are programmed at once. Apparently, a hierarchically organised group of programs has to unfold sequentially. Presumably, the formulation of one program takes place as the other, already formulated, proceeds. We shall return to this problem below.

Finally, some links have been omitted from the model for the sake of clarity. A control link exists between the effectors and the receptor system to allow control of the ocular muscles. Links also exist between the effectors and the proprioceptive and expropriocepive systems, the latter being further linked to the receptors.

A REVIEW OF THE LITERATURE

The main contention of the model which has just been presented is that in guiding themselves around the objects and surfaces in the world, animals do not use vision as a continuous source of information about their dynamic relation to the environment, but sample this information only intermittently, using that information to construct programs which can then be run off "blind". Our task now is to uncover any evidence which may exist in the literature to support such a notion before committing ourselves to an empirical investigation.

In our theoretical analysis, we saw that most models of control stress the closed-loop, continuous nature of control. This poses an immediate problem, however. Since there is an infinite number of points between Sw and Iw whenever these do not correspond, it is obviously impossible for a finite system to guide a mismatch through any such infinite series. Control must therefore operate on blocks of such points which must then be treated as single "units". But this raises a fundamental question: when is "continuous" control discontinuous?

Reaction Time

The problem of defining the limits to continuous visual control has been attacked in a number of ways. In the first place, we know that a response cannot follow immediately upon receipt of a stimulus, because before any response can be effected a number of conditions has to be met. The stimulus information must be relayed from the periphery, decisions about how to act formulated, appropriate motor responses planned, and the corresponding coded commands relayed to the effectors. All these operations take time. Under favourable conditions, where the subject knows that a stimulus is due, knows what form that stimulus will take, and knows what response is required of him, the reaction time (RT) is never less than .2 seconds (Woodworth and Schlossberg, 1954). This, then, would represent a first limiting factor to continuous control. When the testing conditions are not so favourable, RT is easily increased. When S is rendered uncertain about the lengths of time which will elapse before onset of the stimulus (foreperiod uncertainty) the basic RT is increased to about .6 secs. (Klemmer, 1957). In most studies, the foreperiod is varied within very modest limits (usually no more than several seconds of uncertainty being used). When the uncertainty generated is more akin to that found in the real world (response required several times per day, or once every several days), RT is again increased. Warrick et al. (1964) performed such an experiment and obtained RTs of about .8 secs. This probably represents the maximum limit to RT occasionable by foreperiod delays (except when the stimulus is completely missed, as sometimes happened in the above study). RT can be manipulated in other ways as well, however, simply by varying other sections of the simple RT paradigm. Thus when complexity is increased by requiring S to respond to only one of a group of possible stimuli, forcing him to make a discrimination and then a choice of response, RT can easily be raised to just under 1 sec. (Donders, 1868; Merkel, 1885). This effect is old and well known. When the task is yet further complicated by demanding a separate response to each of a number of separate stimuli, RTs of 1 second and more can be obtained, due to the increased response selection demands (Woodworth and Schlossberg, 1954). Thus as the task increases in its approximation to the complexities of natural behaviour, so does the RT increase. That increase can be shown to vary logarithmically with the induced complexity (Hick, 1952). Just how this complexity, defined in the mathematical terms of information theory, can be equated with the complexities of natural behaviour is a difficult problem, but we are surely right in supposing that in natural situations, RT will frequently be considerably greater than 1 sec.

The Psychological Refractory Period

Any voluntary movement has a reaction time, which we have seen is never less than about .2 sec. Similarly, the voluntary correction of a movement also has a reaction time. According to Vince (1948) the sooner the signal indicating that a correction must be made follows the signal for the original movement, the longer RT to the second movement will be. Under conditions where S is half-expecting to have to make a correction, the RT to the corrective movement can easily reach .3 sec. (Hick, 1949). This period following initiation of a movement during which further movements have increased latency is called the "psychological refractory period" (Craik, 1948). Various theories have been proposed to explain it (e.g. Welford, 1952; Elithorne and Lawrence, 1955; Broadbent, 1958). Here, then, we find a further limitation to the possibilities of continuous control. Since a voluntary response to visual information takes at least .2 secs. and since a further correction cannot begin to take effect until at least .3 secs. later, this theoretically eliminates the possibility of corrections occurring more frequently than once every .5 secs. (Poulton, 1954). From this we might conclude that continuous control in practice means control effected no more frequently than once every half second. Such a supposition has, in fact, been evidenced empirically by Craik (1947; 1948) and by Vince (1948). In these classical tracking studies, subjects were asked to keep a pointer fixed on a target line in the face of external influences forcing the pointer off to one side. An analysis of the track records shows that corrections were being made on average every .5 secs. The result strongly supports the intermittency claim made above. Furthermore, Woodworth (1899) has shown that when subjects are asked to draw lines corresponding to a standard form, performance is better when visual information about the response is available, until the frequency of responding reaches 2 per second. At that response rate, it made no difference whether S had his eyes open or closed during the drawing period. Again, this would indicate that responses taking .5 secs. or less cannot be corrected on the basis of visual information.

A number of deviations from this .5 second limitation must be noted, however. Several studies have found that vision can have an influence at less than this critical time. Pew (1966) asked subjects to keep a light fixed on a target on an oscilloscope by means of two buttons, one of which caused acceleration to the left, and the other to the right. When the target was blanked out for periods of up to 410 m.sec. the modal time before a correction was initiated once the target came on again was 300 - 350 m.sec. Keele and Posner (1968) asked subjects to make discrete aiming responses at a target $\frac{1}{4}$ inch in diameter and 6 inches away from the home station. Movements were trained to take approximately .15, .25, .35, and .45 secs. On half of the trials the lights were out. The existence of visual information made no difference to performance when movement time was less than

190 - 260 m.sec. Beggs and Howarth (1970) asked subjects to make a vertical aiming movement at a target. As the arm came up, it passed through a photo-electric beam which extinguished the lights. When this happened 290 m.sec. or less before the hand reached the target position, accuracy was not affected. At longer intervals, it was disturbed. These studies all imply that visual information can have an influence at something less than .5 seconds.

The first thing that we should note here is the discrepancy between the critical times in the different experiments. Again, we may judge these differences to reflect the role of different degrees and types of task complexity. The fact that the times here are shorter than those obtained in the studies discussed above should not disturb us unduly, however. Craik himself obtained some corrections at .25 sec. intervals; though he also noted many that required at least 1 second. Clearly, something must be said about the varying times obtained within and between experiments.

The experiments of Keele and Posner, and Beggs and Howarth, while designed to show the minimum time during which a visual correction can be made, cannot be considered to have genuinely done so because in both cases the target position was specified <u>in advance</u>. This means that initial RT together with the accompanying psychological refractory period is absent in these experiments, because the stimulus is constantly available, and the decision about when to act is left with the subject alone. This means that subjects could, in principle, use this information as <u>feed-forward</u> to formulate a program for action. In the Pew study, the subjects do not have quite this information, but have the means of controlling the moving light. Since they know from their use of the buttons which direction the light is moving in, and since they must have built up some idea of the speed at which the light moves, this information must also be seen as constituting feedforward. But we have already seen that feedforward aids performance in RT experiments. When uncertainty is reduced by making the time at which the stimulus arrives predictable, RT is correspondingly decreased. (Klemmer, 1957; Wahrick et al., 1964). When in a choice RT experiment the probabilities of the various stimuli are manipulated, it can be shown that responses speed increases with stimulus probability (Hyman, 1953; Fitts et al., 1963). Furthermore, it can easily be shown that the continuity characteristically seen in tracking tasks is a function of the subject's ability to anticipate what the approaching track will be like due to regularities in layout (Poulton, 1950) or to see various distances ahead (Crossman, 1960). With the general pattern of the movement planned, the system is free to pick up any consequent errors and correct them. A single reaction time would then suffice to make one correction, since an RT is shorter than the critical times observed in each of these experiments. The fact that at these lower times the performance is only marginally higher than in the non-visual condition, and much lower than in the longer visual conditions further suggests that only a single correction is being made. These experiments, then, instead of showing the minimum time at which a visual correction can be made, ~~instead~~ seem to evidence the very programming strategies and consequent intermittency of functioning which we are ourselves trying to show. A genuine case of the minimum time at which visual information is useful would occur only when a discrete signal appears (for example, an animal runs into the path of locomotion at a point .5 sec. in front of S) and evasive action has to be taken. If he has forwarning of the existence of the intrusion, then we allow him the opportunity to use feedforward mechanisms to alter his performance.

From these data it appears reasonable to assume that .5 secs. constitutes a basic unit of intermittency. Two points must be made in qualification, however. We have no reason to believe that .5 sec. forewarning is enough to accommodate the majority of behavioural changes which would be necessary in the world. We have already seen the differences in time necessary to formulate responses in choice RT experiments as opposed to simple RT. If we now consider the decisions and responses normally required in the world, it will be apparent that the complexity vastly exceeds that manipulated in the laboratory. When simple tracking adjustments may easily require 1 second for correction, how long, then, would a complex behavioural adjustment be expected to take? There has been no systematic research done on the times necessary to make "ecological" adjustments of the type we are considering, but if we accept Hick's (1952) demonstration that time increases logarithmically with complexity, we can be fairly certain that biological actions like those we considered above will take considerably longer than .5 secs. to accommodate.

It can be seen, then, that there is a number of factors limiting the possibilities of continuous control. We should note, however, a fundamental difference between the limitations outlined above and the theoretical position being advocated here. The limitations we have just discussed are essentially limitations in the system's ability to handle incoming information: there is no implication that information pick-up is intermittent. Indeed, in the tracking studies upon which most of this research is based, the pick-up of information is said to be continuous because it is never possible to tell when an error in tracking will occur, and so the system must remain constantly on the alert for such errors. Nevertheless, the fact that the system must operate by means of response intermittency indicates that some form of programming of actions for the future must be taking place in order to generate the smoothness of performance which is characteristically found whenever S can see some distance ahead along the track.

Open-loop Functioning and Ballistic Control

If we accept as a first approximation that .5 to 1 second represents a limit to the possibilities of visual correction, we can show that a variety of behaviours must in consequence be guided independently of "current" visual information. In the first place, we may consider all those behaviours which simply take less than the critical time for execution. Such behaviours are much more common than we might at first suppose. According to Tinbergen (1951), much of the behavioural regulation observable in animals consists of two phases. The first phase consists of "a sequence of reactions to external stimuli that continuously correct the direction of movement in relation to the spatial properties of the environment" (1951, p. 87). Tinbergen calls this section of an act a taxis; that is, a guided orientation relative to a target. The second component comprises "a more or less fixed pattern ... which, once released, is integrated by internal mechanisms only, quite often independent of further external stimulation" (ibid, p. 86). This component is termed a fixed pattern. This duality of orientation mechanisms has been known for some time. The distinction was first made by Lorenz (1937), who called the visually-guided component a "Taxiskomponente" and the ballistic, fixed pattern an "Erbkoordination". The terms clearly correspond to the distinction between open- and closed-loop control which we discussed earlier. One section of the act is guided by closed-loop, feedback circuits, the other by pre-planned, open-loop sequences which are not modified after initiation. This type of control system is frequently referred to as a "dead-reckoning control system" (McFarland, 1971). Examples of this type of control are common. We have already drawn attention to Messenger's (1968) report of prey capture in the cuttlefish. The animal orients to the prey by means of closed-loop mechanisms and then strikes with a 30 m\sec. movement of the tentacles. The act has been well documented by Wells (1958), 1962). A similar method of capture can be seen in the mantid, which has been extensively investigated by Mittelstaedt (1957). In this case, capture is effected by a rapid movement of the forelegs. Other common examples are to be found in the frog, which captures prey by means of a rapid flick of the tongue (Tinbergen, 1951), and in the firefly *photus* which orients to brief flashes of light. Since it can be shown that fireflies orient accurately to such stimuli even after the stimuli have been extinguished, it is clear that the behaviour is not continuously guided but is planned and executed as a whole (Mast, 1912).

The activities which we have just examined represent examples of *single* reflex like acts which, due to the necessary speed of execution, must be performed ballistically. There are, however, many cases where much more complex acts must be performed ballistically. We may, for example, consider those acts which are composed of rapidly-executed *groups* of movements. Such grouped movements must often be executed ballistically because they are frequently so closely "spaced" that they cannot be continuously guided in sequence from one movement to the next along the chain. As an example we may take the finger strokes of a musician which can reach a frequency of 16 per second in some passages (Lashley, 1951). Because of the speed at which such a passage must be played, the movement sequences have to be planned ahead of time and run off as unguided wholes. Other activities where such chunking of behaviour will be required are to be found in typing, singing and in speech. Of course, there must exist some limit to the size which such programs can be. In some cases, a complicated passage may consist of a number of such programs guided on to each other in sequence. In this case, the units of behaviour have ceased to be notes, and have become programs for the execution of groups of notes. There is some evidence that "trills" may be guided in this way (Deutsch and Clarkson, 1959).

It should be noted at this point, particularly with regard to the latter, grouped movements, that these acts are not <u>of necessity</u> performed rapidly and therefore ballistically. All of them are capable of slow, more deliberate execution and hence of more continuously guided control. The need for programming in these cases arises mainly as a result of the need for speed. Although the effect of speed on motor functioning is exceptionally clear in these examples, its influence is much more widespread than we might at first assume. Let us consider, for example, van Danzig's (1969) examination of the activities involved in painting. Van Danzig claims that there exist some three classes of stroke which can be discerned in painting or drawing. We may distinguish "spontaneous" strokes which are commonest in free sketching and which are said to be ballistically triggered. The evidence of this claim is that such strokes, even when quite inadequate for the artist's purpose, are never interrupted part-way through their execution, but are always completed and do not differ in form from any other stroke of the same class. Corrections are effected only after the stroke has been completed. It is for this reason that sketches normally take the form of many short, sharp strokes rather than single lines. The acts for each stroke are ballistically executed. A second class of stroke, which van Danzig terms the "inhibited" class, are commonest where the artist is copying from a model. In this case, the strokes show "discontinuous and often non-logical changes in the line", as the artist strives to exactly replicate the original. Finally, we may distinguish "mechanical" lines. These strokes are uniform from beginning to end of the stroke. They are commonest in traced drawings.

Denier van der Gon and Wienecke (1969) have examined these classes of stroke carefully in the situations where they are said to arise; in free sketch, copying and tracing. Strokes of the first class are characterised by heavy pressure at the start of the stroke, which tails off gradually and consistently as the stroke proceeds. Correspondingly, the line is thicker and darker at the start, with this also gradually fading. The copied strokes showed an evenness of pressure, thickness and darkness not found in the free sketch strokes, together with peculiar variations in the form as the artist tries to change his stroke during execution as he sees that he is veering from the original. In tracing, the lines were smooth and uniform in all respects, and consequently easily detectable. These differences in stroke-type have been widely used by art critics to detect forgeries. The copier is unable to produce the same ballistic strokes as the original artist, and has to resort to class 2 strokes of the restrained type. This can easily be picked up by the critic, however, and immediately leads to the copier's denouncement (Van Danzig, 1969).

Ballistic acts were apparently also common in the writing of the old Chinese bamboo writers, who deliberately cultivated the skill because it was impossible to retouch their work once it had been executed. Furthermore, the accepted form of the work came to depend on such a ballistic execution, with the varying thickness and darkness of the strokes being considered vital. No Chinese character can be successfully obtained through tracing or carefully copying. Only when the character is executed as a whole is the correct form obtained (van der Tweel, 1969).

It seems clear, then, that some forms of representational skill require the ability to execute ballistically at least part of the time. This seems to be true of ordinary handwriting as well. The principles delineated above were used by Denier van der Gon and Thuring (1965) to examine this mode of representation. In relatively fast handwriting it was found that speed was constant throughout, indicating that subjects were not attempting to guide, or correct errors. This effect persisted irrespective of the size of the writing, although it might be expected that large writing would be bound to be subject to more control. No such control was evident. In slow writing, by contrast, such constant speed was absent. The temporal pattern was jerky and discontinuous, suggesting that in this case guidance was operating. Denier van der Gon and Thuring were able to show that the stretch reflex in the hand is suppressed during fast hand movements and present during slower ones. This would suggest that fast hand movements are executed open-loop as programmed wholes because the mechanism of correction in such cases is shut off. The implication is that this is typical of all fast movements. If this is true, then programming must be far commoner than we ordinarily think.

Perceptual Adaptation and the Development of Perceptuo-motor Co-ordination

So far, we have dealt mainly with acts which are executed as unguided wholes as a result of the speed with which it is necessary that such acts be executed. These limitations have been discussed as if they were due to limitations in the ability to use information available. However, there is much evidence to support the claim that even when visual information could be used in a more or less continuous fashion so far as limiting factors like speed are concerned, nevertheless control is still effected by means of programmed acts. Let us now examine the literature in support of this claim.

It has been known for some time that when a subject puts on a pair of laterally-displacing prisms, he misreaches for objects placed in front of him (Held, 1958). This happens irrespective of the mode of orientation employed: it makes no difference whether the subject is asked to reach for the object or walk towards it (Hay and Pick, 1966). The effect is furthermore obtained even if S can see his hand and arm during the reaching period. Indeed, even in this case where S can see his arm outstretching in front of him, it requires rather careful visual guidance to lock hand and object together. This difficulty suggests that such acts are not being continuously guided but are executed unchanged after initiation, or at least are corrected at intermittent intervals of fairly large extent. Furthermore, Rock (1966) has claimed that up to 70% of adaptation to such a shift is obtained after the first attempt, even when S can see neither his original attempt to locate the object, or his second, modified, attempt, but only the end result of the action. In this case there is no possibility of continuous visual guidance, since S has no visual exproprioceptive information with which to effect such guidance. The effect must be due to a reformulated program for reaching based on the perceived error at the end of the sequence, together with the information about the previous program. The fact that 70% adaptation is obtained after the first trial, at which point none of the characteristic post-adaptation shift is obtained, indicates that the effect is not due to a proprioceptive shift in the felt position of the arm, but to a reformulated program for action.

A further finding we should note in this context is the fact that it takes so long to obtain full adaptation. Although 70% is obtained after only one trial, it takes some time - a time which is furthermore variable depending on the conditions - to fully adapt. Again, this can only indicate that the process is not one of simple visual guidance. The interpretation that S is using programs which must be adjusted on the basis of the new information is much more consistent with the results.

Finally, a consistent finding in prism adaptation experiments has been that adaptation is only obtained - or at least is far better - when the subject is able to move his arm or body himself. When the process is passive, as when he is wheeled around or has his arm moved for him, the adaptive shift is small. Again, the fact that visual information alone is insufficient to being about an adaptation shows that the problem is not one of simple visual guidance.

A variety of further examples of this kind can be found. When displacing prisms are placed on young chickens, they mispeck at grains of food placed before them (Hess, 1956). Although their actions, and the result consequent upon them, are evident, these chickens never achieve any degree of adaptation at all to the distorted information. Again, it is clear that the chickens do not use vision as a simple visual guider. The fact that adaptation is never achieved shows clearly that the animals are not continuously guiding, but have programs for behaving, programs which in this case are not modifiable on the basis of experience. The chick learns nothing from its mistakes.

Sperry (1943) rotated the eyes of newts through 180°. When this had been done, the animals would respond to prey in the left half of the visual field by striking to the right and vice versa. Sperry (1951) performed a similar intervention on the eyes of frogs, after which a prey-object placed in front of the subject was responded to as if it were placed behind, and vice versa. By appropriate surgical intervention, animals could be made to respond to the opposite half of any section of the visual field. The animal never achieves any degree of sensory-motor recoordination. These results again strongly suggest that the animals are not using vision as a constant source of visual feedback, but rather use it to construct programs for action. Visual information about the state of execution of the act is available, but does not seem to be used to guide the progress of the act once it has been started. The act seems to be executed as a unified whole, uninfluenced by feedback.

This position is further supported by studies of the development of perceptuo-motor abilities in infancy. As examples, we may note the development of the placing reaction in very young kittens. It is known that uncertain reaching is obtainable at the 20th day of age, but that a full reaction cannot be expected much before the 30th day (Norton, 1974). The fact that the full reaction is not found before the 30th day cannot be said to be due to mere physical weakness, since the physically demanding part of the behaviour is already obtained. It is once again clear, then, that we are not here dealing with a system designed simply to monitor current position and effect appropriate changes. The system clearly functions at a more complex level than this. This basic finding is widely obtainable. In baby macaques, inaccurate, ballistic reaching is apparent at 3 - 10 days, but a full response is obtained only after some fourteen days, and the time necessary may even reach 56 days (Wilson and Riesen, 1956). Again, the effect is not due to physical demands, since the demanding section can be seen at an early stage.

These developmental "anomalies", at least so far as the cybernetic models we discussed earlier are concerned, have their counterparts in human development also. Visually guided reaching, containing the basic structure of a mature reach, can be seen in newly-born infants if conditions are favourable (Bower, 1974). This elementary form of reaching disappears, however, at about the fourth week and does not reappear until the fourth or fifth month. Both the early and the later reaching show all the features of mature reaching, however, except for quantitative differences, such as success rate, which is about twice as high at the later age. Nevertheless, newborn infants have a success rate of around 40%. Again, the cybernetic models we discussed above have difficulty coming to terms with such findings. If the child can reach successfully at 4 weeks, why is it that the behaviour disappears only to reappear after a considerable time lapse? Why is there now greater accuracy in spite of no practice being apparent in the intervening period? Once more, the observed behaviour does not seem to coincide with any simple explanation.

It can be shown in a much more direct way that the reaching of infants is not in fact controlled by continuous visual guidance, but rather by programs, even at as early an age as this. First of all, it can be shown that a neonatal reach contains all the elements of anticipation. The fingers stretch according to the size and shape of the object to be grasped, and accommodate during the reach section of the act in anticipation of the point of contact. If tactual contact is lacking, as by the use of a virtual object, the infant becomes upset, indicating that they expect the tactual consequences of pairing the hand with a seen object in space (Bower, Broughton and Moore, 1971). Further evidence that even at this age infants do not simply use vision as a constant source of feedback information, comes from the finding that infants can successfully reach for an object even in total darkness. If the object is shown when the lights are on, and then, after the infant has just initiated a response, they are extinguished, the child nevertheless can reach out and catch the object with very high accuracy (Bower and Wishart, 1972). This can only mean that vision was not necessary for control of the act after initiation.

The research on the effects of early visual deprivation conform closely to the view that visually guided reaching is not effected by means of continuous visual control. If a baby monkey is reared with normal vision but without sight of the limbs, only a few hours of limb-exposure is necessary to generate ballistic, partially-accurate reaching. Several days of exposure are necessary, however, to generate full visual reaching. The fact that the largest portion of the act is obtained almost immediately, with only fine adjustments lacking, indicates that simple visual control is not operative (Held and Hein, 1967). A similar result is obtained with children who lose sight early, but who recover it in late childhood or adulthood. In these subjects, inaccurate, "ballistic" reaching can be observed within a few days, although several weeks are necessary for the revival of visually controlled prehension. In the congenitally blind who later recover sight, the ballistic stage is almost never passed, with the full prehension never developing (Jeannerod, 1975b). In kittens, 15 weeks of visual deprivation allows almost immediate, inaccurate reaching. More accurate orienting requires a considerably longer time (Vital-Durand et al., 1974).

These various results are not the result of motor difficulties: in all cases the limbs are healthy and developed. The animals can obviously do the physically exacting parts of the act, that is, the stretching out of the limbs to the general area of the target. Only the last, zoom-in portion is weak. Clearly, therefore, the system does not operate by means of simple visual control, for if this were the case, such disjunctions would not arise. The results seem to indicate that the problem of perceptuo-motor control is far from as simple as the cybernetic models we discussed above would imply. It appears, indeed, that not only is control achieved by some means other than simple visual guidance, but that control depends on more than one mechanism (Schneider, 1967; Trevarthen, 1968; Jeannerod, 1975a).

Leaping

There is one large and important class of movements which, on theoretical grounds, cannot be guided in a continuous way after initiation. This concerns those movements which we may term leap movements. Once the leap has been initiated, both the zenith of the leap and the horizontal distance to be covered are determined, and cannot be substantially changed. This means that the point of contact with the ground at the end of the leap must be determined before initiation of the act, and is expressed in the thrust exerted at take-off. After this, the relation of the centre of gravity of the body follows a pre-determined path: and while minor changes can be effected by moving the limbs, the landing point of the centre of gravity of the body as a whole is determined. The smoothness with which leaping movements normally seem to be executed suggests that such alterations are exceptional, or at least severely limited in extent.

Although we may not think at first that leaping is a common mode of locomotion, it is in fact, a very common mode indeed. It is not restricted to the kangaroo or frog: the vast majority of antelope and gazelle locomote by means of powerful leap sequences, the zeniths of which may reach considerable heights, and may carry the animals over many metres (Gray, 1968). In animals for which the leap is not the characteristic mode of locomotion, the leap nevertheless frequently plays a fundamental role. Its importance to the cat and the flying fox is obvious. However, its use is necessary to any animal which should at any point wish to jump a fence, rock or stream. Finally, and most important of all, whenever locomotion becomes rapid, the mode of locomotion becomes, in effect, a series of leaps. This applies equally to man with his bipedal mode of locomotion and to the quadrupeds who spend remarkably little time in contact with the ground while running (see, for example, Bernstein, 1967). We are not here dealing with a trivial or specialised mode of locomotion, then, but with a general and typical mode, widely found among the more sophisticated living organisms.

As we have seen, these actions cannot be altered during execution. For this reason, the projected point of contact with the ground will have to be decided in advance, at least in cluttered environments where locomotion has to be planned with regard to the layout of impedances. Here, then, is another reason why it is necessary to program actions ahead. The units by which locomotion is accomplished, like the units of musical skill, necessitate it. Furthermore, for reasons which have already been examined, we cannot expect control to be effected at the end of each successive leap, for speed of movement frequently precludes this. For example, both the horse and cheetah, when travelling at moderate speed, take about 2½ strides per second (Hildebrand, 1959). The reaction time considerations which have already been discussed would therefore rule out the possibility of control being exerted more often than once every two or three strides. A good racehorse can easily cover twenty feet in a stride; the celebrated 19th Century racehorses Eclipse and Flying Childern, when galloping at liberty, could cover 25 feet per stride, or approximately 82 feet per second. Clearly, this sort of behaviour is severely dependent on the ability to plan series of actions ahead of time.

Timing Events in the External Environment

So far we have concerned ourselves exclusively with the case of programming as a result of the animal's own movement relative to the environment. There is, however, an obverse case where the environment, or parts of the environment, move towards the animal. These may be other animals, or pieces of environmental material like rocks or boulders. Sometimes these objects may become sophisticated, like arrows or bullets. Such objects, especially if they are aimed in the direction of the animal, must be caught or avoided, and occasionally the skills involved in such activities become highly developed, as in cricket or tennis. Such skills depend on the programming abilities we have been discussing. Consider, for example, an object pitched at a speed of 100 feet per second. In .25 secs., the object will travel 25 feet: in .5 seconds, it will travel 50 feet. This means that the last point at which a batter can effect a correction to his plan for striking the ball will be when it is still at a considerable distance. Considering how much more complicated is the response of a batsman to an approaching ball than the response of a subject to a stimulus in a reaction time experiment, it can easily be seen that such responses will have to be organised well in advance. The question has been examined in a series of experiments by Whiting (e.g. Whiting, Gill and Sanderson 1970; Whiting and Sharp, 1974; Sharp and Whiting, 1974). In these experiments, tennis balls were projected from a mortar-like machine to subjects standing 22 feet away. The room was always in darkness when the ball was launched and also when it was caught, but was illuminated for a period at a variable point during the flight. It was found that a viewing period of as little as 80 m.sec. was sufficient to enable subjects to catch the balls if the information was given at approximately 125 - 160 m.secs. before contact. At both earlier and later times, the viewing period was of less value. The finding that visual information available at less than 125 - 160 m.secs. before contact is of progressively less value to the success of the catch strongly supports the argument that programming is indeed necessary for success in these tasks.

Reading and Speech Perception

There are many other skills in which the intermittent nature of information pick-up and control is to be found. One such skill is reading. Although this skill differs from those which have principally concerned us here in that it has no direct or manipulative effect on the external environment, it shares with those skills its exploratory mode of operation which is designed to derive information about the environment.

A theory of continuous control applied to reading would hold that the essential elements for reading are letters, and that reading is accomplished by identifying these. There seems little doubt, however, that reading is not normally controlled in this way. As early as 1885, Cattell showed that with a tachistoscopic exposure of a tenth of a second, no more than four unrelated letters can be identified. If the letters form a word, however, many more than four can be identified, and all the letters of several words can be identified if they form a sentence. Clearly, the ability to recognise the word or sentence does not lie simply with the ability to identify all of the letters. This conclusion is further supported by the results of Pillsbury (1897) who gave subjects tachistoscopic presentations of words like FOYEVER and DANXE. These words were reported by subjects as FOREVER and DANGER, the subjects failing to recognise the "spelling mistakes" in the stimuli. Miller, Bruner and Postman (1954) asked subjects to identify tachistoscopically presented words which varied in their approximation to normal English. They found that while recall was better the nearer the word was to standard English, substantial differences were tolerated without the subjects being aware of these differences. Again, these results imply that reading is not dependent on the ability to identify all the letters of the words. Indeed, when a letter-by-letter approach is forced on subjects, reading becomes virtually impossible. Newman (1966) and Kolers and Katzman (1966) used <u>successive</u> presentation of letters in a tachistoscope. When words are presented in this way, subjects find it impossible to identify even familiar words. There seems little doubt, then, that reading is not accomplished by identifying each letter in a sentence in turn. The basic chunks can, and apparently often are, larger than this.

There is information that the pick-up of information during reading involves information chunks of more than the single word. This information can be derived, first of all, from a consideration of reading speeds. A person with a reading speed of reasonable size, say 2,000 words per minute, is hardly likely to be identifying every word on the page, far less every letter. That it is not necessary to identify every word on a page to find the meaning of a sentence is evident from the results of a number of studies. Tulving and Gold (1963), for example, presented subjects with sentences of the following kind: "Far too many people confuse Communism with ....". When passages were created with gaps of this sort in each sentence, it was found that neither reading speed nor the meaning obtained from the passage was affected suggesting that reading involves cognitive as well as perceptual anticipation. Levin and Turner (1966) and Levin and Kaplan (1966) have investigated perceptual anticipation by examining the distance ahead the eye gets when a subject is reading a passage aloud. At various points the lights were turned out and the subject was asked to keep reading. It was observed that he was frequently able to continue reading for many words. There was a strong tendency to read as far as the next phrase boundary, though this was often enlarged to accommodate a grammatical boundary and fluctuated according to the degree of structural constraint. These constraining factors have been reviewed in detail by Gibson (1969). What is clear from these studies is that reading does not involve the processing of each constituent letter or even word. Reading involves the processing of chunks of varying size, the size depending on the conditions under consideration. When a response to the information is required, as when the subject is asked to read aloud, it is clear that the information is being picked up in advance and decisions formulated before the point at which the words have to be actually uttered. In reading as in other forms of motor behaviour it is not possible to use a system of continuous information pick-up and control. The system has to operate discontinuously.

The intermittency seen in reading has its parallel in speech perception. The smallest unit in speech perception is usually taken to be the phoneme (Neisser, 1967). We can then ask if perceiving speech is a process of identifying all the phonemes in a string and constructing speech out of these elementary units. This would, of course, be analogous to the process of reading by means of identifying all the letters.

That the concept of the phoneme has some psychological reality has been demonstrated by Liberman (1957). Using a machine that could produce sounds, he presented subjects with series of syllables varying from 'ba' to 'da' and on to 'ga'. When listeners were given the task of discriminating these sounds one from the other, it was found that this was much easier to do between instances of different phonemes than between two sounds belonging to the same phoneme class.

That this constitutes proof that the auditory system is tuned in terms of phonemes has been attacked, however. Ladefoged (1959) has pointed out that the sounds presented were in fact syllables rather than phonemes, and that the results imply nothing about the elements of which those syllables were composed.

A number of studies exist which support the notion that the syllable is a basic unit in speech perception. Cherry (1953) showed that when a message is alternated between the two ears, this has no effect on shadowing at very slow or at very fast alternation speeds. At intermediate speeds, however, ability to shadow is grossly affected. This effect was investigated in detail by Huggins (1963, 1964), who claimed that the effect was due to the breaking up of critical units of speech perception. He argued that if it is the case that speech is perceived in terms of segments of roughly equal size, then it should be possible to pinpoint a critical rate which maximally disturbs perception. In fact, the alteration speed which seems to be most damaging is agreed upon rather closely in different studies (Cherry and Taylor, 1954; Schubert and Parker 1955; Huggins 1954), and falls at .36 words, or about..6 syllables per uninterrupted half-cycle (Neisser, 1967). This data, then, implies that the syllable may indeed constitute a unit in the perception of speech.

There is, however, evidence that speech can be understood by means of much larger units than this. Fodor and Bever (1965) and Garrett, Fodor and Bever (1966) presented subjects with a tape-recorded message on top of which was placed a click or hiss. The subjects' task was to identify the point at which the hiss was superimposed. It was found that subjects erred by hundreds of milliseconds and several syllables. The breaks tended to be perceived as occurring at, or around, grammatical boundaries in the sentence (Garrett, Fodor and Bever, 1966). This suggests, then, that subjects are picking up and responding to the sentence in large chunks. In some cases at least, the units of speech perception are rather large.

It is clear from these results, as it was in the case of reading, that there is no single unit upon which speech perception depends. The units vary according to a number of factors such as the deployment of attention, and varies from the syllable to the phrase at least. It is not dependent on the monitoring of a fixed sequence of units. The process is much more one of intermittent pick-up of information. Any form of continuous control model therefore does not seem capable of explaining these facts.

Predicting the Properties of Objects

The two skills we have just considered, reading and speech perception, differ somewhat in that reading involves the pick-up of stimulus information in advance of the point at which it is to be used. In speech perception, the situation is somewhat different. The listener cannot "look ahead" in the literal sense, as he can in reading, because there is as yet no stimulus to be surveyed. In this case, the subject's ability to respond to information in chunks must depend on his ability to anticipate what is to be said, and thus to respond to units larger than that which is currently being uttered by the speaker. Understanding speech is therefore a case of feedforward in a clearer sense than we have seen it up till now. There exists another class of behaviour in which feedforward is seen in a relatively "pure" form, however. Whenever we lift objects, we use feedforward to judge the force necessary to get the object off the ground. We do not exert the same force when we lift a ping-pong ball as we do when we lift a brick. That this is true is clear whenever we misjudge the weight of an object, as when we assume that an empty box contains a heavy object. This feedforward has in fact offered developmental psychologists a means of studying weight conservation in infants (Mounoud and Bower, 1975). The infant's arm can be seen to fly up as he overestimates the critical force necessary to raise the object, and to fall as he underestimates the weight. Even at this age, feedforward of this kind is apparent.

In the reading and speech-shadowing studies which we have examined, we have seen a mechanism with which the subject both responds to information which has already been picked up by the perceptual system and simultaneously picks up information for the future. This responding and simultaneous pick-up has not been thoroughly examined in any of the studies we have so far considered. There does exist, however, a series of studies which have in fact examined in a more rigorous way, the ability of subjects to perform these two functions at the same time. This has been the aim of a large number of tracking anticipation studies. These studies address themselves to the following fundamental problem: how does intermittent pick-up of information nevertheless render performance smooth and continuous?

Tracking Anticipation Studies

The evidence from these studies suggests that subjects try in various ways to take RT lags into account by operating "ahead" of the input. One piece of evidence in favour of this is that if in a dynamic tracking task the tracking object is stopped when the alignment with the target is perfect, the subject nevertheless goes on for one reaction time, throwing a correct alignment off course. He knows that if the tracking object had continued it would have erred in the opposite direction and consequently a compensation had been prepared in advance (Craik, 1948; Poulton, 1953).

There is a number of studies showing this kind of preparation of responses in advance. The information on which such projections are based are of various sorts. Poulton (1952, 1957) used tracking tasks with constants or statistical properties which could be known. Thus the target may move in predictable directions at predictable rates. When these properties are known tracking is greatly improved as against cases where they are not. Similarly, when a view of the approaching track is available, time on target increases. Poulton (1954) and Crossman (1966) found that a .4 second preview of the oncoming track reduces errors to the same extent as an 8 second preview. A preview of .3 seconds led to significantly more errors. It should be noted that the size of the preview will have to increase as a function of the speed of the course if the accuracy of performance is to be maintained, and this will at times mean that the degree of preview has to be much larger than .4 seconds. Ellson and Gray (1948) found that pursuit tracking of simple harmonic inputs (which are highly predictable) produced errors of practically zero, even when no preview was available, indicating that subjects can learn the structure of the track over a period of time and match their responses to it very accurately. When the structure of the track becomes more complicated, so that the subject cannot easily predict the structure, responses tend to fall at least one reaction time behind the target (Poulton, 1954; Legge and Barber, 1975). This lag disappears when preview of the type noted above is made available. Leonard (1953) has shown that performance with advance information is smoother because much less time is taken up with pausing, and more with performance.

These studies all strongly support the notion that behaviour is not continuously guided, but is executed in chunks on the basis of intermittently acquired information. They also suggest that subjects are capable of engaging in the pick-up of information for the control of future activity while simultaneously effecting decisions already formulated. It seems quite possible for both activities to proceed at once.

Temporal Structure

We have so far dealt mainly with programming as a result of limitations in ability to make responses quickly on the basis of information picked up, a situation which leads to the need to pick up information in advance and use it to prepare programs which are then held in readiness for the point at which they are useful. We must now look at a rather different set of reasons why programming is necessary. These reasons have to do with the essential structuring or patterning of behaviour. This temporal patterning is apparent in most behaviour. As an example, let us consider language. Any meaningful sentence must be endowed with an overall structure, namely, a syntactic structure. Such a structure is not, of course, inherent in the words of the sentence themselves. It consists of a set of rules for the use of words which is superimposed on them in order to render the group meaningful. As Lashley (1951) points out, the word "right" (when spoken) is noun, adjective, adverb and verb, has four spellings and at least ten meanings. The meaning of the word in any given sentence cannot therefore depend on anything but a set of broad grammatical relations which relate it to the other words of the group. In order to issue a meaningful sentence, therefore, these relations must be invoked in advance; the structure cannot be applied as the speaker goes along. When we consider the great differences which are found in the rules governing different languages, this fact is doubly strengthened. The same argument applies to the understanding of language also. Lasheley gives as an example the Cree word "kekawewechetushekamikowanowow". The pronunciation of this word provides no difficulty to the Cree speaker even if he has not seen it before, because he can apply the structure of the Cree language to it. But this structure is not apparent in the word (although it is implicit in the word), but depends on the listener or reader for its extraction. The listener must bring a plan for interpreting the stimulus, to the stimulus. That "plan of interpretation" is one type of program, related to those which are being discussed here.

These structures themselves form a kind of program, then. But they in fact go further than this. They enable the possibilities of genuine anticipation of future stimulation (i.e. feedforward). It is this which gives meaning to the eye-voice span experiments which we reviewed earlier. The anticipation is expressed in terms of (principally grammatical) structure, or more correctly, to parts of that structure. That this is so can be seen if we consider the types of errors typically made in language production. Spoonerisms, for example, in which the speaker says "our queer old dean" instead of "our dear old queen", and typing mistakes of the sort "htis" or "htse", operating "backwards" in time, indicate that responses are formulated and being held in readiness until needed. The acts are clearly patterned in advance, but for some reason the order of production can sometimes become upset.

Internalised Programs for Action: Reaction Chains and Vacuum Activities

The importance of an overriding temporal structure which the subject brings to the stimulation available is apparent also when we consider what ethologists call "reaction chains" (Tinbergen, 1951). According to ethologists, many apparently unitary behaviours are in reality chains of separate reactions strung and bound together by internal unifying forces. The animals are thus not responding simply to perceptual information, but accommodate that information to an internal plan of action. The reactions of foraging honey bees to flowers, for example, begins with a response to visual information in which colour plays a dominant part. At this stage, yellow and blue flowers are particularly attractive. However, if a model of such flowers is prepared, bees will very seldom alight on them. The bee will hover for a short time at a distance of about 1 cm., and will then lose interest. This is because the model is not appropriately scented. If such a scent is available, then the bee will alight, and the next reaction in the chain can be released. What is important here is that the information has to be available to the bee in the correct order: a strong odour is no inducement to a bee and cannot be used to control its chosen path of movement if the appropriate visual information was not available first. Here, then, we see a temporally ordered plan which determines the information which the bee will respond to at any time. This structuring force exists within the bee and is independent of the information available at the eye (von Frisch, 1927).

This kind of temporal structuring can be seen in the hunting behaviour of the digger wasp Philanthus Triangulum. A hunting female flies from flower to flower in search of bees. At this stage she is totally unreceptive to the scent of bees, even when that scent is strong enough to be detected by the human nose. Any visual stimulus of the right size and movement, however, will release the first reaction in the chain and the wasp will wheel towards the object and ~~however~~ hover 10 to 15 cms. away. Only at this point does the animal become sensitive to bee-scent, for if a dummy is constructed which lacks the scent, the animal veers away. A scented dummy, however, immediately initiates the next reaction in the sequence (Tinbergen, 1935). Again, the animal does not respond simply to perceptual information indicating the existence of bees. That information is responded to only if it becomes available at the appropriate point in the chain. Here, then, we see the existence of internalised 'programs' for hunting or for nectar-collecting which are used for the guiding of these activities. Many other reaction chains of this type can be found in animal behaviour (see for example, Tinbergen, 1951; Marler and Hamilton, 1966; Hinde, 1966).

Many other examples of internalised programs for action of one sort or another are available in the literature on animal behaviour. Excellent examples of internalised programs of considerable complexity are to be found in what Lorenz (1957) terms "vacuum activities". Vacuum activities are responses, sometimes of considerable complexity, which are seen in the absence of releasing stimuli. Lorenz (1937), for instance, observed a repeated performance of the whole behaviour pattern of insect hunting in the starling, beginning with watching the prey through catching, killing and swallowing, all in the absence of any discernible stimulus whatever. Kluyver (1942) observed similar insect hunting behaviour occurring <u>in vacuo</u> in the European Waxwing during cold and frosty weather when no insects had been available for some time. Tinbergen (1951) reports the whole of the complex zig-zag dance of the stickleback, which is used to attract a female, occurring in an empty tank. Many further examples of this kind may be found in the literature. Young cormorants have been observed to go through all the motions of nest-building with considerable accuracy while still in the nest themselves. The Bengalese Finch will perform all the sequences observed in nest-building, including gathering the materials, in an empty cage. Buzzards can be seen to go through the motions of digging out wasps nests only a short time after hatching. Further examples of such behaviours are widely documented. See, for example, Tinbergen (1951); Manning (1972).

These examples, then, give credence to the view that behaviour in animals can be guided by means of internalised programs for action. Sometimes, these programs are wired into the system, as some of the programs described above seem to be, and others seem to be developed and stored. Some of the programs may consist of fairly general "instructions" rather than a set of precise motor actions. The examples of reaction chains like insect hunting behaviour may fall into this category. Others, however, seem to contain within them a much more precise statement of the motor sequences involved. Examples of this may be found in vacuum activities, like the nest building programs found in Bengalese finches and cormorants.

Efference and the Role of Peripheral Feedback in the Control of Acts

The role of proprioceptive information about the ongoing control of an act has been considered vital, at least since the early work of Mott and Sherington (1895) and Sherrington (1931). Both these studies involved the deafferentation of a single limb, and it was found that this form of intervention produced total incapacitation in that limb for any form of purposeful activity. The effect is generally obtained in studies of this kind (see Taub and Berman, 1968) and the fundamental role of peripheral feedback seemed established.

However, a series of studies by von Holst and Mittelstaedt (e.g. von Holst and Mittelstaedt, 1950; von Holst, 1954; Mittelstaedt, 1958) seemed to indicate that activity might be controlled by means of two components. These have been succinctly summarised by Gibson (1966) as follows:

> '... Whenever the brain sends out a command for a certain movement it stores a copy. When the input of any receptor reaches the brain, it is automatically compared with the current stored copy. If it matches, the input is taken to be a case of proprioception - a feedback. If it does not match, the input is taken to be a case of exteroception - a feed-in ...'.
>
> 1966, p.39

It will be clear that this is basically a closed-loop theory, though one with a difference. In it, the motor commands are prepared in advance and executed. To this extent, it compares to the position advanced here. It does not, however, assert that these commands are in themselves sufficient to control behaviour: such control depends on the existence of "reafference" from the eyes or the proprioceptive system and asserts that this is essential for a decision about the nature of the event to be possible. A number of studies has, however, attempted to show that a formulated series of commands are in themselves sufficient to control behaviour.

An early finding in support of this came from a clinical observation by Lashley (1917) of a patient suffering from gunshot wounds in the leg. The patient had suffered proprioceptive loss, yet still was able to move his leg when asked and to relocate it at specified points with considerable accuracy, even with the eyes shut. This would suggest that information about the current position of a limb is not always essential, at least for decisions about rather gross acts.

More carefully controlled studies on the same lines have been conducted, in particular by the Taub-Berman group. For instance, Knapp, Taub and Berman (1958) trained monkeys in shock-avoidance, which was accomplished by means of arm flexion. After deafferentation, the animals' performance dropped somewhat, but quickly regained the former level. Untrained deafferented monkeys were quite capable of learning to make the response. A similar finding was found in food-deprived monkeys who, when the good arm was straitjacketed, learned to push the deafferented arm through the cage for food (Knapp, Taub and Berman, 1963). It appears from this that some form of intentional behaviour is possible without feedback. Furthermore, tasks of a much more delicate nature can also be performed by deafferented animals. The monkeys can be trained to grasp an object to avoid shock. The form of the grasp and the pressure exerted did not differ from that exerted with the normal limb (Taub, Ellis and Berman, 1966).

The unilaterally deafferented animal fails to use the injured arm for any response unless forced to do so, however. The limb is not used for ambulating, climbing or anything even when the good limb is engaged in another task (Taub and Berman, 1968). However, the bilaterally deafferented animal is not so restricted and such animals make very extensive use of both limbs. According to Taub and Berman (1964) the animals are capable of moderately fast ambulation, of climbing, of lateral climbing and of performing delicate tasks like lifting peanuts out of a well. When the animals are blindfolded they continue to be capable of such behaviour according to Taub and Berman,

> '... the degree to which the movements of these animals with both forelimbs deafferented approximated to normal patterns of movement was truly striking and cannot be overemphasised'.
>
> 1968, p.177.

The difficulty in using the unilaterally deafferented limb was explained by Taub and Berman in terms of inhibitory forces operating between pairs of limbs, but we need not deal with that here. The important finding from the present point of view is the extent to which behaviour could be carried out in the absence of all peripheral information, and even without visual information, about the position and changes of position of the parts of the body. These findings strongly support programming systems of the sort proposed here.

Conclusions

The main argument of this theoretical discussion has been that behaviour is not controlled on the basis of "current" information available at the receptors at any given moment, but on the basis of previously acquired information which is used to construct programs for action. It is argued that these programs are themselves sufficiently accurate to enable fairly complex interactions within the environment to take place independently of further information during the execution of the program. However, normally visual and other forms of information will be used to monitor the execution of the program and to initiate any modifications necessary, but their role during such periods will be low-key. It is in the formulating of such programs and in the subsequent monitoring that vision (and to a lesser extent in man, the other senses) is argued to play its major role. The evidence reviewed above seems to be highly consistent with such a theoretical position, and should be taken as an encouragement to proceed to an experimental investigation designed to show more clearly the hypothesised programming abilities and to elucidate their underlying characteristics.

As a final note to this review of the literature, there is the evidence of the blind. Although the quality of the information available to the blind is immensely poorer than that available to the sighted, and this is bound to have a profound effect on their ability to get about in the world, we may also note that the blind person also shows the example par excellence of continuously controlled locomotion. The advance pick-up of information for the blind person is limited by the length of his cane, and represents a foreknowledge of about one metre. His ability to program actions for the future is therefore severely limited. The inadequacy of such a method for getting about in the world should be apparent to us all.

