VISUALLY CONTROLLED LOCOMOTION AND VISUAL ORIENTATION IN ANIMALS*

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A general theory of locomotor behaviour in relation to physical objects is presented. Since the controlling stimulation for such behaviour is mainly optical, this involves novel assumptions about object perception and about what is called 'visual kinaesthesia'. Evidence for these assumptions is cited. On the basis of this theory it is possible to suppose that animals are visually oriented to the surfaces of their environment, not merely to light as such. In short, it is possible to explain why they seem to have space perception. Implications of this approach for maze-learning are pointed out.

I. INTRODUCTION

The locomotion of animals seems to be controlled by optical as well as by other kinds of stimulation for, in many species, locomotor behaviour ceases when optical stimulation fails, as in total darkness. In bats, to be sure, we now know that locomotion occurs in darkness under the guidance of auditory stimulation, or echolocation (Woodworth & Schlosberg, 1954, 359 f.), but this interesting discovery only serves to emphasize the importance of vision for the majority of animals in the business of getting about the environment, of avoiding obstacles, and of seeking food. Students of animal behaviour have long been concerned with locomotion at the level of reflexes and forced movements, but not at the level of averting collisions or of approaching goals: there is a considerable literature on phototropisms, taxes, and kineses (e.g. Fraenkel & Gunn, 1940), but almost nothing on such acts as the pursuit of prey or the flight from a predator. The reason for this failure is probably connected with the generally accepted assumption that the ability of an animal to respond to light and the ability of an animal to respond to objects are quite different problems. The first is supposed to be physiological and the second psychological. A tropism implies only a sensory process, but a response to an object at a distance implies a perceptual process and this is much more complex. The physiologist is willing to study the former but he is glad to turn over the latter to the psychologist. The problem of how we respond to objects at a distance has been, in truth, a puzzle for psychologists ever since Bishop Berkeley. Depth or space perception has been taken to be an internal process involving the interpreting or organizing of sensations. Theories of this process have never achieved either simplicity or plausibility and, if it is a process of association, the difficulty arises of why animals do not make more errors than they do in the acquisition of locomotor behaviour. The writer has argued (1950) that the only way out of this theoretical muddle is to discard the original assumption about sensory response to light on the one hand and perceptual response to objects on the other. Perhaps the distinction was based on a mistaken conception of vision in the first place. If the theories of space perception do not provide an adequate explanation for the visual control of locomotion in animals, let us

* The first draft of this paper was written in 1955–6 at Oxford University under a Fulbright award. The author wishes to thank Prof. George Humphrey, members of the Institute of Experimental Psychology, and others at the University for kindnesses beyond the demands of academic courtesy. He also thanks these and many other investigators visited during the year for cordial and stimulating discussion.
forget about the former and pay heed to the latter. Locomotion is a biologically basic function, and if that can be accounted for then the problem of human space perception may appear in a new light. The question, then, is how an animal gets about by vision. How does it react to the solid surfaces of the environment without collision whenever there is enough light to see them by? What indicates to the animal that it is moving or not moving with reference to them? What kind of optical stimulation indicates approach to an object? And how does the animal achieve contact without collision? What governs the aiming and steering of locomotion? (The problem of 'roundabout behaviour' in the presence of a 'barrier', as it appears in the writings of Lewin (1933, 1935) and later Hull (1938, 1952) is a different question. It is as close as psychologists have come, however, to a psychology of locomotion.)

II. POSTULATES FOR A GENERAL THEORY OF THE VISUAL CONTROL OF LOCOMOTION

The starting point for a theory of locomotion in the higher animals would be the fact that they have evolved eyes (Walls, 1942) which can register not merely light but the objects of an illuminated environment. The optical basis for this assertion has been accumulating for years but the conclusion has not generally been drawn despite its having radical implications for a theory of behaviour. The function of a highly developed mosaic of visual receptors is to respond to what might be called the projective capacity of light. When light is many-times reflected in all directions from an array of surfaces—when it 'fills' the environment as we say—it has the unique property that reflected rays will converge to any point in the medium. The objective environment is projected to this point. If an eye is placed at this point, it can register a sector of the projection by the familiar process of the formation of an image. The central hypothesis of the theory to be presented is that the patterns and the changes of pattern of this projection are stimuli for the control of locomotion relative to the objects of the environment. For the sake of explicitness, it might be well to list the assumptions singly. The first six assumptions deal with the projection of light to the position of a motionless animal, that is, with the optic array to a stationary point. The remaining postulates assume an animal in motion and deal with the optic array to a moving point.

1. The locomotor environment of animals consists of the surfaces or interfaces between matter in the solid state and matter in a liquid or gaseous state. This generalization holds for aquatic, terrestrial, or aerial environments, and for animals at various phylogenetic levels.

2. Solid surfaces generally reflect rather than transmit light. They also generally prevent rather than permit locomotion. Consequently, the remaining liquid or gaseous regions of the environment constitute a medium both for the transmission of light and for the movements of organisms.

3. If the environment is illuminated there will occur a many-times reflected flux of light in the medium. If the solid surfaces and their parts vary in reflectance a projection of these differential reflectances is obtainable at any point in the medium.* That is, the rays converging to this point will have different intensities (and frequency compositions) in different directions. They constitute what may be termed an optic array.

* This is a simplified statement, holding for an ideally diffuse illumination. In other conditions of illumination, what we loosely call 'shadows' as well as reflectances must enter into consideration. The extent to which animals can discriminate in their behaviour between shadows and solid surfaces is a complex problem which can here be omitted.
An eye is a device which registers some portion of the ‘pattern’ or ‘texture’ of an optic array to a station point. Conversely, the pattern of an array is a stimulus for an eye.

This postulate needs explanation. Eyes, to be sure, are of different types in different animals (Walls, 1942). At one extreme, a pair of eyes can include nearly the whole pattern of a $360^\circ$ optic array, each eye registering an approximate hemisphere with little overlap. This is the case with fish. At the other extreme, a pair of eyes can register overlapping sectors or cones of the frontal optic array, each picking up the same pattern from a slightly different station point. This is the case with primates in whose case the eyes are mobile and co-ordinated, being capable of exploratory (saccadic) fixations and convergences. The total array can then be registered only by rotating the eyes and head. The registration process is successive, not simultaneous, since different angular sectors of the array are picked up at successive moments of time. Nevertheless, by a mechanism as yet not well understood, successive registration seems to be equivalent to simultaneous registration.

The pattern of an optic array was said to be a ‘stimulus’ for an eye. For animals with fixed eyes on either side of the head this assertion is plausible. Each eye registers its own hemisphere. For animals with mobile eyes at the front of the head, however, the assertion is not so obvious. The total pattern of the spherical array is then, strictly speaking, a potential stimulus as distinguished from the momentarily effective stimulus which exists for a single eye-posture. The pattern of a single entering sheaf of rays is only a sample of the whole pattern projected to a point in space. But the whole pattern may and will be picked up if the animal looks around. In an even more abstract sense the whole flux of focusable light pervading the medium is a potential stimulus which can be sampled at various station-points in the medium, although it must be explored by locomotor rather than by oculomotor action. It is, of course, unorthodox to assume that the focusable light converging to an eye is something to which the word ‘stimulus’ should be applied. We have generally believed that only the focused light constituting the retinal image excites receptors. But this physiological conception of the stimulus has been a source of paradox and confusion in psychology. In fact, it does not apply. The image is a stimulus for the retinal mosaic, to be sure, but not for an eye. Focusable light is the stimulus for an eye, which responds first by focusing it. The image is no more than a response-produced stimulus. A retinal image is not a thing with definite boundaries in any case. The retina continually moves behind it, with both large and small excursions, so as to bring the fovea to different bits of detail. A continually new sample of the pattern of the world gets projected on the retina. Images are the necessary means by which an animal exploits the capacity of light to project reflecting surfaces to any given point in a transmitting medium. The light converging to such a point is the external, stable, and relatively permanent stimulus for an eye.