PART II

INTERMITTENT PICK-UP AND THE CONTROL OF LOCOMOTION

INTRODUCTION

It is now necessary to begin an experimental investigation into some of the more central concepts introduced in Part I. The main argument, of course, has been that behaviour is not controlled on the basis of current information at the receptor, but on the basis of previously-acquired information. More specifically, it is argued that vision is used only intermittently, and that the information acquired is used to construct programs for action which can then be run off independently of further visual information. It is by means of such programs that behaviour is controlled, rather than through some "direct" visuo-motor link. The intermittency for which we have argued, is said to be achieved by means of the two major elements in the model presented in Fig. III; that is, by means of the absolute distance perception overlay (ADPO) and the programming system (PS). Our first task must therefore be to test whether behaviour can indeed be controlled on the basis of intermittently-acquired information. If it is possible, we may then progress to a more detailed consideration of the mechanism responsible for it.

EXPERIMENT 1

CONTROL OF LOCOMOTION IN THE ABSENCE OF VISUAL INFORMATION

Introduction

When the basic properties of the model being proposed here were first in the course of elaboration, a large number of pilot studies were carried out into as many aspects of the problem as possible. At the end of this series of studies, a short, basic experiment was conducted to demonstrate the fundamental effect which underlies all of the research reported below. It concerns itself with the simplest possible case of the skill in question: namely, can subjects accurately walk up to and locate a single target placed at a distance, when no visual information is available from the point at which the act is initiated. Experiment 1 examined this question.

Method

Design

The experiment was conducted in a large room (a former lecture-theatre) from which all seating had been removed. Some tables and other objects were to be found around the edges of the theatre and some equipment and experimental apparata were situated at one end, where there was also a stage. The size of the free area in which the experiment took place measured approximately 14 x 9m. The floor of the theatre sloped slightly from one end to the other, but this did not prove to be a disturbing factor as evidenced by the results of pilot studies in which the subjects were asked to walk both up and down the slope under the conditions of the present experiment. The performances did not differ. In the current experiment subjects walked perpendicular to the line of slope in any case. No tendency was found for subjects to veer downhill as they moved between the starting-point and the target area. It is likely that the limited distances used in these experiments were responsible for the lack of directions bias.

Four locomotor distances were chosen at 2, 5, 8 and 10 metres. These distances were chosen simply for convenience as constituting a fairly representative selection of distances in the target from near to moderately distant space. The target area was indicated by an easily-distinguishable line drawn on the floor together with a wooden marker placed on the left-hand side of it. The subject's task was to line himself up directly opposite the marker, with the feet centred squarely on the line. However, whenever subjects expressed a preference for one method of lining against another, this was allowed. For example, some subjects wished to line their toes up against the market rather than the centre of the foot. These wishes were always respected. In general, however, it was considered more natural that subjects should attempt to line their <u>bodies</u> up with the marker rather than in any other way. A single line rather than any other form of target was used because of the accuracy of measurement which the single line allowed. The result of each trial at the 8 and 10 metre distances was indicated by means of a small chalk mark, a different colour being used for each trial. Care was taken that these marks should be invisible to subjects at the starting-point. Since this could not be guaranteed at the 2 and 5 metre distances, the scores at these distances were measured directly, and no marks indicating performance on previous trials were made at all. This method of recording the data enabled the experiment to progress fairly quickly.

In view of the possibility, partially supported by evidence from the blind, that subjects might gain some cues about the distances involved by means of echo-location, it was decided that this source of variance should be controlled. It is true that in the adult human ear these abilities are rather crude (Bower, 1976); nevertheless, the availability of any cues about the positions of objects in the experimental field of activity is potentially disruptive.to the essential nature of the task. For this reason, auditory information was excluded throughout the experimental session. This was achieved by recording a white noise on to an ordinary cassette tape and then playing this to subjects through a pair of headphones attached to a portable tape-recorder slung across the subject's shoulder. The apparatus did not prove particularly cumbersome or restrictive and was effective in almost completely isolating the subject from external sounds: for example, the experimenter could not make himself understood even by shouting. The surface on which the experiment was conducted was smooth and flat and hence no tactual ones which could be used to gauge distance were available. In this way, with all other sources of information controlled, the task was rendered a purely visual one.

Two conditions of testing were employed. In condition 1, all visual information was excluded at the point at which each trial was initiated. No attempt was made to control the amount of visual information in any other way, and vision, when available at all, was available under normal, full-cue conditions. The exclusion of vision was achieved by means of blacked-out goggles which the subject carried on his head throughout the experiment.

In the theoretical discussion in Part I, we drew attention to the need for some definition of "adequacy" in evaluating performances made in perceptuo-motor behaviour. Although we could simply consider the errors made in this experiment and leave it to the reader to decide whether or not this performance was indeed adequate by using some "intuitive" notion of adequacy, we have already drawn attention to the desirability of a more objective definition. It was therefore decided to run Condition 2, a condition in which visual information is continuously available during the course of locomotion, to assess the accuracy normally achieved when the eyes are open during locomotion. One limitation was placed on subjects' use of vision, however. They were asked to refrain from looking directly down at their feet as they approached the target line and guiding them carefully on to the target. The reason for this was that it is not usual to carefully guide the placement of the feet in this manner when walking about normally in the world: and while subjects can, by carefully bringing their feet into line with the target, achieve virtually zero error, it was considered that this would constitute a highly artificial response. Subjects were therefore asked to refrain from doing this. They were allowed, however, to glance across at the marker opposite which they were attempting to line themselves, and no restrictions were imposed in any other way. Only the careful, visual guidance of the feet on to the target was disallowed. In this way, the results of the visual condition are likely to bear a far closer relation to the accuracy normally achieved whilst moving about in the world than would otherwise be the case. This method was therefore taken to constitute the correct control in the present experiment.

Procedure

Practice Session - Before the experimental session began, subjects were given a short practice session in order to accustom them to the task. The amount of practice necessary varied from subject to subject, but in no case was more than 2-3 minutes of practice required. It should be remembered that this task, conducted under such isolating conditions, is highly unusual and a number of subjects were disturbed by it initially. It proved necessary for the experimenter to establish a rapport with these subjects to secure their trust that no dangers were involved. In order to instill that confidence the practice trials were necessary. The trials were conducted at some distance from the experimental set-up and did not involve the use of fixed distances. Instead, a much more casual approach was adopted, with the experimenter simply indicating a variety of distances and asking the subject to try to reach them. One important consideration at this stage was to persuade the subjects to walk in as natural and uninhibited a manner as possible. This was important, because it had been found in pilot studies that subjects who used an unnatural and excessively slow gait tended to make fairly substantial errors; whereas, if the same subjects walked naturally, they made very small errors. For this reason, it was felt that the behaviour should be kept as normal as possible. The role of "unnatural" modes of locomotion and of time restrictions will be considered in detail below.

It proved possible to "prime" subjects in this way for the experimental session with only a few minutes practice. Such practice was never carried on beyond the point at which confidence to walk naturally was instilled. In this way, it was hoped that no exterior learning effects would influence subjects' skill, and that a measure of their "natural" ability would be obtained.

Experimental Session - Before each trial began, S stood lined up at the starting-point. The white noise was turned on and S was allowed to survey the layout and decide for himself when to commence the trial. He then pulled the goggles over his eyes and immediately started to walk. E stood to one side and checked that the goggles were properly fitted. At the end of each trial, S stopped and waited while E marked the spot reached (in the case of the 8 and 10 metre distances) or measured the error (in the case of the 2 and 5 metre distances). E then turned S, who was still blindfolded, around and walked him back to the starting-point. In this way, S was denied all feedback about his performance on that trial. Once returned to the starting-point, S removed the goggles and surveyed the target again before commencing the next trial. Three trials were presented at each of the four distances, making 12 trials per condition for each subject. The trials were randomised with respect to distance. The non-visual condition (Condition 1) was always run first in order to avoid the possibility of unwanted learning effects which might have been generated if any visual trials were presented before the completion of the non-visual trials. With the non-visual condition performed first, any differences between the two performances would only have been accentuated.

Subjects

Ten subjects took part in the experiment, five male and five female. Six were students at Edinburgh University; the others were employed in various occupations. The ages fell between 21 and 35. None was aware of the purpose of the experiment or of the predicted results.

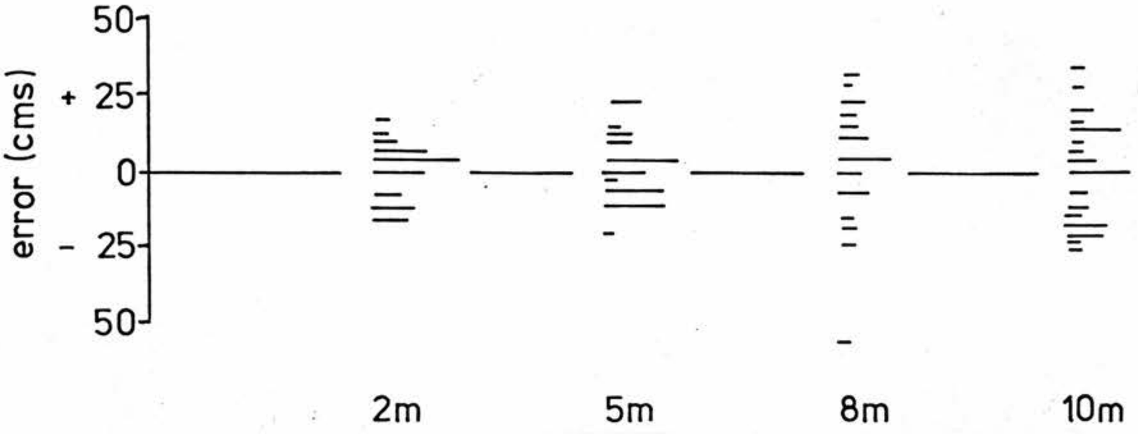
Results

The essential results of this experiment are to be found in Figure 1.1, which shows the variance of error obtained at each of the four locomotor distances used. The results of the non-visual condition (Condition 1) are found in Figure 1.1a, and the results of the visual condition (Condition 2) in Figure 1.1b.

The results of the experiment clearly support the predictions. When subjects are asked to walk up to and locate a target placed at a distance of up to 10 metres, they can apparently do this as accurately when the eyes are closed throughout the locomotor period, as they can with eyes open. This is clearly seen from an examination of the variance of error obtained in the two conditions: in all cases, the variance in the one condition mirrors that obtained in the other. The trend was assessed statistically by means of the F-test for homogeneity of variances which was applied to the corresponding distances in the two conditions. No significant differences were obtained (2x2, F=1.08; 5x5, F=2.18; 8x8, F=2.23; 10x10, F= 1.47. All insignificant at α =.01, one-tailed test). It appears, then, that the consistency of subjects' responses is roughly equal in the two conditions.

While the above analysis shows that the subjects were equally <u>consistent</u> in the two conditions, it is also possible to gauge their <u>accuracy</u> in locating the target line by calculating the mean error obtained at each distance. Means and standard deviations of errors are presented in Table 1.1.

Condition 1 (non-visual)



Condition 2 (visual)

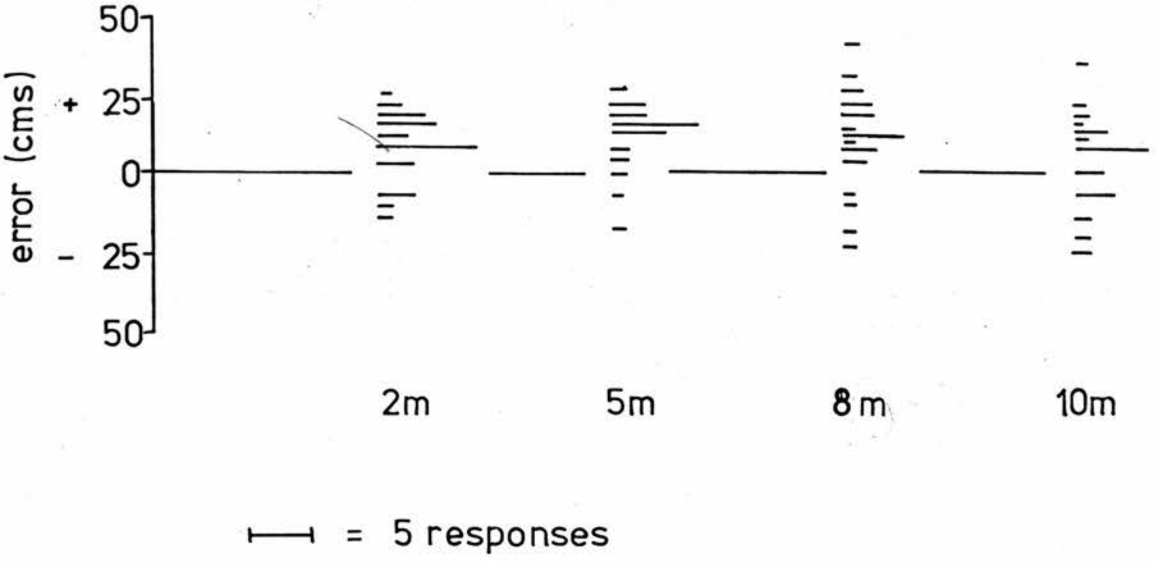


FIG 1.1 Distribution of judgments at each distance.

TABLE 1.1

Means and Standard Deviations of Errors in Both Conditions

(Experiment 1)

	Distance (metres)			
	2	5	8	10
Condition 1	1.51 ± 7.9	-.72 ± 10.63	-2.28 ± 19.03	0.41 ± 14.71
Condition 2	9.67 ± 7.61	13.92 ± 6.72	10.61 ± 12.74	.91 ± 12.12

Error in cms.

An examination of this Table shows that there is a tendency for subjects to be more accurate in the non-visual than the visual condition. At the first 3 distances (2, 5 and 8 metres) the mean error in Condition 1 is noticeably smaller than in Condition 2, though the effect is not found at 10m. The trend was examined statistically and found to be reliable. None of the errors in Condition 1 proved to deviate significantly from zero (2m, $t=.61$; 5m, $t=.21$; 8m, $t= .38$; 10m, $t = .09$, all insignificant at $\alpha = .01$, one-tailed test). In Condition 2, the deviations were significant at the first three distances (2m, $t=4.03$; $p < .01$; 5m, $t=6.52$, $p < .01$; 8m, $t=2.63$, $p < .01$). The difference at 10m was not significant ($t=.24$, n.s.). However, the difference in accuracy between the two conditions is very small. Table 1.2 shows the percentage of responses falling within 12, 18 and 24cms. of the target. It can be seen that 83% of all responses in both conditions fell within 18 cms. of the target. No difference in the accuracy ratio can be found until we examine those responses falling within 12 cms. of the target, where performance is higher in the non-visual condition. But at this level it seems likely that the error term is capable of absorbing most of the differences found. Accuracy in both conditions is clearly very high.

TABLE 1.2

Percentage of Responses falling within 12, 18 and 24 cms. of the Target Line

	Distance (cms.)					
	12		18		24	
	Condition		Condition		Condition	
	1	2	1	2	1	2
2 metres	87	67	100	93	100	100
5 metres	83	53	87	87	100	97
8 metres	50	50	77	70	87	90
10 metres	63	60	73	83	93	93
Total	71	58	83	83	95	95

An examination of Fig. 1.1 and Table 1.1 shows that the variance of error remains substantially the same between different distances in the two conditions. However, it can be seen that the variances at 2 and 5m. are somewhat narrower than at 8 and 10m. The effect was examined statistically at α=.01, one-tailed test, and found to be reliable in both conditions (Condition 1 - 2x5, F=1.81, n.s.; 5x8, F=3.2, $p < .01$; 8x10, F= 1.67, n.s. Condition 2 - 2x5, F= 1.28, n.s.; 5x8, F=3.6, $p < .01$; 8x10, F =1.11,n.s.). Performance would appear to be superior at the shorter distances in both conditions.

Discussion

The two general predictions which the present experiment was designed to test, were that subjects have the ability to locomote accurately to locations up to 10 metres away when vision is excluded during the locomotion and that the errors made under this condition would not differ substantially from those made when vision is available. These general predictions seem to be well confirmed by the present experiment. The vast majority of the responses in both conditions (83%) fell within 18 cms. of the target line, and almost all responses (95%) fell within 24 cms. In fact, only six responses in Condition 1 and 7 in Condition 2 fell outside this 24cm. range. These results therefore strongly support the prediction that a high degree of accuracy can be attained even when visual information is excluded during the execution of the act.

The prediction that performance would be as high in the non-visual as in the visual condition is similarly confirmed. Indeed, we saw from Tables 1.1 and 1.2 that there is a tendency for performance to be better in the non-visual condition. The reason for this discrepancy is not clear. It may be that those subjects who claimed that they were trying to line their toes up into the target line were in fact orienting in terms of the centre of the foot. We noted earlier that the centre of the foot is a meaningful measuring-point to take as it corresponds to the centre of gravity of the body. Whenever the body as a whole is being transported through the environment, it would seem sensible that the accuracy of these transportations would be best expressed in the positioning of the centre of gravity rather than in terms of some more arbitrary criterion like the toes. If this were so, then the mean error obtained in the visual condition when a centre-of-the-foot measuring criterion was employed, would fall closer to the position of the target line. Of course, by the same token we would expect the mean error in the non-visual condition to shift downwards. But it is unlikely that the mean error obtained in either condition would then differ significantly from zero. It will be possible to examine this issue in subsequent experiments by taking a measure of the position at which the centre of the foot falls relative to the target line in the case of every subject, and seeing if the effect obtained in Experiment 1 persists. At any rate, this finding clearly substantiates our prediction that performance in the non-visual condition would reach the same standard of accuracy as performance in the visual condition. We may justifiably conclude that performance in the non-visual condition is "adequate" by this criterion.

We may use the results of Table 1.1 to examine another aspect of subjects' performance in this experiment. A widely held belief in perceptual psychology is that error in perceived distance increases with increasing physical distance and that at distances of only 2 - 3 metres the error is already substantial (Gilinsky, 1951; Künnappas, 1962; Legge and Barber, 1975). The results of the present experiment contradict such accounts. Firstly, as we have already seen, subjects' performance with vision excluded was as good as when vision was available. Since subjects in the former condition have no possibility of re-gauging the distance to the target on the basis of visual information after locomotion is commenced, and since the resulting performance is as good as when such visual information is available, this implies that the subjects were indeed able to accurately apprehend the distance of the target in advance of the point at which the act was initiated. Secondly, we have seen that the mean error in Condition 1 falls very close to the position of the target line. If we had found the mean error to fall at some fairly substantial distance from the target, and if that distance increased as total distance to the target increased, we would have been forced to consider the possibility that the error contained a component of perceptual error. However, the distribution of error fell squarely across the target line, and did not show any tendency to increase as total physical distance increased. This finding therefore implies that relatively little error accrued to subjects' ability to perceive the distances involved. It would appear that subjects have the ability to apprehend distance in fairly exact terms, at least at distances of up to ten metres.

An important finding in the present experiment is the small but significant increase in variance obtained at 5 metres. The effect was obtained when we examined both the variance of error at the different distances (Fig. 1.1) and the range of error (Table 1.2). It is not yet clear what is responsible for this "threshold", but if the effect were to prove reliable, it might offer a way into the mechanism underlying the ability.

A finding which is of immediate concern, however, is the fact that the effect is obtained not just in the non-visual condition, but in the visual condition as well. There seems no reason to expect the accuracy obtained at 2 and 5 metres in Condition 2 to break down at 8 and 10 metres however, since visual information is as readily available at these latter distances as it is at the former. An important possibility suggested by these results is that subjects were functioning in the same way whether vision was available or not: that even when vision is available during locomotion, subjects continue to construct programs for action in advance which could then be run off independently of further visual information about the location of the target; that functionally-speaking, subjects may at times be "blind" during the locomotion period even when vision is available. This important conclusion will require far stronger evidence before being readily acceptable but such an explanation is certainly consistent, and indeed the most consistent explanation of the data obtained in Experiment 1.

One final point must be made concerning the analysis of the results. It will have been noticed that one per cent. was the minimum level of significance accepted in this experiment. Although the five per cent. level is frequently taken as the minimum acceptable, it was decided that a higher level should be chosen in the present study. The reason for this was simply that it was felt that any effects of the importance of those predicted here should evidence themselves far more clearly than at the 5% significance level. Although in some research it is difficult to get control over all the relevant variables and hence to maximise the desired effect, making 5% significance acceptable, it was considered that no such argument could be made about the present research. Consequently, results failing to reach significance at the 1% level were not considered. The reader may judge for himself the justice of this strategy as he reads through the experiments.

Conclusions

From the results of the present experiment, it seems we can draw positive conclusions with respect to the stated hypotheses. It seems that subjects do indeed have the ability to program behaviour in advance of the point at which it is needed and in a form sufficiently precise to rule out the need for further information after the act is initiated. Whether or not vision can normally be "turned off" as completely as it was in Condition 1 is debatable but seems unlikely. We know, for example, that locomotion over uneven ground is hazardous and difficult in the dark, and it is unlikely that a program could take into account all the undulations of the surface in order to smooth out these difficulties during the period when vision would be excluded. It seems probable that control of variables of this sort would frequently have to continue during the execution of a programmed act and that we could not therefore really expect a subject to operate completely "blind" during the execution period. Nevertheless, it is clear that a subject in this condition can achieve a great deal with no vision at all. The role of vision during such periods can apparently be very limited.

EXPERIMENT 2

THE RANGE OF DISTANCES OVER WHICH LOCOMOTION CAN BE CONTROLLED IN THE ABSENCE OF VISION

Introduction

In Experiment 1, we obtained evidence which strongly suggested that subjects have the ability to control their behaviour on the basis of intermittently acquired information. It appeared that control on the basis of such information could be as effective as when vision is freely and continuously available. Two questions follow naturally from this finding: firstly, we can ask what the total range of distances over which this ability can be extended are; secondly, we can ask in what form a breakdown in the ability will manifest itself. Experiment 2 is designed to answer these questions.

Method

Design

The design of Experiment 2 followed closely the basic design of Experiment 1. The experiment was conducted in a large area of open ground (a temporary car park). The experiment was conducted out of doors for two reasons: firstly, because it did not prove possible to find an indoor area sufficiently large to accommodate the long distances used in Experiment 2, and secondly, because it was felt desirable to perform the experiments under as natural conditions as possible. One important factor, for example, was felt to be the surface on which the experiment took place. It was felt desirable that the surface should not be too smooth or artificial and the one chosen, which was rough and rather stony, was thought to fulfil this condition. The area on which the actual experiment took place formed a wide runway for purposes of access to the parking spaces. Since the park was for long-term parking, interruptions were rare, but the park was usually sparsely populated in any case, testing times being chosen in accordance with low usage.

The locomotor distances chosen were 3, 6, 9, 12, 15, 18 and 21 metres. The distances were laid out along two pathways which lay in parallel and approximately 6 metres apart. The total number of trials were divided equally between these pathways in order to rule out as far as possible any possibility of the subjects gaining tactual cues from the variations in surface texture and consistency which could then be used to gauge the distances. The target position was always indicated by a wooden marker, which was placed about 1 metre to the subject's left, and the subject's task was defined as in Experiment 1, as being to line himself up directly opposite the marker. Unlike Experiment 1, however, no target line was painted on the surface opposite the marker. This was simply because target lines would not have been visible at the longer distances. Each attempt at locating the target was indicated by coloured markers, different colours being used for each trial, which were pushed into the ground. Because subjects could see the markers at the 3 metre distance, responses at that distance were measured directly.

As in Experiment 1, auditory information was excluded by means of white noise played through a pair of head-phones attached to a portable tape-recorder. The procedure was effective in eliminating almost all auditory information (see Design, Experiment 1).

Two conditions were employed. In Condition 1, all visual information was excluded during locomotion. However, in Experiment 2 this was not achieved by means of blind-folding: instead, subjects were simply asked to shut their eyes. There was a number of reasons for this change of procedure. First of all, there was the very real danger that subjects, walking for such long distances over such a rough surface, might stumble and fall. It was felt that if this did happen subjects must be able to use their eyes to right themselves, or to protect themselves as they fell. If a blindfold were worn, this would not be possible. In fact, it was discovered early on that subjects were not prepared to tolerate blindfolding under these circumstances for these very reasons, and that when they were blindfolded, their locomotion became slow and hesitant. For these reasons, it was decided to dispense with the blindfold in experiments of this type. It was considered, however, that the subjects chosen were sufficiently mature to conduct the experiment as instructed.

Condition 2 was exactly the same as Condition 1, except that in this condition the subject kept his eyes open as he walked up towards the target. As in Experiment 1, this was considered to represent a "control" case of simple visual guidance.

Procedure

Practice Session - As in Experiment 1, subjects in Experiment 2 were given a practice session to accustom them to the task. This practice session was kept to a minimum, however, and never amounted to more than a minute or two. In fact, it proved easier to prime subjects for Experiment 2 than it did for Experiment 1, in spite of the greatly increased distances involved. This was principally because of the increased space around the subjects, with the consequent lessening of the dangers of collisions. The practice trials were always conducted at some distance from the experimental set-up to prevent learning of the distances involved. Subjects were encouraged to walk in as natural and uninhibited a manner as possible. Practice was given at a group of short distances, and also at long ones.

Experimental Session - Before each trial began, S stood lined up at the starting-point while the marker was placed in position, one marker only being used. E was careful never to inadvertently provide S with distance information by walking along the locomotion path, but rather approached in a circumventory manner. Similarly, E always withdrew before the trial began. S was fitted with the white noise apparatus at the beginning of the session and, with the exception of short rest periods, this was not then removed until the end of the entire session. S was allowed to survey the layout at the beginning of each trial, and decide for himself when to commence. At the end of each trial, S remained with his eyes closed until E marked the spot with a marker pin or measured the error (in the case of the 3m distance). E then turned the subject, who remained blindfolded, around and led him several metres back towards the starting point before allowing him to open his eyes. It was for this reason that a single target market only was used. Had a series of markers been used, S could have gauged some of the distances as he walked back to the start. It did not prove practicable to lead S all the way back to the start at the end of each trial, as this would have further increased the length of an already lengthy experiment. The procedure followed seemed to keep time to a minimum while ensuring control over all relevant sources of variance. Trials were randomised within each block of seven distances, and the blocks of trials were executed on each of the two pathways alternatively. Thirty-five trials were given in all in each condition, 5 at each distance. Performance at each distance was taken by measuring the positions of the centre of the foot. This measurement was taken for reasons already elaborated on in Experiment 1 (see Discussion) as representing the most meaningful measure of accuracy. The experiment was conducted under two conditions, visual and non-visual. The non-visual condition was always given first. Because of the length of time to conduct the experiment (approximately one hour for each condition), the experiment was conducted on two different occasions, Condition 1 first, Condition 2 second. The same subjects were used on both occasions.

Subjects

Nine subjects were used, five male and four female. All were students at Edinburgh University and ranged in age from 20 to 28 years. No subject was familiar with the purposes or predicted results of the experiment.

Results

The essential results of Experiment 2 are presented in Figs. 2.1 and 2.2 which show the variance of error obtained at each of the seven locomotor distances. Fig. 2.1 shows the results of the non-visual condition (Condition 1) and Fig. 2.2 the result of the visual condition (Condition 2). The figures show all the individual judgments made by the group of subjects, and hence provide a graphical representation of the raw data.

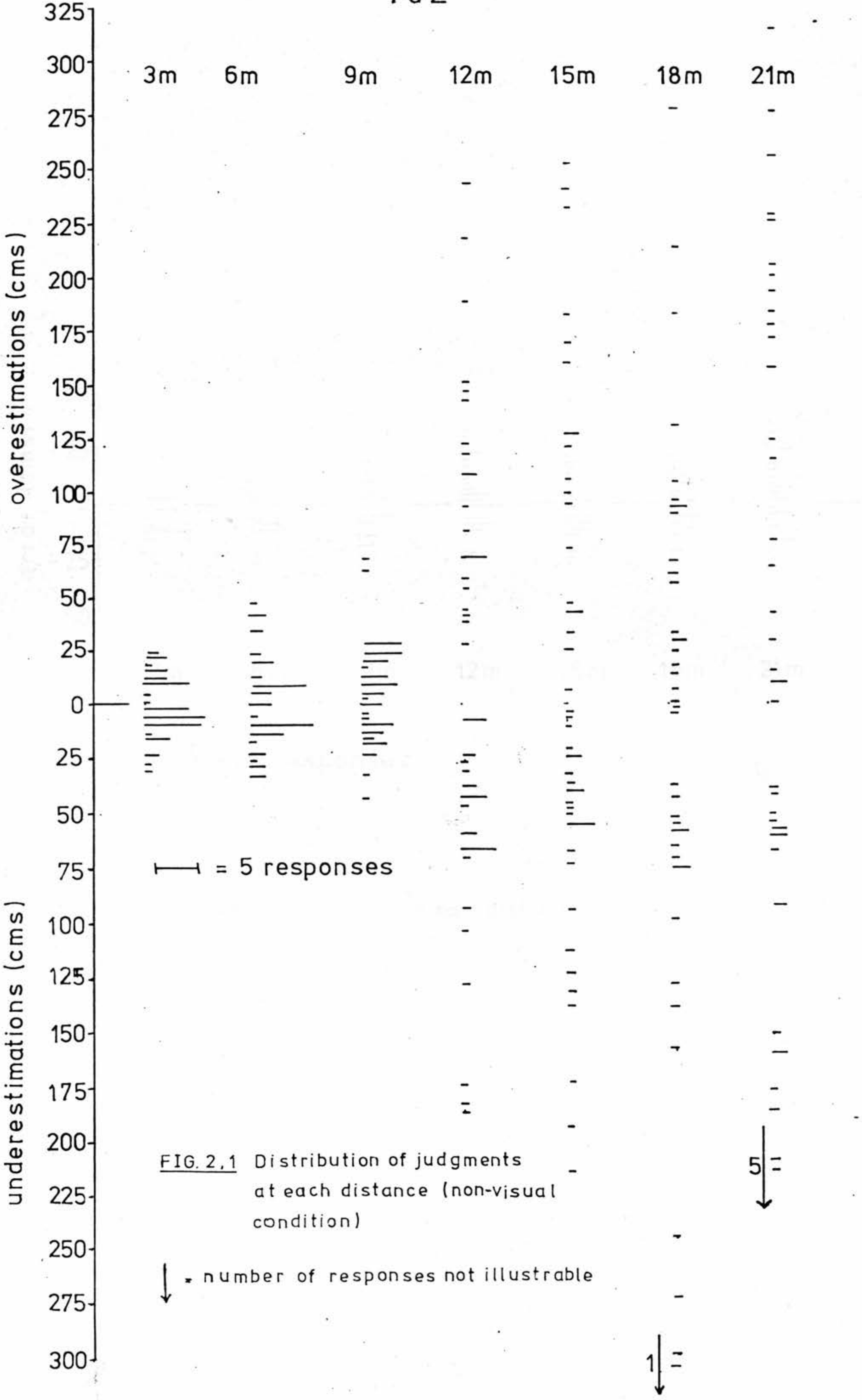


FIG. 2.1 Distribution of judgments at each distance (non-visual condition)

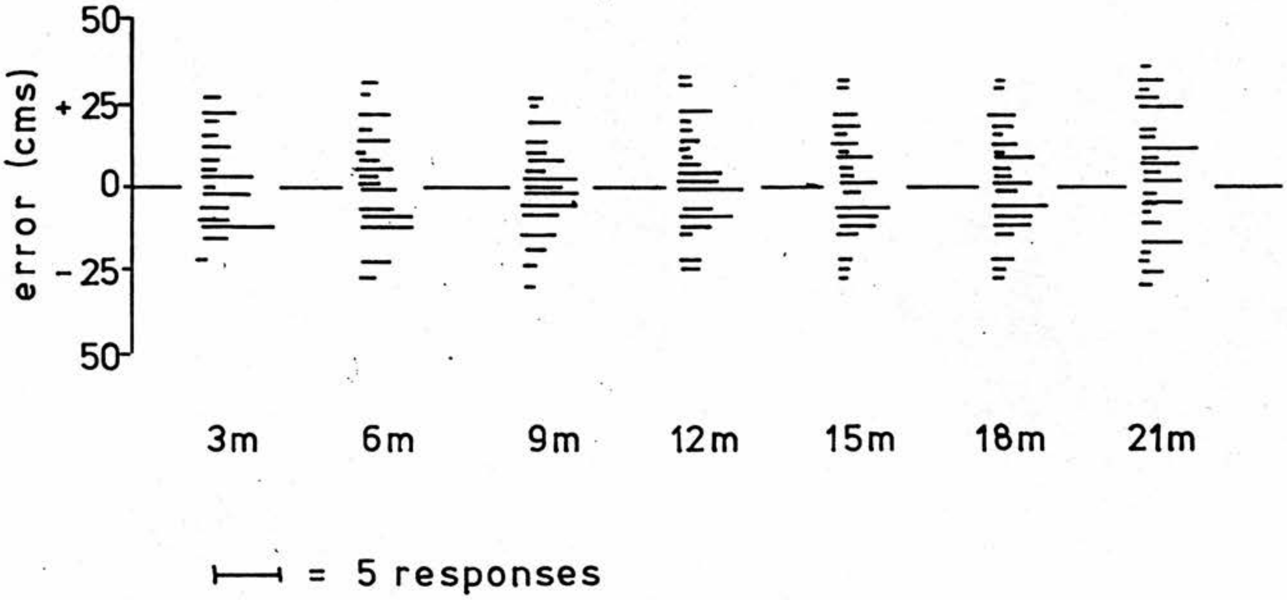


FIG 2.2 Distribution of judgments at each distance (visual condition)

The first point which should be made about these results is that they confirm the results obtained in Experiment 1. Figs. 2.1 and 2.2 show that the errors made at the 3, 6 and 9 metre distances in Condition 1 closely reflect those made in Condition 2. F-tests performed on the corresponding distances in the two conditions revealed no significant differences in the variances (3x3, F=1.5; 6x6, F=1.87; 9x9, F=2.61; all insignificant at $\alpha = .01$, one-tailed test). As in Experiment 1, subjects appear to perform equally consistently whether vision is available or not. The average deviation from the target can be gauged from Tables 2.1 and 2.2 which show the mean error obtained at each distance in each condition. It can be seen that the mean error, as in Experiment 1, is somewhat larger in the visual than in the non-visual condition, but in neither case did the error deviate significantly from zero (highest deviation = 7.09 ± 22.42 $t = 2.13$, n.s. at $\alpha = .01$, one-tailed test). The general accuracy in the two conditions can also be gauged from Table 2.3 which shows the percentage of responses falling within 12, 18 and 24 cms. of the target line. It can be seen that 84% of all responses in both conditions fall within 24 cms. of the target. No differences in accuracy ratio were found at any of the distances used. These results in general, then, provide strong support and confirmation of the results obtained in Experiment 1.

The main purpose of Experiment 2 was to find if there is an identifiable limitation to subjects' ability to control their activity in the absence of visual information during the course of the activity, and if so, to specify the point at which the ability begins to break

TABLE 2.1

Means and Standard Deviations of Error at each Distance for the Group (Condition 1)

Distance 3		6		9		12		15		18		21	
M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
-.37	14.98	1.81	21.02	7.09	22.42	15.94	100.7	4.73	116.3	-26.38	139.42	16.22	198.46

error in cms.

TABLE 2.2

Means and Standard Deviations of Error at each Distance for the Group (Condition 2)

Distance 3		6		9		12		15		18		21	
M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
3.67	12.24	3.12	15.36	3.6	13.87	3.02	15.55	2.14	15.29	3.02	16.51	3.48	15.87

error in cms.

TABLE 2.3

Percentage of Responses falling within 12, 18 and 24 cms. of Target

	Distance (cms.)					
	12		18		24	
	Condition		Condition		Condition	
	1	2	1	2	1	2
3 metres	56	60	78	75	91	95
6 metres	47	60	62	68	78	80
9 metres	42	57	62	72	82	90
Total	48	59	67	71	84	88

down. The results of Experiment 2 enable us to give an unequivocal answer to this question. It can be clearly seen from Figure 2.1 that the variance remains quite stable up to 9 metres, but then rises dramatically between 9 and 12 metres, stabilising again at 12 metres and above. This would allow us to pin-point the limitation in ability at somewhere between 9 and 12 metres. These trends were examined statistically by means of the F test for homogeneity of variances and were strongly confirmed. No differences were found between consecutive distances at 3, 6 and 9 metres (3x6, F=1.57; 6x9, F=1.13, both insignificant at $\alpha = .01$, one-tailed test). At 9 and 12 metres, the difference was significant for above the one per cent. level set (F=26.63). No differences were found between consecutive distances at 12, 15, 18 and 21 metres (12x15, F=1.33; 15x18, F=1.44; 18x21;

F= 2.03, all insignificant at $\alpha = .01$, one-tailed test). It should be noted, however, that there is a gradual increase in the variance over distances on either side of the threshold. Thus, while no differences are found between the variances at successive distances, over a wide range the variances become larger (3x9 metres, F=2.24, $p < .01$; 12x21 metres, F=3.88, $p < .01$; 15x21 metres, F 2.91, $p < .01$). These results, then, appear to show that there is a gradual increase of variance to be expected as physical distance increases on either side of the threshold. The dramatic increase obtained at 12 metres, however, is clearly of a different order, and seems to represent a much more profound limitation in the ability to locate the target. The results in general point strongly to a sharp threshold in the accuracy with which activity can be controlled under the conditions employed in Experiments 1 and 2, when the distances involved exceed 12 metres.

An examination of the variance obtained in Condition 2 also confirms the experimental predictions. It was hypothesised that in Condition 2, the variance obtained would remain relatively stable over all distances. An examination of Figure 2.2 confirms this hypothesis. No significant differences were obtained between the variances at any of the locomotor distances (251.86, highest variance x 149.82, lowest variance, F=1.68;n.s. at $\alpha = 0.1$, one-tailed test). The hypothesis that in Condition 2 performance would remain stable throughout seems confirmed.

An examination of the results of individual subjects reveals a close conformity to the pattern of results obtained for the group. Fig. 2.3 shows the errors made at each distance by each subject in Condition 1. It can be seen that the general trend of the group data

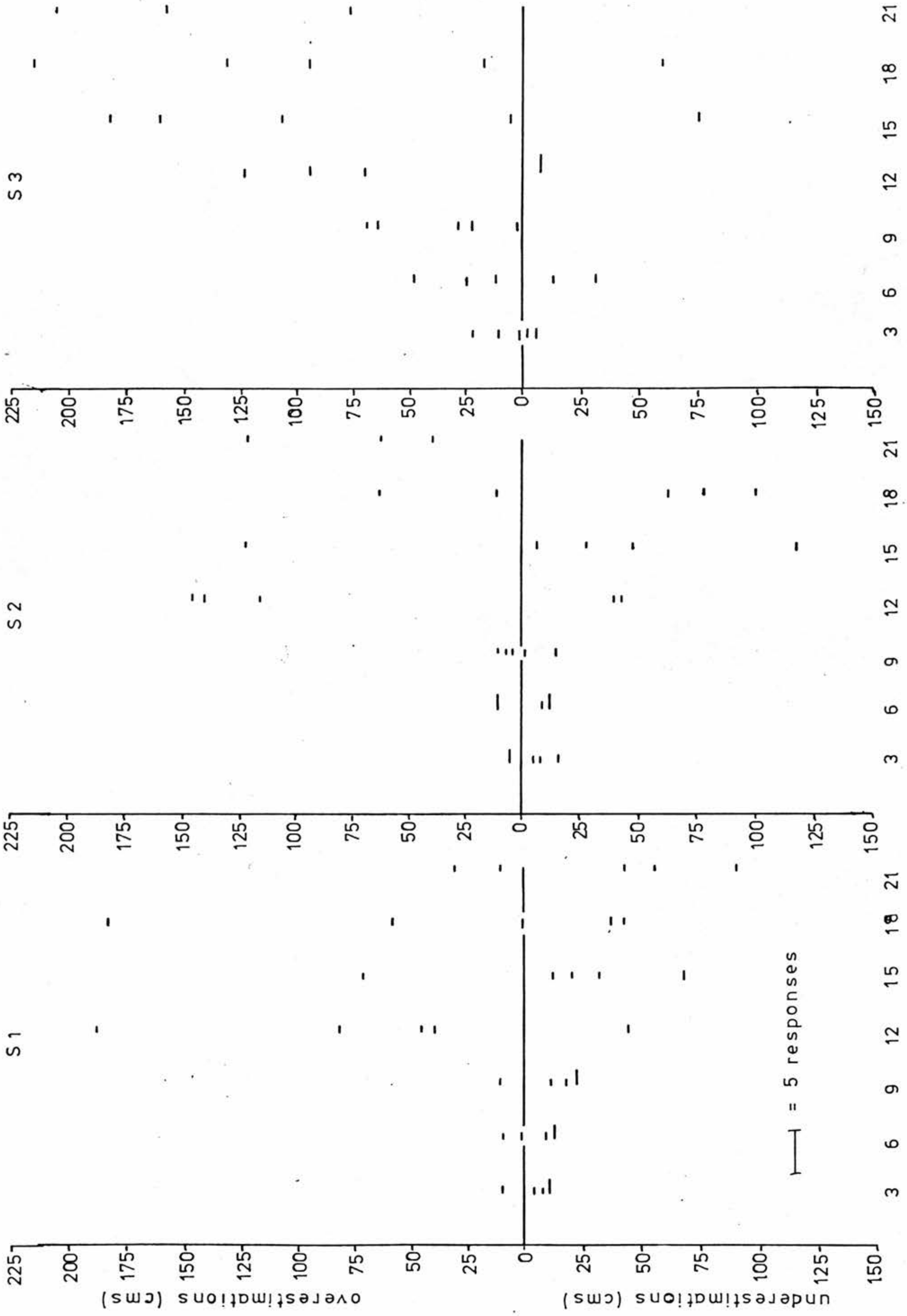


FIG. 2,3 Distribution of judgments in Condition 1.
(individual subjects)

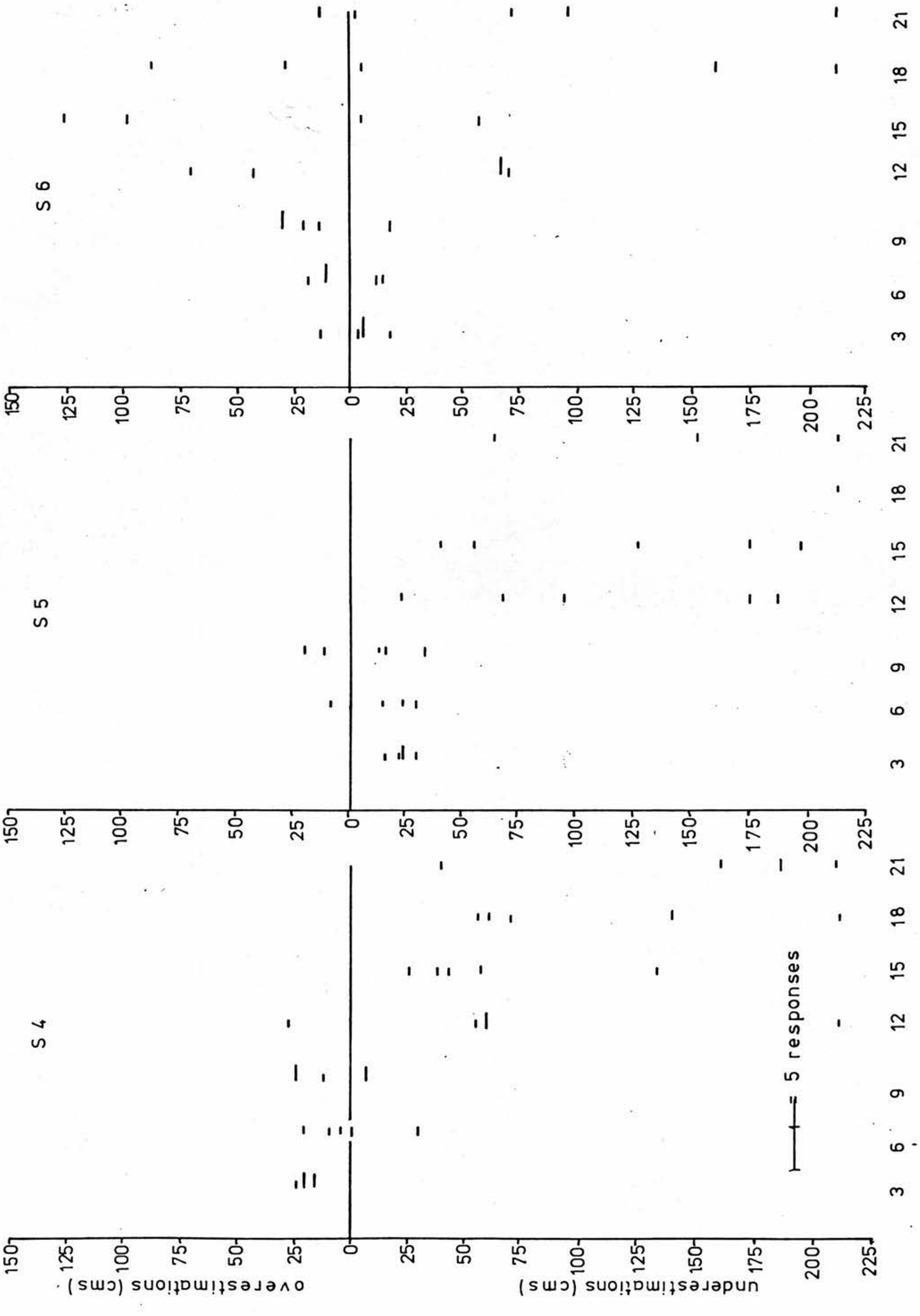

S 4
S 5
S 6
150
125
100
75
50
25
0
25
50
75
100
125
150
175
200
225
overestimations (cms)
underestimations (cms)
3
6
9
12
15
18
21
= 5 responses

FIG 2,3 (contd.)

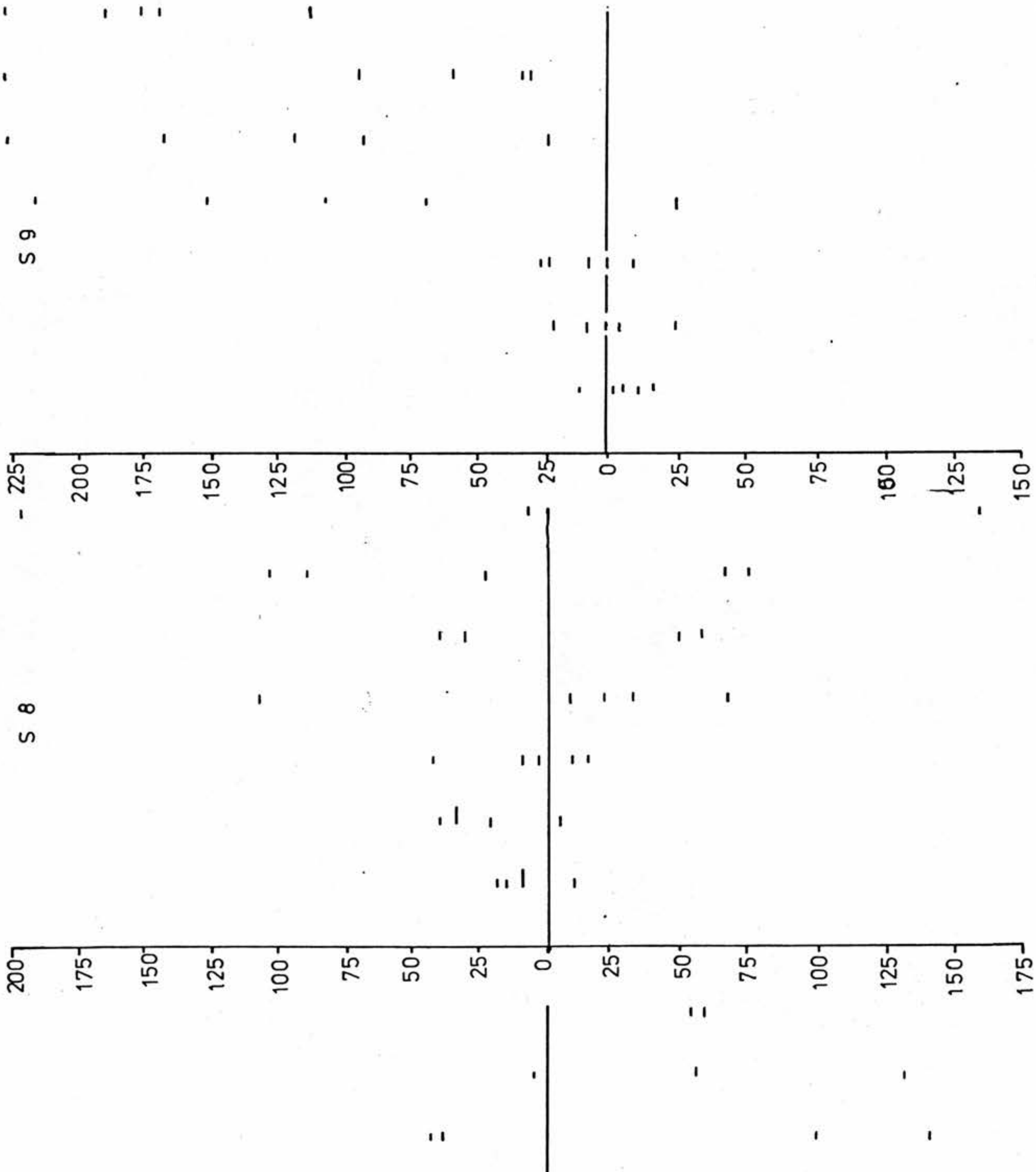

S 9
S 8
S 7
3
6
9
12
15
18
21
overestimations (cms)
underestimations (cms)
225
200
175
150
125
100
75
50
25
0
25
50
75
100
125
150
175

FIG. 2,3 (contd.)

is repeated here. In all but one case (subject 3) it can be seen that error remains low at the first three distances, mirroring that of the group as a whole. At 12m. the error rises greatly, stabilising off at a high level. The threshold is seen in all subjects though the clarity varies. The thresholds were examined statistically by means of the Mann Whitney U test, the results of which are presented in Table 2.4 In all but two cases (subjects 3 and 8) the effect was found to be highly significant. In the case of subject 8 the trend, although not reaching significance, can be clearly seen. In subject 3, the increase in error seems to be more gradual with error beginning to accumulate as early as 6m. Here too, however, the trend towards increased error at 12m. is apparent, and at 15m. the threshold effect is clearly seen. These results in general then, conform closely to those of the group as a whole.

TABLE 2.4

Mann-Whitney U-values for Error Scores of Individual Subjects

	Distance Comparisons					
Subject	3x6	6x9	9x12	12x15	15x18	18x21
1	10	5	0*	6	11	13
2	5	11	0*	8	13	7
3	2	10	9	8	12	5
4	8	10	0*	8	4	9
5	12	10	1**	12	-	-
6	8	3	0*	9	12	10
7	13	11	0*	9	10	11
8	5	7	6	9	9	5
9	13	11	1**	11	10	4

* - $p < .004$ one-tailed test: ** - $p < .008$ one-tailed test
All other cells insignificant at $p = .01$, two-tailed test.

We have so far considered only differences in the variance of errors around the target line and hence the consistency of subjects' performance. However, it is possible to calculate the mean error obtained at each distance and hence the mean position where subjects judged the target to be. If in the group as a whole or in individual subjects there were any tendency to consistently err in one direction or another, this might well prove to reflect certain characteristics of the system. For this reason, the mean error obtained at each distance has been calculated and presented in Tables 2.1 and 2.2. An examination of this task shows that the mean error in all cases falls only marginally short of zero (the target position), with all but one mean falling at less than 15 cms. from the target. A statistical analysis was carried out, the results of which are presented in Table 2.5.

TABLE 2.5

t-values from Data in Tables 2.1 and 2.2

Condition 1		Condition 2	
Distance	t	Distance	t
3	.91	3	2.02
6	.58	6	1.36
9	2.13	9	1.74
12	.10	12	1.30
15	.27	15	.94
18	1.27	18	1.23
21	.55	21	1.47

all insignificant at $\alpha = .01$, one-tailed test

No mean in either condition was found to deviate significantly from zero. It appears that there is no tendency for subjects as a whole to consistently over- or underestimate the distances.

The position is somewhat more difficult to evaluate in the case of individual subjects. In some cases (subjects 1, 2, 6, 7 and 8) there does not appear to be any strong tendency to err in one direction more than the other. In two cases, however, (subjects 3 and 9) there does appear to be some tendency to overestimate, and in three further cases (subjects 4, 5 and 7), there seems to be a tendency to underestimate (see Figure 2.3). The small number of trials at each distance makes it impossible to assess the tendencies at any one distance statistically, nor is it possible to consider responses occurring on either side of the threshold. A crude assessment of the significance of the tendencies to over or underestimate the distances can be made by considering all over-estimations against all underestimations without taking distance into account. A sign-test analysis was conducted in this way. In no case did the tendency to err in a particular direction reach significance. The results of this analysis therefore fit well with the results for the group as a whole.

Discussion

We stated earlier two essential purposes of Experiment 2. Firstly, it was intended to use this experiment to check the basic results of Experiment 1 and to check certain anomalies in the results of the first experiment. Secondly, it was intended to establish if possible the range of distances over which the results of Experiment 1 could be obtained and to discover the nature of any limitations to this ability which there might be. Experiment 2 seems to have been effective in satisfying both these conditions.

An examination of the results obtained at the first three distances used shows a clear correspondence with the results of Experiment 1. In all cases, performance in Condition 1 matches that of Condition 2. It can be seen that 84% of responses in Condition 1 fell within a radius of 24 cms. from the target, and that percentage remained stable between conditions. No differences were found between the variances in the two conditions. In no case did the mean error fall at a significant distance from the target line. These results therefore present a strong confirmation of the results obtained in Experiment 1. It appears that subjects can indeed move from one spatial location to another when vision is not available during the walking period, and can do so as accurately as they can when vision is available.

It will be remembered that in Experiment 1 the mean error obtained in the visual condition was significantly greater than it was in the non-visual. A potential explanation of this discrepancy offered, was that the system of measurement used may not have been completely appropriate. It was argued that the centre of the foot is the most meaningful measuring-point to take since it corresponds to the centre of gravity of the body. It was felt that when the body is moved through the environment, the success of these movements would be best expressed in the positioning of the centre of gravity (i.e. the centre of the foot). However, some subjects claimed a subjective desire to line the toes up to the target, and this desire was respected. It was suggested in the discussion to Experiment 1 that had the centre of the foot been adopted as criterion instead of the toes, then the mean error in Condition 2 would have moved down and the difference from zero become insignificant. It was decided to employ this procedure in Experiment 2 to test the possibility. The results seem to confirm the hypothesis. An examination of Tables 1.1 and 2.2 shows that the mean error has shifted downwards in Experiment 2 and that the differences from zero in this experiment are not significant. The mean error in Condition 1 has remained roughly stable and similarly does not differ significantly from zero. These results, then, confirm on the one hand the prediction that performance in the two conditions would be equal, and secondly, supports the claim that the centre of the foot constitutes the best measure of accuracy which can be used. This procedure was therefore employed in all subsequent experiments.

There is a second discrepancy between the results of Experiments 1 and 2 which must be noted at this point. An examination of Figs. 1.1 and 2.1 reveals that the variance in Experiment 2 is greater than in Experiment 1. If we examine the distances corresponding most closely in the two experiments we find that the effect is statistically reliable (2x3, $F=3.6$, $p < .01$; 5x6, $F=3.91$, $p < .01$; 8x9, $F=3.1$, $p < .01$). One possible explanation of the discrepancy is the difference between the targets used in the two experiments. In Experiment 1, the target took the form of a narrow marker and a line drawn on the floor. In Experiment 2, by contrast, no line was drawn on the surface, and the target marker was much larger (because of the longer distances used). In fact, the edge of the marker opposite which the subjects were asked to line themselves measured approximately 5 cms. and this alone would be likely to reduce the accuracy. This, together with the lack of a target line, means that the target was defined much more broadly in Experiment 2. In view of these two discrepancies between the experiments, it is perhaps not surprising that the variances between them differed. However, in both cases the responses in the non-visual condition were found to correspond to those of the control condition in that particular experiment, irrespective of the differences as a whole in the results of the two experiments. The general results of the two experiments are therefore clearly in close agreement.

The main purpose of Experiment 2 was to see how far the ability evidenced by Experiment 1 could be extended, and to see in what way the ability broke down. The dramatic threshold seen in Fig. 2.1 shows clearly that the ability breaks down somewhere between 9 and 12m. at a point not far in advance of the distances we have been examining already. The results of Experiment 1, which showed that the performance could be maintained at 10m. would suggest that the break-point occurs somewhere between 10 and 12m. This would seem to rule out the possibility of a gradual increase in error across distance: the limitation seems to express itself in a rather sharp threshold. The result of the group as a whole is supported by the results of the individual subjects. Fig. 2.3 shows the sharp threshold of the group results in the individual profiles of seven out of the nine subjects, with the results of the other two subjects, while not satisfying a statistical criterion, lying clearly in the right direction. These results, then, strongly suggest that under the conditions employed in Experiments 1 and 2, the ability under consideration is limited to distances of less than 12m.

The fundamental problem posed by Experiment 2 is to discover what is responsible for the threshold obtained there. One possibility which may be considered is that the threshold is caused by perceptual error.

It is possible that at the critical distance of 10-12m. some critical element of perceptual information ceases to be available, producing a corresponding increase in error. This possibility seems unlikely, however, for reasons which were first considered in Experiment 1. We have already seen, in the group results of Experiments 1 and 2, that the mean error obtained at each distance does not deviate significantly from zero. This finding holds for the distances between 12 and 21m. as it does for the distances below the threshold. The error at the longer distances takes the form of an increased <u>variability</u> in the positions which the subjects take to be the position of the target. This finding strongly detracts from any explanation in terms of perceptual error, since such an error would be expected to reveal itself in the form of a change in the mean position to which subjects oriented, with relatively little change in the variance. The evidence normally taken as evidence of perceptual error is of this sort. The fact that no significant changes in the mean error are found above the critical distance therefore militates against any such interpretation of the present results. A consideration of the results of individual subjects reinforces this point. It can be seen in Fig. 2.3 that there is little consistency in the responses of different subjects at distances above the threshold. For example, the response profiles for subjects 6 and 8 show a tendency for responses to be distributed on both sides of the target line, and consisting of both over and underestimations. In the case of subjects 3 and 9, there is a tendency to over-estimate the distances and in the case of subjects 4 and 5, a tendency to under-estimate. This diversity of responses between different subjects seems to rule out the possibility that the error is the result of a missing critical perceptual component, because the direction of error varies so widely between subjects. The limiting factor, whatever it is, does not appear to be exerting a uniform effect on all subjects. The fact, in particular, that different subjects err in different directions, seems to rule out perceptual error as an appealing explanation of the results.

One possible explanation of this effect has to do with reports frequently given by subjects about their attempts to orient to targets at distances of more than 12m. They commonly report that, when they begin to walk towards the target, they "know" where it lies, but that by the time they have begun to reach its general vicinity they have lost that awareness. At that point they begin to make inferences about its likely position, based on any form of information available; that in fact they begin to use cognitive strategies to make up for the lack of other means of knowing where the target lies. This type of explanation of the response obtained at these longer distances does seem to accord quite well with the results. We saw in Fig. 2.3 that subjects react in rather different ways at distances greater than 12m., some apparently over-estimating the distances and others under-estimating. At the same time, there is no clear consistency in their responses, and the variances among their scores is very high. These results accord quite well with the view that they are caused by the adoption of rather vague and general strategies on the part of the subjects to cope with the situation as well as possible. It would be just such general coping strategies that would be expected to generate the kind of vague consistency found in the profiles of individual subjects.

Finally, it will be remembered that in Experiment 2 subjects were not blindfolded, but were merely asked to shut their eyes. It was hoped that the subjects chosen were sufficiently mature to perform the task as directed and to keep their eyes closed during the experiment. The results show that subjects were indeed honest about this. The distances were presented to subjects randomly, yet the further distances were consistently misjudged while the nearer ones were not. This is, if anything, the opposite of what would be expected if the subjects were malingering, because it is at the longer distances that they would undoubtedly be most tempted to open their eyes. The consistent pattern of results obtained, indicates that the subjects did not cheat.

Conclusions

The results of Experiment 2 seem to confirm the results of Experiment 1 and indicate very strongly that the ability is limited to distances of less than 12m., at least under the conditions employed in these experiments. The limitation is very clear and can be seen in the profiles of individual subjects and not merely in the pooled data of the group. The limitation seems to take the form of a sharp threshold rather than a gradually increasing error with increasing distance. The causes of this limitation will be examined in depth at a later stage, for they offer a key to a deeper understanding of the basic mechanisms. However, this will be deferred till a later stage. At present, we will continue with the problem of demonstrating the system's capabilities and limitations. Once these have been dilineated in greater detail we will be in a better position to delve beyond to the underlying mechanisms supporting the abilities.

EXPERIMENT 3

CONTROL OF LOCOMOTION IN A CLUTTERED ENVIRONMENT I

Introduction

So far we have concerned ourselves with only the simplest possible case of the skill in question: namely, with walking up to a single target placed at a variable distance. However, it is obvious that if the skill is to be useful in the natural environment, it should be more extensive than this. For example, when the environment is cluttered it may be necessary to take into account more than a single obstacle or target when formulating the program. Indeed, it is in such cluttered environments that programming would be of greatest importance, since in open territory the need for it is markedly reduced. Since the environment with which animals interact is indeed normally filled with impedances of one kind or another, it would seem that animals would have to be capable of formulating more complex programs than we have concerned ourselves with up till now. Experiment 3 therefore increases the complexity of the task by placing four obstacles in front of subjects and asks the following question: when accomplishment of an act entails the circumvention of a number of obstacles placed in the path of locomotion, to what extent can this group of obstacles be taken into account in the formulated program?

Method

Design

Experiment 3 was conducted on the same location as Experiment 1, that is, in a large lecture-theatre from which all seating had been removed. Some tables and chairs and various pieces of experimental equipment were distributed around the edges of the theatre, but this left a free area measuring approximately 14x9m. where experiments could take place.

Figure 3.1 shows the general layout of Experiment 3. A partial grid measuring 7 by 4m. was laid out on the floor and two layouts of obstacles placed within it. The distances between the obstacles were uneven, and the obstacles were laid out in such a way that subjects were forced to re-orient their bodies as they circumvented one obstacle in order to get into position for the approach to the next. The layout of obstacles was deliberately chosen to form a task of fairly extensive complexity. The partial grid was designed to provide a metric for the examination of the subjects' responses during subsequent analysis, but was restricted to the form seen in Fig. 3.1 to avoid giving subjects too artificial a surface to walk on, and also to minimise the possibilities of subjects using the grid to try to gauge the distances to the obstacles. Since two layouts of obstacles were used, with the distances between the different obstacles varying, this gave four locomotor pathways on which the experiment could be conducted. It was considered that a reasonable number of tracks was desirable because of the reduced likelihood of subjects picking up special cues about a particular pathway which might then be used to improve performance. With four pathways in use, this meant that no more than six trials were ever given on one pathway during the course of the whole experiment. The obstacles were represented by coloured patches measuring approximately 30x30cms. which were taped to the floor. The purpose in using patches rather than real objects was obviously to avoid the cues about performance which would become available.whenever the subject struck

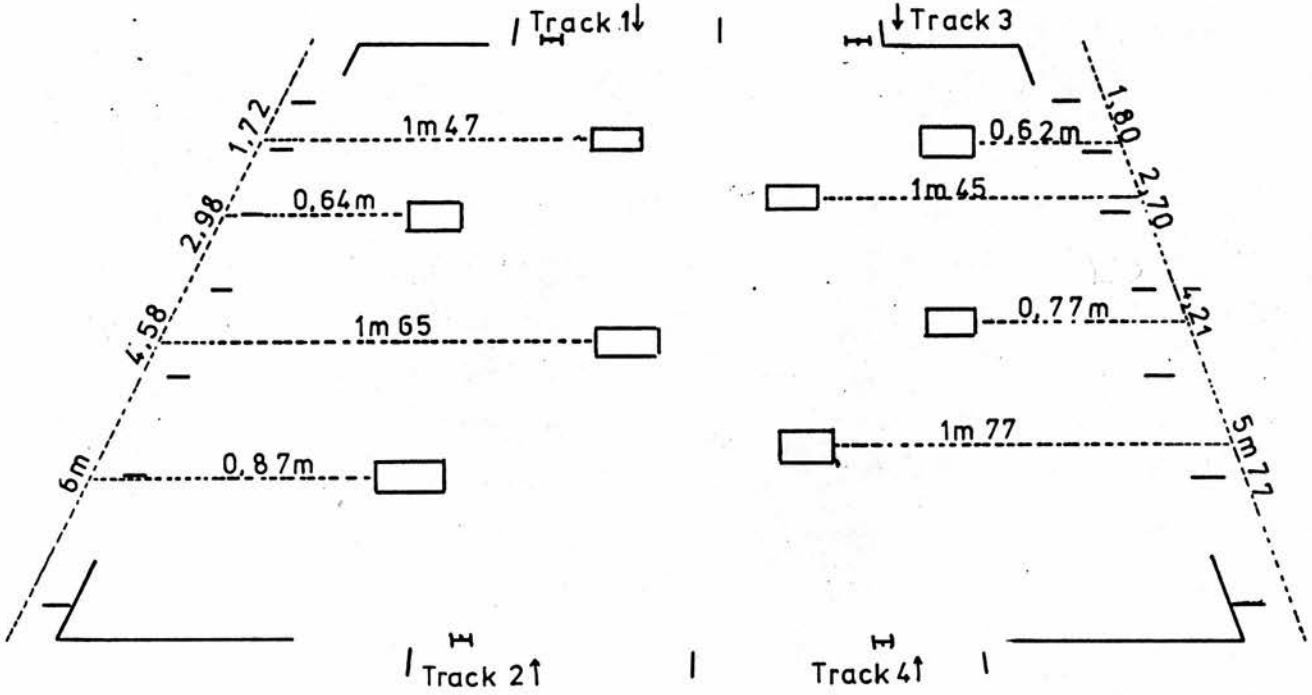


FIG. 3,1 General layout of Experiment 3.

(or indeed, did not strike) an obstacle.

Subjects' responses were filmed by means of a Sony Rover TCR2 portable video recorder andcamera for subsequent analysis. The apparatus was set up on a platform situated at the bottom end of the lecture theatre at a height of approximately 15ft. and at a distance of some 18-20m. from the far end of the grid. The camera zoom was adjusted so that the grid just fitted into the viewfinder, thus providing maximum definition. The entire session was recorded for each subject and stored as a permanent record.

Because of the possibility that subjects might gain cues to distance by means of the auditory system, this source of information, as in other experiments, was controlled. This was achieved by means of the white noise apparatus which has already been described in Experiment 1, and which was effective in eliminating almost all auditory information.

Two conditions of testing were employed. In Condition 1, all visual information was excluded at the point at which each trial was initiated. As in Experiments 1 and 2, no attempt was made to control the amount of visual information in any other way. Condition 2 was exactly the same as Condition 1, except that vision was not excluded during the course of the trials. This condition was thus meant to represent a case of simple visual guidance, and performance under these "normal" conditions was used as a control performance against which to evaluate orientations executed "blind".

Procedure

As in previous experiments, S was given a short instruction period before the experiment proper began followed by a short practice on a layout of objects set aside from the experimental layout. This practice was merely to make sure that S knew how he was to go about circumventing the obstacles, and to let him try the routine for himself. S performed these circumventions with eyes open, so there was in fact no true practice session in this experiment. This preliminary period took only a few minutes.

At the beginning of each experimental trial S stood lined up at the starting-point. The white noise was turned on and the filming commenced. S was allowed to survey the layout and choose for himself when to begin the trial. When the trial had been completed, S was allowed to use vision to line himself up for the next trial. This procedure continued until all trials in Condition 1 had been completed. Three trials were given on Tracks 1 and 3 and two on Tracks 2 and 4, making ten trials in all for each condition. The trials were presented on each track alternately. Condition 1 was always run first to avoid any unwanted learning effects generated by subjects seeing the results of their behaviour in Condition 2. The entire procedure took approximately 30-40 minutes.

Subjects

Eight subjects took part in Experiment 3, five male and three female. All subjects were students at Edinburgh University and were aged between 19 and 28 years. No subject understood the purpose or predicted results of the experiment.

Results

Transcription of data

The information recorded on video-tape was played on to a television monitor with a 19 inch screen. The image on the screen simply showed the outline of the grid and the obstacles, with the subject visible at the top of the track concerned. A sheet of transparent paper was fixed to the screen and the outline of the grid and obstacles traced on to it. The film was then run through in slow motion. As the subject moved through the layout of obstacles, the position and direction of each footfall was recorded by drawing onto the paper a line running along the length of the subject's foot. This method made it possible to record the position of each footfall relative to the obstacles. At the end of each trial the tape was wound back to the beginning and replayed at normal speed. This made it possible to check that the data had been properly recorded from the tape. A new sheet of paper was used for each trial and these were carefully coded. This method of transcription enabled a detailed pictorial record of subjects' behaviour to be obtained which could then be used for subsequent quantitative analysis. In addition to this record, however, the tapes were played through at normal speed and scrutinised for any information which could be obtained to supplement the transcribed data. These viewings were particularly used to check dubious effects in the pictorial records.

Analysis of Results

A very gross measure of subjects' success at overcoming the obstacles in Experiment 3 is given in Table 3.1 which shows the percentage success at circumventing each of the four obstacles. It can be seen that the success rate in the visual condition is virtually 100%, as is performance at the first two obstacles in the non-visual condition. At the third obstacle in the non-visual condition, however, performance is substantially reduced and at the fourth obstacle is very poor.

TABLE 3.1

Percentage successful circumventions at each obstacle

	Obstacle			
Condition	1	2	3	4
Visual	100	98**	100	96*
Non-Visual	100	96	64	50

** - all on Track 1
* - all on Track 4

This analysis gives only the vaguest and least satisfactory account of performance, however. In the first place, we cannot accept the fact that the subject has circumvented an obstacle as evidence of "successful" performance. To do this we would have to know in more detail the relation of the subject's path of locomotion to the obstacle. Secondly, it is obvious that a proportion of the errors at a given obstacle are affected by, and may even be due to, errors at the previous obstacle. For these reasons, the basic circumvention figures shown in Table 3.1 give only a rough indication of performance.

An essential problem in Experiment 3 is to reach some general definition of the task which faces subjects. This analysis of the results may begin by attempting to reach such a definition. One outline of the problem is shown in Figure 3.2, which defines the problem in terms of two components. Firstly, the subject has to walk through a certain set of distances defined by the separation of the obstacles and the space needed to clear them. Secondly, these distances must be linked by a series of angles through which the subject must turn in order to set himself up for the approach to the next obstacle. If the subject gets both of these components right, he will negotiate the obstacles successfully. It is argued, then, that errors can be of two sorts. Subjects can misjudge the distances between objects, or they can misjudge the angles to be turned through in order to meet them.

This outline seems to represent the most likely definition of the task facing subjects in Experiment 3. The critical problem now is to define what these distances and angles should be. An approximation to the optimal distances and angles could be reached by a process of simply trying to estimate what these should be, but in line with the methods adopted in previous experiments, these can be more objectively defined by the results of the visual condition which constitutes a control in this respect. The results of the non-visual condition can be compared to these and the types of discrepancies scrutinised.

The process by which the distances and angles were calculated was as follows: at each obstacle, subjects tend to take two, or possibly three paces to complete a circumvention. These circumventions are linked by a series of paces leading from one obstacle to the next. The best and most accurate way of assessing both angles and distances seems to be to join the most extreme foot placements at each successive obstacle. When this is done, the resultant path is found to run very close to the actual path taken by the subject, but offers a far more adequate unit than the "raw" path for quantitative analysis. The estimates form a series of simple zig-zag lines which can then be used for quantitative evaluations.

In the case of the non-visual condition, the situation is somewhat more complicated since the pathways do not always run between the obstacles as in the visual condition (because of angular errors). However, the same essential procedure was followed. The most extreme foot positions were linked through the pathways which the subjects followed. This produced the same form of results as in the visual condition, but in this case the points oriented to represent where subjects apparently thought the correct turning points to be. Examples of the process for each condition are shown in Fig. 3.2

When the procedure described above was followed, the results shown in Tables 3.2 and 3.3 were obtained. Table 3.2 shows the means and standard deviations of the lengths of the path segments in the two conditions: Table 3.3 shows the means and standard deviations of angles. No estimate has been calculated for the final distances and angles as the subject's task after reaching the final obstacle was defined as being simply to leave the grid area, and the diversity of angles and distances would therefore be high and of no real interest.

It can be seen from Table 3.2 that the differences in distance walked in the visual and non-visual conditions are very slight. Distances in the non-visual condition are generally shorter, but the effect is small. A statistical analysis on corresponding distances

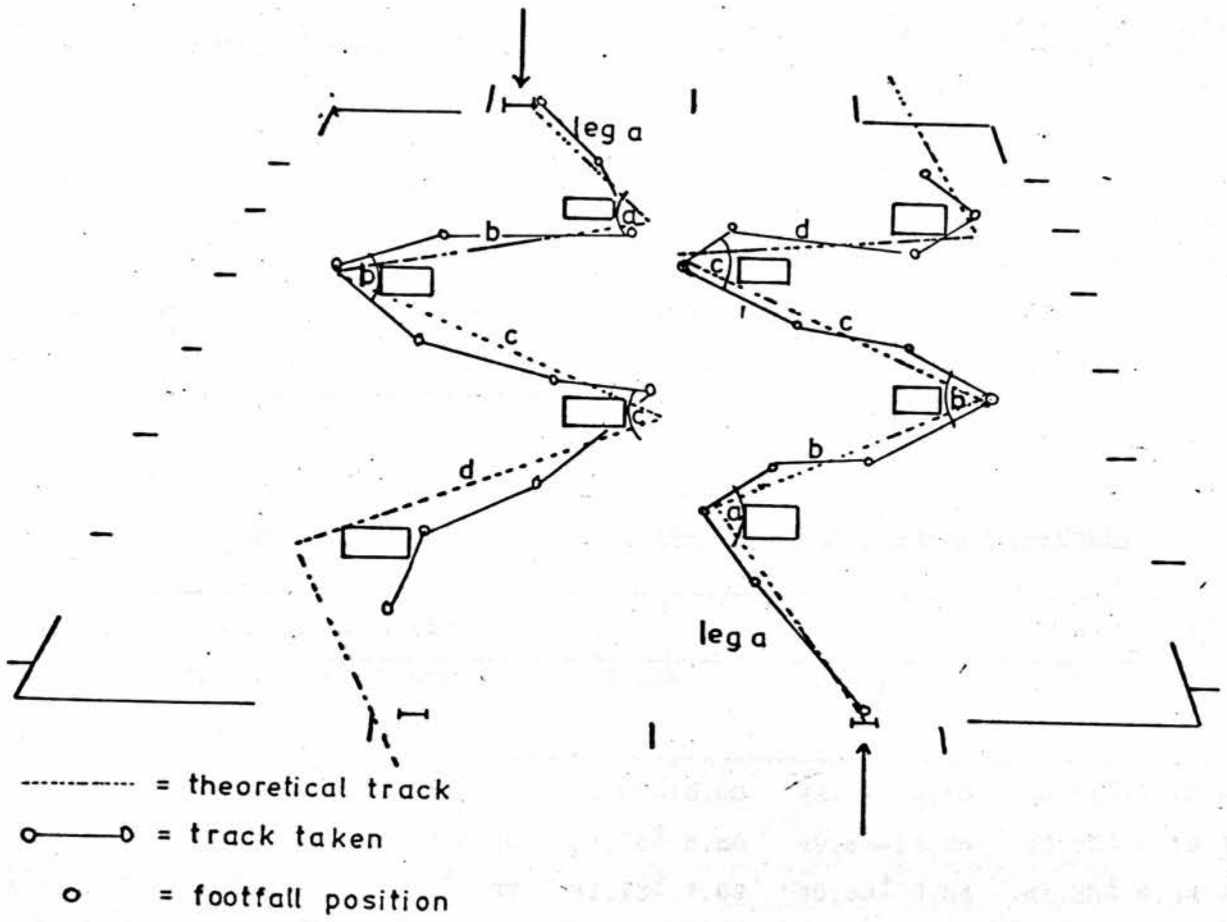


FIG. 3,2 Outline of the problem facing subjects in Experiment 3.

TABLE 3.2

Means and Standard Deviations of Distances Walked in each Leg

	Visual Condition				Non-Visual Condition			
Leg of Track	Track 1	Track 2	Track 3	Track 4	Track 1	Track 2	Track 3	Track 4
a	4.21±0.67	5.32±0.69	6.13±1.23	8.22±1.06	5.42±0.95	4.80±0.95	8.65±1.21	5.82±1.43
b	10.45±1.07	9.36±1.41	13.55±1.23	10.24±1.69	10.03±1.08	8.98±1.31	13.15±1.56	10.98±1.75
c	11.04±1.33	10.12±1.32	11.04±1.52	9.67±1.37	10.06±2.33	9.47±2.82	9.36±2.23	9.24±1.75
d	12.91±1.37	10.32±1.54	10.63±1.37	8.81±0.99	11.84±1.81	10.84±2.26	9.00±1.14	7.84±1.86

TABLE 3.3

Means and Standard Deviations of Angles Turned Through

	Visual Condition				Non-Visual Condition			
Angle	Track 1	Track 2	Track 3	Track 4	Track 1	Track 2	Track 3	Track 4
a	43 ±7.15	37.04±4.65	62.81±6.72	65.88±15.99	42.71±14.13	40.54±11.10	58.44± 5.74	64.19±10.55
b	36 ±5.27	36.61±6.92	35.63±4.30	52.08± 5.66	49.88±14.25	45.50± 9.16	45.50± 9.16	45.56± 7.96
c	31.65±3.63	30.65±5.33	28.50±4.37	31.13± 7.07	40.83± 6.54	41.38± 8.54	41.63±12.66	46 ± 9.21

in the two conditions showed all differences to be insignificant (see Table 3.4). The distances walked do not seem to differ in the two conditions.

By comparison, it can be seen from Table 3.3 that the angles through which subjects turned to approach the next obstacle in the series varied greatly between conditions. On all four tracks, the second and third angles turned through are much larger than in the visual condition, though this effect was noticeably absent at the first angle. The statistical analysis shown in Table 3.5 confirms this: subjects clearly tend to stretch the length of the path out like a concertina. The general effect is shown in Fig. 3.3 which shows the mean paths followed by subjects relative to the obstacles in each condition. The influence of the angular errors is clearly seen in the stretching of the pathways in the non-visual condition. It is clear, however, that the distances have remained remarkably constant in the two conditions.

The most interesting finding to emerge from Experiment 3, then, is that error seems to accrue principally to the angles and not to the distances. This result would suggest that subjects are able to assess a group of distances even when these are laid out in a rather complex way as in Experiment 3. However, it would seem that subjects have some difficulty in re-orienting the body axis as they pass one obstacle in order to get lined up for the next.

The general result of this analysis, namely that errors are due mainly to angular and not distance misjudgments, can also be seen from a careful analysis of the individual response records.

Each response was examined individually and those in which errors were made were selected out and examined closely. It was possible to

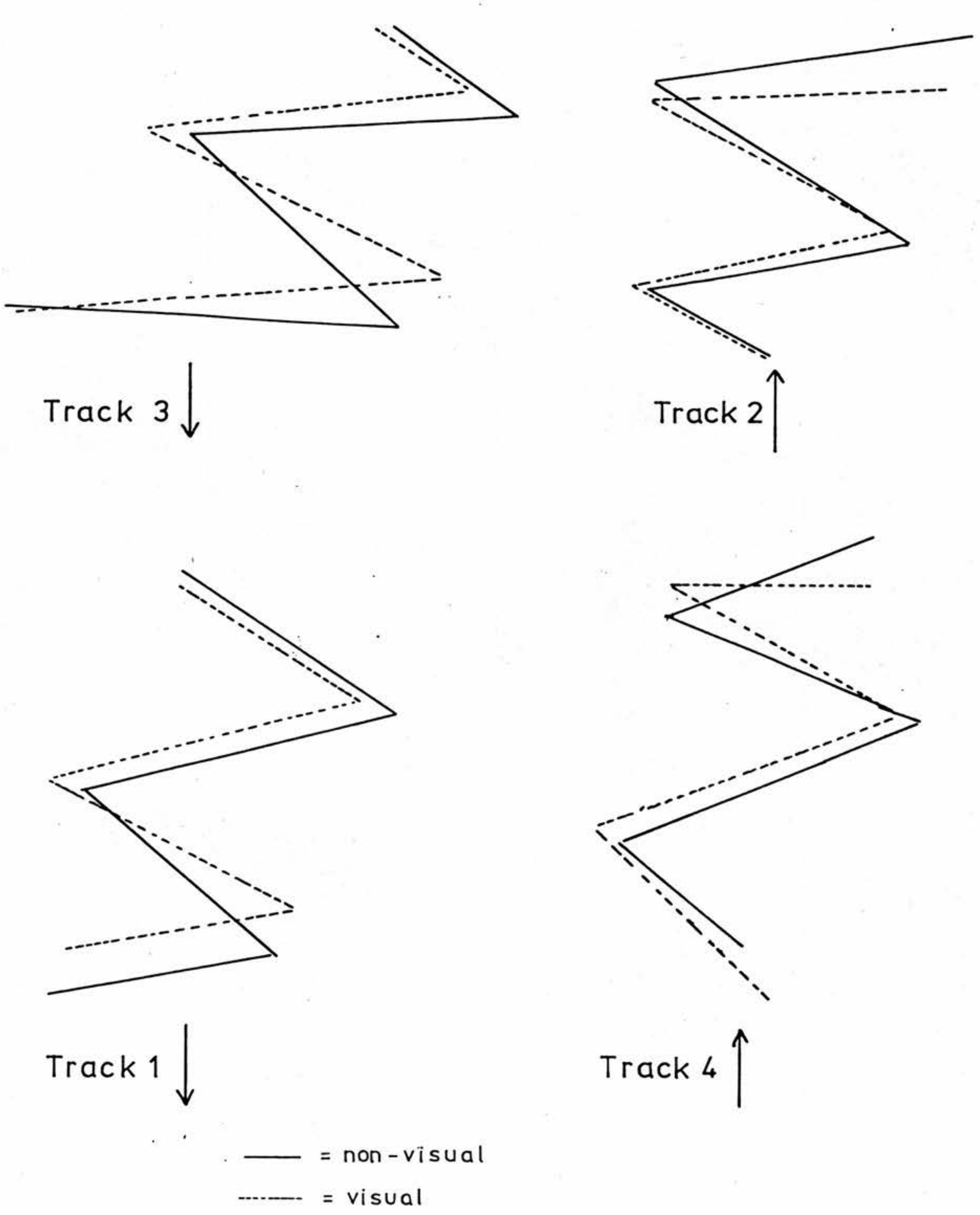


FIG 3,3 Mean paths followed by subjects in each condition

TABLE 3.4

t and F Values from Comparisons of Distances Walked in Each Leg in the Two Conditions

	Track 1		Track 2		Track 3		Track 4	
	t	F	t	F	t	F	t	F
Leg a	.93	2.00	2.60	1.88	1.44	1.03	1.64	1.82
b	1.70	1.03	1.09	1.16	.71	1.61	1.47	1.07
c	2.51	3.07*	2.32	4.57*	2.32	2.15	1.59	1.63
d	2.61	1.74	1.18	2.16	2.58	1.45	2.62	3.53*

TABLE 3.5

t and F Values from Comparisons of Angles Turned Through at Each Obstacle in the Two Conditions

	Track 1		Track 2		Track 3		Track 4	
Angle	t	F	t	F	t	F	t	F
a	0.09	3.91*	1.62	5.70**	2.09	1.37	0.89	2.30
b	14.75**	1.18	4.31*	4.24*	6.67*	4.54*	1.69	2.39*
c	8.42**	3.25*	5.93**	2.57	6.73**	8.39**	7.11**	1.70

* $p < .01$

** $p < .001$

all other cells insignificant

classify these errors into four basic categories:

(1) angular error

(2) distance error (over or under-estimation)

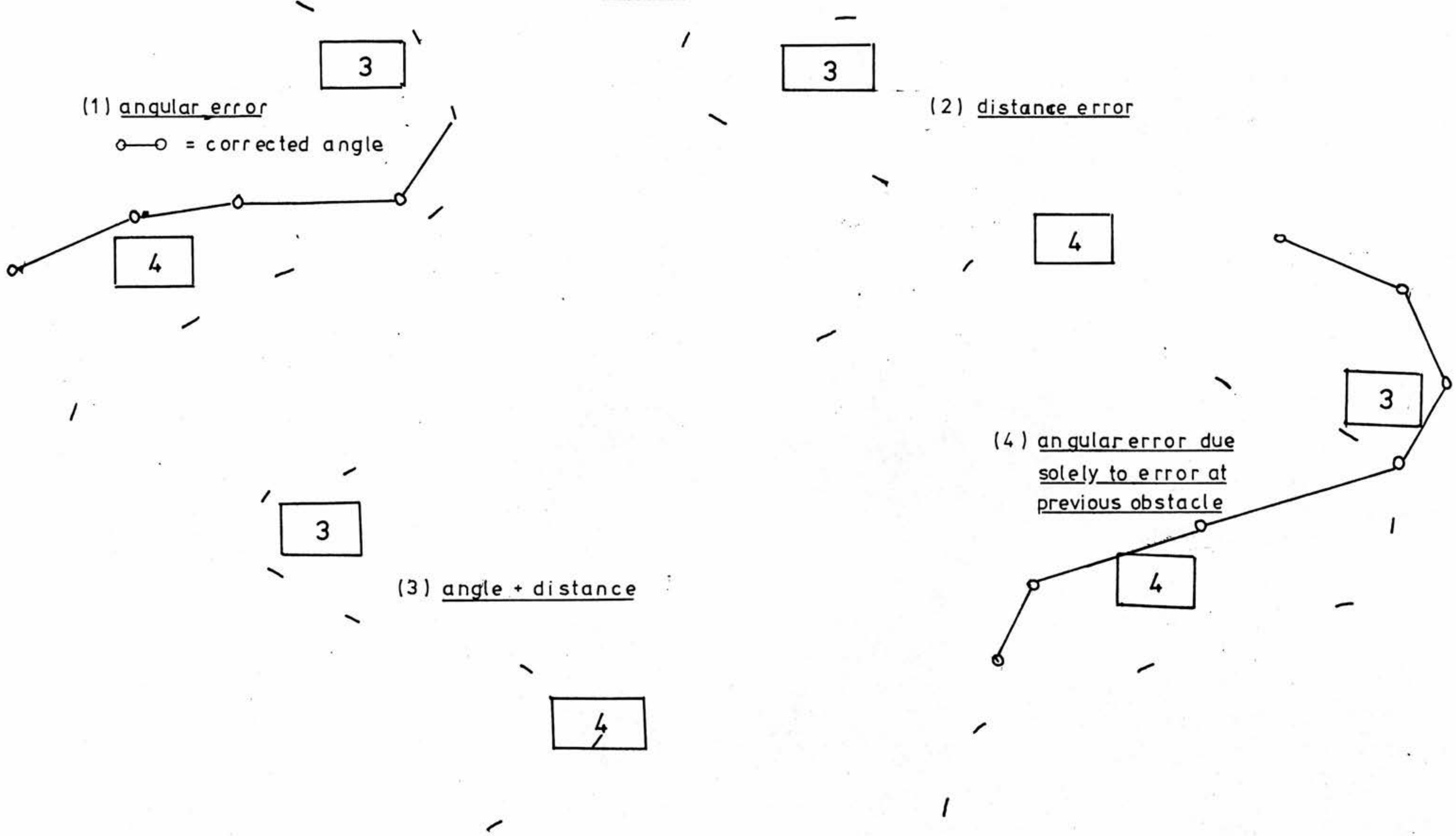
(3) angular and distance error

(4) errors (distance or angular) due solely to error at the preceding distance.

Examples of each of these errors are shown in Fig. 3.4. The method of determining which of these categories a particular error fitted was fairly simple. In each case, the angle turned through and the subsequent distance walked were measured. The angle was then adjusted to bring the subject into the correct relationship to the obstacle. If, after this angular adjustment, the path now led the subject round the obstacle, and if the distance walked was in reasonable correspondence with the mean distance in the visual condition, this was taken as a case of angular error.

Sometimes the errors were due, wholly or in part, to distance misjudgments. Detecting distance errors involves a problem: an apparently underestimated distance (evidenced by the fact that the subject stops short of the target) may in fact be a "correct" judgment executed after an overestimated preceding distance. The problem also works in reverse. It is not always clear, therefore, which type of distance error is operating. To control for this ambiguity, whenever a distance was apparently over or underestimated, that distance and also the preceding one was measured and compared to the mean result of the visual control. The extent to which the distances obtained corresponded to the control mean, dictated the class of error invoked. In fact, the type of distance error made

FIG. 3.4 Examples of types of error made by subjects.



was always very clear.

It is obvious that if errors are made at a particular obstacle, then that error may well carry forward to the next obstacle in the series. In order to obtain evidence on "genuine" errors made at that distance, it would therefore be necessary to control for these errors carried forward. For this reason, whenever an error was made at the third obstacle, an angular and/or distance correction was effected at that obstacle. This allowed determination of whether any error had actually been made at the fourth object, and if so, to determine its extent more correctly.

The method for determining and correcting distance errors has already been explained. The method of adjusting the angles was to transcribe that path taken on to a piece of tracing paper, and then, keeping the axis of rotation the same in both cases, to rotate the path until the best fit to the obstacles was obtained. The original path, together with the adjusted path could then be traced onto a third piece of paper. It is the results of this process which are shown in Fig. 3.4.

Once the errors made in Experiment 3 have been examined in this way it is found that the four categories suggested above account for all the errors made. The result of the analysis is shown in Table 3.6.

The first result in this Table to be noted is the decrease in the number of "real" errors at obstacle 4 after correction. In Table 3.1 we show that only in 50% of cases did subjects succeed in circumventing the obstacle. After the correction procedures discussed above have been applied, the success ratio rises to 70%.

TABLE 3.6

Percentage of Errors Falling into Each Error-category

	Obstacle	
	3	4
Error due solely to error at previous obstacle	0	20
Angle error	17	24
Angle and distance error	14	2
Distance error	5	4
Total error	36	50

It can be seen from Table 3.6 that the vast majority of errors are angular or have an angular component. The results of this individual-response analysis therefore confirm and amplify the results of the general analysis shown in Tables 3.2 and 3.3. It would appear that subjects are highly accurate at judging the distances involved in Experiment 3. Most of the errors which were obtained seem to have been the result of misjudgments of the angle to be turned through in order to be adjusted for the approach to the next obstacle.

Discussion

Experiment 3 began by asking if the accuracy attained in earlier experiments, where subjects were told to locate a single target with vision excluded, could be matched when he is forced to locate a number of targets. From the results of Experiment 3 it seems possible to say that subjects can indeed respond to a group of obstacles or targets with a very substantial degree of accuracy. After corrections are made for errors due entirely to errors made at earlier obstacles, the total success at each obstacle is as follows: obstacle 1, 100%; obstacle 2, 98%; obstacle 3, 67%; obstacle 4, 70%. This result indicates quite a degree of accuracy in the task.

The hypotheses in Experiments 1 and 2 were formulated with respect to distance only, whereas in Experiment 3, the hypotheses considered both distance and a series of angular re-orientations of the body. If we begin by considering only the distance responses shown in Fig. 3.3 it can be seen that it is equally possible for subjects to respond to four targets as it is to one. The statistical analyses shown in Table 3.4 confirmed this: in no cases were the differences between the two conditions statistically significant. The variances remained fairly constant between the conditions, indicating that subjects were equally consistent in the two cases, though in one or two cases the differences were significant. Similarly, the means did not differ. This result is supported by the findings of the individual response analysis shown in Table 3.6, which shows that only a small proportion of all errors made involved distance misjudgments. These findings suggest a considerable degree of accuracy in identifying the distances which have to be covered to locate the targets.

As we noted above, there are two components of performance in Experiment 3, one concerning distance and the other angles. The most interesting finding of this experiment, shown in Table 3.3, is that most of the error obtained is due to angular errors and not distance ones. It can be seen very clearly from Table 3.3 that subjects tend to strongly over-estimate the angles in the non-visual condition, a finding confirmed by the statistical analysis shown in Table 3.5. The mean angles turned through are significantly greater in almost every case. It can also be seen that the variance of the angles tends to be greater in the non-visual than the visual case, showing that subjects are less consistent in their responding in the non-visual condition. These findings, too, are supported by the results of the individual response analysis, which shows that the greater part of the errors made involve angular misjudgments. The influence of angular errors on performance is best seen in Fig. 3.3 which shows the mean paths followed in the two conditions. It is apparent that angular deviation is responsible for the greatest portion of the error. The basic result of Experiment 3 therefore seems to be that subjects are able to identify the set of distances involved very well but have considerable difficulty in negotiating the angles. The question then arises as to why this should be.

There are two possible general causes of the differences in angle between the two conditions which are immediately evident. The first is that some perceptual information necessary for correct determination of the angle is missing which, if available, would have enabled the subjects to circumvent the obstacles more accurately. The second possibility is that subjects know what angle to turn through, but for some reason are unable to execute the turn as intended. This then would not be a perceptual error, but an error in translating information into a plan of action.

The latter interpretation of the results has relatively little evidence to support it. It is true that the variance among angles in the non-visual condition is higher than in the visual, suggesting an inconsistency in executing whatever plan is guiding the behaviour, and this would support the notion that the error is partly due to some form of execution problem. However, the fact that the mean angular turn at the second and third obstacles deviates so much from the angles found in the visual condition argues against this sort of interpretation. Although it is possible that subjects might make a constant execution error producing the larger angles found, the fact that these are found only at the latter obstacles militates against such an interpretation, for as we saw in Table 3.3, no differences in angle were found at the first obstacle. By contrast, this finding strongly supports the hypothesis of perceptual error. The hypothesis of perceptual error would predict that when the obstacle is located close to the subject (with the possibilities of perceptual misjudgments thereby minimised) the performance should be relatively good, whereas when the obstacles are at some distance, performance should be poor. This is in fact just what was found. At the first obstacle, which lay only a short distance from the subject, it appears that the angle can be judged rather well. At the subsequent distances, however, the angular error is very large and this would support the argument that the effect is largely perceptual. Just why the effect takes the form of an overestimation is more difficult to answer, and this question will require investigation at a later date. But it seems a not unreasonable hypothesis on the basis of the results of Experiment 3 that the errors in Condition 1 were due to perceptual error of some sort to a considerable degree.

Conclusions

The results of Experiment 3, then, seem to fit rather well into the theoretical position advocated in the present thesis. It seems that subjects are capable of apprehending a group of distances and not just a single one. It also appears that this information can then be used to guide behaviour with considerable accuracy as compared with the corresponding accuracy obtained in the visual condition.

It appears, however, that this ability to apprehend distance does not generalise to the ability to re-orient the body directionally. When subjects are asked to do this, the performance after the first turn is very low. It appears that these errors may have a perceptual component responsible for them, though the precise nature of the perceptual error is unclear. Novel experimentation would be required to answer this problem satisfactorily.

EXPERIMENT 4

CONTROL OF LOCOMOTION IN A CLUTTERED ENVIRONMENT II

Introduction

The results of Experiment 3 seemed to suggest that subjects have the ability to take at least four obstacles into account when formulating a program for action. This result was somewhat confused, however, owing to the fact that subjects were asked to walk through a layout of obstacles demanding major re-orientations of the body at each one. This re-orienting proved difficult and the source of the error in the resulting performance was somewhat unclear. For this reason, a further experiment was conducted which bore a close resemblance to Experiment 3 but where distance and angles as sources of error were separated as far as possible. This was done simply by eliminating the major directional re-orientations made in Experiment 3 so that the task involved mainly distance judgments. Of course, the circumvention of obstacles always entails some form of angular adjustment, but in the present experiment these adjustments were minimised. The hypothesis which Experiment 4 was designed to test may therefore be stated as follows: when a subject is asked to circumvent a group of obstacles in the path of locomotion, so long as no major directional re-orientations of the body are necessary at each obstacle, the subjects' performance when vision is excluded will closely mirror that obtained when vision is continuously and freely available. Experiment 4 was designed to test this hypothesis.