The presence or absence of a solid environmental surface in any part of the optic array is specified by the textured or textureless character, respectively, of that part. In other words, textured light indicates the differentially reflecting structure of a solid surface, which stops locomotion. Untextured or homogeneous light indicates an unobstructed medium of water or air, into which locomotion can proceed indefinitely (Gibson & Dibble, 1952). The presence of a solid object in the environment is specified by a textured cone in the optic array with a
distinct boundary, and the absence of an object is guaranteed by the absence of such a stimulus (Gibson, 1951).

This assumption, it may be noted, contradicts the classical distinction between sensory and perceptual processes. The present tacit agreement as to where the responsibility of the visual physiologist ends and the responsibility of the visual psychologist begins is thereby destroyed.

(6) In so far as the physical solids of the environment are rigid and permanent (as contrasted with fluid and morable) the pattern of the optic array at any point in the medium is unique and permanent. That is to say, there is, and will be, one and only one pattern for each station point. It is also assumed that no considerable section of a natural environment is a duplicate of another—that models or copies of environing spaces are created only by man. An important consequence of this assumption is that the difference between the patterns of the optic arrays at any two station points is a unique difference which depends only on the difference between the points (Nicod, 1930). We may call it a unique transformation.

(7) An animal which moves passes through a continuous series of station points. Each eye is therefore presented with a continuous family of transformations, and this family is unique to the particular path of locomotion. With an animal which does not change its position, the eyes are presented with what may be called a continuous non-transformation of the optic array, that is, a static pattern.

The classical geometry of perspective will describe the static pattern of the optic array, that is, the projection of an environment to a stationary point. The geometry of 'motion perspective' (Gibson, Olum & Rosenblatt, 1955) will describe the 'flow pattern' of the optic array, that is, the projection of an environment to a moving point. The geometry of motion perspective has been exemplified by an analysis of aerial flight with reference to a plane surface. It is interesting to note that the flow pattern is independent of the static pattern that carries it; the same flow pattern may be embodied in any number of static patterns.

(8) An eye is a device which registers the flow pattern of an optic array as well as the static pattern of an array. Conversely, such a family of continuous transformations is a stimulus for an eye. There are quite specific forms of continuous transformation, and the visual system can probably discriminate among them (Gibson & Gibson, 1957). This mode of optical stimulation is an invariable accomplishment of locomotor behaviour and it therefore provides 'feedback' stimulation for the control and guidance of locomotor behaviour. It might be called visual kinaesthesia.

The last assumption asserts something like an unrecognized sense modality. Visual kinaesthesia is, of course, supplementary to the recognized mode of proprioceptive kinaesthesia. It differs, however, in several ways. First, it seems to provide information about movements of the animal relative to the environment, not about movements of parts of the body relative to other parts, as the muscle-sense does. Secondly, it seems to provide information about displacements rather than information about accelerations and gravitational forces, as the vestibular sense does. Thirdly, the displacements registered have reference to the stable solid surfaces of the environment; displacements with reference to the medium of air or water, in the case of flying or swimming animals, are given only by proprioceptive kinaesthesia. Kinaesthesia has long been defined as the sense of bodily motion. It was described by Sherrington fifty years ago (1906). It depends on the sensitivity of receptors in the muscles and joints to compression, on the sensitivity of a statocyst to force, and also on the sensitivity of the skin to deformation. Visual kinaesthesia
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depends on the sensitivity of a retinal mosaic to an overall change of pattern. To suggest
that the eye can serve as a kinaesthetic organ is somewhat upsetting; for one thing it
violates our notion of the eye as an exteroceptor in Sherrington’s classification of extero-
ceptors, proprioceptors, and interoceptors. There is some inadequacy, however, in all
attempts at anatomical classification of fixed senses. Kinaesthesia, as usually understood,
is actually several different forms of sensitivity to several different kinds of motion: of the
muscles, the joints, the endolymph, and the skin. Why not admit optical motion? The
fact is that animals seem to pick up stimulus information from the sea of energy around
them through multiple channels and in various ways. Seemingly redundant information
is not neglected; on the contrary, many supplements and concomitants and combinations
of energy seem to be received at the same time. And the transformations in the field of
view are very useful information.

Consider the case of a fish maintaining its position over the bottom of a flowing brook,
or the case of a bird hovering over the same bit of land in a wind. It must move relative
to the medium in order to be motionless relative to the solid substratum. For this,
obviously, it must rely on vision. It has to maintain an unchanging pattern of the optic
array. Transformation of the array is an index of motion relative to the substratum, and
a completely reliable one. By visual kinaesthesia the animal can co-ordinate its behaviour
to the environment while at the same time by muscular kinaesthesia it can co-ordinate
its locomotion to the medium.

Is there evidence to show that the ocular mechanism in animals can actually register
the flow pattern of an optic array, as assumed? Animals, including insects, are said to be
very sensitive to ‘motion’, and there is observational evidence from zoology and ethology
(Tinbergen, 1951) suggesting that animals make specific responses to specific kinds of
moving objects in the environment. If they are sensitive to objective motion in the en-
vironment it is likely that they are also sensitive to subjective movement in the environ-
ment (Gibson, 1954), but the question has not been specifically studied. There is, of course,
plenty of evidence to show that animals have pattern vision in varying degrees, and
experiments on form discrimination make a large literature in comparative psychology.
Whether they have change-of-pattern vision is another question, and this has scarcely been
investigated. But it is very likely that they do. The compound eyes of insects, particularly
those with a relatively coarse mosaic, may prove to have greater acuity for differences
between transformations than they do for differences between forms. There is evidence
to prove that human observers are very sensitive to optical motions. They can detect
motion parallax in the field of view with very great precision (Graham, 1951), and they
can utilize the shadow transformations on a translucent screen for accurate judgments of
changing depth (Gibson & Gibson, 1957).

III. FORMULAE FOR A THEORY OF VISUAL CONTROL OF LOCOMOTION

We are now prepared to apply the postulates to the problem of how an animal gets about
in a stable environment, approaching goals, avoiding obstacles, and even responding to
moving objects such as a prey or a predator. By these assumptions, transformations of the
total optic array to a moving point serve for the control of locomotion relative to the total
environment. Transformations of a smaller bounded cone of the optic array (a closed
contour with internal texture in the visual field of the animal) serve for the control of
locomotion relative to an object in the environment. A formula will be given for each of the following aspects of locomotor behaviour: beginning forward locomotion, ceasing locomotion, reversing locomotion; steering toward a specific place or object; approaching without collision; avoiding obstacles; pursuit of a moving object; and avoiding a moving object. The formulae will be in verbal rather than mathematical form, but they are capable of the latter kind of statement.

(i) Starting, stopping, and backing-up

The flow pattern of the optic array during forward displacement vanishes during non-displacement and is reversed during backward displacement (seventh assumption). A human observer who attends to his visual sensations can note a sort of ‘expansion’ or ‘contraction’ of the patchwork of colours in his frontal visual field as he moves forward or backward. Actually there is a centrifugal flow of the structure of the optic array from a pole in the direction of displacement, the flow being graded in proportion to the nearness of the corresponding surface (Gibson et al. 1955). (This graded centrifugal flow of an optic array from an environment of solids has the interesting property of being capable of continuing indefinitely without the consequence that the pattern as a whole becomes larger. Elements or forms of the pattern are magnified as the corresponding objects get nearer, but new elements emerge to take their place in the array. The structure of such an array consists of forms within forms to an unlimited density. The reason for this fact is that the environment of animals is itself structured at any level of magnitude; it is composed not only of mountains and trees but also of crystals and cells.) There is a corresponding centripetal flow toward a pole in the direction opposite the displacement. These flow patterns depend on the configuration of the reflecting surfaces in the environment but they are independent of any particular configuration. To begin locomotion, therefore, is so to contract the muscles as to make the forward optic array flow outward. To stop locomotion is to make the flow cease. To reverse locomotion is to make it flow inward. To speed up locomotion is to make the rate of flow increase and to slow down is to make it decrease. An animal who is behaving in these ways is optically stimulated in the corresponding ways, or, equally, an animal who so acts as to obtain these kinds of optical stimulation is behaving in the corresponding ways.