Method

Design

The design of Experiment 4 followed rather closely the design of

Experiment 3. The experiment was conducted in the same large lecture-theatre in a free space measuring approximately 14 x 9 metres. A partial grid was laid out on the floor and two layouts of obstacles were placed within it. The distances between the obstacles were exactly the same as those the subjects had to walk in the different legs of Experiment 3 so that, in terms of distance, the two experiments were equivalent. However, in Experiment 4 the obstacles were not laid out so that the subjects would have to re-orient the body axis in order to reach the next obstacle. Instead, the obstacles were laid out in a straight line. In this way, the angular re-orientations necessary at each obstacle in Experiment 3 were eliminated. Of course, subjects still have to turn through an angle at each obstacle, but perceptually these lie along a straight line and there are therefore no angles to be discerned for performance to be successful. It is also unnecessary for subjects to alter the general orientation of the body axis throughout the present trials. In this sense, angular deviations are eliminated in the present study. The general layout of the experiment is shown in Figure 4.1

In all other respects, the design of Experiment 4 was the same as in Experiment 3.

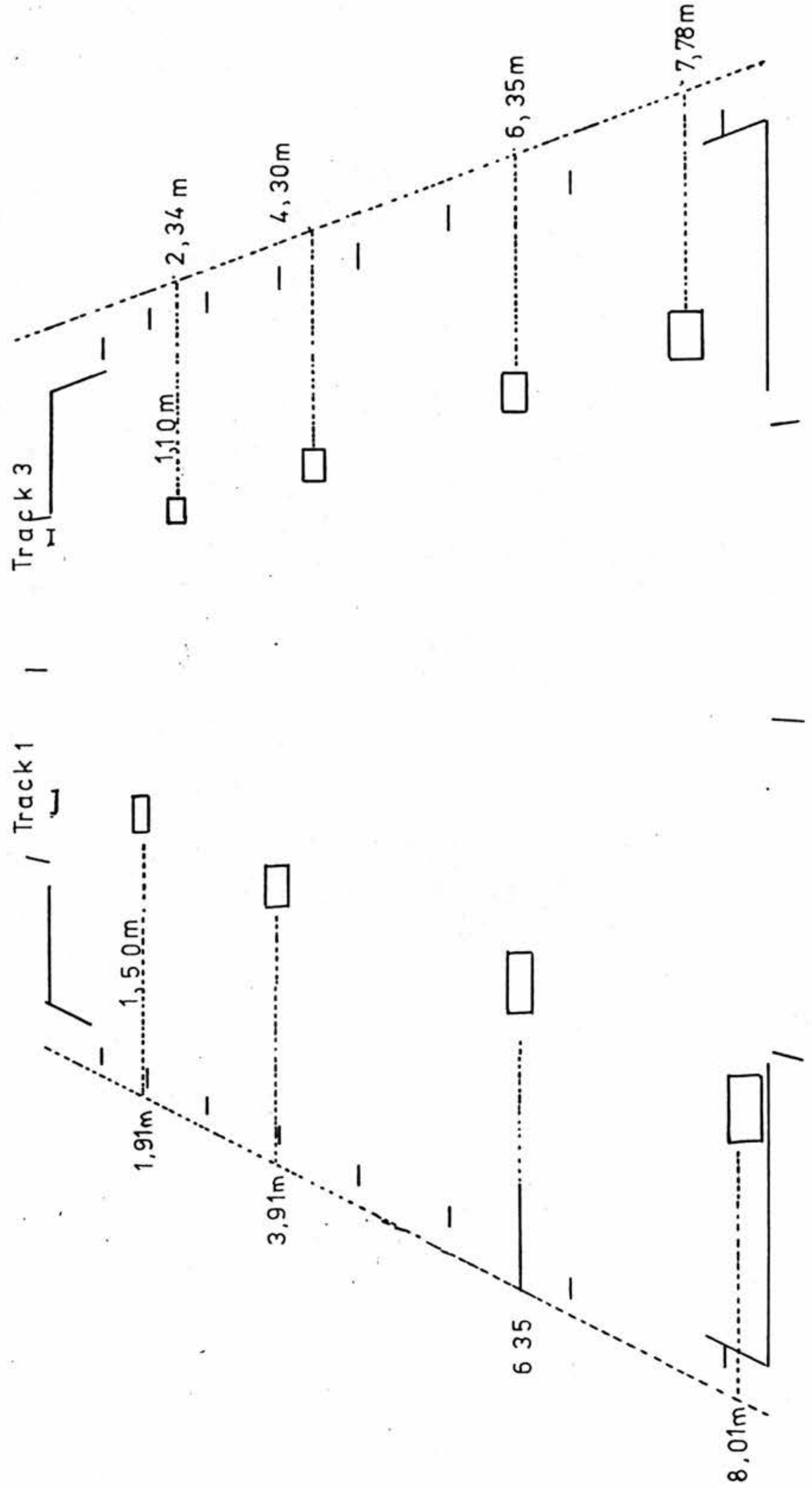
Procedure

The Procedure in Experiment 4 was exactly as in Experiment 3.

Subjects

Nine subjects took part in Experiment 4, 5 male and 4 female. Eight of the subjects were students at Edinburgh University, the ninth was a medical technician. The subjects were aged between 18 and 25 and were all entirely unaware of the purpose or predicted results of the experiment.

FIG.4.1 General layout of Experiment 4.



Results

Transcription of Data

The method of transcribing data was exactly as employed in Experiment 3. For a description, see the results section of that Experiment.

Analysis of Results

As in Experiment 3, we can obtain a rough indication of subjects' success in each condition simply by calculating the percentage of circumventions at each obstacle. The results of such an analysis are shown in Table 4.1.

TABLE 4.1

Percentage Circumventions at Each Obstacle

	Obstacle			
Condition	1	2	3	4
Visual	100	100	100	100
Non-Visual	100	99	92	93

It can immediately be seen that the success ratio in Experiment 4 is markedly higher than in Experiment 3. As in Experiment 3, however, this analysis offers only a rough account of performance. It is obvious that errors made at a given obstacle may well lead to errors at subsequent obstacles, thereby over-estimating the "real" error; though in this case we could claim that a "true" estimate of performance would only be higher than that which has already been seen in Table 4.1. However, circumvention of an obstacle does not in itself imply adequate or good performance. Adequacy must be more closely related to performance under the control condition of normal visual guidance.

A more detailed analysis of the results is possible if the methodology employed in Experiment 3 is followed. It will be remembered that in that experiment, the subject's essential task was to walk through a certain set of distances linked by a certain set of angles. It seems that a similar definition of the task can be employed here.also. The only difference concerns the angles to be turned through. In the earlier experiment, these forced subjects to make major re-orientations of the body axis after each obstacle. In the present case, the angles do not involve such major re-orientations. Nevertheless, some form of angular deviation is necessary. The task can therefore be described as essentially the same in both cases.

The best way of deciding whether or not performance in the non-visual condition is adequate is to adopt the procedure followed in Experiment 3 and compare the distances and angles produced in the two conditions. The method by which this was done has already been described and need not be reiterated here. Table 4.2 shows the mean distances walked by subjects in each leg in each condition, and Table 4.3 shows the mean angles turned through at each obstacle. It can immediately be seen that the differences between the distances in the two conditions are small, though there is a tendency for these to be somewhat larger in the non-visual condition. Table 4.3 shows a similar result for the angles. A statistical analysis was conducted and confirms that the differences between both distances and angles , excepting three cases, are insignificant. Performance in the two conditions seems to be roughly equal. The results of the statistical analyses are shown in Tables 4.4 and 4.5. The mean pathways followed in the two conditions are shown in Fig. 4.2.

TABLE 4.2

Means and Standard Deviations of Distances Walked in Each Leg (both Conditions)

	Condition 1				Condition 2			
	Track 1	Track 2	Track 3	Track 4	Track 1	Track 2	Track 3	Track 4
Leg a	2.83± .50	3.23± .16	4.10± .46	4.80± .91	2.63± .39	3.27± .35	3.85± .57	4.94± .74
Leg b	5.67± .73	5.27± .98	8.18± 1.64	6.53± 1.07	5.30± .72	4.80± .70	7.74± 1.39	5.87± 1.14
Leg c	6.92± .79	6.55± 1.00	6.38± .84	6.70± 1.15	5.60± .53	6.17± .79	6.01± .80	5.88± .64
Leg d	8.01± 1.12	6.70± 1.15	5.64± .93	4.42± 1.18	7.74± .95	6.08± 1.03	4.49± 1.18	4.19± .81

TABLE 4.3

Means and Standard Deviations of Angles Turned Through at the First Three Objects (both Conditions)

	Condition 1				Condition 2			
	Track 1	Track 2	Track 3	Track 4	Track 1	Track 2	Track 3	Track 4
Obstacle 1	75.66±12.38	68.63±10.74	71.55±15.24	85.05± 9.57	82.59±14.50	75.44±11.86	78.83±14.26	94.11±16.66
Obstacle 2	68.59± 8.13	56.59±10.23	69.27± 9.35	69.55±12.68	72.48± 8.76	62.19± 8.30	73.33± 8.89	76.17±10.17
Obstacle 3	72.44± 8.93	67.88± 9.36	65.92±11.98	61.27±20.13	75.70± 8.12	73.04±11.34	71.36± 8.23	62.22± 8.24

TABLE 4.4

t and F Values from Comparisons of Distances Walked in Each Leg in the Two Conditions

	Track 1		Track 2		Track 3		Track 4	
	t	F	t	F	t	F	t	F
Leg a	2.00	1.67	0.40	4.00	2.50	1.52	0.70	1.51
b	2.64	1.02	2.14	2.80	1.23	1.39	2.44	1.87
c	2.29	2.21	1.73	1.61	2.18	1.11	0.92	3.22*
d	1.35	1.39	2.48	1.25	5.75*	1.62	0.85	2.11

TABLE 4.5

t and F Values from Comparisons of Angles Turned Through at Each Obstacle in the Two Conditions

	Track 1		Track 2		Track 3		Track 4	
Angle	t	F	t	F	t	F	t	F
a	2.65	1.37	2.37	1.22	2.54	1.14	2.63	3.03
b	2.32	1.16	2.36	1.52	2.29	1.11	2.27	1.55
c	1.99	1.21	1.95	1.47	2.67	2.12	0.24	5.97*

* $p < .001$

all other cells insignificant

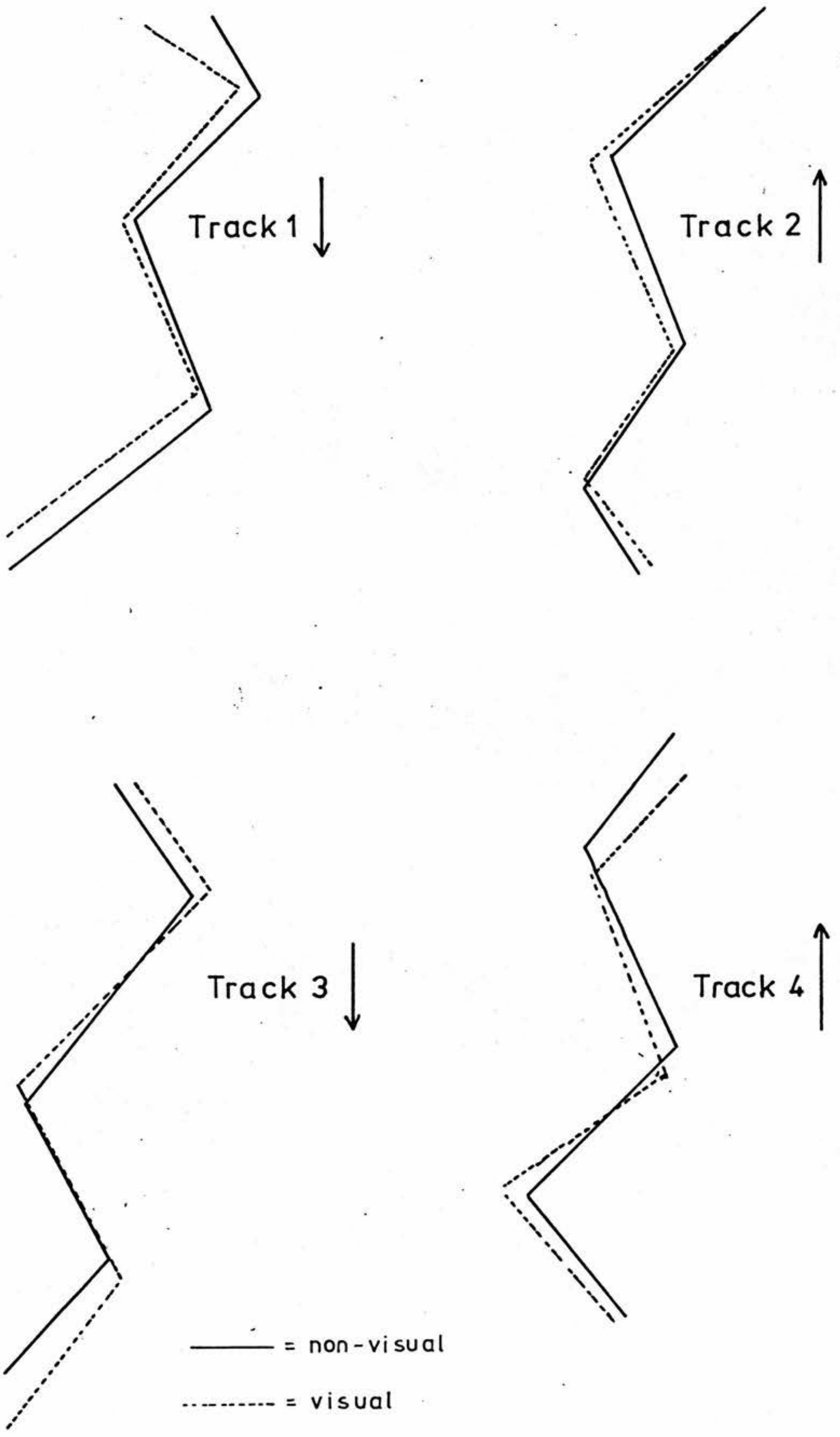
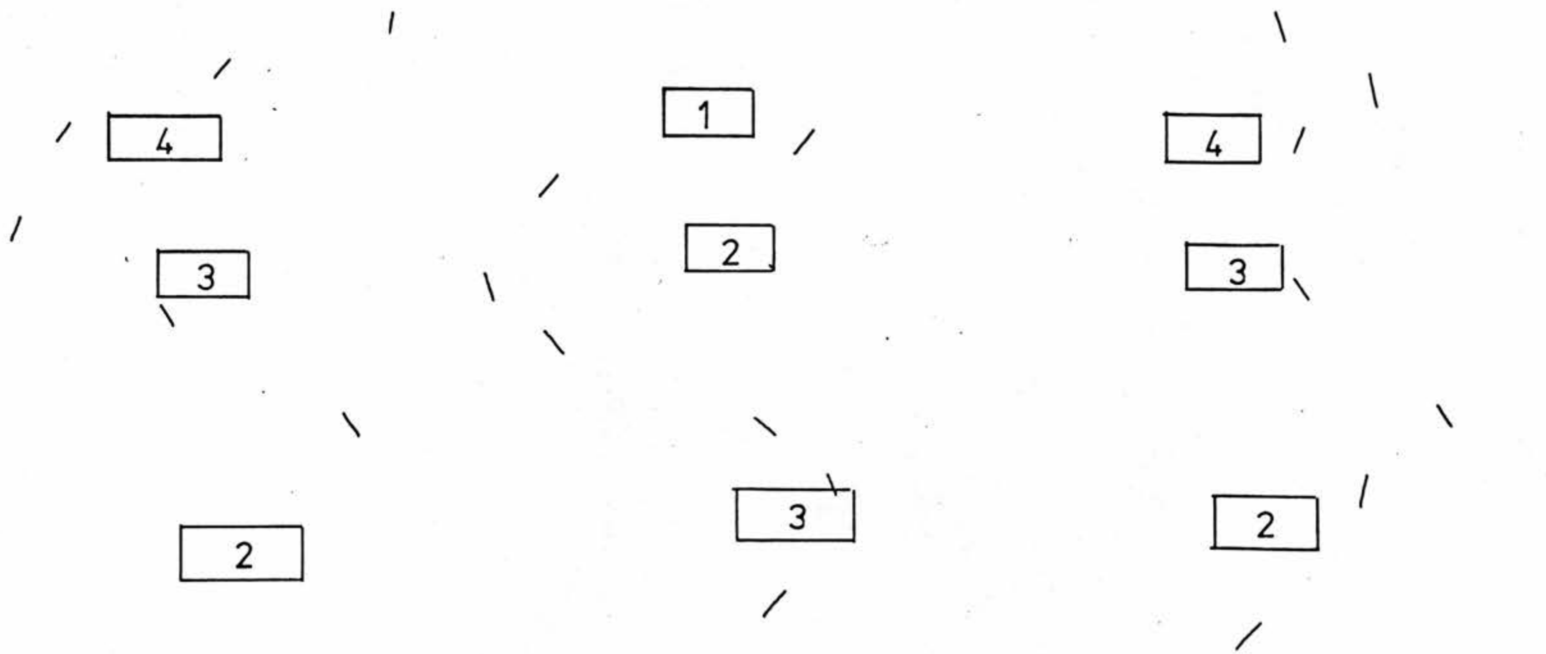


FIG. 4.2 Mean paths followed in each condition.

In Table 4.1 we saw that in only a very few cases did subjects fail to circumvent an obstacle, a finding in agreement with the results of the main analysis shown on Fig. 4.2 When the response profiles are examined, individually, it is found that the errors obtained fall into the same kind of categories as in Experiment 3. The total number of errors made was 14. Six of these were due to angular errors, 4 to distance errors, 3 to a combination of distance and angle errors and 1 was due solely to an error at the previous obstacle. Angular errors were therefore involved in nine cases and distance errors in seven cases. Examples of the different types of errors are shown in Fig. 4.3. The analysis of the individual errors was accomplished by means of the same method as was employed in Experiment 3.

Discussion

The purpose of Experiment 4 was principally to back up the results of Experiment 3, which argued that subjects have the ability to find their way around a series of obstacles when vision is excluded during the course of the act. In Experiment 3, it appeared that subjects could estimate the distances rather well, but their overall performance did not reflect this completely clearly because large errors accrued to the angular re-orientations of the body which were demanded in that experiment. In Experiment 4, the large-scale re-orientations were eliminated by placing all the obstacles to be overcome in a straight line. This also eliminated the need for a capacity to discriminate the angles to be turned through, which was suggested might be the fundamental cause of the angular errors obtained in Experiment 3. In this way, the dominant problem in Experiment 4 was to judge distance correctly.



(1) angular error

(2) distance error

(3) angle + distance error

FIG. 4,3 Examples of types of error made by subjects.

The results of Table 4.1 suggest that subjects can indeed judge the distances involved to a high degree of accuracy. In no case was an obstacle circumvented less than 92% of the time. Furthermore, when a more detailed analysis is made of the distances and angular turns taken by subjects, it is clear that performance in the two conditions is very similar. These findings strongly suggest that subjects are indeed as capable of apprehending the distances of four obstacles as they are of apprehending one, and that on the basis of this a performance can be achieved which is as good as would be achieved when vision is continuously available. The results of Experiment 4 therefore strongly confirm the predictions.

One possibility which must be taken into account is that subjects might be setting up a program to take them round the first obstacle only, and then simply repeating this program at each subsequent obstacle. This argument would claim that the distance of only one obstacle (the first) is apprehended, and that success at the subsequent obstacles is an artefact. In fact, such a possibility was considered while both Experiments 3 and 4 were being designed, and the distances separating the obstacles were chosen specifically to exclude spurious "abilities" of this sort. This is particularly noticeable on tracks 2 and 4, where two of the obstacles are much closer together than the other two. However, it might be argued that an artificial strategy of the kind described above might produce successful circumventions at some obstacles. That subjects are not operating by means of such strategies can be seen quite readily, however, from Tables 4.2 and 4.3. Both the mean distances and the mean angles differ substantially at the different obstacles, yet show consistency with other trials at the same distance even when these are made by other subjects. The fact that these vary consistently according to the obstacle in question suggests that subjects are not repeating a single set program at each of the obstacles in the series. It appears that subjects' responses are fitted to the series of obstacles as a whole.

An interesting finding which should be considered is the percentage of errors which are attributable to distance and angular misjudgements in the two experiments. In Experiment 3 only 20% of the errors made involved distance misjudgments. In contrast, 54% of the errors made in Experiment 4 involved distance errors. Again, this fits well with the hypothesis that the main source of error in Experiment 3 was the angular re-orientations which subjects had to make. In Experiment 4 where such re-orientations are less complex it would be expected that errors, where they occur, would be more likely to be caused by distance misjudgments. The fact that this is what was found adds further weight to the claim that it was indeed the angles that caused the errors in Experiment 3. It should also be remembered that a small number of angular errors occurred in the visual condition of Experiment 3. This again supports the notion that angular re-orientations are difficult and constitute a strong source of error.

One final point may be made. In Experiment 3, we said that performance was good except for the angular errors. However, this may be, the results of that experiment indicated that it would be an unwise strategy to attempt to circumvent such a layout of obstacles in the real world in the absence of vision during execution of the act. Under the conditions of Experiment 4, however, where the task is less complex, such a strategy becomes markedly more feasible. On only a small number of occasions is collision likely to ensue. Of course, this does not mean that vision can be completely excluded on such occasions; but it does allow the possibilities of diverting vision to other tasks, with the role of vision in control being temporarily minimised. It appears that under the conditions of Experiment 3 this cannot be done with the same degree of surety. When major re-orientations of the direction of locomotion are necessary, it appears that visual information must be obtained and used.

Conclusions

The results of Experiment 4, then, do seem to confirm the experimental predictions. It seems that subjects do indeed have the ability to program a group of four distances with as much accuracy as they can program a single distance, and that such a program can be executed as well as when vision is available. The limitations of such an ability are as yet unknown. We cannot place a limit on the number of obstacles which can be taken into account in the formulation of the program, nor can we be sure of the range of distances over which they can be executed, though obviously the result of Experiment 2 has an over-riding bearing on this last question. These are problems which must be faced in future experiments. But that subjects do have the ability to circumvent a group of obstacles placed in the path of locomotion when vision is excluded during the period when the obstacles are being circumvented, now seems clear.

EXPERIMENT 5

PROGRAMMING AND VISUAL CONTROL IN NATURAL BEHAVIOUR: AN OBSERVATIONAL STUDY

Introduction

Up until this point the experiments which have been conducted have involved a degree of artificial manipulation of normal conditions to produce the effects observed: though a primary consideration throughout has been to keep the conditions as natural as possible and to avoid any form of manipulation which was not essential. A great advance, however, would be to demonstrate that the effects obtained under experimental conditions can also be obtained under natural conditions in the "real world". This would be doubly desirable in the present case, as it has been explicitly hypothesised that the abilities and strategies observed in Experiments 1-4 are actually used in the real world, even when visual information is continuously available and could be consulted at any time if desired. An important problem would therefore be to demonstrate, not only that such programming is possible as we have shown in the preceding experiments, but also that it actually operates under normal circumstances. Experiment 5 represents such an attempt to demonstrate programming under normal conditions.

The ideal demonstration that programming operates in natural behaviour would be to observe subjects performing some everyday task and then to analyse this performance with a view to showing the hypothesised mode of operation. Unfortunately, it is extremely difficult to find totally natural behaviours which can be examined in this way. There is, however, one large class of behaviours which can be described as at least semi-natural which can be studied. These behaviours are to be found in *sports*. These activities are quite natural in the sense that no manipulation is exerted on sensory input, or in the athlete's ability to pick up such input. Nor are any constraints put on the athlete's use of their motor system, though normally they are trained to maximise its efficiency. Sporting activities can sometimes be said to be artificial, however, in the sense that the task does not always correspond to tasks which subjects are normally faced with in their daily lives. However, allowing for this degree of artificiality, it is clear that sports offer the possibilities of investigating perceptuo-motor behaviour in a more natural form than is otherwise possible. The study of sports also offers certain advantages to studying other forms of behaviour, since sportsmen are normally trained to use their bodies in the most effective manner. It would be expected from this that the characteristic mode of operation of the perceptuo-motor system would be more clearly seen in such subjects than in others, because the athletes are trained to eliminate peripheral, random or unnecessary aspects of their behaviour and in this way "purify" the act. Consequently, whatever effects are observed in such subjects are more likely to reflect basic features of the underlying system than would be the case with untrained subjects. For these reasons, the study of sporting performance seems likely to be valuable.

There is a number of sporting, and particularly athletic, activities which could be studied in an effort to demonstrate the hypothesised nature of control. A number of these will be considered below, but the specific event selected for detailed study was the long-jump. This event was considered especially suitable for study for a number of reasons. Firstly, it proved much easier to obtain data from the long jump which could be subjected to detailed quantitative analysis. Other events which might have proved to be reasonable alternatives were less suitable from this point of view. The second reason was that the long jump seemed, on grounds which we will outline below, to be an event which was more likely than most to demand considerable motor programming for performance to be successful on a consistent basis. For these reasons, the long jump seemed the most reasonable event in which to try to find evidence of the programming strategies seen in earlier experiments.

The Long Jump

Obviously, the primary task of the long jumper is to obtain as long a jump as possible, while at the same time making no faults. However, we are not concerned here with the jump itself. Our concern is with the considerable accuracy with which a skilled long-jumper can reach the launching board. The athlete's task is to get as close as possible to the front of the board while, at the same time, never going beyond it. This must furthermore be accomplished whilst maintaining maximum speed from the run-up. For example, an athlete who, after a 40 metre run, can get to within 10cm. of the front edge of the board two-thirds of the time has an accuracy of 0.25%. The question is how such accuracy is achieved.

Most long jump coaches stress the importance of developing a stereotyped run-up. This run-up starts with an accelerative phase, sometimes followed by a coasting phase, and ends with a few strides, often referred to as the "gather", the purpose of which is to get the athlete into a good posture for the jump while, at the same time, maintaining speed. Coaches usually regard the run-up as a completely pre-determined act which is executed independently of visual information during the course of the act, and further argue that this is a desirable situation on the grounds that the process of picking up visual information and initiating adjustments to the stride pattern on the basis of it could only reduce fluency and hence the effectiveness of the run-up. The run-up in their view then, consists of an entirely pre-determined series of motor actions, run off open-loop with no attention paid to visual information during the course of the act.

That the run-up to the long jump is executed in precisely this way seems unlikely, however. It seems indisputable that error is bound to creep in to the program is executed because of varying internal and external conditions. Considering the accuracy which the athletes are required to achieve, it seems unlikely that very much variation could be tolerated before performance would deteriorate below the level of acceptability. For this reason, it seems certain that the athletes do use visual information to control performance. If this is so, there are three fundamental questions we can ask:

(1) What is the form of an athlete's pre-determined run up for the long jump?

(2) When, if at all, during the run-up does an athlete use visual information about the distance from the board to make adjustments to the remaining studies?

(3) What type of adjustments are made?

From the results of our earlier experiments, it is possible for us to make certain predictions about the answers which we will find to these questions. It will be remembered from Experiments 1 and 2 that subjects were able to control their behaviour over distances up to ten metres when vision was excluded during the execution of the act. This was taken to imply that the subjects were able to appreciate in motor terms their distance from the target when the distances involved were of this order but not when they were longer. It might be hypothesised, then, in the case of the long jump, that no adjustments on the basis of visualinformation could be made until the subject is within the distance range of approximately ten metres. At this point, however, we should expect considerable adjustments to be observable as the athlete identifies his relationship to the board and attempts to correct the error which has crept in. From the results of our earlier experiments, we would predict that the athlete would use the information now available to him to formulate a program to get him to the take-off board with as much accuracy as possible. Experiment 5 was designed to test these predictions.

Method

Film Recording

Three athletes were filmed during normal training sessions at Meadowbank Stadium, Edinburgh, where the Tartan long jump track runs along the foot of the stand. A 16mm movie camera was mounted at the back of the stand, about 30m from the track, and was panned to follow the athlete down the track. The films were shot through a telephoto lens of 50mm focal length at 48 frames per second, with a 1/300 sec. shutter speed.

To record the positions on the track of athlete's footfalls, hence giving information about stride length, measuring strips were placed down the two sides of the track. These marker strips were painted black, with white stripes at 10cm. intervals and larger stripes at 1.00m. intervals. The positioning of the athlete's footfalls could then be measured from single frames of the film by lining the athlete's toe with the corresponding points on the two marker strips. This method was effective in controlling the influence of linear perspective which was apparent as the camera was panned round. A simple test showed the accuracy of the method of measurement. Shoes were placed on the track at irregular intervals and their position carefully measured. Later, their positions were measured by experimenters who were unaware of the results of this measurement from the films. The results of this test showed that the measurement from the film was accurate to about one centimetre.

The duration of a stride was estimated by counting the number of frames between successive footfalls and multiplying by the mean time interval between frames, as determined by a calibration check on the camera. The accuracy of measurement of the stride duration was about 7%.

The Athletes

Three athletes took part in the study: Myra Nimmo, a 22 year old British International long jumper of Olympic standard, whose best jump was 6.54m; Valerie White, a 19 year old Scottish International long jumper, whose best jump was 6.03m; and Fiona Macaulay, an 18 year old Scottish International 100m. hurdler and good club long jumper, whose best jump was 5.78m.

Each athlete was filmed during two training sessions a week or more apart. A session consisted of either six jumps or six run-throughs. Each athlete used a standing start from a measured mark and jumped from her right foot. None used any check marks down the track. Myra started about 40.00m. from the board and used a 21-stride run, which she reported to be eight strides "drive", eight strides "coast" and five strides "gather". Valerie used an 18-stride run starting at about 32.10m. and Fiona a 19-stride run starting at about 34.40m. Myra and Val used a hitch-hang technique, Fiona a hang technique.

While each athlete had developed a consistent run-up, their coaches had not observed any sign of them making visual adjustments to their strides when approaching the board. Indeed, their coaches were somewhat sceptical about the possibility that they were making adjustments, as were the athletes themselves.

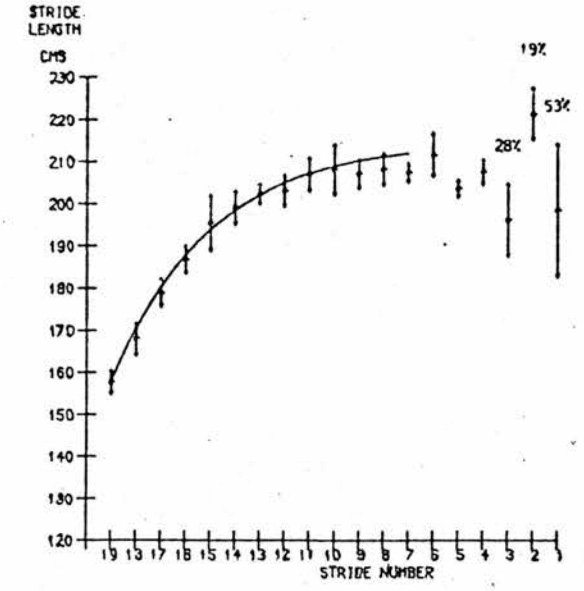
Results

The Acceleration Phase of the Run

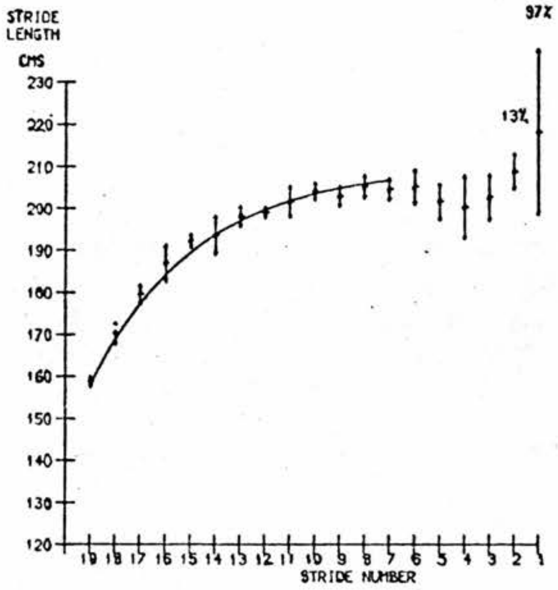
The mean stride patterns for each subject are shown in Fig. 5.1. The strides are numbered backwards from the board; for example, stride number 1 is the final stride to the board, number 2 is the penultimate stride and so on. In this system, the board is represented by 0. The points in Fig. 5.1 represent the mean stride lengths over six runs, the vertical bars the standard deviations of the stride lengths. Data was not obtained on Myra's first two strides.

It can be seen that during the accelerative phase of the run, up to about six strides from the board, the stride lengths were reasonably consistent across runs and progressively increased down the track, except for Myra who levelled off after stride 10, during her planned "coasting" phase. Furthermore, each athlete maintained a fairly constant tempo: about 4.1 strides per second for Myra and Valerie and 4.4 for Fiona.

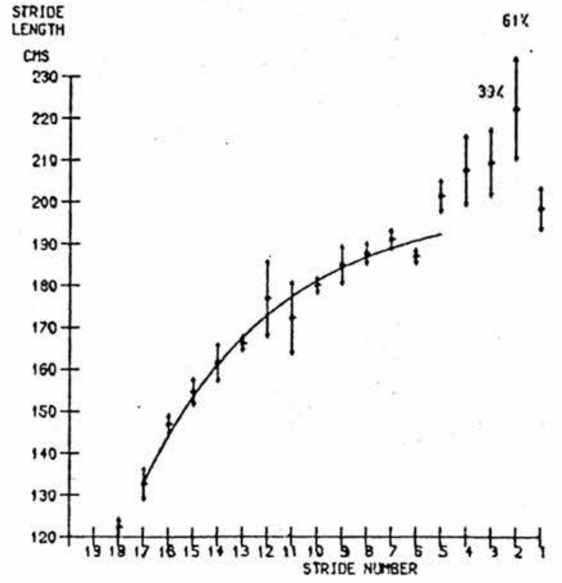
FIG.5.1 Mean stride lengths for each subject,



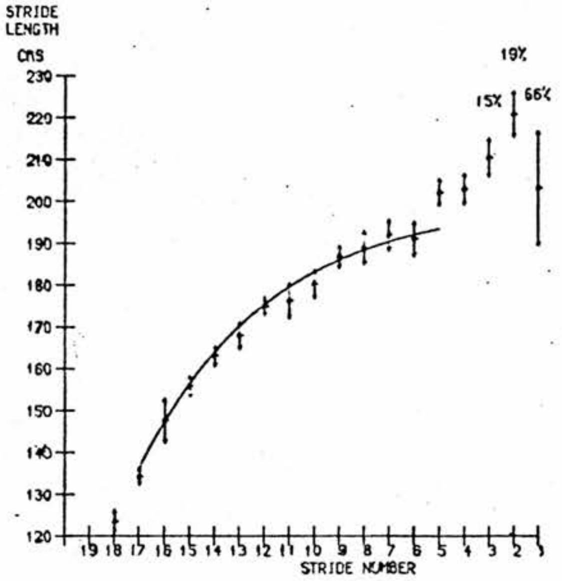
MYRA - 6 JUMPS



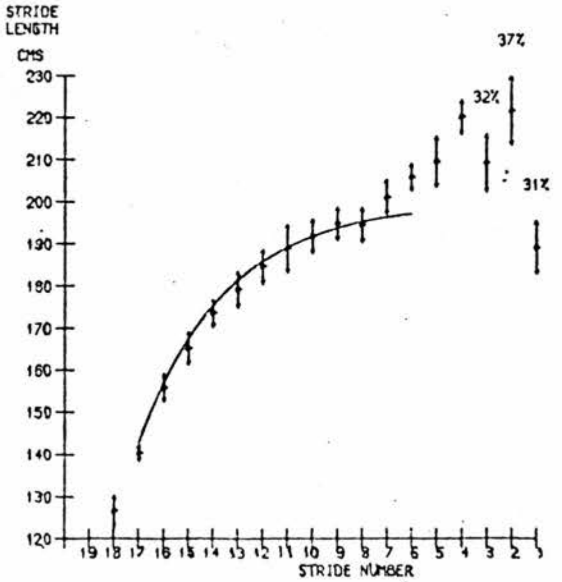
MYRA - 6 RUN-THROUGHS



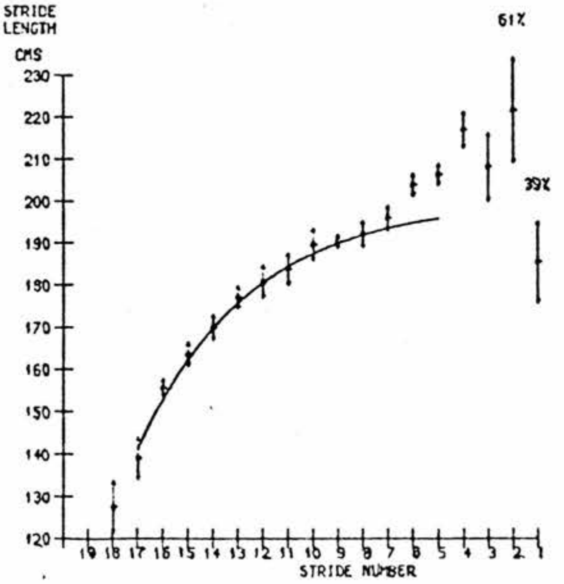
VAL - 6 JUMPS



VAL - 6 RUN-THROUGHS



FIONA - 1ST 6 JUMPS



FIONA - 2ND 6 JUMPS

These results, then, are indicative of the pre-determined program which the athletes are trained to develop during their career. This program is obviously designed to take account of the accelerative phase of the run by systematically increasing stride length at a constant tempo. The best estimate of the stride pattern of this program is given by the mean stride lengths shown in Fig. 5.1. The theoretical curves which have been added to the figure show how the stride pattern might have been generated. They correspond to an athlete exerting a constant effort against a force that increases with the athlete's speed, as muscle resistance apparently does. It can be seen that the curves fit the data points of the accelerative phase of the run rather well. It is clear, however, that the final strides do not conform to this pattern.

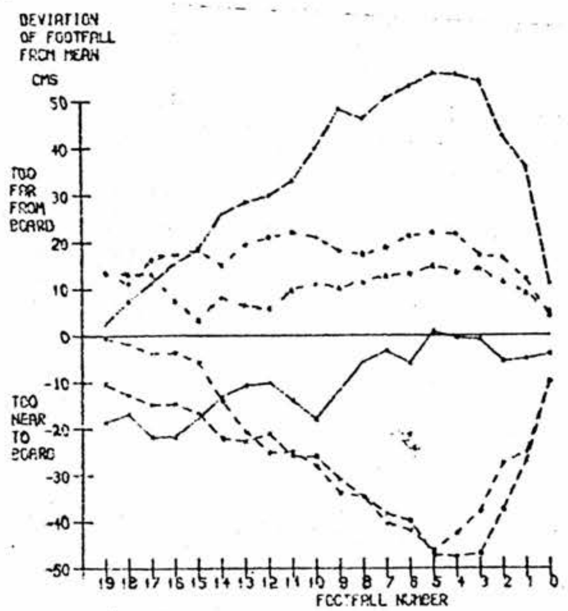
Visual Adjustments to the Strides

Though the stride lengths during the accelerative phase were reasonably consistent across runs, they were not perfectly so. As was predicted, a fair degree of error occurred during the execution of the program. It appears that this had a cumulative effect on footfall position down the track.

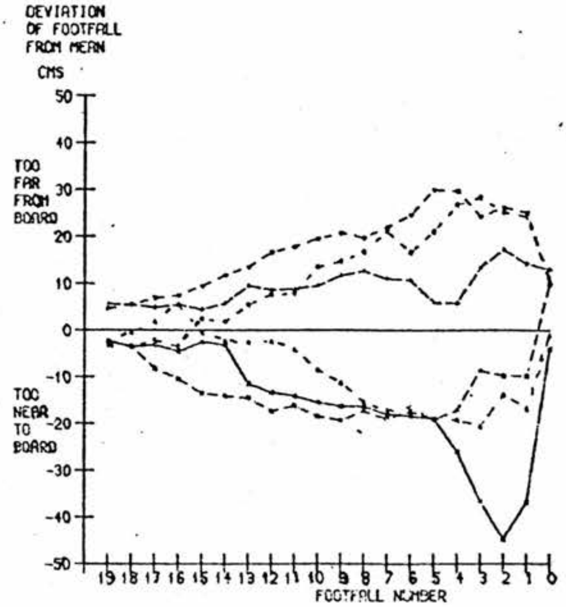
Figure 5.2 shows how the athlete's footfalls tended to deviate more and more from their mean as she moved down the track. It can be clearly seen that the variance builds up until the last few paces from the board where it suddenly began to ~~deteriorate~~ diminish and the footfalls converge on the board. For example, in her six jumps, the position of Myra's footfall 4 varied considerably with a standard deviation of 40cm., while at the board the standard deviation was only 8cm.

The curves of Fig. 5.2 are summarised in Fig. 5.3 which shows the

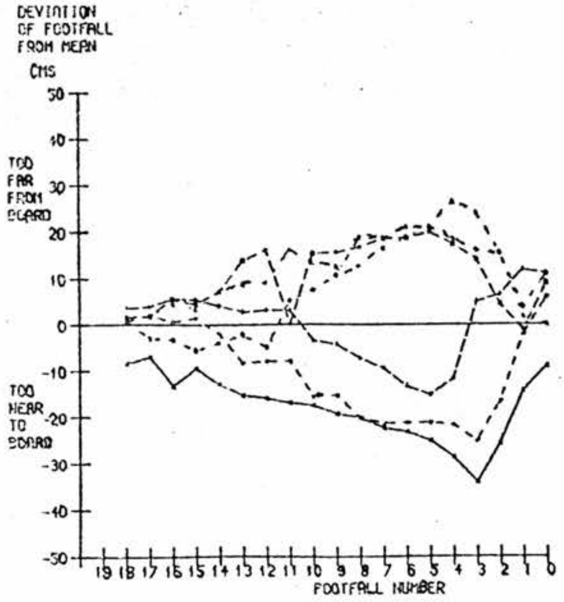
FIG. 5.2 Deviations of footfalls from the mean.



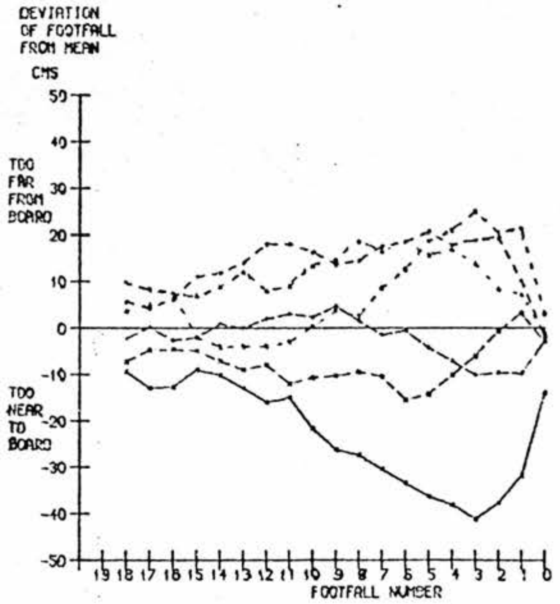
MYRA - 6 JUMPS



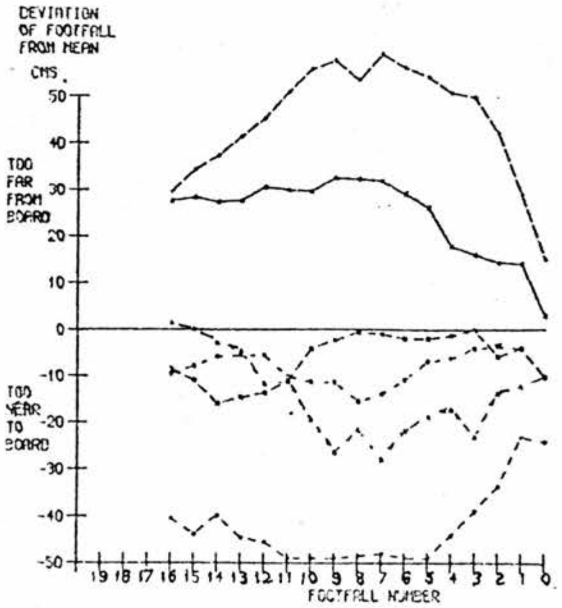
MYRA - 6 RUN-THROUGHS



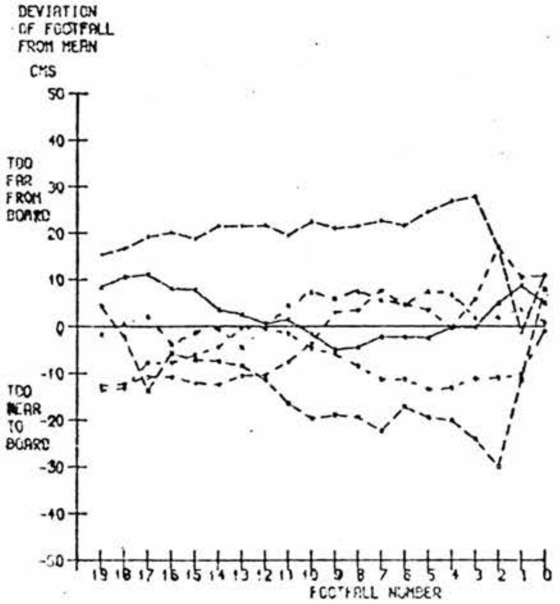
VAL - 6 JUMPS



VAL - 6 RUN-THROUGHS



FIONA - 1ST 6 JUMPS



FIONA - 2ND 6 JUMPS

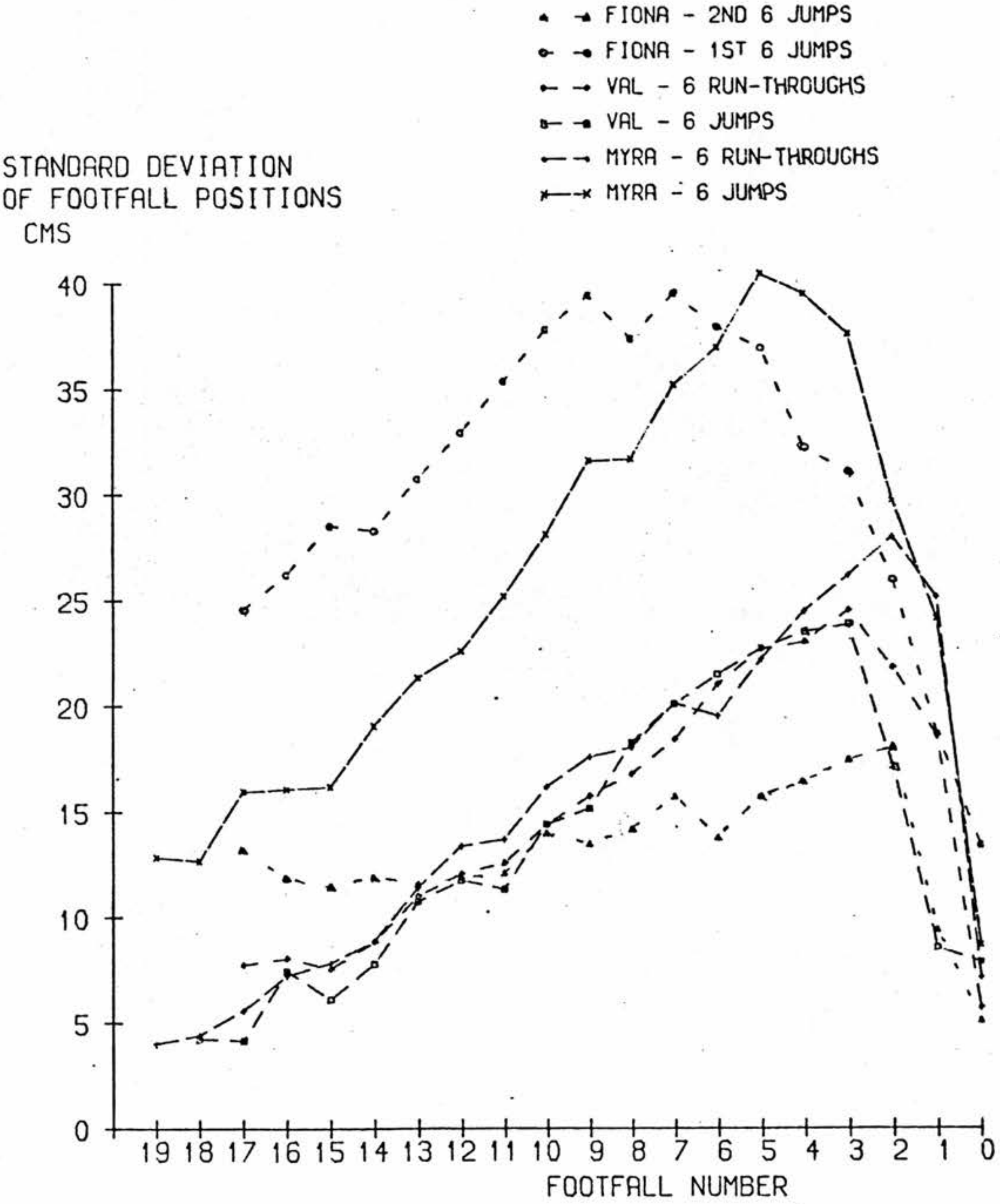
standard deviations of footfall position down the track for each athlete and each session. In all cases, the standard deviation increased down the track until the athlete was a few strides from the board, when it rapidly decreased.

There seems to be only one explanation for this sudden decrease in the variance of foot position: the athletes were visually adjusting their final strides to zero-in on the board. This explanation has further evidence in support of it. Correlations were calculated between each stride length and the distances of preceding footfalls from the take-off board. The correlations were high and positive only for the last few strides. In other words, the lengths of the last few strides were highly correlated with the distance to the board, whereas the preceding stride lengths were independent of the distance. This finding, then, also supports the argument that the athletes were adjusting the pace lengths on the basis of visual information during the last few strides, but not at any of the earlier ones.

The visually-adjusted strides, as evidenced by the correlational analysis, are shown in Fig. 5.1. The number printed over each stride is an estimate of the percentage of the total adjustment which was made on that stride. These percentages were derived from linear regressional analyses of the length of each adjustment stride on the total length of the adjustment strides.

Myra, in her six jumps of which three were no-jumps, appears to have started her gather for the jump with stride 6, which was slightly longer on average than the preceding strides. The stride pattern of her gather became most pronounced as she approached the board, taking the form of alternating longer and shorter strides. This holds for

FIG. 5, 3 Standard deviations of footfalls.

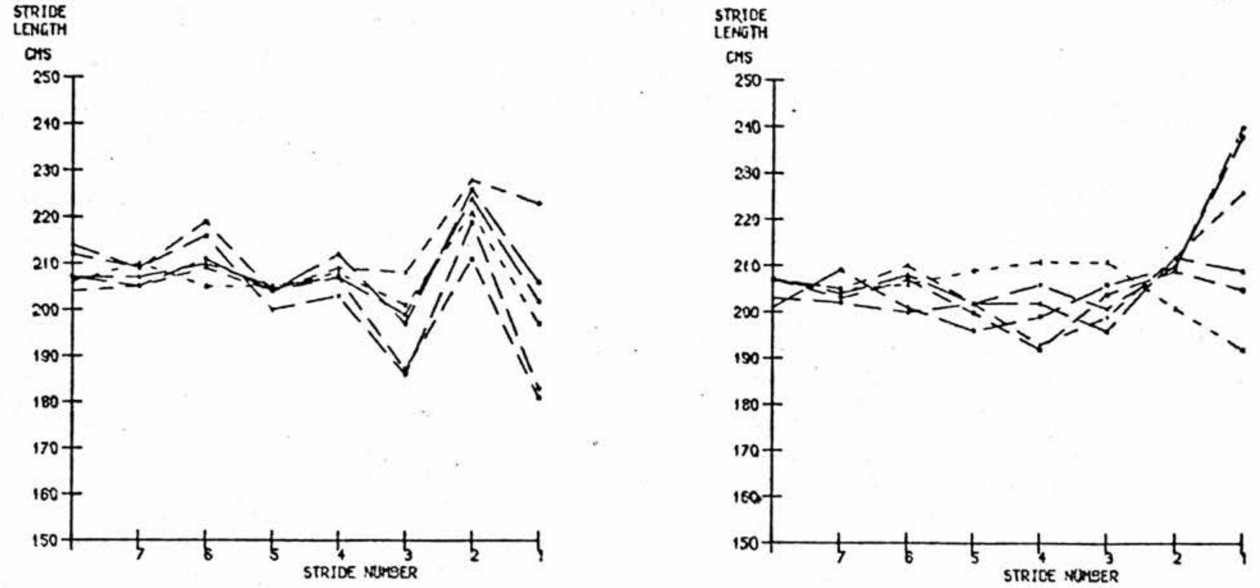


each of her jumps as shown in Fig. 5.4. The pattern over these final strides looks like a kind of rehearsal for the jump, taking the form: long, short, long, short, long, this final "stride" being the jump. Visual adjustment seems to take place over the last three strides with about 50% of the total adjustment being made on the final stride, which varied considerably in length from 1.81m. to 2.23m. with a mean of 1.99 and a standard deviation of 16cm.

Her gather pattern did not emerge in her six run-throughs, however, of which two were "no-jumps". In fact, no consistent pattern was evident (see Figure 5.4). She visually adjusted over the last two strides, as compared with the last three in her jumps, with about 85% of the total adjustment being made on the last stride, which again varied considerably in length from 1.92m. to 2.40m, with a mean of 2.18m. and a standard deviation of 19cm. (It should be mentioned that she was recovering from a left foot injury at the time of her run-throughs, but it is unlikely this had much bearing on the different gather and adjustment patterns she showed).

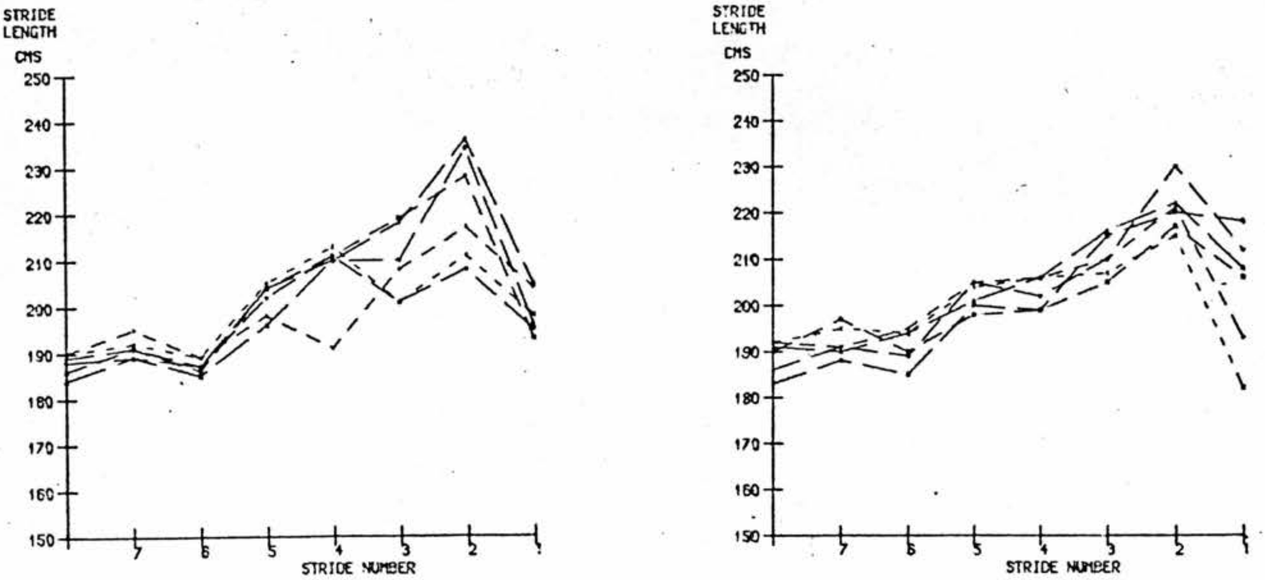
Valerie, in her six jumps, of which one was a no-jump, appears to have started her gather with a shorter stride 6 followed by steadily increasing strides up to the final shorter one to the board. She visually adjusted on strides 3 and 2, but kept her final stride more or less constant (mean 1.99m., standard deviation 5cm.). While her gather pattern was somewhat similar in her six run-throughs, of which five were "no-jumps", there was one important difference. In the run-throughs she visually adjusted over all the last three strides and particularly the final one, on which 65% of the total adjustment was made and which varied considerably in length from 1.82m. to 2.18m. with a mean of

FIG. 5.4 The last eight strides.



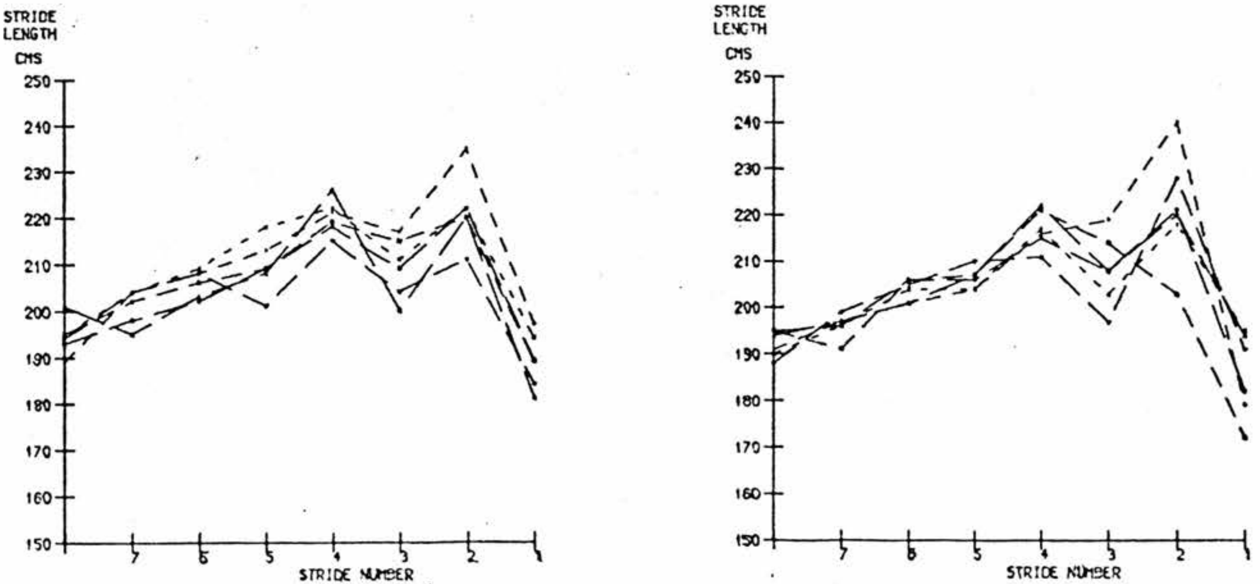
MYRA - 6 JUMPS

MYRA - 6 RUN-THROUGHS



VAL - 6 JUMPS

VAL - 6 RUN-THROUGHS



FIONA - 1ST 6 JUMPS

FIONA - 2ND 6 JUMPS

2.03m. and a standard deviation of 13cm. The pattern of her run-throughs, with the greatly increased share of the adjustments loaded on to the last stride, is in clear accord with Myra's.

Fiona showed a similar gather pattern to Myra in her two six-jumps sessions which involved four and one no-jumps respectively. The pattern was a longer stride 4, a shorter stride 3, a longer stride 2, and a much shorter final stride. In her first session, she visually adjusted over the last three strides about equally. However, in her second session she adjusted over the last two strides only, with about the same percentage of the adjustment on the final stride as in the first session.

This difference between the sessions is interesting. It is probably related to the fact that the peak standard deviation of footfall position in the first session was about twice that in the second. This difference seems to have been due mainly to the higher variability in the starting position in the first session (see Figure 5.3). In other words, her positional errors when approaching the board were on average greater in the first session. It is therefore likely that she was able to detect her error further from the board and so adjust her strides earlier.

From these results, then, it seems that all three athletes begin their run-up with an accelerative phase which is largely pre-determined and which seems to be run off independently of visual information about the distance of the take-off board. At about 6 paces out, they begin a "gather" phase in preparation for the jump and this is seen in the changed characteristics of the stride pattern at this point (see Fig. 5.1). Although it might be concluded from this that visual adjusting is already taking place, this does not seem to be the case. According to the correlational analyses, visual adjustments take place over the final three paces only, though the preparation of these paces (certainly pace 3 itself) would have to take place somewhat earlier. It is possible that the "gather" phase represente the formulation point for these final strides.

Discussion

At the beginning of this study, we stated that its major purpose was to show in behaviour which was as natural and unmanipulated as possible, the basic strategies which were seen in Experiments 1-4 and which we claimed operated in all normal behaviour. In particular we wished if possible to show:

(1) that visual information about distance from the launching-board can only be used to adjust the athlete's stride-pattern at distances of approximately 10 metres or less.

(2) that this information is used to formulate a program to bring the athlete onto the launching-board.

The results of Experiment 5 seem to have some bearing on these questions. With regard to the first question, it does indeed seem that information can only be used at fairly near distances. We saw in Figs. 5.1 and 5.3 that the stride patterns of the three athletes remain reasonably consistent up until the last six paces or so, where the characteristics of the pattern change. It can be seen from Fig. 5.1 that six paces represent a distance of approximately 12 metres from the launching board for all three athletes. This, then would be in fairly good agreement with the results of preceding experiments.

However, we cannot accept that simply because the characteristics of the stride-pattern change at 6 strides out, this represents the point at which visual information begins to be used. We saw from the correlational analyses that visual adjustments seem to be made only to the last three strides, with the largest part of the adjustments coming on the penultimate - and in the case of Myra - the ultimate stride. This finding would suggest that adjustments are made over the last 6 metres or so. Although this is less than the 10 metre limit we find in Experiment 1, it is consistent with the first hypothesis formulated, namely that the possibilities of visual adjustment are restricted to distances fairly close to the take-off board. It should be clear, however, that the decisions about the lengths of these strides would have to be taken <u>at least one stride in advance</u>. This would bring the decision about stride 3 back to stride 4 at least, and therefore to a distance of approximately 8 metres. Since we find the athletes to be running at a speed of some 4 to 4.5 strides per second, it would seem likely that a decision would have to be formulated even earlier than this, at perhaps 2 strides distance (.5 seconds) at least. This might place the beginning of the formulation of visual adjustments at 10 metres quite easily. This finding would seem to fit rather well with the results of earlier experiments.

The second hypothesis, that the visual information once picked up would be used to formulate an accurate program for action which could then be run off as a whole is more difficult to demonstrate. In the case of Valerie's six jumps (see Fig. 5.1) there is evidence that some form of program was in existence at pace 3, because the largest part of her adjustments were made on stride 2, with virtually none occurring on stride 1. This would imply that these two strides had been planned in advance at a point no earlier than stride 3, or some 6 metres from the board. It is also clear, however, that some adjustment was made to pace 3 itself. Whether this adjustment and the subsequent adjustment at pace 2 were planned at the same time cannot be determined, but one might expect that if this were the case the adjustments would be more equally shared out between the strides. On the other hand, we saw from Fig. 5.4 that the athletes' final paces took the form of a kind of gallop; long, short, long, short. It might be that this was a deliberate strategy for making adjustments through the long paces and with the preferred leg. If this were so, it might not be so unlikely to find the adjustment load shared out unequally after all. At any rate, there is clearly evidence from Valerie's jumps that some form of program was determined, at least as early as three paces out, which remained unchanged.

The results from Fiona's jumps are in rather good agreement with those for Valerie's. Again, it can be seen that the large part of the adjusting is done on the penultimate stride, though in Fiona's case, a fair proportion of adjustment is carried on to the final pace. In the case of her first jumps, however, the load is more or less equally shared over all three strides; which does fit with the programming argument. The effect is not obtained on her second session, however. In Myra's case, the largest adjustment is not made on stride 2 but on stride 1, with only smaller adjustments occurring in the two preceding strides. Again, we cannot be certain where the planning of these visually adjusted strides took place.

Although it is clear from these results that some form of visual adjustment begins to be exerted on stride 3, it is very difficult to say whether these strides were executed as a programmed whole, with no further visual adjustment, or not. It certainly seems from the results of Valerie's six runs that a program to take her through the last 2 paces at least had been planned, but in other cases it is more difficult to be sure. We must also bear in mind that a program could be formulated which was subsequently seen to be inaccurate, and a final desperate attempt made to change it at the last stride. Something of this kind might be evidenced by comparing the success of the different jumps but these were not measured and this kind of analysis cannot be made.

Something must now be said about the discrepancies between the jumps and run-throughs. The aim of a run-through is, of course, literally to run through the program for the approach to the board, both to practise executing the program and to enable adjustments to be made to the starting position to suit the conditions. We have already seen that neither Valerie nor Myra's run-throughs completely fulfilled this aim: the gather and adjustment patterns were substantially different from the jumps (see Fig. 5.1). An important question was why this should be. One possibility which fits quite well with the current arguments, is that the jump forms as integral part of the final phase of the run-up. Indeed, from the theoretical arguments put forward here it would have to be. But in a run-through this final part of the program is missing. It should surely not be surprising, then, to find that the final part of a run-through is different from the form of a full jump when a substantial portion of the normal program is missing. To re-create a part-program must be very difficult indeed.

Conclusions

The results of Experiment 5 seem to offer some fairly convincing evidence in favour of the experiments reported earlier. The limited range over which it seems to be possible to make visual adjustments fits well with the findings reported earlier, showing that adjustments are apparently made over distances of some 6 metres (the final 3 paces). Since these paces (or pace 3 at least), would have to have been planned somewhat earlier, it seems quite reasonable that visual adjustments were first initiated at 8 or even ten metres. Obviously, this fits quite well with earlier results.

Whether the visually adjusted strides were planned as a whole and then executed as such is much more difficult to say. The only way this could really be tested would be to ask the athletes to close their eyes for the last three strides and note the resulting performance. The present study having been purely observational, this question cannot really be answered. It seemed that Valerie in her six jumps had programmed the last two strides at least, as a whole, but we cannot draw any firm conclusions about the other subjects. However, since the final pace alone would have to be planned one pace in advance (i.e. at pace 2), then programming over a distance of 4 metres at the end of the run-up would have been necessary, at least. Some form of programming on the basis of visual information must therefore have taken place.

SUMMARY AND GENERAL CONCLUSIONS ON PART II

In Part I of this thesis a theoretical position was taken in which it was argued that organisms do not guide their behaviour relative to the environment on the basis of current information available at the receptor, but on the basis of previously-acquired information. According to this argument, information available at the eye is sampled only intermittently and this intermittently-acquired information is used to formulate programs for action. It was argued that such programs are normally sufficiently accurate to rule out the need for further ~~us~~visual guidance during the execution of the program, though vision may undoubtedly be required for other forms of control during this period (e.g. for balance control). At any rate, the existence of programs of this sort substantially reduces the work-load of the visual system for considerable periods. Since it is argued that this mode of operation is natural and in continuous use, we have argued that programming is the main activity for which the visual system is used. Otherwise, so far as guidance is concerned, the task of vision is to be responsive to unforeseen circumstances, or to engage in activities other than the guidance of activity.

If the arguments on the programming strategy, and on the accuracy of the programs, is correct, it should be relatively easy to obtain evidence in support of them. The purpose of the five experiments reported in Part II was to do exactly this: to provide a body of evidence demonstrating that behaviour can indeed be controlled accurately on the basis of previously-acquired information.

In Experiment 1 an attempt was made to show the accuracy with which behaviour could be controlled on the basis of previously-acquired information in the simplest possible situation, where the subject has to locate a single target placed at a distance. In Experiment 2, that ability, which seemed well-supported by the results of the first experiment, was found to be limited to distances of 10m. and under, with a dramatic threshold in ability occurring somewhere between 10m. and 12m. and with error over all subsequent distances tested (i.e. up to 21m.) remaining consistently high. In Experiments 3 and 4, programming ability was examined in more complicated situations where a group of "targets" had to be negotiated, and in the case of Experiment 3, where a number of re-orientations of the body were also required. The results of Experiment 4 indicated that subjects were indeed as capable of negotiating a group of (in this case, 4) targets as of negotiating one. In Experiment 3 it was found that subjects were not capable of successfully programming a series of directional manoeuvres, though the distance estimations made in this experiment were in complete agreement with the results of Experiment 4. In Experiment 5, an attempt was made, in a purely observational study, to show programming in operation in natural behaviour, or in behaviour which was as near to natural as we felt it possible to get. The evidence of this study also proved consistent with the results of the more experimental studies, though the data ~~was~~ were less clear on some counts, as could only be expected with a study of this kind. In general, however, these studies all seemed highly supportive of the theoretical position adopted in Part I.

There is a number of matters arising from these experiments which now require discussing. A first priority in this respect must go to the threshold obtained in Experiment 2. Obviously, we would like to know what is responsible for the limitation, and indeed, we might expect to gain some further insight into the system through such an investigation. However, since this matter is taken up at length in Part III, it need not be considered at greater length at this stage.

Experiments 3 and 4 raise a number of questions which were not dealt with in more experiments themselves. In both these studies, for example, we found that subjects were capable of negotiating four obstacles so far as the distance dimension was concerned. One question arising from this, however, is how many such obstacles could be negotiated. Clearly, the number cannot be infinite. What kind of restrictions are there on the numbers which can be effectively negotiated, and what sort of errors arise when this number is exceeded? These questions might well prove to have interesting outcomes. Similarly, we might ask what would happen if were to use groups of obstacles which varied substantially in size. The distances between the obstacles could be varied in many ways, for example, by grouping them close together at a distance from the subject, or by distributing them in small groups with larger spaces between. Again, we might ask what kind of results could be expected under these conditions. Another possibility would be to vary the behaviour required in relation to the obstacles, for instance, by asking the subjects to jump over the obstacles instead of circumventing them. This last possibility is in fact attacked in one way in experiments reported below where subjects are asked to <u>run</u> to targets instead of walking, but the behavioural variations that are possible are much more extensive than this. All these variations to the situations employed in Experiments

3 and 4 could be carried out, then, and it is possible that some of them might turn up interesting results. However, it was felt that the purpose of this series of experiments, and of this thesis as a whole, should not be to follow up every possible avenue of research, but rather to concentrate on establishing broad principles which could then be examined in finer detail at a later stage. It was felt that the experiments reported were successful in establishing the basic principle towards which they addressed themselves; namely that the subjects' abilities were not limited to single targets, but that groups of reasonable size could be negotiated as well. It was therefore felt unnecessary to include further experiments of the type noted above in the present program of research. However, in those areas where a variation was considered to have a direct theoretical relevance to the theoretical position advocated, that variation was examined. It will be seen in Part III that some such variations to the conditions in Part II have been employed.

In Experiment 5, we attempted to show programming in operation in a more natural setting than we had employed up till then. That attempt was fairly successful, showing, as it did, behaviour patterns which were consistent with the arguments advocated on the nature of control. It seems likely, however, that a certain degree of manipulation of the situation might prove useful. For example, we were unable to say with certainty whether or not the usually-adjusted strides were planned and executed as a whole. One simple way of determining whether or not they were, would be simply to ask the athlete to close his eyes at the last three paces, and examine the resulting stride pattern. Other variations could also be attempted to elucidate the nature of the control. It seems as if a mixture of natural conditions with experimental manipulations of this sort might prove very valuable.

There are many other sporting events where locomotor programming strategies should be necessary. One obvious example is the triple jump, which is very similar to the long jump from our point of view. However, the task for the triple jumper, once he has hit the take-off board, is not to jump but to ~~step~~ hop. Because of this difference, we might find interesting differences in the form of the visually-adjusted strides preceding the step. We should note in this respect the differences obtained between a full jump and a run-through in the long jump study.

Other events which could be investigated in this way are the pole-vault and the high jump. Similar problems are faced by the bowler, particularly the fast bowler, who takes a long run, in cricket. One very good event for study is the steeplechase. In this event, fences are placed at distances of approximately 300m round the track, and one water-jump is always included. In such a long and tiring event, the runners' task is to keep his rythm as smooth as possible: the athletes cannot afford to have to strain to overcome a fence. For this reason, the approach to the board must be regularised in advance, and adjustments made at some distance from the fence are often quite visible. The advantage of this event over the long-jump is that the athletes do not have a set number of strides to fit into the run-up: the approach to the fence is more fluid than this. To this extent also, it is more natural. The examination of such an event should therefore be interesting. It did not prove possible to examine this event at the present time, unfortunately, partly because of methodological difficulties, and also because no steeplechasers were available at the time. But this event may well prove a valuable subject for future study. One final series of events where programming should be evident is swimming events. The swimmers must always know at some point in advance where the edge of the pool lies so that they can make their turn as swiftly as possible; they cannot afford to look at the end of each stroke. Here too, then, we might expect to find evidence of programming.

With a view to examining these possibilities, a number of athletic training films was obtained of all the events noted above. These films consisted mainly of Olympic and European Championship events with a few simpler training films. These were examined carefully for any evidence of the effects under consideration. In a number of cases, the results were highly encouraging. This was particularly true of the steeplechase where, as we noted above, there was a good number of visible adjustments. This held also for the swimmers, though most clearly for the crawl and backstroke events, where checks on the distance to the edge are more evident. There seemed to be a tendency for the swimmers to check at some strokes out, though this was not always evident. The quality of the films sometimes precluded accurate estimations. Even in the long jump and triple jump events, where visual adjusting, as we have seen, is not easy to demonstrate to the naked eye, was occasionally visible even in the performance of athletes like Ralph Boston, one of the greatest long jumpers of all times. It was these findings which initially encouraged us to do the more thorough investigation reported in Experiment 5. But it should be clear that the study of other athletic and sporting events is likely to prove highly valuable in the future.

From the results reported in the five experiments of Part II, then, it seems we can claim to have quite satisfactory evidence of the adequacy of control when this is achieved on the basis of previously-acquired information, with no current information being allowed to influence control. We now require to go beyond this outline, however, and indicate in greater depth than we have done up till now, how this guidance is achieved. To do this is the problem of Part III of this thesis.

PART III

THE MECHANISM UNDERLYING INTERMITTENT CONTROL

INTRODUCTION

In Part II an attempt was made to demonstrate that subjects have the ability to control their behaviour on the basis of intermittently-acquired information. In Part III, our concern is to try to understand how this kind of control is achieved. It was argued in Part I that distances are perceived in terms of motor actions, and this would suggest that control is achieved on the basis of a series of such formulated motor actions. However, as we shall see, this does not provide a complete picture of the skill. The process appears to be more complicated that this.

Perhaps the best place to start such an investigation of the mechanism underlining the ability reported in Part II would be with the threshold in ability obtained in Experiment 2. The result of that experiment is reproduced in Fig. IV. As can be seen, the accuracy of the orientations breaks down suddenly and dramatically at 12m, the high degree of error obtained at that distance being carried forward to all subsequent distances tested. It seems not unreasonable that if we could understand what is responsible for this breakdown in ability, we might correspondingly gain some insight into the nature of the system.

There seem to be three potential explanations of the break-down which are immediately obvious.

(1) It may be that some critical element of perceptual information ceases to be available at distances of more than 12m. Since this information is no longer available, accuracy suffers accordingly.

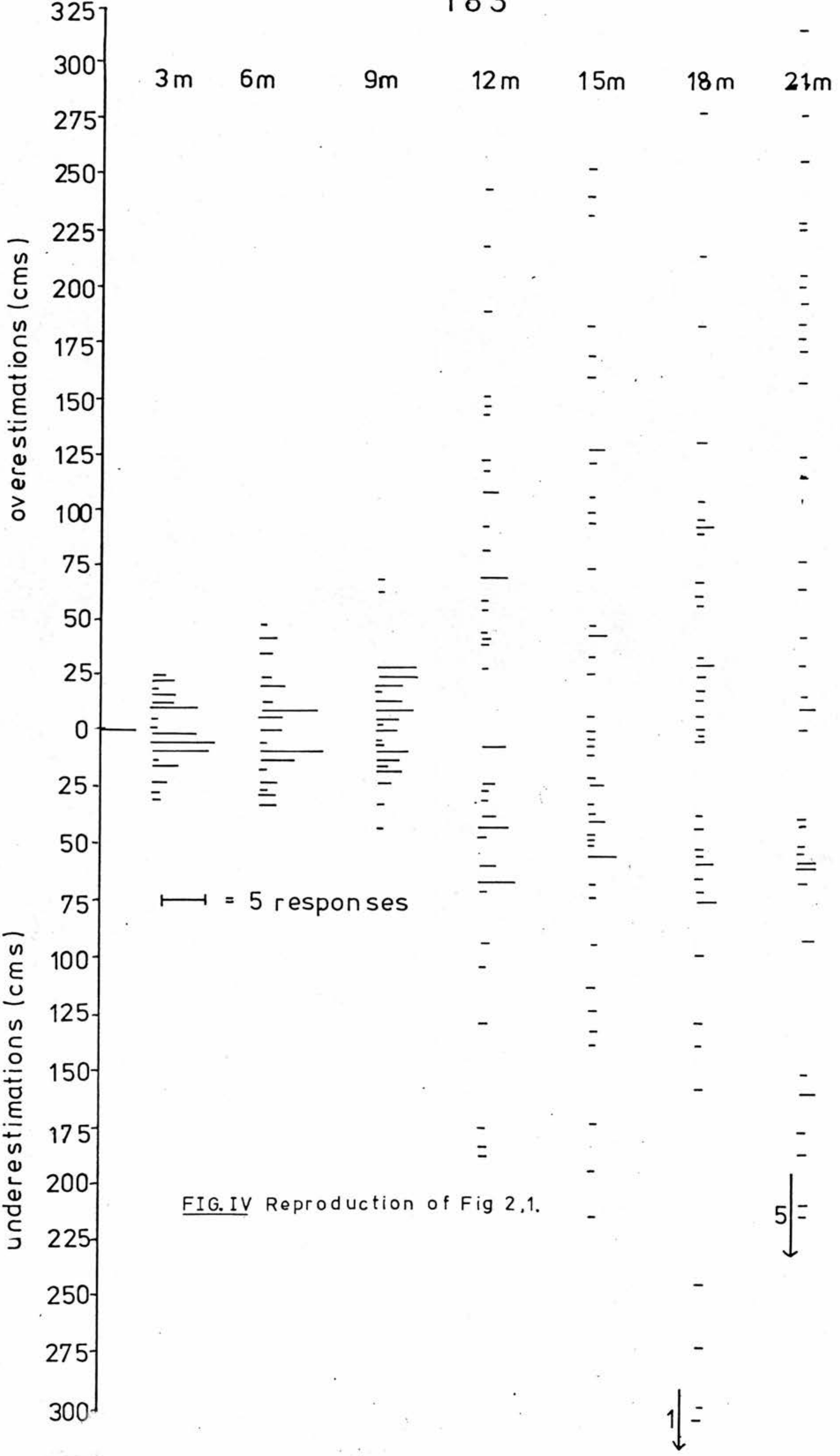


FIG. IV Reproduction of Fig 2,1.

(2) It is possible that the trace of the information acquired, whatever form that information takes, is subject to decay over time. This would mean that, by the time the subject has reached the vicinity of 12m. the trace has faded to such an extent that it can no longer be used to control the behaviour. The fact that the threshold in Experiment 2 was so sharp would suggest that decay has relatively little effect until some vital information is lost, at which point the possibilities of further guidance are lost.

(3) It is possible that the system is subject to "limited programming capacity". This would mean that the system is capable of holding a certain amount of programmed action, or of information in some other form, but that beyond this no further information can be stored.

Possibility number 3 may immediately be seen as rather unlikely. We argued in Part I that distances are apprehended in terms of motor actions. In the case of locomotion, the units of motor activity in terms of which distance could be perceived, would most likely be some form of pace or stride. In this way a target might be perceived as lying six paces away. (The perception might be in terms of some other motor unit, but this will not affect the present argument). It seems highly unlikely, however, that a program for walking one pace could be considered more complex, from a storage point of view, than a program for walking n paces. No difficulty can arise so long as n is known. Of course, it might be that subjects are not capable of appreciating beyond a certain point, the number of motor units required to reach that point, but then this has become a case of possibility number 1, namely a problem of perceptual rather than storage or programming error. It certainly seems plausible that an error of this sort might exist, though it would seem more likely in this case that error would increase more gradually as the subject reaches a field of uncertainty about the distance, culminating in a high, consistent level of error.

Possibility number 2, that the error is due to fading of the trace of the information stored, irrespective of the form that information takes, is also plausible. Again, the fact that a dramatic threshold is obtained would suggest that there comes a point when some vital information is lost, with performance correspondingly falling at that point. Since possibilities 2 (temporal decay) and 1 (perceptual error) seemed the more plausible alternatives at this stage, it was decided to begin the analysis by examining them. It was also decided that the more appropriate of the two to begin with was the possibility of temporal decay. This was, firstly, because it seemed the simpler of the two problems to investigate, and secondly, because, as we shall see, the results of a temporal experiment are capable of ruling out perceptual error as an explanation altogether. For these reasons, the hypothesis of temporal decay was attacked first.

EXPERIMENT 6

TEMPORAL LIMITATIONS IN THE ABILITY TO CONTROL BEHAVIOUR IN THE ABSENCE OF VISION I

Introduction

If the threshold of Experiment 2 was caused by some form of temporal decay of internalised information, there are two simple methods by which the role of decay could be determined. These are examined in Experiments 6 and 7 respectively. The first method, adopted in Experiment 6, is to artificially manipulate the experimental conditions under which Experiment 2 was conducted in such a way as to force subjects to take the same time to reach targets at distances of, say, 9m. or 6m. as was originally taken to reach 12m. This would involve manipulating the time elapsing between the point at which vision is excluded and the point at which the target is reached in such a way that the total time taken to reach the shorter distances now equals or exceeds the time taken to reach the threshold distance in Experiment 2. If the threshold had been due to temporal factors, then by manipulating time in this way it should be possible to bring the threshold down from 12m. to 9m. and further. The extent to which the threshold obtained at these distances reflects the thresholds obtained at 12m. would then give a measure of the effect of temporal factors. This question is therefore examined in Experiment 6.

Method

Design

The general design of Experiment 3 closely followed that of Experiments 1 and 2. Four locomotor distances were chosen at 3, 6, 9 and 12 metres. These distances were chosen as the 3 "high-performance" distances of Experiment 2, together with the threshold distance. The locomotor pathways were laid out in the car park as in Experiment 2. The target positions were indicated by a wooden marker which was placed on the left-hand side of the subject's path. As in the previous experiments, echo location and other forms of auditory cue were controlled by the use of white noise which was played to subjects throughout the experimental session. This was effective in eliminating almost all auditory information.

The experiment was performed under three conditions:

Condition 1 (Control). This condition was a replication of Condition 1 in Experiment 2, except that the experiment was conducted over the first four distances only. The purpose of this condition was to obtain an estimate of the time taken by subjects to reach the different distances. The condition was conducted with vision excluded simply because of the possibility that there might be time differences between conditions where vision is available and where it is not.

Condition 2. This condition employed a time restriction such that subjects were forced to take the same time to reach the target position at 9 metres, as they had taken to reach 12 metres in Condition 1. This was achieved by using a 2 second delay between the point at which S shut his eyes and the point at which he began walking.

Condition 3. This condition employed a further time restriction such that the time taken to reach the target at 6 metres was the same as that taken to reach 9 metres in Condition 2, and 12 metres in Condition 1. This was achieved by using a 4 second delay between the points at which vision was excluded and S started walking.

Procedure

The general procedure of Experiment 3 was similar to that followed in Experiments 1 and 2. Before the experiment proper began, a short practice session was held to accustom subjects to the task and to ensure that they understood the instructions. The practice trials were held at some distance from the experimental layout to avoid learning effects from practising on the experimental pathway. The procedure followed was similar to that followed in previous experiments.

The experimental procedure was as follows:

Condition 1. S stood at the starting-point and the white noise was turned on. S was allowed to decide himself when to exclude vision. As soon as he did this, he informed E, who stood behind him, by saying "now". Immediately, E started a stop-watch and waited until S had reached the target position, when the watch was stopped and the time taken recorded. If S over-estimated the distance of the target and walked past it, the time recorded was the time to reach the target only. This measure, together with the associated error on that trial, thus gives a measure of the fading which had taken place by the time the target had been reached, and of the total time which achieved it. Whenever S stopped short of the target, the time recorded was the time taken to reach the point at which he stopped. Again, the time taken to reach such a point would give a measure of the time necessary to achieve sufficient fading to reduce accuracy to the level obtained on that trial.

Condition 2. The procedure in Condition 2 was identical to that followed in Condition 1, with one exception. S was instructed that once he had closed his eyes, he was to stand still until told he could begin walking. As in Condition 1, S indicated that he was about to close his eyes by saying "now". Immediately, E started the stop-watch and began timing. After two seconds delay, E informed S that he could commence the trial, simply by tapping his shoulder. S had been instructed that he was to begin walking immediately he received this signal. Although this method is extremely simple, it nevertheless proved effective in gaining fairly strict control over the time lapse between closing the eyes and reaching the target. The method was therefore successful in forcing subjects to take the same time to reach 9 metres as they took in Condition 1 to reach 12 metres.

Condition 3. Condition 3 was performed exactly like condition 2, except that the delay period employed was four seconds. This delay thus forced subjects to take as long to reach a target at 6 metres as they had taken to reach 9 metres in Condition 2 and 12 metres in Condition 1.

Each subject was presented with three trials at each distance in each condition, making a total of 36 trials in all. It was considered that the number of trials could not be increased beyond this, because of the influence of fatigue which proved very strong. It was also felt that cognitive efforts on the part of the subjects began to play a role when the experiment was lengthened beyond that used here, and this was testified to by subjects in pilot studies. Each trial was marked, as in Experiment 2, by a coloured pin pushed into the ground, except at 3 metres where these were visible and a direct measurement was taken. After each trial S remained with eyes closed until E turned him around and walked him back to the starting-point. In this way, subjects received no information about the success of previous trials. The trials were conducted equally on the two pathways to avoid the pick-up of tactual cues from the ground surface which might be used to help gauge the distances.

The conditions were presented successively, with the control condition being presented first, followed by Condition 2 and then Condition 3. The presentation of trials was randomised within each condition.

Subjects

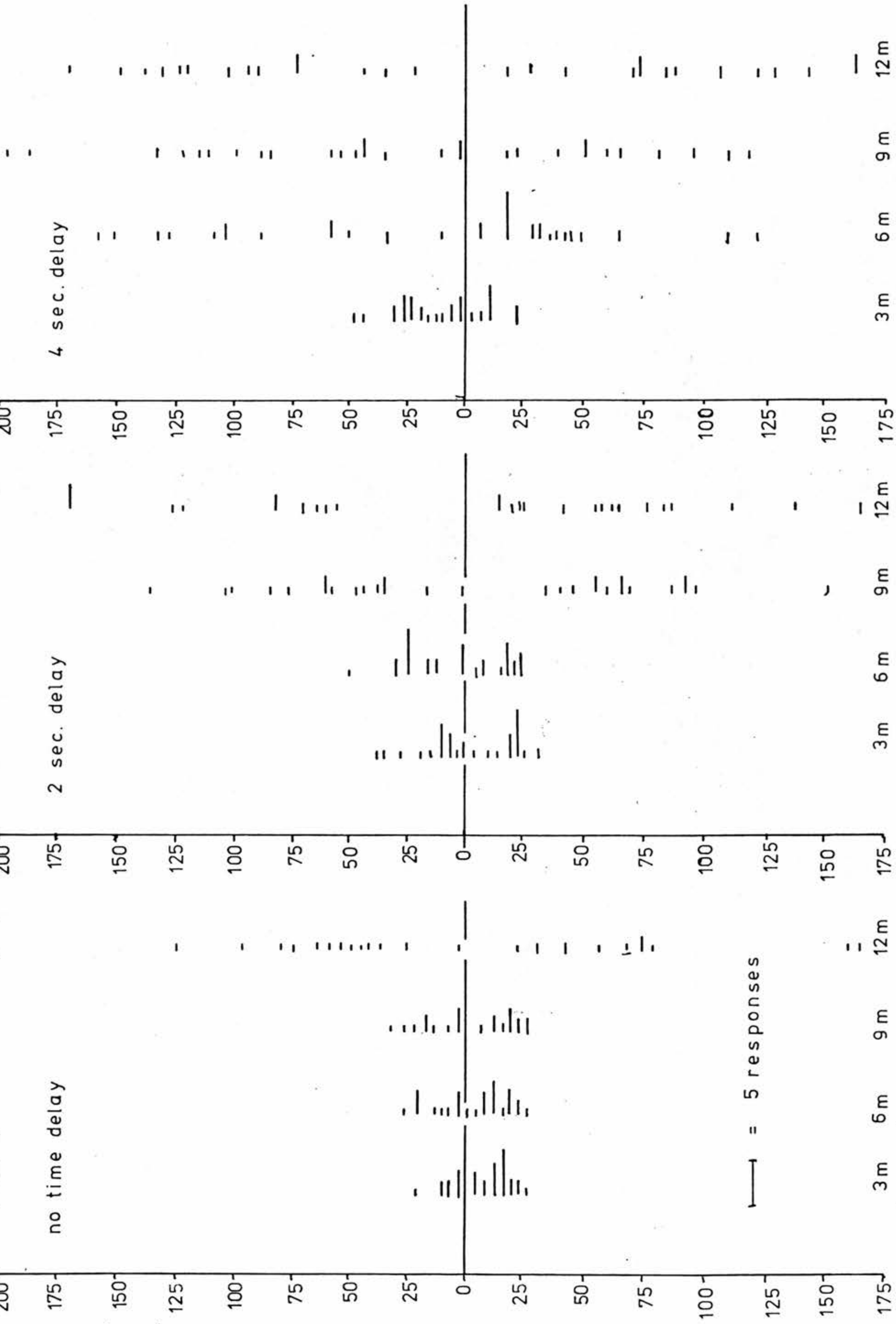
Ten subjects took part in Experiment 6, seven male and three female. All subjects were students at Edinburgh University, and were aged between 19 and 28. No subject was aware of the purpose of the experiment, or of the predicted results.

Results

Table 6.1 shows the mean times taken at each distance in each condition. It can be seen that the mean time taken to reach 12 metres in Condition 1 was 9.06 seconds. It can also be seen that the time delays employed in conditions 2 and 3 were effective in producing comparable mean times at 6 and 9 metres (10.16 seconds; 9.84 seconds). The experimental manipulations therefore seem to have been successful in creating the conditions for an examination of the influence of temporal parameters on performance.

The basic findings of Experiment 6 are presented in Fig. 6.1 which shows the distribution of variance obtained at each of the distances used. Fig. 6.1a shows the results obtained in condition 1 (no time delay). Fig. 6.1b the results of Condition 2 (2 seconds delay) and Fig. 6.1c the results of Condition 3 (4 seconds delay).

FIG. 6.1 Distribution of judgments at each distance in each condition.



Differences within Conditions

It can be seen from Fig. 6.1a that the results of Condition 1 are in very good accordance with the results of Experiment 2, and constitute a replication over the first four distances of that experiment. No differences can be seen in the variance of the error at the first three distances, but at 12 metres, the sharp threshold first seen in Experiment 2 is obtained. A statistical analysis confirmed this trend. No differences were found in the variances at 3 and 6 metres ($F = 1.78$ n.s.) or at 6 and 9 metres ($F = 1.54$ n.s.). At 9 and 12 metres the difference was highly significant ($F = 17.98$, $p < .001$). These results then offer a clear confirmation of the results of Experiment 2.

It is clear from Fig. 6.1b that the predicted results of Condition 2 are also confirmed. This figure shows that the threshold found at 12 metres in Condition 1 has now been shifted down to 9 metres in Condition 2. The variances on either side of the threshold appear to be roughly equal. Again, a statistical analysis confirms these trends. The difference between the variances at 3 and 6 metres was not significant ($F = 1.01$ n.s.). At 6 and 9 metres the difference was highly significant ($F = 16.38$, $p < .001$). The difference between the variances at 9 and 12 metres was not significant ($F = 1.64$ n.s.). These results clearly confirm the hypothesis formulated with respect to Condition 2.

Fig. 6.1c shows the variance of error obtained when a 4 second delay is added to subjects' locomotion times. These results are also in line with the experimental predictions. It can be seen that the threshold which in condition 2 lay at 9 metres has now been relocated at 6 metres. The difference between the variances at 3 and 6 metres proved statistically significant (F = 14.45, $p < .001$). No differences were obtained between the variances at 6 and 9 metres (F = 1.78 n.s.), or at 9 and 12 metres (F = 1.57 n.s.). These results therefore also confirm the experimental hypotheses.

TABLE 6.1

Means and Standard Deviations of Times Taken to Reach each Distance

	Condition		
	1 (no delay)	2 (2 sec. delay)	3 (4 sec. delay)
3 metres	3.08 ± .58	5.41 ± .47	7.20 ± .34
6 metres	4.83 ± .51	7.15 ± .41	10.16 ± .76
9 metres	6.64 ± .69	9.84 ± 1.02	12.71 ± 1.01
12 metres	9.06 ± 1.30	12.31 ± 1.21	14.35 ± 1.30

Differences between Conditions

The variances obtained between corresponding distances in the different conditions also accord with the predictions. No differences were found between the variances at 3 metres in the different conditions (cons 1 x 2, F = .95, n.s.; cons 2 x 3, F = 1.09, n.s.; cons. 1 x 3, F = 1.77 n.s.). At 6 metres the difference between conditions 1 and 2 was insignificant (F = 1.79 n.s.), but the difference between conditions 2 and 3 was highly significant (F = 13.43, $p < .001$), as was the difference between conditions 1 and 3 (F = 23.98, $p < .001$). At 9 metres the difference between conditions 1 and 2 was significant (F = 1.46 n.s.). At 12 metres no significant differences were found between the variances in the different conditions (cons. 1 x 2, F= 1.74 n.s.; cons 2 x 3 F = 1.39 n.s.; cons 1 x 3, F = 2.41 n.s.). These results then agree completely with the experimental predictions. Apparently, whenever the time taken to reach a target exceeds the time taken in condition 1 to reach 12 metres (approximately 9 seconds) then, irrespective of the distance of the target, performance suffers acutely. The results of the statistical analyses are summarised in Tables 6.2 and 6.3.

Although it is clear from the results so far that whenever time to locate the target exceeds 9 seconds, performance can be expected to deteriorate, it is in fact possible to make a closer examination of the role of time in determining error, and also to identify more precisely the critical time point at which performance breaks down. Fig. 6.2 and Table 6.4 show the error obtained with increasing time, and were calculated irrespective of the distance covered in that time. For the sake of clarity scores are grouped at 1 second intervals as shown in Table 6.4.

An examination of Fig. 6.2 and Table 6.4 suggests that the critical time-point at which performance breaks down occurs at approximately 8 seconds. Up until that point performance appears to hold relatively stable, though one or two larger errors were obtained between 7 and 7.9 seconds. At 8 - 8.9 seconds performance can be seen to decrease in consistency, and that inconsistency appears to remain roughly steady over further time intervals. Statistical analysis confirms this trend. It can be seen from Table 6.5 that no differences are obtained between consecutive time intervals between 2 and 7 seconds, but at 7 and 8 seconds the difference in the variances is highly significant ($F = 23.17$, $p < .001$). At intervals of 8 - 13 seconds, the differences

TABLE 6.2

F Ratios Obtained between Distances in Each Condition

Source	Distance	F	Source	Distance	F
Condition 1	3 x 6	1.78	Condition 3	3 x 6	14.45*
	6 x 9	1.54		6 x 9	1.78
	9 x 12	17.98*		9 x 12	1.57
Condition 2	3 x 6	1.01			
	6 x 9	16.38*			
	9 x 12	1.64			

TABLE 6.3

F Ratios Obtained between Conditions at Each Distance

Source	Condition	F	Source	Condition	F
3 metres	1 x 2	1.95	9 metres	1 x 2	19.00*
	2 x 3	1.09		2 x 3	1.46
	1 x 3	1.77		1 x 3	27.72*
6 metres	1 x 2	1.79	12 metres	1 x 2	1.74
	2 x 3	13.43*		2 x 3	1.39
	1 x 3	23.98*		1 x 3	2.41

* $p < .001$.