(ii) Steering and aiming

The centre of the flow pattern during forward movement of the animal is the direction of movement. More exactly, the part of the structure of the array from which the flow radiates corresponds to that part of the solid environment toward which he is moving. If the direction of his movement changes, the centre of flow shifts across the array, that is, the flow becomes centred on another element of the array corresponding to another part of the solid environment. The animal can thus, as we would say, ‘see where he is going’. The act of turning or steering is, therefore, a visual as well as a muscular event. To turn in a certain direction is to shift the centre of flow in that direction relative to the fixed structure of the optic array. The amount of turn is exactly correlated with the angular degree of shift. The behaviour of aiming at a goal object can now be specified (although the properties of a figure in the field of view which arouse this behaviour have not yet been described). To aim locomotion at an object is to keep the centre of flow of the optic array as close as possible to the form which the object projects.
(iii) Approaching without collision

Approach to a solid surface is specified by a centrifugal flow of the texture of the optic array. Approach to an object is specified by a magnification of the closed contour in the array corresponding to the edges of the object. A uniform rate of approach is accompanied by an accelerated rate of magnification. At the theoretical point where the eye touches the object the latter will intercept a visual angle of $180^\circ$; the magnification reaches an explosive rate in the last moments before contact. This accelerated expansion in the field of view specifies imminent collision, and it is unquestionably an effective stimulus for behaviour in animals with well-developed visual systems. In man, it produces eye blinking and aversive movements of the head, even when the stimulus is a harmless magnification of a shadow on a translucent screen. At lesser intensities this 'looming motion', as it might be called, presumably yields lesser degrees of aversion, or a slowing down of approach. The fact is that animals need to make contact without collision with many solid objects of their environment: food objects, sex objects, and the landing surfaces on which insects and birds alight (not to mention helicopter pilots). Locomotor action must be a balance between approach and aversion. The governing stimulation must be a balance between flow and non-flow of the optic array. The formula is as follows: contact without collision is achieved by so moving as to cancel the centrifugal flow of the optic array at the moment when the contour of the object or the texture of the surface reaches that angular magnification at which contact is made.

(iv) Steering among obstacles

Fish, birds and arboREAL animals live in a cluttered environment, that is, one whose open spaces are encroached upon by solid surfaces. Nevertheless, they swim, fly, or take a course among these obstacles with great precision. Many species do so only when the medium is illuminated, that is, they depend on vision. The obstacles are specified in the optic array by contours with internal texture; the open spaces are specified by the areas between such contours. The background areas may be untextured homogeneous colour, like the sky, or densely textured surface colour, like the earth. The question is, what governs the taking of a course during such locomotion? Symmetrical magnification of a textured contour specifies a collision course toward an obstacle, but a skewed magnification, where the centre of flow is outside the textured contour, specifies a non-collision course. So long as an animal keeps the focus of centrifugal flow outside the textured contours and within a homogeneous or densely textured area, he will not collide with a solid object. This formula, it may be noted, is simply the reciprocal of that for aiming at a goal object. The properties of a textured contour by which is specified either an obstacle on the one hand or a goal object on the other have not yet been considered.