All other cells insignificant at = .01, one-tailed test.

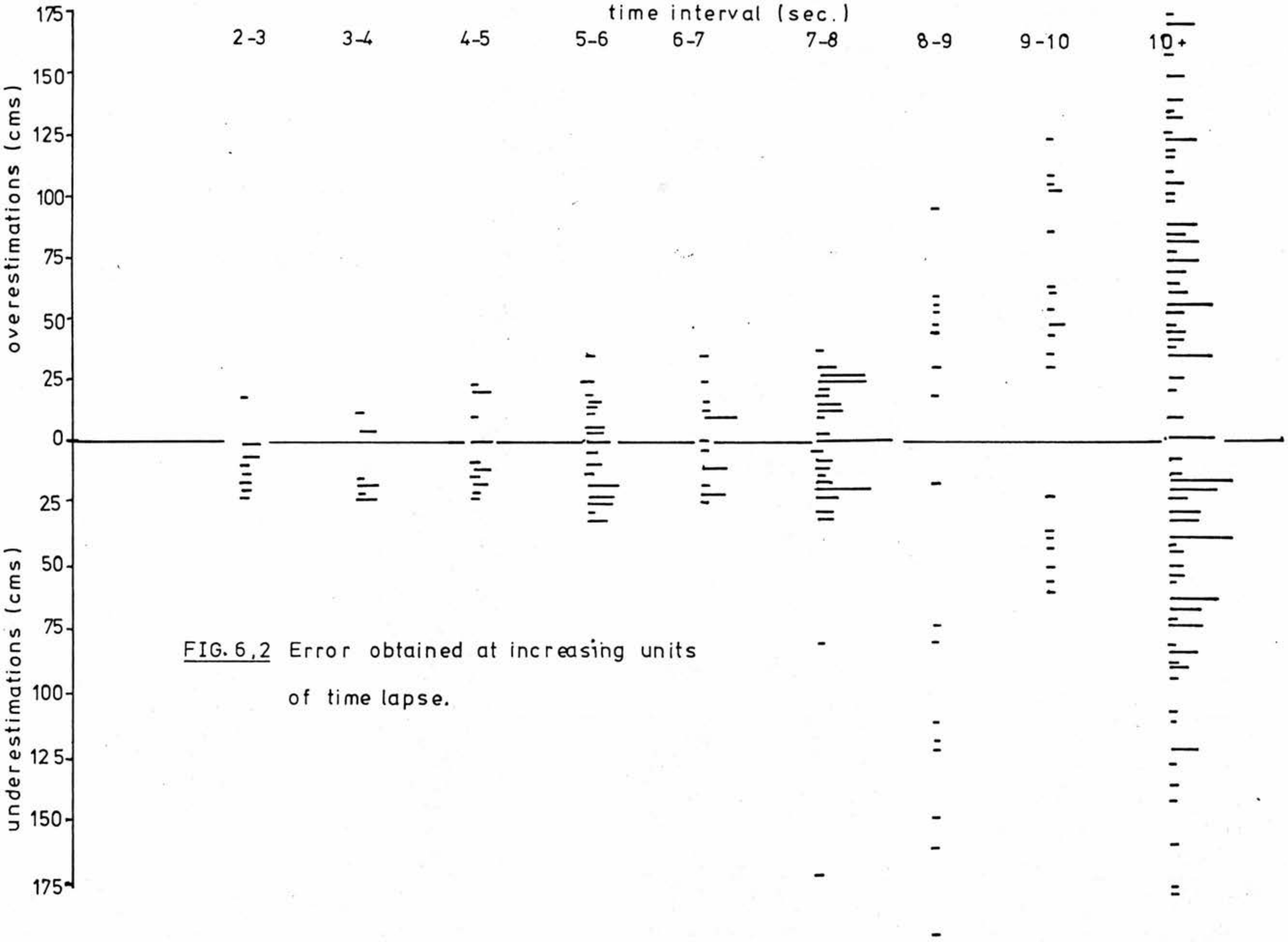


FIG. 6,2 Error obtained at increasing units of time lapse.

TABLE 6.4

Variance as a Function of Time (Condition 1)

Time											
2-2.9	3-3.9	4-4.9	5-5.9	6-6.9	7-7.9	8-8.9	9-9.9	10.10.9	11-11.9	12-12.9	13
54.54	68.38	110.57	154.44	127.92	160.07	3708.10	1552.46	3009.72	2975.42	4997.93	5298.43

TABLE 6.5

Obtained F-ratios on Data of Table 6.4

Source (time interval)	F
$\frac{2}{3} - \frac{3}{4}$	1.35
$\frac{3}{4} - \frac{4}{5}$	1.62
$\frac{4}{5} - \frac{5}{6}$	1.40
$\frac{5}{6} - \frac{6}{7}$	1.21
$\frac{6}{7} - \frac{7}{8}$	1.25
$\frac{7}{8} - \frac{8}{9}$	23.17*
$\frac{8}{9} - \frac{9}{10}$	2.39
$\frac{9}{10} - \frac{10}{11}$	2.61
$\frac{10}{11} - \frac{11}{12}$	1.65
$\frac{11}{12} - \frac{12}{13}$	1.68
$\frac{12}{13} - \frac{13}{13+}$	1.06

* $p < .001$

All other cells insignificant at $= .01$

between the variances are insignificant. These results then seem to confirm that the critical break-point in performance occurs when the time between closing the eyes and reaching the target exceeds about 8 seconds.

The hypothesis that the thresholds in Experiments 2 and 6 are due to temporal trace delay is further supported by the results presented in Fig. 6.3. This figure shows the relationship between time and performance at times below the 8 second threshold, and at times above it. It can be seen from Fig. 6.3a that at sub-threshold times the relationship between time and performance is well described by a linear rule, yielding a Pearson r of .92. This indicates that below the break-point, 85% of the variance is accounted for by temporal factors. Above the break-point, however, the relationship between time and error is considerably less clear. Fig. 6.3b shows the regression line obtained from a Pearson 5 of .69. The best-fitting line in this case accounts for only 48% of the variance and did not satisfy a statistical criterion as differing significantly from zero (t = 1.92; not significant at α = .05, one-tailed test). The results may be interpreted as suggesting that at times of less than the break-point, the relationship between time and performance is close with increases in time producing linear increases in the variance among scores. At 8 seconds, however, a break-point occurs and above this point the relationship is far from clear. It seems that further increases in time are capable of producing some influence on performance but to a far lesser degree, with time now accounting for only the half the variance it accounted for at less than 8 seconds. This result would suggest that some fundamental information ceases to be available at the 8 second breakpoint, yielding greatly reduced accuracy.

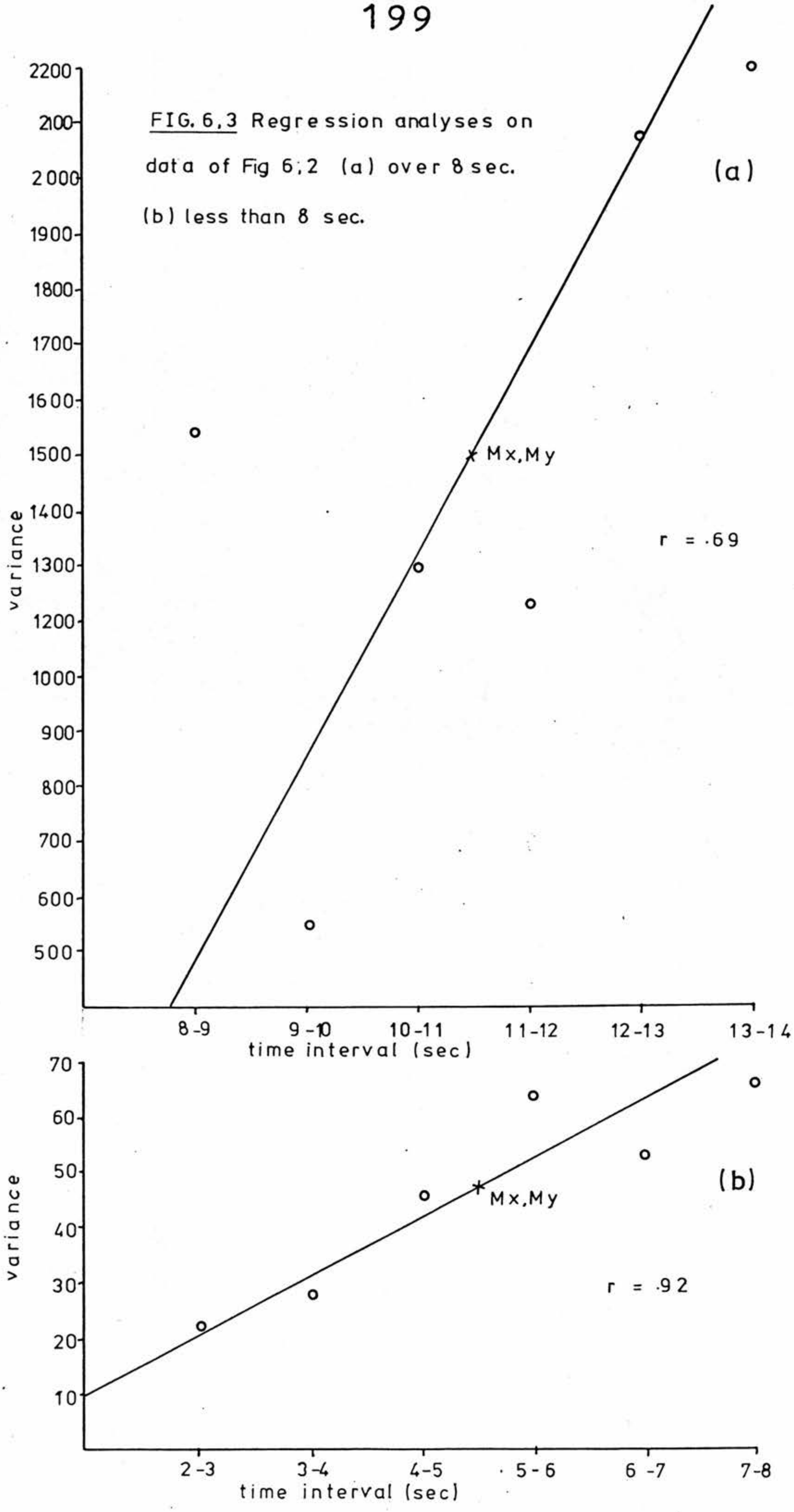


FIG. 6,3 Regression analyses on data of Fig 6;2 (a) over 8 sec. (b) less than 8 sec.

Because this vital information is no longer available, further increases in time have a markedly reduced effect on performance. From Fig. 6.3b it seems that some usable information continues to be available after eight seconds, as evidenced by the fact that 48% of the variance is still accounted for by temporal factors but it is clear that this information is of markedly reduced value for guiding behaviour. The fact that the relationship between time and variance can no longer be adequately accounted for by a linear rule suggests that performance now depends considerably less on the passage of time.

Discussion

The first result of Experiment 6 which should be noted is the confirmation, clearly seen in Fig. 6.1a, of the results of Experiment 2. No subject taking part in Experiment 6 had taken part in Experiment 2, and the results obtained in the control condition of the second experiment thus provide an independent confirmation of the results of the first experiment. This was confirmed by a statistical analysis of the variances at corresponding distances in the two experiments, which showed no differences between the two. We are therefore justified in drawing weight from the first part of Experiment 6 for the conclusions drawn from the results of Experiment 2.

The general prediction which the present experiment was designed to test stated that the dramatic increase in the variance obtained at 12 metres in Experiment 2 was caused by temporal decay of the trace of a program formulated to enable S to reach the target. It was hypothesised that by the time the S had reached the vicinity of 12 metres in Experiment 2, this trace had decayed to such an extent that it could no longer be used to locate the goal. To test the hypothesis that the error at 12 metres and above was due to time factors of this sort it was arranged that subjects should take a similar time to reach targets at the shorter distances of 9 and 6 metres. The prediction was that whenever the time to reach the target exceeded some critical point corresponding to the time taken to reach 12 metres, then performance would show a corresponding deterioration irrespective of the distance.

We can see from Table 6.1 that the essential conditions for a test of this hypothesis have been achieved. The mean time taken to reach 12 metres in Condition 1 was 9.060 secs. According to the predictions, therefore, whenever a response takes a time equal to or greater than this, we may expect the performance to suffer accordingly. It can be seen that this time is exceeded in 3 cases: the mean times to reach 9 metres in Conditions 2 and 3 are 9.84 and 12.71 seconds respectively. The mean time taken to reach 6 metres in Condition 3 is 10.16 seconds. According to the hypothesis therefore, the variance at these distances should match those obtained at 12 metres. An examination of Fig. 6.1 shows that this is true. In Condition 1 only responses at 12 metres took more than the critical time, and the error at this distance is high. In Condition 2, however, the responses at 9 metres exceeded 9 seconds, and a greatly increased error is seen among the scores at this distance. In Condition 3 the critical time is exceeded at 6 metres as well. Again, the performance is found to deteriorate dramatically when this time limit is exceeded. The differences between the variances taking less than the critical time are all insignificant, as are the differences between the variances obtained for times greater than the critical one. These results, then, strongly confirm the experimental predictions. It would appear that the dramatic threshold obtained in Experiment 2 and Condition 1 of Experiment 6 is determined to a very substantial degree by the times taken by subjects to reach the target.

These results so far allow us to say that temporal factors are responsible to a large degree for the results obtained in Experiment 2. It is possible to go beyond this, however, and pin-point more accurately the critical time-lapse which causes performance to deteriorate. This was attempted in Fig. 6.2 and Table 6.4 which show the error obtained at increasing units of time. It is immediately clear that the critical time-point we are looking for occurs at approximately eight seconds. One or two large errors are obtained below this point, in the 7-7.9 second range, but it is clear that some much larger increase in error is to be expected at 8-8.9 seconds than at any lower interval. This was attested to by the results of a statistical analysis which revealed that the change in variance at eight seconds was very highly significant ($F = 23.17$; required F for significance at $\alpha = .01$ with 10 and 63 degrees of freedom = 2.72). Differences between the variances at other consecutive distances all proved insignificant. This seems to highlight the region of eight seconds as critical to performance.

The results of the regression analyses shown in Fig. 6.3 are extremely interesting with regard to the basic hypothesis that the thresholds are due to time factors. We saw in Fig. 6.3a that times between 2 and 8 seconds exert a gradually increasing effect on performance as time increases. Time at this stage accounts for 85% of the variance between scores. Beyond the threshold of 8 seconds, however, the role of time seems far less clear. The best-fitting line describes the date rather poorly, accounting for only 48% of the variance. Furthermore, a statistical analysis did not allow us to conclude that the correlation between time and variance (.69) differed significantly from zero. It seems that time is having a far less direct influence on performance above the threshold.

These results may be interpreted as being highly supportive of the temporal decay theory. As time increases from 0 to 8 seconds, its effect on performance seems to be direct and linear. At 8 seconds a sudden dramatic increase in error occurs. This is followed by error which may continue to increase with time, though this is not entirely clear, and in any case, now accounts for only half the variance it formerly accounted for. This would seem to suggest that as the trace decays, some information begins to be lost which reduces the accuracy of performance proportionately. At about 8 seconds, however, some vital information is lost, and the performance shows a dramatic drop. in accuracy. Beyond this point it is not clear what is happening. Since some 48% of the variance at this point is still accounted for by time, it may be that there remains some vestige of usable information which continues to fade over a longer period with consequent continuing decrease in performance. It seems, however, that performance now depends considerably less on the passage of time. The trace being now almost completely destroyed, time comes to play a minimal role. These findings, then, fit very well with the hypothesis of temporal decay.

A final point which must be made about the results of Experiment 6 concerns the estimation that the breakpoint occurs at 8 seconds. This was based on the fact that whenever the total time between excluding vision and reaching the target (or stopping, if the distance was underestimated) exceeded approximately 8 seconds. However, this must mean that the initial time till the trace fades is somewhat less than 8 seconds, because obviously the trace must decay at some point before the target is reached. We have, however, no way of knowing at this stage where the critical point really occurs. It may be possible to estimate this more accurately in future experiments, but for the moment we can only note the existence of the problem. Since we cannot go beyond this, we will continue to base time estimates on the time elapsing between exclusion of vision and reaching the target. Obviously, however, it would be desirable to go beyond this.

Conclusions

The results of Experiment 6 seem to fit very well with the hypothesis formulated at the beginning of the experiment. It appears as if some sort of temporal decay is indeed responsible for the threshholds in accuracy found in Experiments 2 and 6. It appears further that these thresholds are to be expected whenever the total time from closing the eyes to reaching the target exceeds 8 seconds, and that the initial time needed for decay must occur at a point of somewhat less than this.

With regard to the alternative explanation of perceptual limitation put forward in the introduction to Part III, it can be said that the results of Experiment 6 throw some doubt on it. The fact that temporal factors were found to account for the greatest part of the variance seen at 12m. would strongly suggest that perceptual limitations were not involved in that particular threshold. However, we may leave a decision on the role of perceptual factors until the second study of temporal factors, Experiment 7, has been reported.

EXPERIMENT 7

TEMPORAL LIMITATIONS IN THE ABILITY TO CONTROL BEHAVIOUR IN THE ABSENCE OF VISION II

Introduction

We saw in Experiment 6 that it was possible to generate the same thresholds in performance as we first saw in Experiment 2 by controlling the time which elapses between closing the eyes and reaching the target. It was found that when subjects were forced to take the same time to reach targets at 6 and 9 metres as they took to reach the threshold distance of 12m. then the pattern of error at the nearer distances mirrored that obtained at 12m. This result was taken to imply that the trace of whatever information is internalised for guiding behaviour fades over time, and that whenever the time taken to complete an act exceeds that time, then the accuracy of the act will suffer. This finding was taken to explain the original threshold found in Experiment 2.

It is possible to test in another way the hypothesis that the major limiting factor under the conditions employed is the time which elapses between closing the eyes and reaching the object. In Experiment 6, this was achieved by artificially increasing the time taken to reach targets at distances nearer than the original threshold distance. It is obviously possible to test the hypothesis in the converse way, however, by <u>shortening</u> the length of time taken to reach <u>longer</u> distances. For example, if subjects can be made to take less than the critical time of 8 seconds to reach a target at 12m, then the threshold found there in Experiment 2 would be expected to move up to

15m, with performance at 12m. mirroring that obtained at 9m. If this were possible, then the evidence and conclusions of Experiment 6 would be greatly strengthened. Experiment 7 was therefore designed to test this hypothesis.

Method

Design

The design of Experiment 7 closely followed that of Experiment 2. Five locomotor distances were chosen at 9, 12, 15, 18 and 21 metres. These distances were selected as being the threshold distances of 9 and 12 metres in Experiment 2, together with the three high error, post-threshold distances. The experiment took place on the same location as Experiments 2 and 3 and used the same pathways. The target positions were indicated in the same way by means of a wooden marker placed on the left-hand side of the subject's path. Echo location and other forms of auditory information were controlled by means of a white noise apparatus, which was effective in eliminating such information from subjects during the course of the experiment.

Since Condition 2 of Experiment 2 acts as a control of how subjects perform when visual information is available during the execution of an act of this sort, it was considered unnecessary to repeat that condition here. Responses at the 9 metre distance also represent a control against which responses at further distances can be evaluated. Since it has already been seen that non-visual responses to targets set at 9 metres do not differ significantly from responses made when vision is available, this is quite acceptable. For these reasons, only one condition was employed in Experiment 7.

This condition was designed to get subjects to take less than the critical time, estimated in Experiment 6 to be 8 seconds, to reach the target irrespective of distance to the target. Some subjects wished to be allowed to walk quickly rather than to run, and so long as this seemed to be done in a natural manner it was allowed. In general, however, it proved necessary to run in order to reach the furthest distances in the time allowed, and subjects were encouraged to use this mode of locomotion.

Procedure

As in the earlier studies, a short practice and instruction period was given to subjects before the experiment proper began. As would be expected, it proved difficult at first to get some subjects at first to cover the distances at a sufficiently fast rate to reach the target within the time allowed. In general, however, it was remarkably easy to perform the experiment when it is considered that they were asked to run distances of up to 21 metres over rough ground in less than 8 seconds with the eyes shut. It will be seen in the results section that subjects were not always successful in covering the distances in the time allowed. In such cases, subjects were encouraged to move faster, and extra trials were given. Where it did not prove possible to get subjects to perform within the limits on all trials, even after a number of extra trials had been given, the responses on those trials were recorded as they were obtained. It was not possible to give subjects too many extra trials because the experiment was already rather long and tiring.

At the beginning of each trial the subject was lined up at the starting-point while the target was placed in position. The white noise was turned on and S was allowed to choose when to begin the trial. S simply closed his eyes and commenced his approach to the target. When the trial ended, he remained with eyes closed until the response had been marked by means of a coloured pin and until E had led him back a substantial way towards the starting-point. Trials were given alternatively on the two pathways, and the presentation of the distances was randomised. Five trials were given at each distance.

As in Experiment 2, no blindfold was used to exclude vision, subjects being asked simply to close their eyes. It was felt impossible to ask subjects to perform Experiment 7 with a blindfold on, because the dangers of Experiment 2 were greatly increased in the present one. Obviously, when running over uneven ground with the eyes shut, there is a considerable danger of stumbling and falling: and indeed, stumbles did occur on occasion. Because of this danger, E always stood part way along the track - though always somewhat back from the subject's path - in order to be in a better position to reach S if he should fall. On the few occasions when this did happen, the trial was obviously scrapped, and a new one initiated.

The danger of malingering by subjects is obviously more important in Experiment 7, since the hypothesis on performance is that it will be high throughout. This means that there is no "variable performance" hypothesis on which to catch malingerers out. For this reason, care was taken in the selection of subjects for the present experiment, all of whom were personally known to the writer and who were considered sufficiently mature to perform the experiment as asked. As an extra control, however, E kept a particularly close watch on subjects to ensure that performance was taking place as demanded. No reason for suspicion arose with any of the subjects.

Subjects

Nine subjects took part in Experiment 7, 6 male and 3 female. All were students at Edinburgh University and were aged between 22 and 30 years. None of the subjects was familiar with the purpose or predicted results of the experiment.

Results

Table 7.1 shows the mean times taken by the subjects as a group to reach each of the five distances. It can be seen that the procedure employed was moderately successful in producing the desired times, though this was not satisfactorily achieved at the 18 and 21 metre distances.

TABLE 7.1

Means and Standard Deviations of Times Taken to reach Each Distance

	Distance (Metres)				
	9	12	15	18	21
Mean	3.99	4.95	5.88	6.93	8.01
S.D.	.90	1.35	1.69	1.84	1.90

The imprecision in controlling the temporal paramaters at the longer distances is evident in Fig. 7.1, which shows the error obtained at each of the five distances. It can be seen that a high percentage of responses at 18 and 21 metres took longer than 8 seconds (responses circled) and this has greatly increased the overall variance at these distances. Nevertheless, it is clear from Fig. 7.1 that the error obtained whenever the critical time falls short of 8 seconds, does support the experimental predictions very well. It is clear that

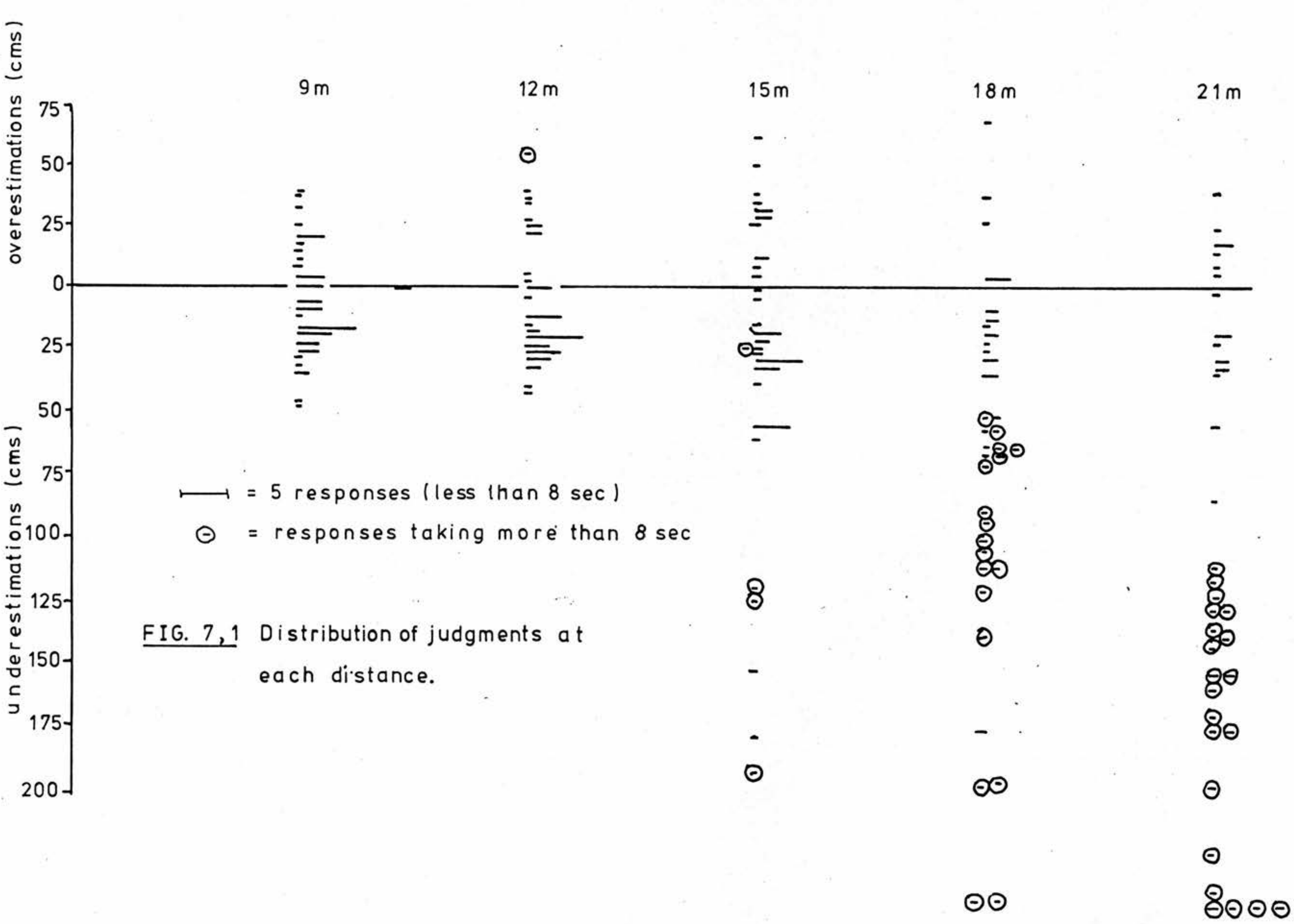


FIG. 7,1 Distribution of judgments at each distance.

the variance among such responses remains very stable over all distances. A statistical analysis confirms this. The variances at 12, 15, 18 and 21 metres did not in case differ significantly from the variance obtained at 9 metres (9x12, F = 1.13; 9x15, F = 2.25; 9x18, F = 2.38; 9x21, F = 2.18, all insignificant at $\alpha = .01$, one-tailed test). The results therefore support the basic hypothesis of Experiment 7. It can also be shown that the variance obtained at 9 metres in the present experiment does not differ significantly from the corresponding variance in Experiment 2 (9x9, F = 1.03, n.s. at $\alpha = .01$). Since the variance at 9 metres in Experiment 2 was larger than that obtained in Experiment 7, this means that the performances at the 12 to 21 metre distances in Experiment 7 did not differ from that obtained at 9 metres in Experiment 2 either. These results, then, fit extremely well with the experimental hypotheses.

The influence on performance of the time elapsing between closing the eyes and reaching the target can be gauged more directly from Fig. 7.2 which shows the error made at increasing time-lapse intervals. It can be seen that the variance remains relatively stable over time lapses of 2 to 7 seconds. After the 7-7.9 sec. lapse, performance continues to remain relatively stable with one or two large errors, but at eight seconds and over it is clear that the error has greatly increased. This is clearly seen not only in the increased variance among scores, but in the average deviation from the target line as well, as can be seen from Table 7.2.

These trends were examined statistically and were confirmed. Table 7.3 shows the results of a comparison of the variances at each time lapse. It can be seen that no differences emerge until the 7 - 7.9 sec. time lapse, where the difference in variance reaches

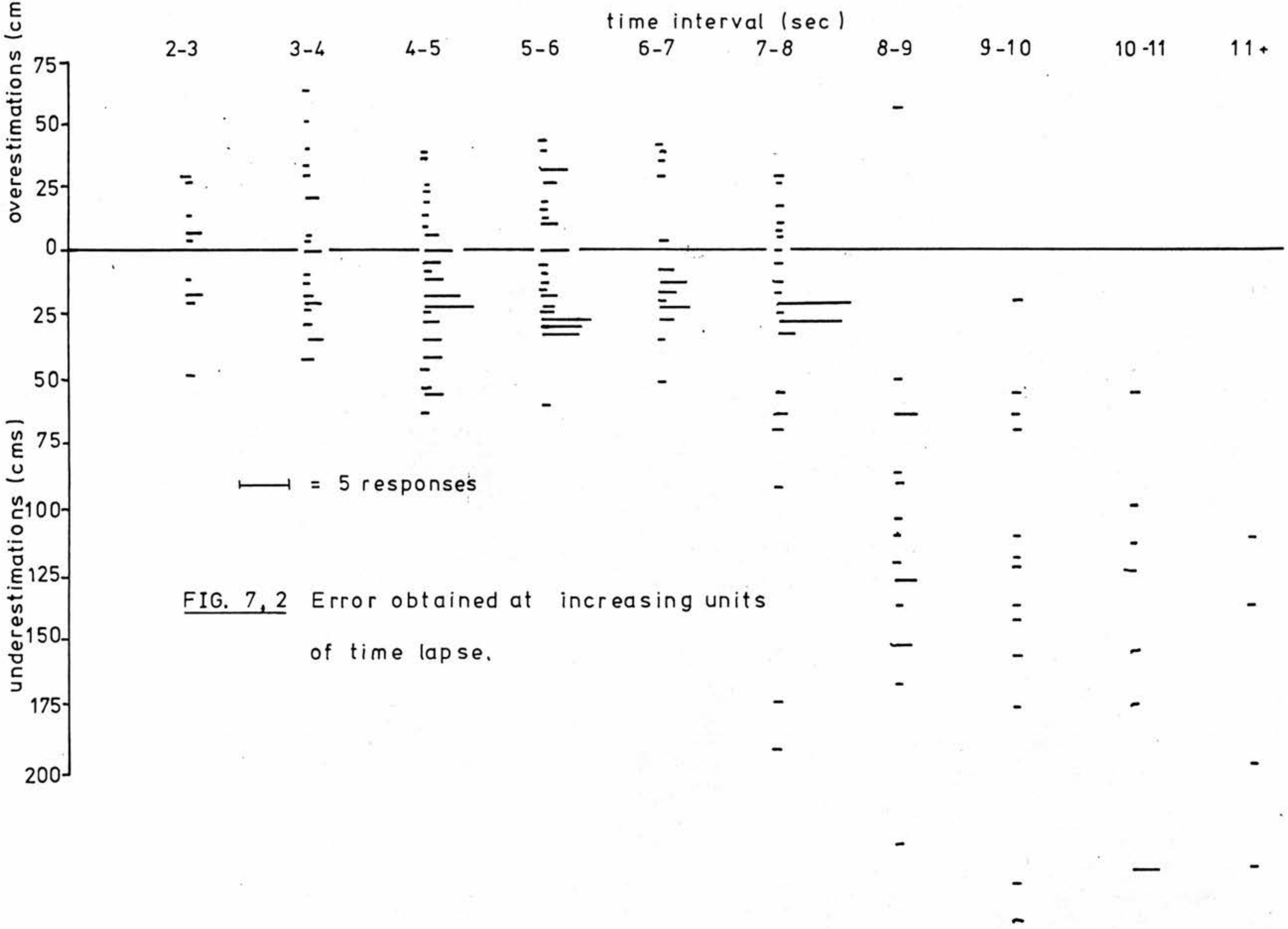


FIG. 7, 2 Error obtained at increasing units of time lapse.

TABLE 7.2

Means and Standard Deviations of Variances at Increasing Units of Time-Lapse

	Time Lapse (Seconds)									
	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-
Mean Deviation	2.4	3.6	-12.0	-9.6	-8.6	-29.0	-112.6	-127.0	-147.4	-193.2
Standard Deviation	23.5	30.0	31.9	25.9	26.2	50.4	65.3	116.9	71.3	86.6
Variance	225.6	371.5	425.8	278.4	286.3	1060.3	1778.6	5697.1	1112.7	3120.7

Error in cms.

TABLE 7.3

F and t Values of Means and Variances Shown in Table 7.2

Time Lapse	t	Time Lapse Comparisons	F
2-3	.34	2/3 - 3/4	1.65
3-4	.66	3/4 - 4/5	1.24
4-5	2.36	4/5 - 5/6	1.05
5-6	2.29	5/6 - 6/7	1.04
6-7	1.51	6/7 - 7/8	3.70^{*}
7-8	4.28^{**}	7/8 - 8/9	1.68
8-9	6.89^{**}	8/9 - 9/10	3.20
9-10	3.92^{*}	9/10-10/11	2.70
10-11	5.85^{**}	10/11-11/12	1.48
11-	4.46^{*}		

* $p < .01$

** $p < .0005$

All other cells insignificant at = .01

significance. The differences at subsequent time lapses were all insignificant. Table 7.3 also shows mean error obtained at each time lapse. At lapses from 2-6.9 secs., the average error did not differ significantly from zero, but in all subsequent cases, the deviations were highly significant. These results, then, suggest that for time lapses of approximately 7-8 seconds and above, performance can be expected to suffer very substantial impairment as compared to shorter time lapses.

The results which have been outlined above are confirmed when we examine the results of individual subjects as well. The profiles for each individual subject are shown in Figure 7.3. Responses taking less than 8 seconds are indicated by dots and those taking more than 8 seconds are ringed. It can immediately be seen that responses taking less than the threshold consistently group themselves around the target line, whereas those taking more than the threshold time-lapse fall consistently and substantially short of the line.

Finally, we can gauge the overall accuracy of subjects in Experiment 7 from Table 7.4, which shows the percentages of responses falling within 30 cms. of the target. The percentage declines somewhat as distance increases, but the mean accuracy over all five distances is 71%. This result therefore adds a final piece of support to the experimental hypothesis.

TABLE 7.4

Percentages of Responses falling within 30 cms. of the Target at each Distance

Distance (metres)									
9		12		15		18		21	
No.	%	No.	%	No.	%	No.	%	No.	%
38	83	31	76	20	56	16	70	12	67

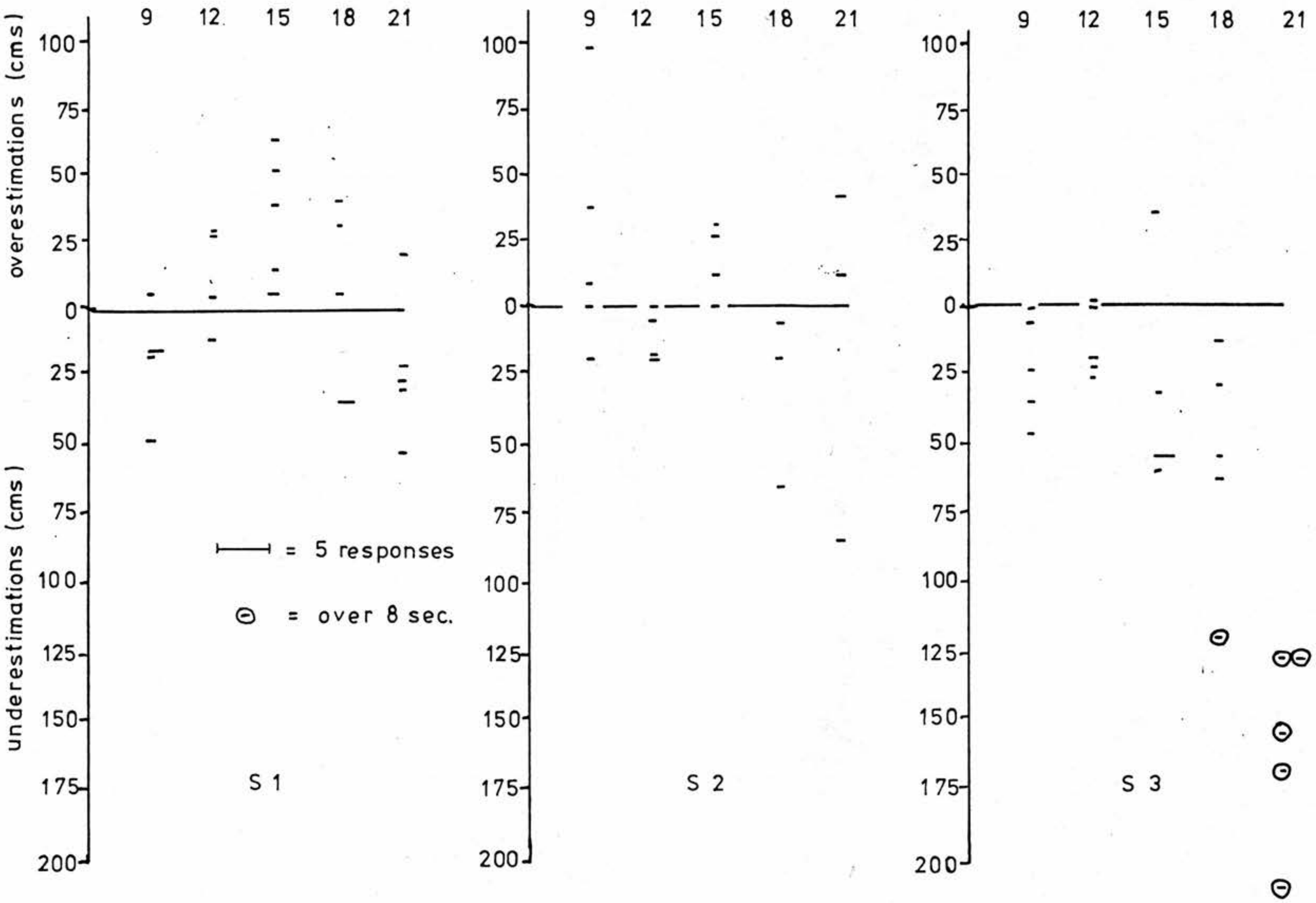


FIG 7.3 Distribution of judgments at each distance (individual subjects).

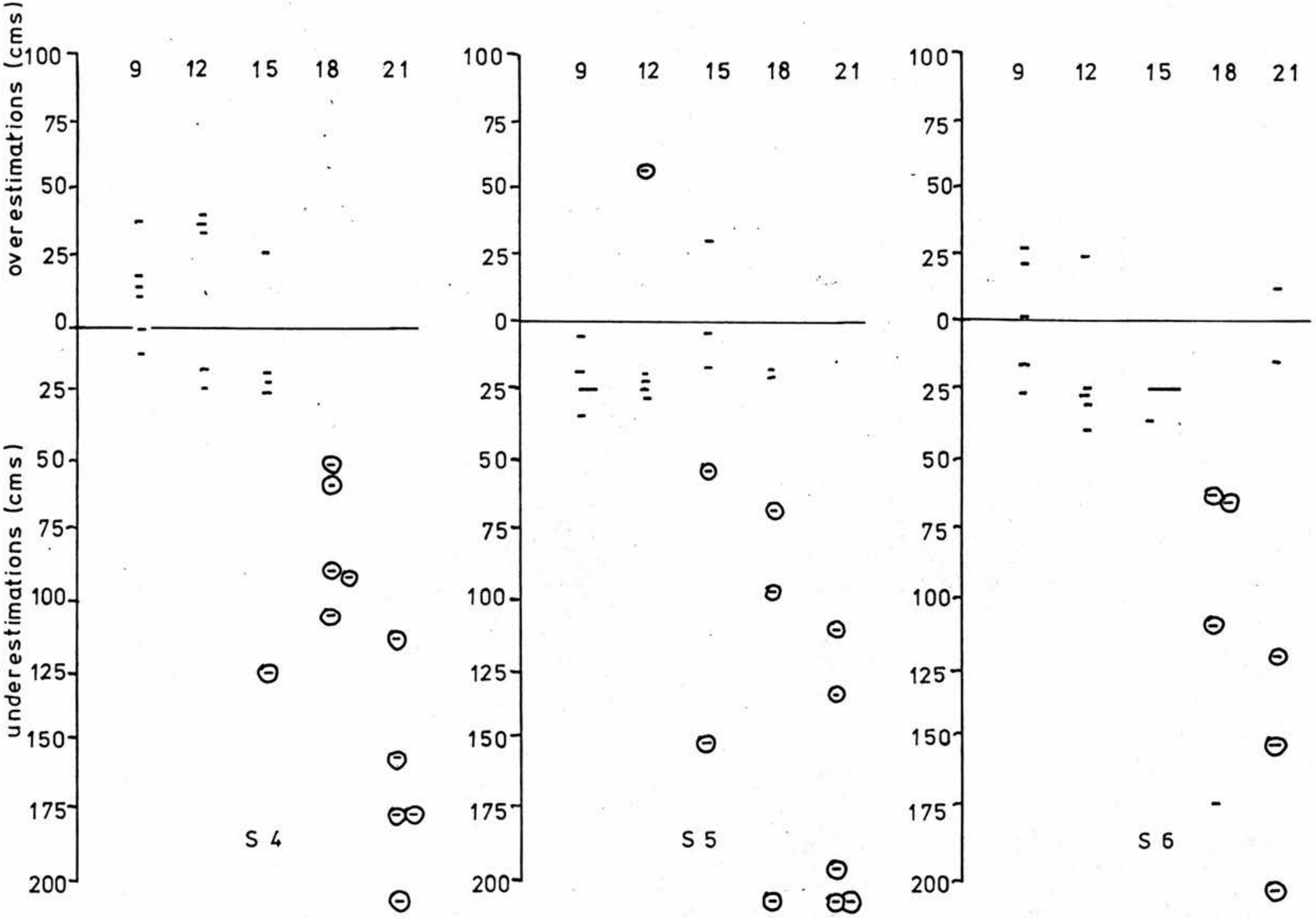

overestimations (cms)
underestimations (cms)
100
75
50
25
0
25
50
75
100
125
150
175
200
9
12
15
18
21
S 4
S 5
S 6

FIG. 7,3 (contd.).

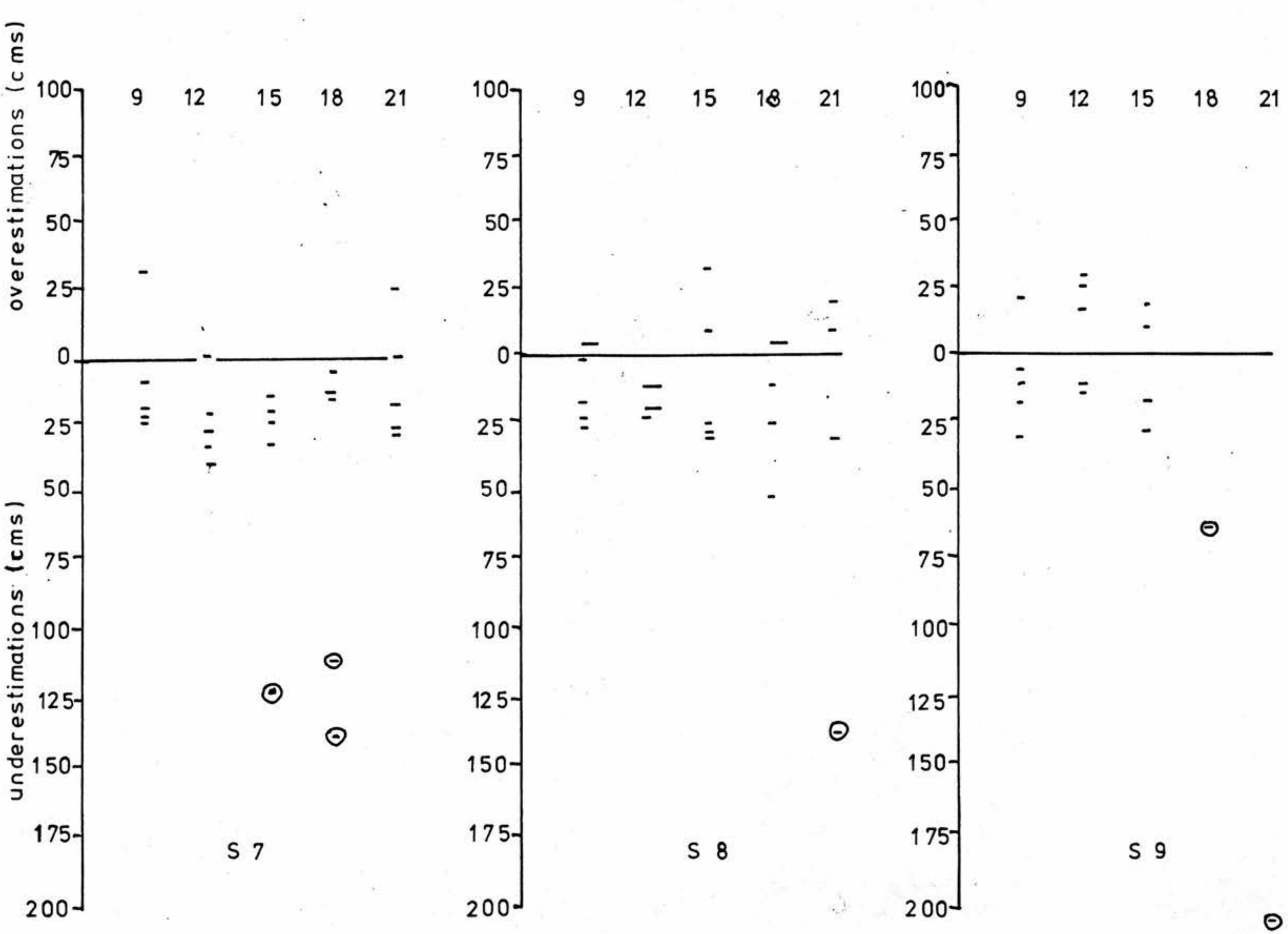

overestimations (cms)
underestimations (cms)
100
75
50
25
0
25
50
75
100
125
150
175
200
9
12
15
18
21
S 7
S 8
S 9

FIG. 7,3 (contd.)

Discussion

The hypothesis which Experiment 7 was designed to test stated that so long as the time-lapse between closing the eyes and reaching a target does not exceed approximately eight seconds, then a subject's ability to locate that target will not differ significantly from his ability to do so when the eyes are open. This hypothesis seems to be confirmed in the present experiment. We saw in Figure 7.1 that whenever subjects took less than eight seconds to reach the target, irrespective of distance, then the performance did not differ either from that obtained at 9 metres, where performance should be high according to the results of earlier experiments, or from the corresponding performances when vision is avilable. The result is evident in Fig. 7.1 which shows the performance of the subjects as a group, and also in Fig. 7.3 which shows the response profiles of the individual subjects. The effect does not appear to be merely a conglomerate group effect, but seems to underlie the behaviour of each subject as an individual as well. These findings therefore greatly strengthen the hypothesis of temporal delay.