(v) Pursuit and flight

Predatory animals pursue and preyed-upon animals flee. These biologically complementary forms of behaviour must both be controlled by transformations of optical pattern. Approach to a stationary goal object has been described. A fugitive goal object is specified when the optic array as a whole flows from a centre, but when a textured contour within it does not expand. The object is then moving away and being pursued. Absolute angular magnification of the contour means catching up and minification of the contour means falling behind. Hence, the rule by which a big fish can catch a little fish is
simple: maximize its optical size in the field of view. From the point of view of the prey, the expansion of a textured contour in the optic array means the approach of something. This in itself may touch off the reaction of flight if it comes within the field of view. Preyed-upon animals need eyes which can register this abstract optical event in the rearward as well as the frontward direction, and very generally they seem to have developed eyes with a panoramic binocular field (Walls, 1942). What exactly is flight? The formula is again simple. It is so moving as to minimize the optical size of the expanding contour. This will necessarily involve a centripetal flow of that hemisphere of the optic array which contains it and a centrifugal flow of the opposite hemisphere. If the optical size of the contour decreases, the animal is getting away; if it increases despite the contraction of the surrounding field, the animal is being overtaken. There is one other geometrical possibility of stimulation: contraction of a contour in an otherwise static array. This means something going away. Probably it does not touch off the reaction of flight as expansion of a contour does in preyed-upon animals. This hypothesis needs empirical testing.

(vi) The complexities of terrestrial locomotion

For simplicity, the formulae of the theory have referred, so far, to locomotion in a medium of water or air. They are sufficient to show the possibilities of a circular control or ‘feedback’ type of stimulus-response analysis for understanding the locomotor behaviour of fish and birds. There are, however, terrestrial animals. The surface of the earth is a substratum. Locomotion can occur, mechanically speaking, in two possible ways: by exerting force against the medium and avoiding contact with the substratum, or by exerting force against the substratum and keeping in more or less continuous contact with it. The latter type, terrestrial locomotion, seems to have developed later in evolution. Terrestrial animals utilize a great variety of mechanical procedures—crawling, gliding, hopping, walking, running and the like, but they all push against the ground in one manner or another. For these animals, touch is available to play some part in controlling locomotion—actually change of contact stimulation, or tactual motion. There is also classical muscle-joint kinaesthesia which, in these animals, is never discrepant with visual kinaesthesia as it may be for the fish or the bird in a flowing medium. Since these modes of controlling stimulation run parallel in terrestrial man, it has been easy for the human psychologist to overlook the visual mode. Only since man began to fly aircraft has the visual component in the guidance of locomotion forced itself on the attention of psychologists. And yet it was always there to be observed. Consider the perception of ‘ footing’ in a man who is making his way over rough terrain. Or, better, consider the oculomotor co-ordinations of a cat, or of any animal which runs with ‘due regard’ to the footing. The visual aspect of the performance is just as precise as the muscular aspect. The animal has only the information supplied by the optical array to a moving point (or a pair of them) and yet it adjusts its behaviour to the convexities and concavities and other physical properties of the surface ahead of it. This consideration reminds one that animals respond to invariants as well as changes of stimulation—to the permanent properties of the environment as well as to their own motions in it. We should return to the problem of the exteroceptive function of vision and note whether the problem is reformulated after first considering its proprioceptive function. Animals are capable not only of locomotion in, but also of orientation to, their environment, that is, of object perception and even what psychologists have called ‘space’ perception.
IV. Visual orientation in animals

Animals are not continually on the move; they sometimes remain at rest. Often the only movements that can then be observed are eye-movements. This means that the resting animal is exploring the optic array even if he is not exploring the environment. It is tempting to believe that the animal is still making some kind of implicit responses to the solid surfaces around him even if he is not explicitly poking his nose into things. He is certainly oriented to gravity and to the substratum when he maintains a constant posture. He is probably also oriented to the distant objects of his environment when he remains in the same place. In the fifth assumption, we may indeed find a basis for the latter kind of orientation. It seems to be possible for him to identify and react to the objects of his world by virtue of the optical properties of the light reflected from them to his eye. One might even wish to suggest that the animal, in his way, perceives the objects of his world.