The high accuracy of the responses can also be seen from Table 7.4 which shows the percentage of responses falling within 30 cms. of the target. The accuracy, by this definition of accuracy, was somewhat higher at the nearer than at the further distances, but the mean percentage falling within 30 cms. irrespective of distance was 71%, indicating a high degree of accuracy. This is, however, lower than in Experiment 2 where 84% of all responses at distances below the threshold fell within 24 cms. of the target. It seems highly likely, however, that this difference is due to the different modes of locomotion used in the two experiments. Experiment 2 used a walk-mode, and it certainly seems likely that this would occasion greater accuracy than running. This is further supported by the fact that in Experiment 7, only 72% of the responses at 9m. fell within 24cms. of the target, compared to 84% in Experiment 2 and 82% in Condition 1 of Experiment 6. The effect is not therefore restricted to the distances beyond 12m. where it might be expected that the variance is only partially due to temporal factors; it occurs at the "high performance" distances of Experiments 1 and 2 as well. Since the only difference in these cases is the mode of locomotion used, it seems that the larger variances found in Experiment 7 are due to this factor. Nevertheless, it must be emphasised that no significant differences were found between variances at less than eight seconds time-lapse, irrespective of the distances involved. The consistency and general accuracy of subject's responses seem to be roughly the same in all the current experiments.

We found in Experiment 6 that the critical time lapse at which performance broke down occurred at approximately eight seconds. Since Experiment 7 was not successful in keeping all responses below eight seconds as intended, it was possible to re-examine the role of time lapse on performance. The results of the analysis of performance in relation to time were shown in Fig. 7.2. As in Experiment 6 it was found that performance at eight seconds was considerably poorer than at the shorter time-lapses. However, the statistical analysis identified 7-7.9 seconds as the threshold time, and this constitutes a deviation from the results of Experiment 6. In fact, an examination of Figs. 6.2

and 7.2 indicates a considerable similarity in the two cases. In both experiments, the majority of responses at 7-7.9 seconds fall within the same range as at lower time-lapses, with only one or two responses deviating from the pattern in Experiment 7. When these responses are removed, the results at 7 seconds fail to differ significantly from those at shorter time-intervals (6x7, F = 1.81, n.s. at $\alpha = .01$, one-tailed test). The result indicates, nevertheless, that time lapses of less than eight seconds can be effective in reducing performance. However, when it is seen that the time-lapses producing the deviant responses at 7 seconds fell at 7.9, 7.9 and 7.8 seconds, it is clear that the essential result of Experiment 6 is upheld. Differences of this order should not force us to change our original proposal that a time-lapse of approximately eight seconds represents the limiting factor to performance accuracy.

In the Introduction to Part III, we indicated three possible causes of the limitation found in Experiment 2. These possibilities were: perceptual limitations, limited information storage capacity, and temporal decay of the trace of the information. It appears that we can now make a decision as to the most likely of the three possibilities. The results of Experiments 6 and 7 almost certainly exclude perceptual limitation as a factor determining performance for distances of up to 21m. at least. In Experiment 6, we saw that the performance deteriorated according to time, not according to distance, but the lack of perceptual determination of performance was most clearly seen in Experiment 7, where it was shown that distances of up to 21m. at least could be reached so long as the eight second rule was not broken. These results therefore enable us to reject perceptual limitation as an appealing explanation of the results. It seems reasonable to reject the hypothesis of limited information storage from these results also. This is because a program formulated to enable S to reach a point one pace away cannot be said to be more complex than a program to reach a point n paces away. The details of the instructions would vary from situation to situation, but the complexity of the overall program remains the same. Of course, a problem might arise when S is asked to formulate this program from the information available, but this becomes a problem of <u>perceptual</u> limitation, and we have already seen that this kind of limitation does not seem to operate within the distance bracket investigated so far. From the point of view of program complexity, a change in the quantitative values of the program units cannot be considered to change the basic complexity of the program. These results therefore strongly implicate temporal decay as the main agent responsible for the results of Experiments 6 and 7. Exactly what form of information it is that decays with time is the subject of the next section of this thesis.

<u>Conclusions</u>

The results of Experiment 7 strongly confirm the prediction that temporal decay is responsible for the thresholds in performance, wherever these occur. The exact interpretation of this result requires a section to itself, and this is the task of the discussion which follows. But the general hypothesis of temporal decay, and the conclusions of Experiment 6, are strongly supported by the current experiment.

GENERAL DISCUSSION OF EXPERIMENTS 6 and 7

The results of Experiments 6 and 7 strongly suggested that the threshold in performance originally obtained at 12m. was due to fading of the information about distance which had been internalised. This conclusion was supported by the finding that through temporal manipulation, the threshold could be brought down from 12m. to 9m. and 6m. Conversely, by shortening the length of time taken to reach the targets, it was shown that the threshold could be moved up at least as far as 21m. These results strongly implicated temporal decay as the cause of the effect.

A question which we can now ask, is the extent to which this finding can be said to throw light on the nature of the mechanism underlying the general ability we are investigating. In Part I, and generally up until this point, we have argued that behaviour is controlled by means of programs for action, these programs containing a specification of the motor actions necessary to accomplish whatever act is under consideration. The motor action contained within these programs would be composed of a group of action units which, in the case of locomotion, would be paces, strides, crawls, hops, or other units typically seen in locomotor behaviour. Thus, a program for action would simply indicate the number of such units required to reach the target under consideration. In this way, we could talk of formulating programs for action and perceiving distance, as being equivalent ways of saying the same thing.

However, while we have argued that such a mechanism is responsible for the abilities seen in Part II, and while we shall continue to argue that a mechanism such as this does indeed play a role in motor control as will be seen more clearly below, it does not seem that this type of mechanism is compatible with the results obtained in Experiments 6 and 7. This is because it does not seem likely that programs of the sort indicated above would be subject to the kind of decay observed in those experiments. With the program defined simply in terms of a given number of action units, it does not seem likely that this form of information would decay until run off or written over in the storage unit. This is because the program would take the form of a set of instructions in which the number of action units necessary for successful performance of the task would be defined. It seems hardly likely that information of this sort would be subject to the kind of strict temporal control seen in Experiments 6 and 7.

If the information used to control activity in these experiments did not take the form of programs, we may ask what alternative form the information might have taken. The alternative which seems most likely is that the subjects retain an image or map of the environment, and use this to guide behaviour in much the same way as they might use visual information directly available at the eye. It is much easier to understand such a map fading in time than to imagine a program fading.

The notion of map being employed here differs considerably from the notion which is normally found in the psychological literature. The notion of map usually employed is that of "cognitive map" (Tolman, 1949), and refers to some form of internalised representation of the layout of an environment. This representation, however, is built up through prolonged contact with the environment concerned, and becomes a more or less long-term fixture within the subject. In this respect, a cognitive map compares to "pre-programs" (see, e.g. Bartlett, 1932); behaviours which have been established after long periods of practice and which can be subsequently run off as ballistic wholes (e.g. tennis serves, golf swings). The evidence that a cognitive map is indeed a map and not a complex program is drawn from studies where the layout of the environment is changed to allow the map to show itself. For example, Spence and Shipley (1934) showed that if blind alleys in a maze were opened, rats would take these new routes to the food-box almost immediately if these were quicker. There was no new learning process. Lashley (1929) found that when the wire mesh over the trap of the maze was accidentally left off, the rats would climb over the walls to shorten the journey. Studies of this kind clearly implicate some kind of internalised map of the environment concerned.

However, these notions of map differ from the notion being proposed here to explain the results of Experiments 6 and 7. In the present case, the map is not built into the system through prolonged exposure to the particular environment concerned, but rather is immediately available to the subject without any preliminary contact being necessary, though for a limited period not exceeding 8 seconds. This map, then, would seem to exist in a kind of short-term memory, disappearing after a certain period whether used or not.

We may well ask why it is that maps of this kind should be necessary: why could behaviour not be controlled simply on the basis of programs as originally suggested? There seem to be two basic reasons for this: first of all, a program for action is to some extent idealised, and it is unlikely that it will normally bear a one to one correspondence with the behaviour executed. For this reason, a program will always have a degree of error associated with it. It should be clear that this error is likely to grow larger and more significant as the program increases in size. We would therefore expect that at longer distances, the error in an executed program would become too great for the program to have been of much value, and we might well predict that the system must be restricted to formulating shorter programs where the accuracy would be sufficient to be valuable. There is evidence to support this notion that programs are of limited accuracy in the results of Experiment 5. Even in the programmed run-up of Olympic long-jumpers the program could not be perfectly realised due to the accumulative error in execution which built up as the athlete proceeded down the tract. If athletes of this calibre, after years of training, cannot achieve greater control of a single locomotor program, this is surely indicative of the basic problem proposed. However, since it is of benefit to the organism for its visual system to be freed from the task of guidance for as long as possible, we might expect that some alternative representation of the environment be retained for longer distances. This representation or map would then allow the subject to turn his visual system to other tasks and use the map to formulate further programs for controlling behaviour as these were necessary. Such a method would clearly extend the periods over which independence of the visual system could be achieved.

A related reason why it is of value to have maps, is that maps give a greater fluidity than programs. If a mismatch occurs between programmed and executed action, it would be difficult to correct this mismatch from a program except by a complicated process of checking size of steps taken against the idealised ones and adding the mismatch on later. But this kind of problem can be solved much more easily if there is an image available which can be updated more directly. For these reasons, then, it would appear that a system capable of retaining short-term maps is likely to have an advantage over systems which are capable only of programming.

This discussion should not allow us to think that programming has no function in the system, however, for it must indeed have a function for reasons outlined in detail in Part I. It was argued that animals must always know at some point in advance what his action-relation to an obstacle is. If he does not have information of that kind, he cannot know how his behaviour relative to the obstacle is to be regulated. This would therefore always involve apprehending in motor terms what that relation is, and formulating decisions in advance of any actions necessary to enable the control desired to take place. For these reasons, it would always be necessary to program in advance.

If it is accepted that the results of Experiments 6 and 7 are more consistent with the concept of map than with the concept of program, there are two questions which may be asked: firstly, we may ask what evidence there actually is for the programs which it has been claimed operate at shorter distances. Secondly, it would be desirable to have evidence supporting in a more direct way the concept of map. It is the purpose of the remainder of Part III to provide such evidence and to try to show how the two mechanisms are linked.

EXPERIMENT 8

THE CONTROL OF LOCOMOTION BY MEANS OF MOTOR PROGRAMS

Introduction

The evidence obtained in Experiments 6 and 7 suggested that subjects were capable of internalising information about the external environment in the form of a map, and of using this map to control behaviour in place of vision. It was argued that this map is used to formulate programs for action in the same way as they can be formulated directly through vision. However, if a map interpretation of the results is accepted, at least provisionally, it must be said that little evidence in support of the concept of map has been obtained at all. Some evidence was obtained in Experiment 5 (long jump) where we saw, particularly in the case of Valerie's six runs, that some form of programming seemed to be taking place, but in general there is relatively little evidence of it. Furthermore, although we have asserted that programs can be formulated over limited distances only, we have no real idea of how extensive such programs can be. The purpose of Experiment 8 was to try to solve both of these problems; to provide evidence, firstly in support of the concept of program in general, and secondly to try to show the kind of distances over which such programs can operate.

In our general discussion of the results of Experiments 6 and 7, we argued against interpreting the results in favour of the concept of program, on the grounds that a program as we had defined it would be unlikely to suffer decay in the way found. Such a form of decay was more compatible with the concept of map. We concluded that programs are used for guidance over short distances, control over longer stretches being accomplished by means of maps.

If this argument is correct, however, we should be able to demonstrate the existence of programs by following the basic method which inspired Experiments 6 and 7. If programs are formulated over short distances only and if they are not subject to decay over time in the way that maps are, then by following the method of Experiment 6 over short distances, we should find the converse result: namely that temporal delay does not affect performance. This can be tested quite easily by extending the range of distances tested in Experiment 6 downwards. It will be remembered that in that experiment, attempts to bring the threshold downwards were not extended beyond six metres. At the time it was felt unnecessary to go beyond this to demonstrate the effect of temporal decay. However, we can now predict that at some distances of less than 6 metres the effect will not hold, due to the existence of programs at these distances. Experiment 8 was designed to test this hypothesis.

Method

Design

The design of Experiment 8 was, in fact, basically a replica of that of Experiment 6, except that the distances employed were different. Six locomotor distances were chosen, at 1, 2, 3, 4, 5 and 6 metres. Distances at less than 6 metres were chosen to see at what point evidence of a program could be found. Six metres itself was chosen as the lowest point at which temporal factors were found to operate in Experiment 6. Unlike Experiment 6, Experiment 8 was performed indoors, on the same location as Experiments 1, 3 and 4. The target was represented by a line drawn on the floor with a wooden marker placed opposite. This marker was moved around by the experimenter, and was used to indicate the target currently being used. As in previous experiments, auditory information was controlled by means of a white noise apparatus.

The experiment was conducted under two conditions:

(1) Experimental Condition. In this condition the time taken by subjects to reach the targets was manipulated in such a way that the critical time point of 8 seconds found in Experiments 6 and 7 was increased by at least 50%. Thus the time elapsing between the point at which vision was excluded and the point at which the target was reached was manipulated so that it equalled not less than 12 seconds in each case. In order to accomplish this, a number of pilot trials were run over the six distances used under the basic, non-visual condition as employed in Experiment 1, and the times to reach the distances measured. These times then made it possible to calculate the delays which would be necessary at each distance, to generate a total time of 12 seconds. The pilot studies were conducted with subjects other than those taking part in the experiment proper.

(2) Control Condition. This condition was simply a replication of the non-visual condition of Experiment 1, using a different set of distances. No time delay was involved in this condition.

Procedure

As with the design, the procedure was similar to that used in Experiment 6. In Condition 1, the procedure was as follows: S stood lined up at the starting point and the white noise was turned on. He was instructed to close his eyes while the marker was placed at the appropriate target point. This was simply to avoid the possibilities of distance cues being picked up from the experimenter's movements between the target points. The subject was then allowed to survey the target and decide for himself when to begin. At the point at which he closed his eyes, he informed the experimenter by saying "Now". A stop-watch was started and timing began. When the appropriate time-lapse for the distance under consideration had passed, E simply tapped S on the shoulder and S immediately began his orientation. Although there has to be a finite time between the point at which S is told to start walking and the point at which he actually begins to do so, this can be controlled after only a very short practice period with the method, which, although extremely simple, proved equally effective in achieving the control over time desired.

Each subject was presented with three trials at each distance in each condition. It was considered that the number of trials could not be extended beyond this because of the role of fatigue, which proved very strong. Indeed, subjects had to be given a short break part of the way through Condition 1, as well as between Conditions 1 and 2, to counteract its effects. The result of each trial was measured immediately by the experimenter because any marks made on the surface would have been visible to the subjects and would have provided an unwanted source of feedback about previous performances.

After each trial had ended, S remained with his eyes closed until E had measured the response, after which he was turned round and walked back to the starting point. In this way, all feedback about performance was excluded. Only after the marker had been placed in position for the next trial was S allowed to open his eyes.

The presentation of trials was randomised within each condition, but the conditions were presented consecutively, with the experimental condition being run first.

Subjects

Nine subjects took part in Experiment 8, 8 male and 1 female. All were students at Edinburgh University, and were aged between 20 and 30 years.

Results

Table 8.1 shows the mean times taken to reach the different distances in the two conditions. It can be seen that the manipulation employed in Condition 1 was effective in increasing the total times to a level some 50% higher than the initial time of 8 seconds. The mean times were, in fact, slightly longer by about half a second than was intended, but this makes no difference to the task. The experimental manipulations seem, then, to have been successful in creating the desired conditions.

TABLE 8.1

Means and Standard Deviations of Times Taken at Each Distance

	Distance (Metres)					
	1	2	3	4	5	6
Time delay	12.68±.74	12.67±.44	12.57±.39	12.66±.56	12.49±.74	12.76±.80
No Time delay	1.34±.48	2.24±.51	3.17±.73	3.67±.62	4.28±.66	5.28±.92

The basic result of Experiment 8 is shown in Fig. 8.1 which shows the distribution of judgments around the target lines in each condition. The effect of the conditions is immediately clear. In Condition 1, a time delay greatly exceeding that which caused disruptions in Experiment 6 apparently has no effect on distances of less than 6m. At 6m, however, the characteristic break-down in performance seen in the earlier experiments is found. The differences between the variances in the different conditions were examined statistically by means of the F test for homogeneity of variances at $\alpha = .01$, one-tailed test. The differences in variance at corresponding distances all proved insignificant except at the 6m. distance where the difference between the conditions was highly significant (1x1, F=1.28, n.s.; 2x2,F=1.10, n.s.; 3x3, F=1.68, n.s.; 4x4, F=1.18, n.s.; 5x5, F=1.20, n.s.; 6x6, F=10.16, $p < .001$). These results strongly support the experimental predictions.

Means, standard deviations and variances of error at each distance in each condition are shown in Table 8.2. It can be seen that the mean errors are practically zero in all cases. The significance of the differences were examined by means of the t-test. In no case was the mean error found to deviate significantly from zero. The results of the analysis are shown in Table 8.3.

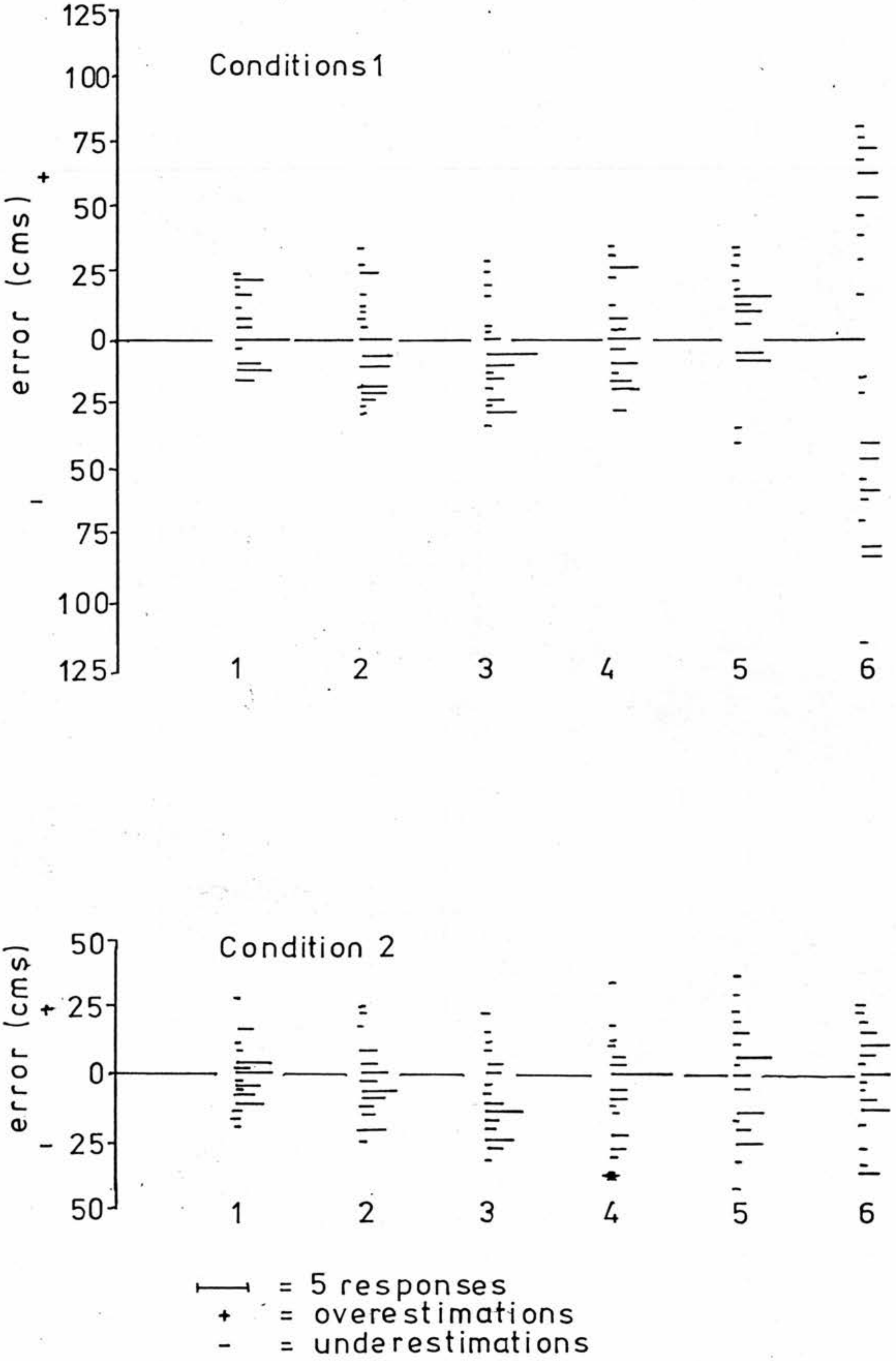


FIG. 8,1 Distribution of judgments at each distance in each condition.

TABLE 8.2

Means, Standard Deviations and Variances of Errors in Conditions 1 and 2

	Distance (Metres)											
	1		2		3		4		5		6	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Condition 1	.74	± 9.8	-6.7	± 10.4	-11.3	± 18.7	.89	± 19.2	6.2	± 19.2	4.8	± 64.6
S^2	40.3		86.2		144.5		153.1		154.1		1739.3	
Condition 2	-.98	± 11.0	-3.1	± 13.7	-9.8	± 14.4	-7.7	± 17.8	-3.4	± 11.1	-2.0	± 10.2
S^2	51.6		78.5		86.2		130.3		184.1		171.1	

TABLE 8.3

Values of t at Each Distance in Each Condition

Condition 1		Condition 2	
Source (Distance)	t	Source (Distance)	t
1m	.10	1m	.10
2m	.41	2m	.21
3m	.36	3m	.59
4m	.03	4m	.31
5m	.21	5m	.10
6m	.01	6m	.06

All insignificant at $\alpha = .01$, one-tailed test

These results, then, are consistent with the findings of previous experiments and conform to the pattern of results obtained in those experiments, which suggest that perceptual error is not attributable as a cause of the variances obtained.

One finding of some interest is the differences in variance found at the different distances in Condition 1. It can be seen that at 3, 4 and 5 metres, the variance is more or less constant, but at 1 and 2 metres it is smaller, increasing over these two distances to reach the plateau at 3 metres (see Fig. 8.1 and Table 8.2). This apparent increase cannot be attributable to increasing time as it could in Experiment 2, for example, because in Condition 1 time was held constant over the six distances. The effect was examined statistically by means of the F test for homogeneity of variances. The differences at 1 and 2 metres, and at 2 and 3 metres were insignificant (1x2, F=2.13; 2x3, F=1.68, both insignificant at $\alpha=.01$, one-tailed test); but the difference between the variances at 1 and 3 metres did reach significance (1x3, F=3.58, $p < .01$, one-tailed test). This would suggest a small threshold at 3 metres due to some factor other than time.

Discussion

In the introduction to Experiment 8 we stated our general purpose to be:

(1) To obtain evidence which would support the notion of program as a general concept.

(2) To try to find out over what distances programs can operate. It was argued that if the temporal limitations obtained in Experiment 6 could be found to be absent at shorter distances, then this would strongly support the

concepts of program and map discussed above. It was also hoped that the range of distances over which programs can operate would be discovered.

The results of Experiment 8 seem to allow us to answer both these questions. Even a delay more than 50% greater than the critical time delay in Experiment 6 was ineffective in disrupting performance. This finding therefore, fits exactly the theoretical predictions. Furthermore, it seems that we can identify the distances over which programming can operate as up to 6m. At that point, the temporal decline found in earlier studies is obtained. These findings therefore enable us to answer both of the fundamental questions posed positively. The results of Experiments 6 and 8 seem to suggest quite strongly that maps and programs exist in a form approximating to that described. It also appears that the distances over which programs can be formulated does not exceed 6m.

One interesting finding of this study is the differences in variance between different distances in Condition 1 (see Table 8.2). It can be seen that there is an increase in variance over the first three distances which seems to become more stable at 3m. and above. These differences cannot be due to the increasing passage of time (as the differences in Condition 2 can) because in Condition 1 the time factor was held constant (see Table 8.1). Consequently, the differences must be due to some other factor. One possibility might be that the effect is due to perceptual error. However, we have consistently argued against the interpretation that perceptual error would be revealed through increased variance. This form of error would be more likely to be revealed in consistent over- or under-estimation, as revealed by the mean errors. In Experiment 8 we found that the mean error does not at any distance deviate significantly from zero. This finding would militate against an explanation in terms of perceptual error.

The interpretation which seems best to fit the results is that proposed in the general discussion of Experiments 6 and 7. There, it was argued that a certain degree of error will always accrue to the execution of a program, a claim which was supported by the results of the long-jump study reported in Experiment 5, where the variance was clearly seen to build up from pace to pace. It would appear that this variance is somewhat lower at 1m and 2m than at larger distances, though the effect seems to have slowed down somewhat at longer distances. This result seems to fit quite well with the interpretation of execution error.

One question which might be asked about the limitation in programming ability is why that limitation should exist at 5m and not at some other distance. The reason that programming does not extend to distances of <u>more</u> than 5m may be due to the accumulative execution error discussed above. The reason that the limitation does not occur at distances of less than 5m may be due to the reaction time arguments proposed in Part I. If we take, as an example of the practical upper limit to human speed of movement, the times of Olympic 100m sprinters we can estimate the minimum distance over which programming should operate to accommodate the possible variations in speed. Such sprinters can run 100m in about 10 seconds. This represents an average speed of approximately 22 mph. At this speed, the sprinters traverse 5m. in .5 seconds. We have already seen in Part I, however, that .5 seconds represents probably the shortest time at which a correction on the basis of visual information can be made. If this argument is correct, 5m would indeed represent something like the shortest distance over which programming should be possible, if it is to accommodate something approximating the full range of speeds of which man is capable. It should be noted that this argument predicts that the programming capacities of different animals must vary. For example, an animal with a top speed of 35 m.p.h. would have to be capable of programming over a distance of at least 8m if it were to meet the .5 sec. limitation to the possibilities of correction. This prediction may be testable, but there does not appear to be any evidence with a direct bearing at present.

Conclusions

The results of Experiment 8, then, seem to support the theoretical position advocated very well. The fact that even a (relatively) massive time delay had no effect on performance at distances up to 5m lends the interpretation proposed considerable plausibility. The results suggest that subjects may very well have the ability to formulate programs for distances up to 5m, with movement over longer distances being accomplished through the retention of maps which can then be used to formulate further programs just as at distances up to 5m these can be formulated directly from vision.

While the results of Experiment 8 seem to fit the theory rather well, it would obviously be desirable to obtain further, preferably more direct, evidence supporting the concepts of map and program. It would also be highly desirable to show more clearly the way in which the two mechanisms co-operate in controlling behaviour, a problem which has not yet been attacked. The task of Experiment 9 is to do just this:

to develop the evidence in support of the two concepts further and to show them operating together to control behaviour.

EXPERIMENT 9

MAPS AND PROGRAMS IN THE CONTROL OF LOCOMOTION I

Introduction

The experiments so far reported in Part III seem to support the existence of two distinct mechanisms by which the abilities seen in Part II are controlled. In Experiments 6 and 7 we saw that accuracy was strongly affected by temporal factors, and this finding was considered to be more consistent with an interpretation in terms of map as defined in the preceding section, than in terms of program. Nevertheless, the results of Experiment 8 strongly implied that subjects are capable of formulating programs for action over distances of up to 5m. The results of these experiments were taken to suggest that behaviour is guided by some sort of co-operative action between these two mechanisms.

With regard to the outcome of these experiments, the aims of Experiment 9 may be stated as follows:

(1) To provide further evidence in support of the concept of map. So far this concept has been demonstrated in only as indirect way through the time limits of Experiments 6 and 7, and while the results of Experiment 8 can be said to support the notion of map insofar as it supports the notion of a <u>limited</u> program, it was considered desirable to obtain further, more direct evidence for the concept. This may therefore be said to be the first aim of Experiment 9.

(2) The second aim of this experiment is to demonstrate the co-operation of the two mechanisms. In our general discussion of Experiments 6 and 7, it was suggested that

maps are retained for use over longer distances than programs, but that programs can be formulated from maps in the same way as they can be formulated directly from vision. The second purpose of Experiment 9 was to try to show this co-operative behaviour in action in a relatively unambiguous form.

The methodological strategy by which these aims were achieved was rather simple. In order to test the first of these, an experimental situation was created in which the possibilities of programming responses in advance were eliminated. This was achieved by defining the task in such a way that the subject could not know in advance what was required of him, instructions being given only after vision had been excluded. If the method is accepted as being successful in eliminating the possibility of advance programming, and performance continues to be succesful, then this would lend strong support for the concept of map.

An attempt was made to fulfil the second stated aim of Experiment 9 by asking subjects to use their map to execute a behaviour which can <u>only</u> be executed as a programmed whole. The example of such a behaviour chosen in Experiment 9 was <u>throwing</u>. It should be clear that the subject has no control over a thrown object once it has been released, and that the success of the throw will depend on the throwing-decisions made before the object is cast. Since these throwing-decisions must be formulated in advance of the point at which the object is released, and since no further corrections can be made after that point, it is clear that throwing does constitute a programmed activity of the kind being discussed here. In order to show that such programs can be formulated from maps a situation was contrived where the subject could never know the distance over which he would be asked to throw until after vision had been excluded. Again, a throw could only be successful under these conditions if internalised information exists on which to base it. Experiment 9 was designed to achieve these aims.

Method

Design

Experiment 9 was conducted on the same location as Experiments 1, 3, 4 and 8; that is, in a large theatre from which all seating had been removed. Various pieces of experimental material and other articles were distributed around the sides of the room, but a free area was left for conducting experiments which measured approximately 14m x 9m.

The experiment was conducted under 3 conditions as follows:

Condition 2. Since in the present experiment Conditions 1 and 3 are control conditions against which the results of the experimental condition should be evaluated, and since these are concerned with control of only one part of the experimental condition each, it will be best to describe this latter condition first. The experimental condition was conducted over a single distance of 10m. This distance was chosen as being the most suitable for the manipulations exerted in the experiment. It also accords well with the results of Experiment 8, representing a 100% increase on the critical programming distance found in that experiment. This would help to sustain the argument that we are dealing with "map-space" only in Experiment 9. The subject's task was defined as being to walk towards the target as in previous experiments, with a view to lining himself up on the target-line if required. However, at a series of pre-determined points along the track subjects were asked to stop walking and to throw a small object carried in the hand the rest of the way to the target. The points at which the subjects had to stop and throw were at distances of 1, 2, 3, 4 and 5m. from the target. These distances over which the object had to be thrown were always unknown to the subjects, instructions being given only some time after vision had been excluded. The object to be thrown was a small wooden block of appropriate size and weight which had previously been determined as being a good throwing object. The target, as in previous experiments, was a line on the floor. In the present study this was a 2" wide length of white tape, which was used rather than a painted line, in view of the longer distance involved in Experiment 9. A line, rather than some other form of target, such as a circle, was used for the increased accuracy of measurement it allows, and because only distance errors were of interest; errors in the left/right dimension were ignored. As in previous experiments, echo location was controlled by means of a white-noise apparatus which subjects carried throughout the experiment. However, the level of noise employed in Experiment 9 was rather lower than in previous experiments. This was because the only practicable way of making subjects stop at an unknown point was to give them a verbal instruction. The level of noise was accordingly carefully adjusted so that maximum isolation was obtained, while still permitting instructions to be heard. Given that the echo location abilities of man are rather crude in any case (see Bower, 1976), it is unlikely that this slightly reduced level of noise made any difference to the subject's ability to use auditory information to control his behaviour. The level chosen allowed only loud noises to be heard, and the subject was as isolated as before from the largest part of the sound-field.

Condition 1. Since in the experimental condition of Experiment 9, subjects were asked to throw an object over a series of distances of up to 5m. it is obviously necessary to have some measure of subjects' general throwing ability, so that the results can be properly evaluated.

In order to obtain such information, a condition was run in which subjects were simply asked to throw objects to the 5 distances involved in Experiment 9, under normal visual conditions. The results of this condition can then serve as a control against which to evaluate the results of the experimental condition. To avoid learning effects this condition was carried out on a different location from Condition 2.

Condition 3. The purpose of the present experiment was stated as being to devise a method whereby advance programming of responses is prohibited. The principal means by which this was achieved was to use a two-part task where the distance over which the second part was to be executed, varied in a way unknown to subjects. There is one way in which performance might be achieved without the use of a map, however. It is possible that the subject sets up a program for walking the 10m to the target. Although the subject never knows in advance the point at which he will be asked to stop and throw, if a program for walking had been set up he nevertheless would know how much of that program had been executed, and how much remained. It is therefore possible that he might be able to convert the remaining part of a program for walking into a program for throwing. Condition 3 was designed to control for this possibility. The means by which this was done was very simple. Since the remaining part of the program for walking tells the subject in some form the remaining number of action units to be executed, subjects were merely asked to convert these action units into a program for throwing. In order to simplify the situation, however, subjects were asked not to convert a given number of paces into a program for throwing, but simply to throw the object a given number of metres, these corresponding to the distances over which the object had to be thrown in the experimental condition. Although it is not as satisfactory to use this method as it would be to use the former, it was felt that if program conversion is possible, a reasonable approximation to the target distances should be seen in the distribution of subjects' responses.

Procedure

Before the experiment proper began, subjects were given a practice session in throwing to develop their ability to a reasonable level for measurement. This practice period was conducted in a quite informal way, with subjects being asked simply to throw the object to the experimenter and to various points on the ground. No measures were taken at this time, the purpose being merely to get the subjects used to throwing the object. The practice session was continued until it became apparent that a reasonable facility had been achieved.

Condition 1. The subject was placed at the starting point with target lines drawn at distances of 1, 2, 3, 4 and 5m. in front of him. He held the throwing object in his hand and was instructed to try to throw the object on to the lines as these were indicated to him. The condition was conducted under normal visual conditions. The target line to which the object should be thrown on any particular occasion was indicated with a pointer by the experimenter, who stood to the side of the lay-out. 4 trials were given at each distance, and these were randomised with respect to distance.

Condition 2. The subject stood at the starting point with the target visible at 10m. As in previous experiments, the subject was allowed to survey the lay-out and decide for himself when to begin the trial. As soon as he excluded vision the experimenter started a stop-watch and began timing. The purpose of this was to ascertain that not more than 8 seconds did elapse between excluding vision and releasing the object. Just before the subject reached the appropriate throwing-point, the experimenter instructed him to stop. In order to avoid any distance information being imparted by the experimenter speaking from the position the subject last saw him occupying, the subjects were informed that E would always give his instructions from a position directly opposite the subject, irrespective of how far he had walked. The level of white noise used was sufficiently high to mask any sounds made by E in positioning himself at the appropriate point. In order to have control over the point at which subjects stopped, the instruction had to be given a little in advance. It should also be noted that because of variations in the size of subjects' paces it could not be guaranteed that they would stop at exactly the point desired on every occasion. Since absolute control over the stopping point was not required, this obviously does not affect the situation, and it was felt unnecessary to make a precise determination of the points stopped at on each occasion. Subjects were instructed that they were to throw the object as soon as possible after being told to stop, but that they should nevertheless satisfy themselves that they were ready to do so. After the object had been thrown, subjects were told to wait until the point of contact had been marked, then were turned around by E and led back to the starting point where they were allowed to prepare for the next trial. The distance the object was thrown was marked by coloured chalk, a different colour being used for each trial. These marks were always made too small to be seen by the subject from the starting-point. In this way, all feedback about performance was excluded. 4 trials were given at each of the 5 distances for each subject. Trials were randomised with respect to throwing distance.

Condition 3. Subjects were led, blindfold, to the location used for Condition 1, and were placed lined up at the starting point. They were then instructed to thrown the object to one of the 5 distances between 1 and 5 metres. This condition was therefore performed *in vacuo*. After each trial the object was brought back to the subject, who remained blindfold throughout the entire condition. As in the previous conditions, 4 trials were given at each of the 5 distances and these were randomised with respect to distance.

The conditions were always run in the same order, beginning with Condition 1, and advancing to Condition 3. Because of the possibility that learning effects from Condition 1 would influence scores in Condition 2, Condition 1 was always described as being merely a more refined extension of the practice period. A short break was given after this condition had been completed. Condition 3 was always run last, because any learning effects from Conditions 1 and 2 could only improve performance and militate against the hypothesis.

Because of the length of time necessary to perform this experiment, it was divided into two sections and run on two separate occasions. Each section contained half of the total number of trials performed in the three conditions, making each section a mini-experiment. The sections were run approximately one week apart.

Subjects

Eight subjects took part in Experiment 9, 4 male and 4 female. All were students at Edinburgh University and were aged between 20 and 25 years. None was familiar with the purposes or predicted results of the experiment.

Results

The essential results of Experiment 9 are shown in Fig. 9.1. Fig. 9.1a shows the distribution of responses around the target line at each distance in Condition 1 (control throwing); Fig. 9.1b shows the results for Condition 2 (experimental condition); and Fig. 9.1c shows the results of Condition 3 (blind throwing).

An inspection of this Figure reveals that the greatest accuracy is found in the control-throwing situation, followed by the experimental condition, with performance in Condition 3 being extremely inaccurate by comparison. The effect can also be seen in Table 9.1, which shows the variances obtained in each condition, together with the means and standard deviations. The trend reflects that found from a visual inspection of the graphs.

TABLE 9.1

Means, Standard Deviations and Variances of Errors in each Condition

	Throwing Distance (Metres)									
	1		2		3		4		5	
1 (throw)	5.62	7.80	2.71	13.32	-6.60	13.68	-19.10	14.28	-19.85	21.96
s^2	25.34		73.82		77.88		85.08		200.93	
2 (walk + throw)	13.32	21.31	6.00	27.24	-3.00	26.16	-1.13	25.46	-15.98	27.94
s^2	189.24		309.22		285.22		270.19		325.10	
3 (throw blind)	43.06	55.66	22.51	55.49	-14.78	65.64	-16.06	103.56	-36.53	87.84
s^2	1290.72		1282.34		1795.37		4468.87		3215.33	

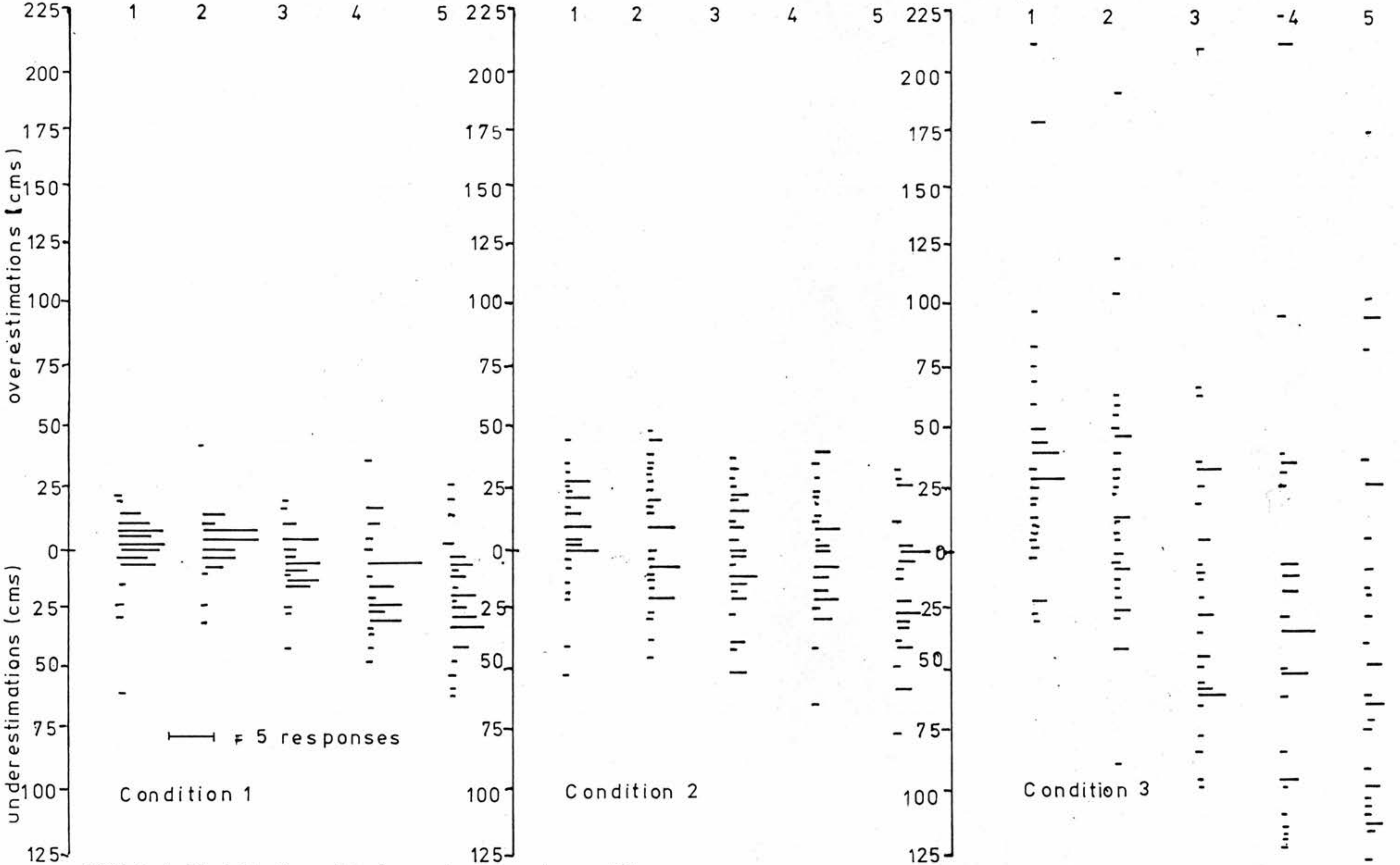


FIG. 9.1 Distribution of judgments in each condition.

The differences between Conditions 1 and 3, and 2 and 3 were evaluated statistically by means of the F test for homogeneity of variances which was applied to corresponding distances in the different conditions. The results of the analysis are shown in Table 9.2. It can be seen that the differences were significant in every case. This finding would suggest that the success of performance in Condition 2 was not due to an ability to transform a program for walking into a program for throwing. The success would seem to be due to some other source of information.

TABLE 9.2

F Ratios from Analysis of Data in Table 9.1

	Throwing Distance (Metres)				
	1	2	3	4	5
Conditions 1x3	50.93	17.37	23.05	52.53	16
Conditions 1x2	7.47	4.19	3.66	3.18	1.62*
Conditions 2x3	6.82	4.15	6.29	16.54	9.89

*n.s. at $\alpha = .01$, one-tailed test

all other cells significant (required F with 31 and 31 degrees of freedom = 2.39)

An inspection of Figs. 9.1a and 9.ab, and of the corresponding cells in Table 9.1, reveals that performance is consistently poorer in the experimental condition than in the control throwing condition. This result is to be expected, however, as the error in Condition 2 is made up of two components. The first of these is error resulting from the walking section of the act. We saw in Experiments 1 and 2 and also elsewhere that blindfold walking produces a variance which, in the case of Experiment 2, amounted to 20cms. at 6m. and 22cms. at 9m.

Since the distances walked in Experiment 9 varied from 5 to 9m., we would expect a similar variance to be associated with the walking element of this experiment. However, in addition to this variance, there is a further variance in Experiment 9 created by the throwing section of the act. The variance in this case is given in Table 9.1. Since both these components, together with their associated variances, are involved in Experiment 9, then the true control variance against which to compare that obtained in Condition 2 must be the sum of the variances from the two components. A linear regression was conducted on the variances obtained at 3, 6 and 9 metres in Experiment 2, and estimates made of the variances at 5, 7 and 8 metres. These variances were then added to those obtained from Condition 1 in Experiment 9. The result of this manipulation, together with the variances found in Condition 2, are presented in Table 9.3.

TABLE 9.3

Corrected Control Variances for Evaluating Results of Condition 2

	Distance (Metres)				
	1	2	3	4	5
Throw (Expt. 9)	10.56	30.76	32.45	35.45	83.72
Corresponding walk (Expt. 2)	88	88	78	76	58
Total	98.56	118.76	110.45	111.45	141.72
Walk + throw (Expt. 9)	78.85	128.84	118.84	112.58	135.46

It can be seen that this manipulation of the results of Condition 1 produces a set of variances which differ only marginally from those obtained in Condition 2. The differences between the variances at corresponding distances in the two Conditions were evaluated by means of the F test at $\alpha = .01$, one-tailed test. The differences failed to reach significance in any case (1x1, F=1.25, n.s.; 2x2, F=1.08, n.s.; 3x3, F=1.08, n.s.; 4x4, F=1.01, n.s.; 5x5, F=1.05, n.s.). This result, then, confirms the experimental hypotheses very well.

The response profiles seen in the case of the group of subjects as a whole can also be seen in the response profiles of individual subjects. Fig. 9.2 shows the judgments made by different subjects in the different conditions. It can be seen that the results confirm those obtained for the group. Performance is best in Condition 1, slightly poorer in Condition 2, and poorest in Condition 3. Unfortunately, no correction can be made to the responses of individual subjects to take account of the error contingent on the walking phase of Experiment 9, but since the other features conform to the group picture, we might reasonably suppose that this would conform as well. The results, then, seem to support the experimental predictions very well.

Discussion

In the Introduction to Experiment 9, we argued that the study had two basic aims: firstly, to provide further evidence in support of the concept of map, and secondly, to show that it is possible to formulate programs from such maps. We may begin our discussion by considering the extent to which Experiment 9 was successful in creating the conditions for a test of these aims.

The main argument underlying the present experiment was that it is possible to eliminate the possibilities of subjects preparing programs for action directly from vision by refusing to define the relevant

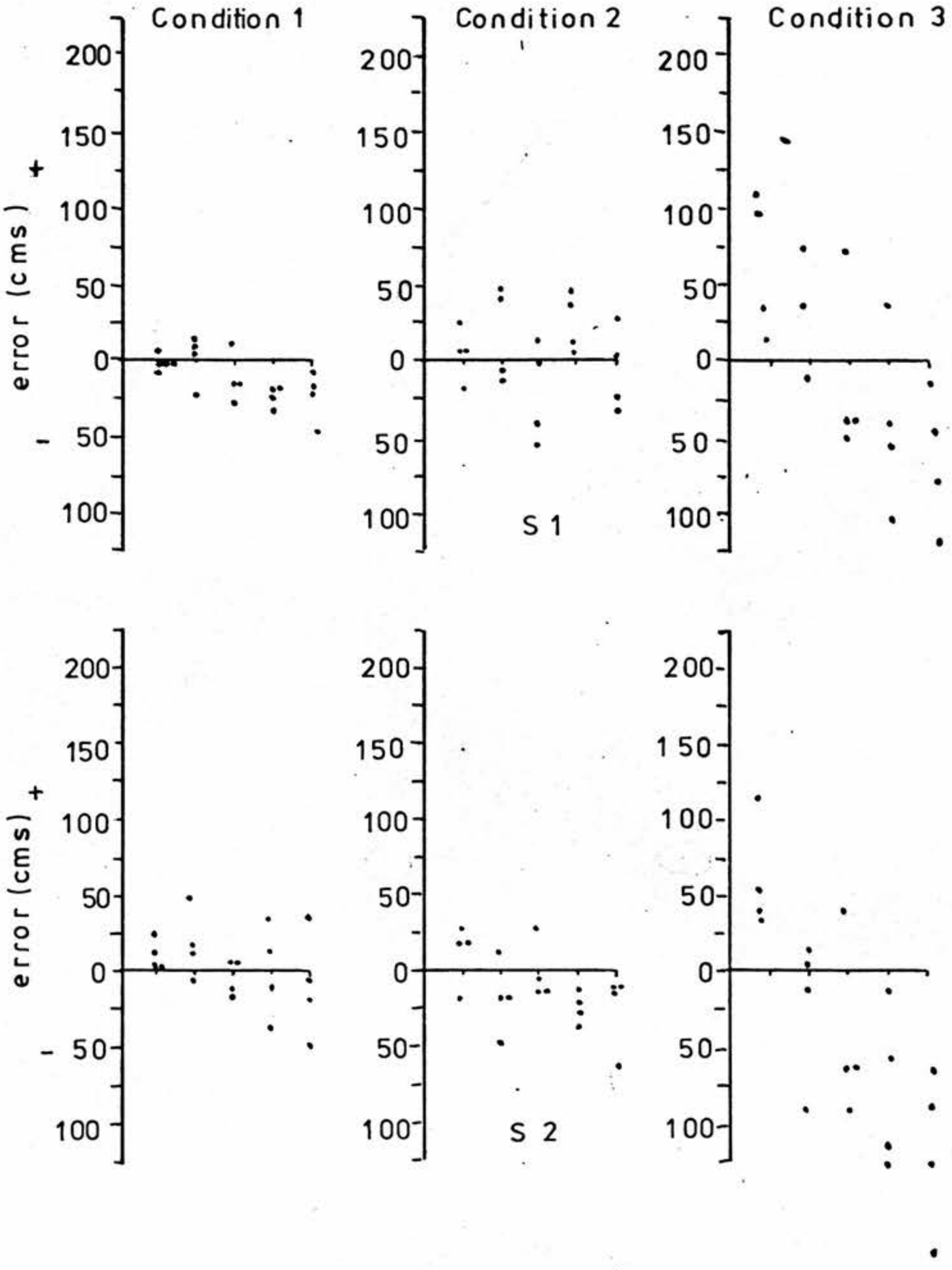


FIG. 9,2 Distribution of error in each condition
(individual subjects)

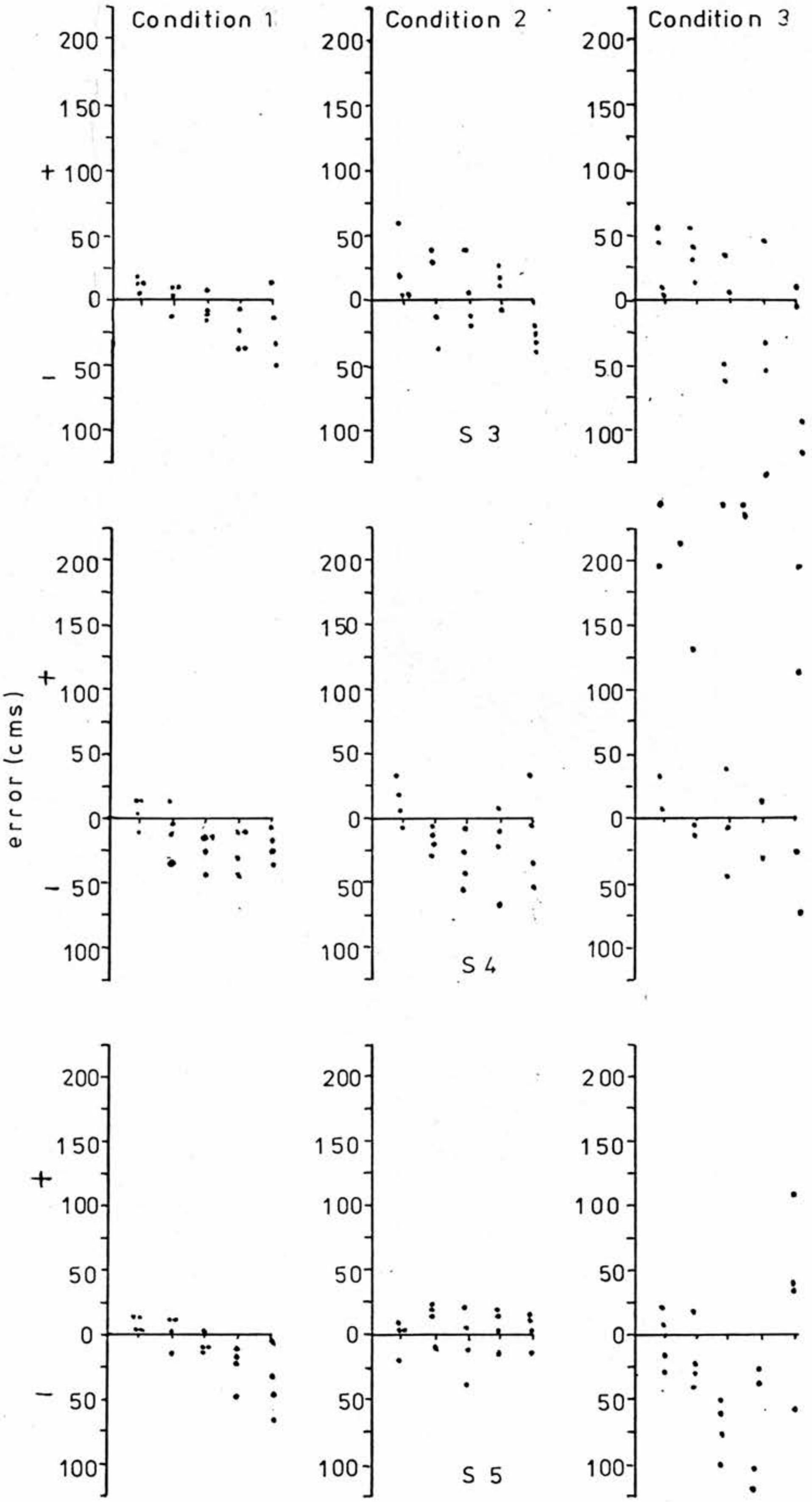

Condition 1
Condition 2
Condition 3
200
150
+ 100
50
0
- 50
100
S 3
S 4
S 5
error (cms)
+
-

FIG. 9,2 (contd.)

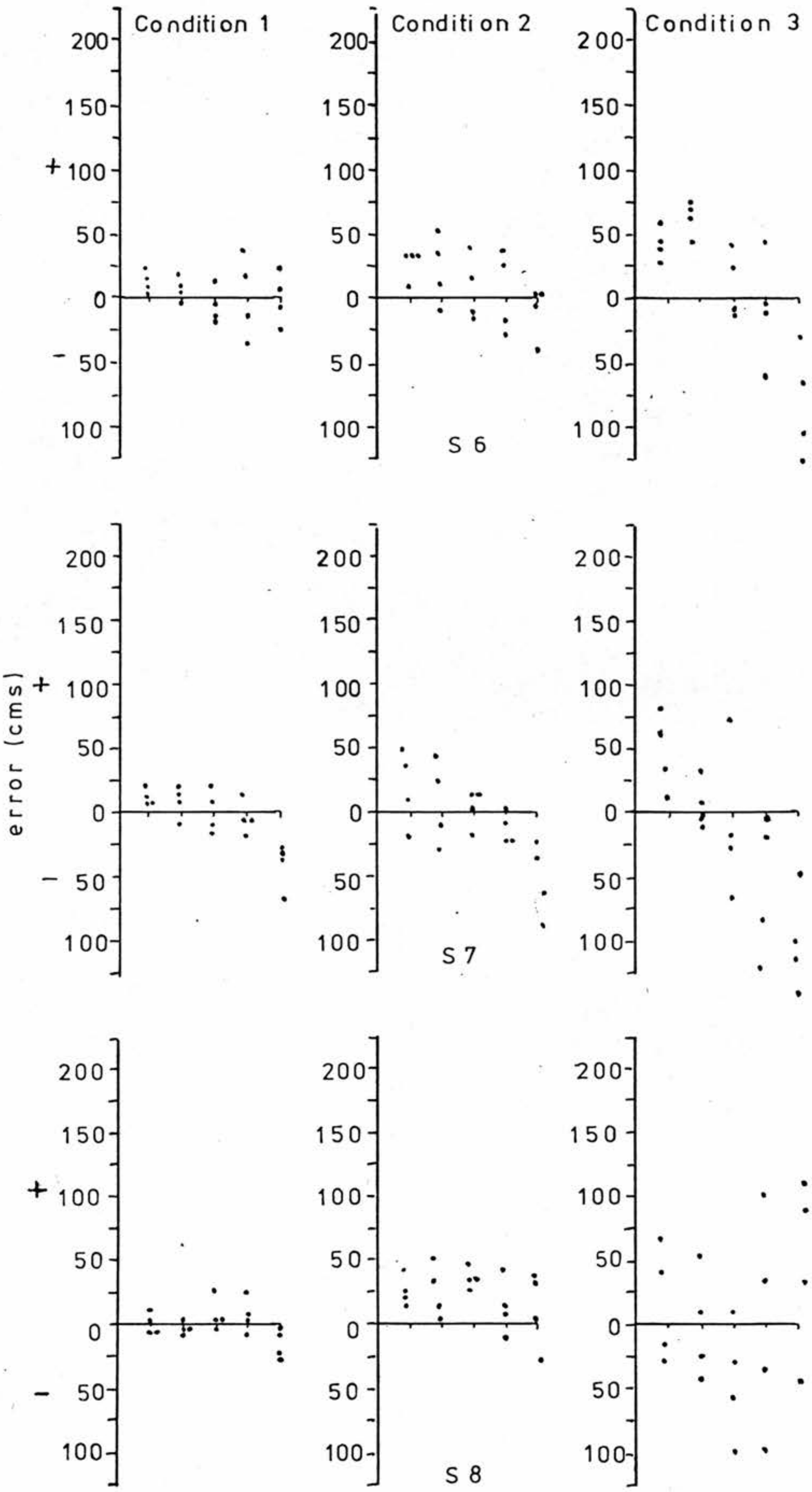

Condition 1
Condition 2
Condition 3
200
150
+ 100
50
0
− 50
100
S 6
S 7
S 8
error (cms)

FIG. 9,2 (contd.)

dimensions of the task until after vision is excluded. In the present case, the relevant dimension is distance from the target. Since the subject never knows in advance how far he will be from the target when he is asked to throw the object he carries, this latter part of the act cannot be programmed in advance. There seem to be only two ways in which a successful performance could be obtained under these conditions. The first possibility is that the subject retains some sort of representation or map of the layout of the environment, and is able to update this position in that map as he moves through the environment. When the subject is called on to organise a different behaviour relative to the target, this would then provide no problem, as the subject can use the information in his map to do so. This is the hypothesis favoured here. There is, however, one competing possibility which must be considered. This is that subjects could, in principle, formulate a program for walking the 10m. to the target. Although the subject is stopped at an unknown point and asked to locate the target by some other means, the subject would then know how much of his program had been executed and how much remained. It is therefore possible that the remainder of his program for walking could be transformed into a program for throwing with sufficient accuracy to enable him to locate the target. In order to provide a convincing test of the map hypothesis, it would therefore be necessary to control for this competing hypothesis.

The results of Experiment 9 seem to fit very well with the prediction that performance would be high in the experimental condition. The accuracy of subjects' performance under this condition is best seen in Table 9.3 which shows the variances obtained at the different distances in that condition, together with the control variance, corrected to take account of the error contingent on walking, together with that contingent on throwing. No differences were found between the corresponding variances in the two cases. The fact that such a high degree of accuracy was attained in the experimental condition implies that subjects were indeed able to formulate their program for throwing on the basis of some form of internalised information.

An attempt was made to examine the possibility that the successful performance was due to the transformation of a program for walking into a program for throwing rather than through the retention of a map, in Condition 3. Program transformation in the present experiment would have entailed the transformation of programs for walking distances of between 1 and 5m. into programs for throwing over these same distances. An assessment of the subjects' ability to do this was therefore arranged. Although, strictly speaking, the subjects should have been asked to throw the object over the appropriate number of paces, this was not done in the present experiment. It was felt that metres fell sufficiently close to pace-lengths to make the results of this condition valid. All subjects claimed to be familiar with metres as measures of distance. The results of the condition, presented in Fig. 9.1c and Table 9.3, show unequivocally that subjects are quite unable to perform this task with accuracy. In all cases, the variances were vastly in excess of the variances obtained in the other two conditions. This finding, then, would seem to fit the experimental predictions very well.

It must be noted, however, that the method employed in Condition 3 bore only an approximation to the proper control for the program-transformation hypothesis. An estimation should have been taken of the number of paces each individual subject would need to reach the targets from the various throwing distances, and subjects should then have been asked to throw the object the appropriate number of paces. The method employed was considerable more artificial and this must be seen as an inadequacy of the design. An attempt to create a more appropriate control is made in Experiment 10.

However, although metres are a rather unecological measure compared to paces, it nevertheless seems clear that such measures, approximating as they do to paces in size, would generate a level of accuracy far higher than that obtained if a program for walking can indeed be transformed into a program for throwing. The fact that accuracy was so poor would suggest that subjects are either not capable of such transformations, or else that no program for transformation existed, which is what we would predict from the results of Experiment 8. The present finding therefore supports the argument that the success of subjects' performance in Condition 2 was due to the retaining of a map which could then be used to control behaviour and formulate programs.

The first aim of Experiment 9 was stated as being to obtain further evidence in support of the concept of map. The second was to show that such maps can be used to formulate programs in the same way as those can be formulated directly from vision. The results of Experiment 9 certainly seem to support this latter hypothesis. We have already indicated that there is no possibility of subjects formulating their throw on the basis of visual information before the trial begins, since they never know in advance what the distance over which the object is to be thrown will be. This would mean that the throw would have to be determined on the basis of internalised information available at the point at which the subject is called in to throw the object. The fact that the accuracy with which subjects were able to reach the target was so high, failing to differ significantly from the control error, indicates that subjects are indeed able to formulate programs from internalised information. The results of Experiment 9, then, seem to support this prediction also.

Conclusions

The results of Experiment 9, then, seem to fit well with the experimental predictions. It certainly seems as if subjects are capable of formulating programs on the basis of internalised information, and furthermore seem to be capable of doing so as accurately as when the programs are based directly in vision. The results also suggest that the programs are based on information internalised in the form of a map, though there remained a certain amount of doubt about this interpretation. One of the purposes of Experiment 10 is to improve this control. In general, however, the results of Experiment 9 are in excellent agreement with the predictions.

EXPERIMENT 10

MAPS AND PROGRAMS IN THE CONTROL OF LOCOMOTION II

Introduction

As we saw in the introduction to Experiment 9, that experiment had two basic aims. Firstly, it was designed to show that programs can be formulated on the basis of internalised information of some sort, and secondly, to show that this information takes the form of a map. The first of these aims was well supported by the results of the experiment. However, it could not be said with absolute certainty that the accuracy obtained was due to the internalisation of a map rather than to some other form of internalised information, because of the weakness of one of the controls.

Experiment 10 represents in some ways an extension of Experiment 9 since it is similarly concerned to obtain information in support of the concept of map, and in doing so attempts to correct the defects of Experiment 9. The main problem of Experiment 9, of course, was that it was not made sufficiently clear whether the subject's successful performance in the experimental condition was due to the retaining of a map or to the transformation of a program for walking into a program for throwing. In that experiment, the problem was attacked by trying to eliminate the possibilities of formulating programs so that a successful performance could then only be attributed to the existence of a map. In the present experiment, subjects were specifically enabled to formulate programs for walking, so that it could be demonstrated directly that these could not be used to formulate programs for throwing. The method by which this was achieved was basically as follows.

The experiment was conducted over a single distance of 5m. This distance was chosen because it had been found in Experiment 8 that programs could be formulated over distances up to 5m. The subject's task varied between the conditions. In Condition 1 the subject was asked simply to walk up to the target and line himself up on it in exactly the same way as in Experiment 8. The subject's task in Conditions 2 and 3 was to walk towards the line with a view to lining himself up on it if required However, at a series of predetermined points, the subjects were asked to stop walking and to throw an object which they carried the rest of the way to the target. The points at which the subjects were asked to stop and throw were at distances of 2 and 3m. from the target. These points at which they were stopped were always unknown to subjects in advance. The object which the subjects were asked to throw was a small wooden block which had previously been found to be a good throwing object. The target, as in Experiment 9, was a length of 2 inch white tape placed on the floor. Distance errors only were measured, errors in the left-right dimension being ignored.

As in previous experiments, echo location was controlled by means of a white noise apparatus, which was carried throughout the experiment. The level of noise employed was as in Experiment 9, and was somewhat lower than in the earlier experiments. This was because subjects were given verbal instructions about when to stop in Conditions 2 and 3, and those instructions had to be heard. The level of noise used was still sufficient to eliminate all but loud noises, and the subjects were still effectively isolated from the largest part of the surrounding sound field.

It will be remembered that in Experiment 8, we obtained evidence which showed that at distances of less than 6m. a time delay of more than 8 seconds had no influence on performance, whereas at distances of more than 6m. the effect of the time delay was to greatly disrupt performance. This was interpreted as meaning that at distances of less than 6m. programs can be formulated, but that at longer distances, only maps exist and these are subject to decay with time. From the results of this experiment and of Experiment 9, we can formulate the following hypotheses:

(1) When subjects are placed in the same experimental situation as in Experiment 9, but with the distance to the target being only 5m., the accuracy of throwing should be high, so long as subjects take less than 8 seconds because they have a map available for formulating the throwing program.

(2) When subjects are asked merely to walk to the target, but are forced to take more than 8 seconds to do so, performance should still be high, because the subjects have a program for walking. (We have already seen in Experiment 8 that performance under this condition is indeed high).

(3) When subjects are placed in the same experimental situation as in Condition 1, except that the total time from closing the eyes till throwing the object is more than 8 seconds, performance should now be poor, because although the subject has a program for walking (see Condition 2), he no longer has a map. Our main hypothesis is that this program for walking cannot be accurately transformed into a program

throwing, and that the accuracy obtained in Condition 1 and in Experiment 9 was therefore due to the retaining of a map.

This methodology has a number of advantages over that employed in Experiment 9. Firstly, it avoids the problems obtained in Condition 3 of that experiment by specifically enabling the subjects to formulate a program for walking. If the results of Condition 3 of that experiment are obtained in the present experiment, then we can indeed conclude that success is due to internalised maps and not due to internalised programs. The second major advantage is that in Experiment 9 we assumed that the program for walking would be defined in terms of the number of paces to reach the target; or that, at any rate, this information would have to be written into the program at some level. Although this is not an unreasonable assumption, and indeed seems to be a necessary assumption to make, Experiment 10 is distinguished by making no assumptions about the nature or form of the program at all. It merely allows the subject to construct a motor program in whatever form this is done, and tests the efficacy with which it can be transformed into a program for the accomplishment of a different activity. The fact that no assumptions are made about the nature of the program in Experiment 10 must surely be seen as an advantage over the method of Experiment 9. This method therefore seems to make an extremely direct test of the hypothesis of map control.

Method

Design

The design of Experiment 10 was very similar to that of Experiment 9.

The conditions of Experiment 10 were conducted under varying temporal restraints. In Condition 1, the total time between the point at which vision was excluded and the target reached was artificially manipulated to take 12 seconds. In this way, Condition 1 represents a replication of the experimental condition of Experiment 8. In Condition 2, subjects' performance was regulated so that the total time did not exceed 8 seconds. In Condition 3, which was otherwise a replication of Condition 2, times were again artificially manipulated to take 12 seconds. Trials were presented randomly with respect to the conditions and the distances.

Procedure

Before the experiment proper began, subjects were given a practice session in throwing as in Experiment 9. This session was conducted in a quite informal way, with the subject being asked merely to throw the object to various points on the floor or to the experimenter. This practice period was continued until it became obvious that the subject had achieved a reasonably accurate and consistent performance.

Condition 1. At the beginning of each trial, the subject was lined up at the starting point. He was allowed to survey the layout and to choose for himself when to exclude vision and commence the trial. As soon as vision was excluded, the experimenter started a stop-watch and began timing. When the appropriate time interval had elapsed the subject was tapped on the shoulder to indicate that he should now begin the trial. When the trial had been completed the subject remained with vision excluded until E measured the error and recorded this on a data sheet. The subject was then turned around by E and led back to the starting point ready for the next trial. Five trials were given in Condition 1. The low number of trials in this condition was simply due to the fact that the condition had already been run as a formal experiment (Experiment 8), and therefore merely represents a control for the results of that experiment.

Condition 2. No time delay was involved in this condition. S was allowed to survey the layout and begin the trial immediately vision was excluded. However, at a point unknown to him which was either 2 or 3m. from the target, he was told to stop and throw the object he carried the rest of the way to the target. As in Experiment 9, it proved quite easy to get control over the stopping point by informing S to stop just before he reached the point concerned. When the object had been thrown S remained with vision excluded until E measured the error in the point at which the object struck the ground and recorded this. S was then led back to the starting point and allowed to begin the next trial. Five trials were given at each of the two throwing distances.

Condition 3. This condition was simply a replica of Condition 2, except that a time-delay as in Condition 1 was employed. S was informed that he should commence the trial in the same way as Condition 1, by being tapped on the shoulder. In this condition, however, E walked alongside the subject until the point where he was to stop was reached and E informed him to do so simply by saying "stop". This was to preclude the distance information which would have been available had E issued the instruction from the subject's starting point. Again, 5 trials were given at each of the two throwing distances in this condition.

Subjects

Eight subjects took part in Experiment 10, 4 male and 4 female. All were students at Edinburgh University and were aged between 18 and 23. None was familiar with the purpose or predicted results of the experiment.

Results

The mean times taken to reach the target or to throw the object in each condition are shown in Table 10.1. It can be seen that the conditions for a test of the experimental hypotheses have been met in each case. In Condition 1, the mean time was consistently less than 8 seconds and in Conditions 2 and 3 were consistently greater, at approximately 12 seconds. This fits well with the intended pattern of times in the different conditions.

TABLE 10.1

Mean times taken at each Distance in each Condition

	Condition				
	1 (Walk)	2 (throw 8 secs.)		3 (throw 8 secs.)	
	All Distances	2m	3m	2m	3m
M	12.16	2.36	3.21	12.36	12.41
SD	.53	.48	.75	.52	.49

The basic results of Experiment 10 are shown in Fig. 10.1 which shows the distribution of judgments around the target line in each of the three conditions. A visual inspection of this figure reveals that the predictions of the study have been broadly confirmed. It can be

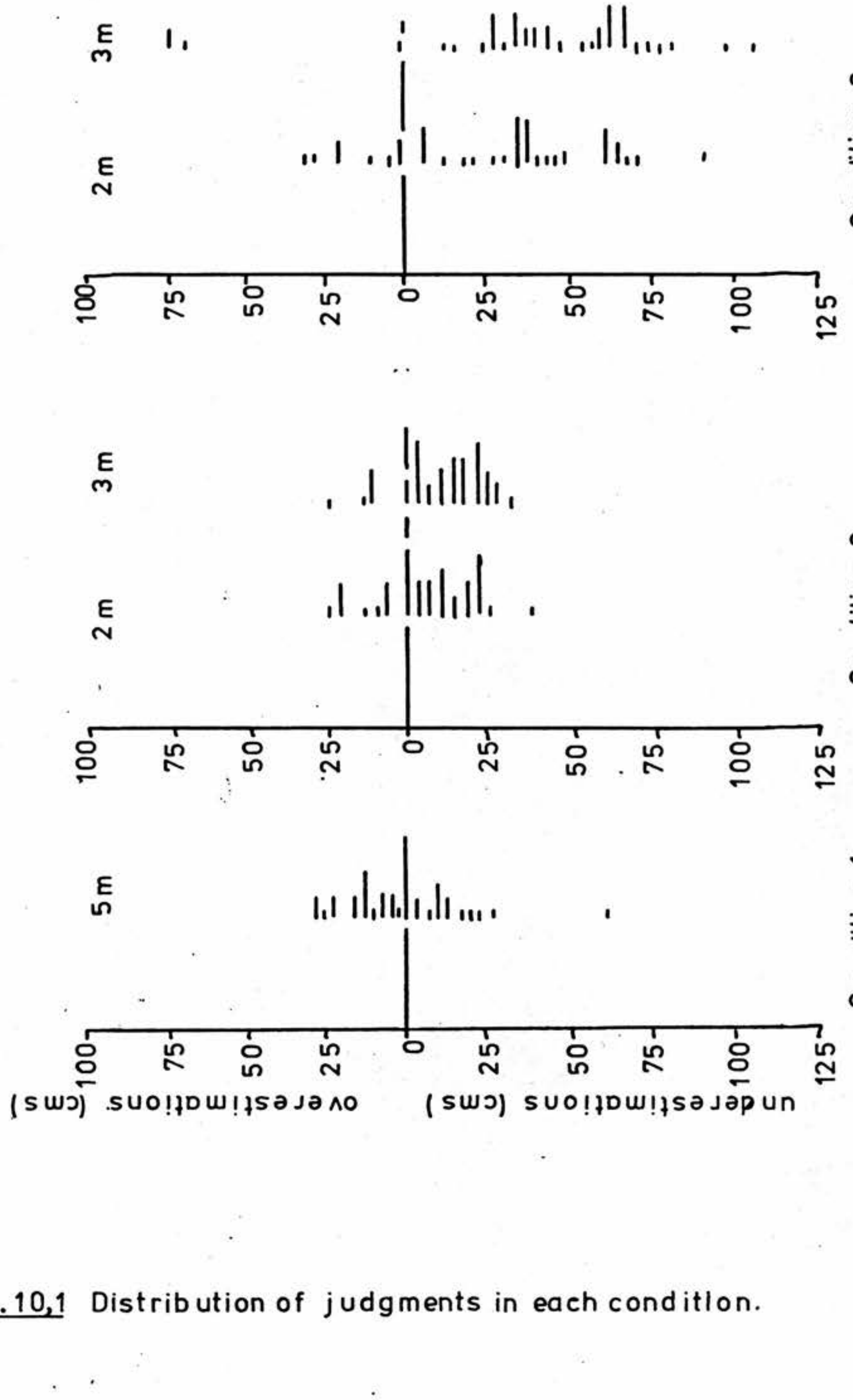


FIG. 10,1 Distribution of judgments in each condition.

seen that in Conditions 1 and 2 performance is high whereas in Condition 3 performance is markedly lower. The effect can also be seen in Table 10.2 which shows the means, standard deviations and variances in each condition.

TABLE 10.2

Means, Standard Deviations and Variances of Scores in Each Condition

	Condition				
	1 (Walk)	2 (throw 8 secs.)		3 (throw 8 secs.)	
		2m	3m	2m	3m
M	2.2	-3.84	-12.43	-24.91	-47.62
SD	18.36	15.79	13.66	31.18	27.58
S^2	140.35	103.78	77.71	405.22	339.86

error in cms.

Statistical analyses were conducted on the variances in the different conditions and the results confirm the trend. The variance obtained in Condition 1 was not found to differ significantly from the variances at either distance in Condition 2 (Con. 1 x Con. 2, 2m, F=1.35; Con. 1 x Con. 2, 3m, F=1.81; both insignificant at $\alpha = .01$, one-tailed test). The differences between the corresponding distances in Conditions 2 and 3 were significant (2x2, F=3.90, $p < .01$; 3x3, F=4.37, $p < .01$). The differences between the variances in Condition 1 and those obtained in Condition 3 were also significant (Con. 1 x Con. 3, 2m, F=2.89, $p < .01$; Con. 1 x Con. 3, 3m, F = 2.42, $p < .01$). These results are therefore highly supportive of the experimental hypotheses.

The variance obtained in Condition 1 was compared to that obtained in the experimental condition of Experiment 8 to see if the result confirmed that of the earlier experiment. The variances were not found to differ significantly (F=1.81, n.s.). The result of Experiment 8 therefore seems to be confirmed by the result of the present experiment.

The results of Conditions 2 and 3 were similarly compared to the corresponding results in Experiment 9. The variances obtained in Condition 2 and the corresponding throwing distances in the earlier experiment were significantly different (2x2m, F=2.98, $p < .01$; 3x3m, F=3.67, $p < .01$). The results of Condition 3 were also found to be significantly better than at the corresponding distances in Experiment 9 (2x2m, F=3.16, $p < .01$; 3x3m, F = 5.28, $p < .001$). This would indicate that while the results of Experiment 10 are in broad agreement with the results of Experiment 9, the differences in methodology between the two experiments have produced differences in degree between the two studies.

Discussion

The purpose of Experiment 10 was to show that the successful throwing performance in Experiment 9 was due to the retaining of a map which could then be used to formulate a program for throwing. It was also designed specifically to show that the accuracy obtained in Experiment 9 was not due to the transforming of a program for walking into a program for throwing, by giving subjects the opportunity to do precisely that. It was hypothesised that only a map would enable subjects to perform well. The hypothesis seems to be well confirmed by the results of the experiment.

In Condition 1, we saw that an 8 second delay caused no description to performance when the subject was asked simply to walk up to the target. In line with the results of Experiment 8, it was concluded from this that subjects can formulate programs for walking when the distances involved are less than 6 metres. In Condition 3, where the same conditions were applied except that at an unknown point the subjects were told to stop walking and to throw an object the rest of the way to the target, performance was very considerably impaired. Since subjects are apparently perfectly capable of walking to the target under these conditions, this result strongly suggests that the subjects had internalised some form of program for walking to the target, but were unable to transform this into a program for throwing. In Condition 2, by contrast, where no time delay was imposed, performance was very considerably better, not only mirroring that obtained in Condition 1, but in fact somewhat better than it. These results, then, fit extremely well with the hypothesis that for a limited period not exceeding 8 seconds, a map of the environment can be retained and used to formulate programs. After this critical time has been surpassed, however, the map has faded. Further programs can not therefore be formulated except by means of transforming the original program. The results of Condition 3 indicate that this cannot be done. The results therefore comply extremely well with the predictions and seem to evidence the existence of both maps and programs for controlling behaviour.

A finding which must be noted is that the performance in Condition 3 is superior to the performance in the "blind throwing" condition of Experiment 9. This suggests that the latter method was perhaps not appropriate, as was suggested in Experiment 9 itself. However, it should be borne in mind that that method could only have been expected to give a very general idea of subjects' ability to transform programs, since the distances over which the subjects were asked to throw the object were defined in metres and it could not be expected that a highly accurate performance be obtained using such an arbitrary method. The fact that in a general way, the results of the two experiments correspond, implies that some trust may be placed in the results of that rather artificial condition. Clearly, however, such "non-ecological" methods cannot be recommended: but in neither case can it be said that subjects have the ability to transform programs with any degree of accuracy.

A further finding to be noted is the greater consistency with which subjects attained the target in Condition 2 than at the corresponding throwing points in Experiment 9. This difference should not be seen as surprising, however, in view of the short distances over which subjects had to walk in Experiment 10. In Experiment 9, subjects walked 8 and 7 metres in order to reach the 2 and 3 metre throwing distances, whereas in Experiment 10, they walked only 3 and 2 metres. It was argued in Experiment 9 that the variance obtained in any such experiment should contain two components: one due to walking and the other due to throwing. A regression analysis conducted on the variances obtained at 3, 6 and 9 metres in Experiment 2 was used to measure the variance to be expected when S walks 2 metres. The variance components at 2 and 3 metres were computed to be approximately 27 and 38 respectively. We saw in Experiment 9 that the variances obtained simply from throwing an object 3 and 2 metres were 32.45 and 30.76, giving theoretical variances for the conditions of Experiment 10 of 57.76 and 70.45. When these theoretical variances were compared to those actually obtained (see Table 10.2), the differences were insignificant (2x2m, F=1.34; 3x3m, F=2.18, both insignificant at $\alpha = .01$, two-tailed test). The results therefore fit extremely well with the experimental predictions.

Conclusions

The results of Experiment 10 accord well with the predictions. It appears that subjects are not able to transform a program for one kind of activity (walking) into a program for a different kind (throwing). This would indicate that the successful performances in the "walk + throw" conditions of Experiments 9 and 10 was due to some other form of internalised information. The results of these experiments, together with the results of Experiments 6, 7 and 8, strongly suggest that the success is due to internalised maps which can then be used to construct further programs as desired.

SUMMARY AND GENERAL CONCLUSIONS ON PART III

It was stated in the Introduction to Part III that the purpose of this section of the thesis was to go some way towards discovering the mechanisms underlying the general ability seen in Part II. It now seems that we may claim to have had some measure of success in this direction.

In Part I it was suggested that subjects are able to formulate programs for action from visual information and that these programs can then be used to control behaviour more or less independently of further visual information. It was this programming ability which was said to underlie the results of the Experiments reported in Part II. However, it can now be said that this does not seem to offer a complete explanation of the results.

Part III began by examining the threshold in performance first seen in Experiment 2, on the grounds that an understanding of this threshold might lead to an understanding of the basic mechanisms underlying intermittent control. In Experiments 6 and 7, it was found that the threshold in accuracy found at 12m. in Experiment 2 is dependent on the length of time elapsing between closing the eyes and reaching the target. Whenever the time lapse exceeds 8 seconds, performance can be expected to deteriorate sharply, at least for distances in the range of 6 to 21 metres. Time seemed to be capable of accounting for almost all of the variance found at the 12m. distance in that experiment.

These findings were taken to militate against the programming explanation of the results of Part II. This was because programs were said to consist of specifications of the motor actions necessary for solution, these motor actions being defined in terms of action units. A program would therefore indicate the number of such action units required to reach the target. However, it does not seem likely that this form of information would decay in the rapid way seen in Experiments 6 and 7 because the program would simply take the form of an instruction as to the number of action units necessary to reach the target. It seems hardly likely that information of this sort would be subject to the strict temporal control seen in these experiments. The alternative explanation of the results offered was that subjects internalise some form of representation or map of the environment and use this to control behaviour in much the same way as vision itself might be used. It was felt to be easier to understand how such a map might fade in time than to understand how a program might fade.

To test the argument that programs would not be subject to strict temporal control and at the same time showing that programs do exist, though at shorter distances only, the method of Experiment 6 was repeated at distances of 6m and under. It was found that a large time delay of over 12 sec. had no influence on performance at distances of 5m and less. This finding fits extremely well with the arguments advanced and seems to show that programming is possible at distances of up to 5m. The concepts of map and program and their mode of operation were further examined in Experiments 9 and 10. In these experiments, an attempt was made to eliminate the possibilities of advance programming on the basis of visual information by using a two-part task, the latter part of which was specified only after vision had been excluded. This would leave only two ways of achieving successful performance. One would be to use an internalised representation of the environment from which the latter part of the act (the throw) could be formulated. The other would be to have a program for walking to the target which could be transformed into a program for throwing. The results of Experiments 9 and 10 suggest that this program transformation cannot be done and this supports the concept of map. In general, then, the results of Part III seem to support the concepts of both map and program and suggest that programs can be formulated from maps as well as from vision.

The results of the experiments reported in Part II may be reconsidered in the light of this modified explanation of the ability. It would appear that maps are involved in most of these experiments. The results of Experiments 6 and 7 certainly imply that they are involved in Experiments 1 and 2 as the later experiments were based on these. Maps would also appear to be involved in Experiments 3 and 4 since the distances involved in these experiments also exceeded the programming limit of 5m. It is therefore possible that some of the errors at the later obstacles was due to temporal decay of the guiding map. To test this possibility, the video-tapes of these experiments were re-analysed with an automatic timer to see if the 8 second limitation came into effect in any cases before the course was completed. In fact, in all cases, the last obstacle had been circumvented before the 8 sec. point was reached. The results of these experiments may therefore be allowed to stand.

The extent to which programming (as opposed to mapping) actually took place in these experiments is not always clear, though the results of Experiments 8, 9 and 10, together with the theoretical arguments on which they are based, imply that it must have. There is certainly evidence that they are involved in Experiment 5 as we saw earlier, but there is also some evidence from other sources. It will be remembered that in Experiment 1, performance at the 2 and 5 metre distances was significantly better than at 8 or 10 metres. Although attention was brought to this finding, no explanation could be offered for it at the time. However, from the results reported in Part III, it might well be expected that performance should be superior at these distances, because at distances of less than 5m, it seems that subjects have both a map and a program for guiding behaviour. It does not seem unreasonable that performance when both of these are available should be superior to performance when only one is available, as is the case at the longer distances. This argument has some further evidence in favour of it in Experiment 2, where performance at 3m. was somewhat superior to performance at 6m, though the difference was not significant. Nevertheless, it was felt in all these early experiments, and in the preceding pilot studies, that at distances of less than 5-6 metres performance was somehow more consistent than at longer distances though this did not always show up as significant in the results. These findings from the earlier experiments are certainly consistent with the map/program mechanism outlined in Part III.

There is a number of questions arising from the results reported in Part III which should be considered at this stage. The first of these concerns the 5m limitation to locomotor programming found in Experiment 8. One question which arises out of this is the extent to which the finding can be said to hold for all forms of behaviour. For example, it might be asked if the accuracy of <u>throwing</u> would deteriorate at distances greater than 5m. It certainly seems that accurate throwing can be achieved from much greater distances than this, as evidenced by the ability of fielders in cricket to drop the ball over the stumps, even when the ball is thrown from the far out-field. Whether there is a "natural" limitation at 5m which can be overcome only with practice is not answerable from the studies reported here, but an examination of programming in alternative behaviours might well prove to be theoretically enlightening.

A second problem concerns the extent to which a map can reflect the information available in the optic array on which it is based. Although it might be argued from the results of Experiments 3 and 4 that the map is capable of representing at least four obstacles, it seems likely that the complexity which the map can take must be limited. How complex an array of obstacles is a map capable of representing? What are the limitations to map complexity, and when this complexity is exceeded what information is represented and what omitted.from the map? Again, these questions might turn up interesting results.

As in Part II, however, it must be emphasised that the purpose of this series of experiments was not to follow up all possible lines of research, nor indeed all of the most interesting ones, but rather to concentrate on providing sufficient information to establish some basic principles which could be examined more closely at a later stage. It was felt that the five experiments reported in Part III were successful in suggesting, albeit in a general way, how the intermittent control seen in Part II might be achieved by means of maps and programs. The results of these experiments were therefore considered to form a reasonable base from which further investigations might take off.

CONCLUSIONS

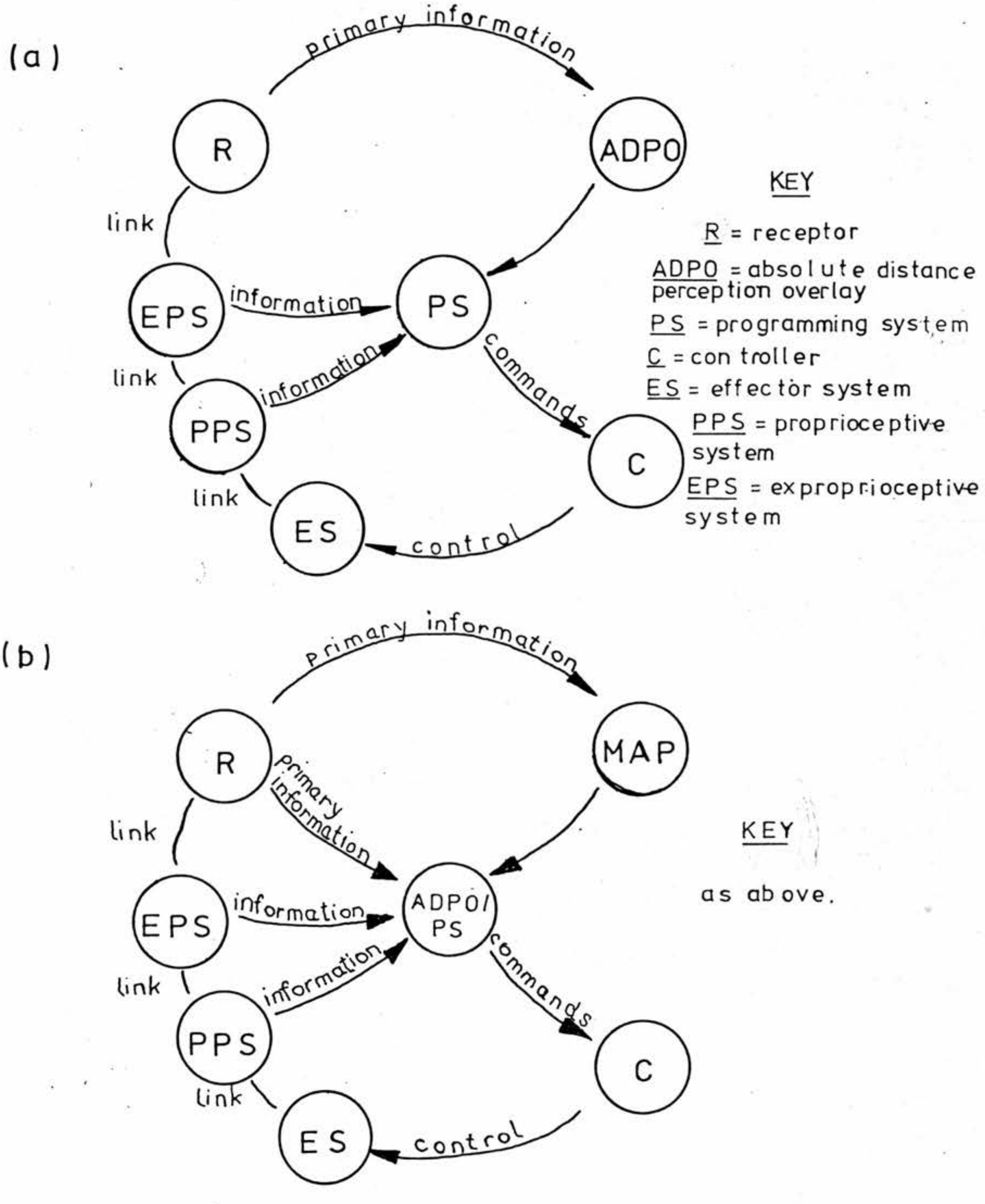
This thesis began with the problem of how animals get about in a complex and cluttered environment, and attempted to outline the basic essentials which any system would have to display in order to come to terms with such an environment. The thesis seems to have been successful in discriminating at least one critical capacity which such a system would have to have in order to realise behaviour at least approaching the complexity typically seen in animals; namely, the capacity for intermittent control. Some of the ways in which this is achieved (by maps and programs) have been outlined and seem to stand as of considerable importance in motor control.

It will be recalled that in the model presented in Part I, the critical elements were the Absolute Distance Perception Overlay (ADPO) and the Programming System (PS). These were the mechanisms by which intermittent control was said to be achieved. However, from the theoretical position adopted here, these elements should not be separated. According to the concept of program outlined here - a concept which was also supported empirically - the two elements cannot be separated and amount to alternative ways of saying the same thing. In Part I, the concepts of absolute distance and programming were kept distinct simply because it is not <u>of necessity</u> the case that these are the same. Absolute distance could be perceived in some quite different ways which could then be translated into programs for action when desired: and at that stage the primary object was to specify the kind of information which would be necessary and the uses to which it would have to be put in order to effect control. However, from the present theoretical position it is argued that to perceive "absolute" distance and to formulate programs for action are functionally one and the same, and this should accordingly be reflected in the model.

A second problem concerns the concept of map, which was not introduced in Part I. This was because the concept only developed out of experimental work reported in Part III. However, in view of these fresh discoveries, the concept should obviously be included in the model. These changes have consequently been made, and the revised model, together with the original, is shown in Fig. V.

One final comment on this model must be made. The Proprioceptive System (PPS) and the Exproprioceptive System (EPS) are concerned to supply information during the execution of programs as outlined in Part I. However, it must be realised that these elements too must operate by means of intermittent control, for they also constitute receptors like the eye, and must be expected to function in a similar way. Intermittency and programming would therefore appear to permeate the system. It seems that this is indeed a central feature of control.

A problem which was raised in the Introduction to this thesis was the extent to which the mechanisms outlined here would hold for different species. For example, since many species seem to use a group of sensory systems to pick up information about the environment, it might be supposed that this constitutes an alternative means of obtaining temporary freedom for any one of the senses. The evidence for this view comes from studies in which the different systems are systematically interfered with, to determine the importance of each to the animal. Watson (1914) observed in the white rat that when the



KEY

R = receptor
ADPO = absolute distance perception overlay
PS = programming system
C = controller
ES = effector system
PPS = proprioceptive system
EPS = exproprioceptive system

KEY

as above.

FIG. V Revised model of perceptuo-motor control.

animals were blinded, their ability at maze learning was little impaired. The same result held when the ears were blocked, the vibrissae cut, the olfactory system destroyed or the soles of the feet anaesthetised. When any one of these systems on its own was eliminated, behaviour was found to be little affected. However, when a group of these are simultaneously removed, behaviour becomes profoundly disturbed. Honzik (1936) found that when, for example, sight, smell and hearing were all eliminated, maze learning became impossible. Riley and Rosenzweig (1957) found that blinded rats make noises, largely with the feet, and use the auditory information generated to detect objects by echo-location. These findings would suggest that some species might indeed find temporary freedom for any one system by switching the control-load over to other systems.

While this might be considered an alternative to the mapping strategy outlined in Part III, the existence of multiple sensory systems cannot be held to rule out the need for programming, for reasons which have been repeatedly emphasised. Evidence of programming is readily found in animals like rats. For example, Carr and Watson (1908) observed in rats which had learned a T maze that when the corridors were lengthened, the rats would turn and run into the side wall. Conversely, when the corridors were shortened, they would run into the wall at the end of the corridor. These findings would strongly suggest that even in species with multiple sensory systems, programming still constitutes an important factor in the control of behaviour. However, it must be recognised that in such species, mapping may be absent; though the existence of multiple systems does not necessarily mean that this will be the case. This problem may be examinable experimentally.

As might be expected, this thesis seems to pose at least as many questions as it answers, and there are many other, potentially valuable questions arising out of the experiments reported which should be examined. Some of these have already been outlined in the general discussions of Parts II and III. Several others in this category may be mentioned. One problem which has not been dealt with properly is the problem of how the system executes a program and picks up information for fresh programs at the same time. There is really no evidence in the thesis on this matter. Similarly, while it has been stressed that a fundamental reason for intermittency is the freedom it gives the system to engage in other activities, no evidence has been supplied on the effectiveness of control when alternative activities are simultaneously engaged in. Both these problems deserve examination. Reference has already been made to the necessity for examining the extent to which the conclusions drawn with reference to locomotion will hold for all motor behaviours. It would seem highly desirable to examine alternative behaviours like reaching or throwing from this point of view. The results of such studies may well be of considerable theoretical value. A final problem which may be mentioned is the problem of how short-term programs and maps of the sort being discussed here are related to long-term ones. Anyone who can get out of bed in the dark and then cross the room to the light switch without bumping into anything would seem to show evidence of having internalised some form of map or program in a long-term form. This kind of mapping and programming is most clearly seen in the blind, who can internalise information about the layout of a room so accurately, that within that environment they may be virtually indistinguishable from a sighted person. Just how such maps are derived is unknown, though one possibility is that a group of short term maps and/or programs become gradually transformed into a more permanent form. The process by which this is done seems eminently worthy of study.

All these problems, then, arising more or less directly out of the experiments reported above seem well worth following up. Perhaps the most interesting and potentially important future work suggested by the results of this thesis, however, is concerned with the blind. The implication of the present research is that the blind person is handicapped, not just by the poverty of the information available to him, but by the way in which that information becomes available. The cane carried by the blind person allows him information about one metre (the length of the cane) in advance. From the results of this thesis, however, it would certainly be predicted that this is too short a time to enable evasive action to be taken if an obstacle is detected. This may well underlie the slow and hesitant gait displayed by many blind people. If information were available further in advance, it might be that this alone would aid blind mobility. There is some evidence that longer canes enable blind people to locomote more freely (Jansson, 1975) and the sophisticated sonar device tested by Bower (1976) seems to improve control considerably. One experimental problem arising directly out of the research reported in this thesis which would certainly have a bearing on this problem, would be to assess the minimum distance ahead which a person must be able to see in order to execute different forms of locomotion (e.g. walking or running). Some theoretical answers to this problem have already been outlined in our discussions of limitations due to processing times and other factors. An experimental examination of this problem might then provide a group of indices of the length of forewarning necessary to aid mobility in different situations. This research would therefore seem to be of potentially great value.

An important implication of this thesis is that absolute distance is perceived up to distances of only 5 metres. Although behaviour can be controlled in the absence of visual information over distances greatly in excess of this (at least up to 21 metres), this was not taken to mean that these longer distances were accurately perceived. On the other hand, the evidence of all these experiments suggested that the errors obtained when the 8 second temporal limitation was exceeded were not strictly perceptual in nature, because the mean error in almost all cases fell on the target line. The problem then arises as to how these different findings are to be explained. This is perhaps the most interesting problem raised by the thesis. The answer may be that there are different "levels" of distance perception, extending from absolute distance perception as seen in Experiment 8 to purely relative distance perception. We should not expect to find a sharp dividing line between these two: obviously, at distances of more than 5 metres, there may well be a gradation in the accuracy of distance perception. For example, the error at 6m. would hardly be expected to equal in magnitude the error at half a mile. It seems more likely that the accuracy of distance perception would decline gradually, perhaps in a series of "steps" until some form of "chance" error is obtained - though just how chance would be defined in the present context is unclear. But again, as stated in Part I, the term "absolute distance perception" would be reserved for those occasions where accurate behavioural responses are achieved. This whole problem deserves detailed study in the future.

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