Animals make different kinds of locomotor reactions to different objects. They approach food or shelter, they avoid obstacles, they pursue prey and they flee the predator. These are discriminative reactions and they require a different kind of stimulus-response theory than do the control reactions heretofore considered. We must now consider actions which are specific to those features of the optic array which do not change during locomotion rather than those which do. Such features of stimulation are not response produced and the responses are not circular. In such behaviour the S-R linkage is between permanent entities of the environment and acts which are appropriate to them. The distinction between an S-R theory of control reactions and an S-R theory of identifying reactions is important for behaviour theory. It is true that an automaton can be designed which will aim at, approach, and pursue a pre-set target (as witness military missiles) and that no automaton has yet been designed which will recognize targets appropriate to its own needs (apart from its designer's) and act accordingly. But it would be wrong to categorize the first kind of reactions as automatic and the second kind as voluntary. This dichotomy is as pernicious as the one between sensory and perceptual processes. The true distinction is probably that between the properties of stimulation which vary over time and those which do not.

(i) Object perception

By the fifth assumption, material objects, substances in the solid state, are specified by the textures and contours of the optic array, and they stop locomotion. However, a solid object, by virtue of its chemistry and biochemistry, may constitute food for an animal. Or it may constitute a mate, or young, or shelter, or an obstacle, or an enemy. These higher-order properties of solids are specified by higher-order properties of the light in the optic array. For example, there is internal pattern as well as texture in the light reflected from an object and there is shape as well as contour. There is a frequency distribution in such light which specifies in a complicated way what men call 'colour'. Moreover, if the object is alive and moves there will be deformations of its contour and internal pattern which specify it as animate, and which may further specify it as one or another kind of animate thing. In so far as an animal can discriminate these variables of the optic array, he can discriminate the properties of objects which render them not only bump-into-able and walk-on-able but also mate-with-able, or get-underneath-able, or edible, or likely to cause pain. And to this extent, he can identify the significant classes of objects
in his environment, that is, he can respond to them differently as the objects themselves differ in biophysical ways (Gibson & Gibson, 1955). These are the so-called ‘goal-objects’ of an animal’s environment, the ones which are related to the animal’s needs, which induce approach or avoidance, and which man describes as having valences or meanings in the perceptual field. The hypothesis is that the values of objects as well as their solidity are specified with some degree of reliability in the optic array. Mere physical solidity has a value for locomotion and collision. Chemical and biological properties of higher order have values for nutrition, reproduction, and survival. The animal’s task is to detect these properties at a distance.

Contemporary behaviour theorists either take for granted that objects constitute stimuli (‘stimulus objects’) and thus beg the question of how objects are responded to, or else they assume vaguely that pattern stimuli are ‘cues’ for behaviour and thus slip around the problem of object perception. (The latter point is illustrated by comparing the use of ‘cue’ by a student of behaviour such as Miller—Miller & Dollard, 1941—who takes the concept very lightly, and a student of perception such as Brunswik, 1956, who takes the concept very seriously.) But this will not do. During locomotion, the patterns at the receptor surfaces of an animal are necessarily in flux, the objects being projected as changing patterns rather than constant patterns. If we wish to believe that an animal can respond to a constant object in the course of his behaviour we should first resolve this apparent contradiction. There are two alternatives. We can assume that the animal somehow constructs a perceptually constant object from the kaleidoscopic field of sensations: this is the starting point for classical theories of perception. Or we can assume that the animal is sensitive to the mathematically invariant properties in the stimulus flux which correspond to the physically constant object: this is the alternative which seems more promising for the future. During the locomotor transformations of the pattern of the optic array the property of colour remains, of course, invariant. During these perspective transformations many geometrical properties such as the kind of texture, or the angularity or curvature of the pattern also remain invariant. There are plenty of invariant variables in the flux of optical stimulation on the basis of which an animal can identify classes of permanent objects. The empirical question is whether animals are, or come to be, sensitive to them.

(ii) Orientation to the visible environment

Animals seem not only to recognize constant objects, but to orient themselves to a constant environment, that is, to any permanent arrangement of solid surfaces. The homing behaviour of many species suggests that the animal is able, on familiar ground, to find its way from any one place to any other significant place; territorial behaviour also suggests that he can respond, in some sense, to the habitat as a whole; and exploratory behaviour suggests a kind of striving to extend the boundaries of this whole. How can this complicated behaviour be supposed to depend on vision? Consider the pattern of an optic array to a stationary position. For land animals the lower hemisphere, roughly, will be textured and patterned by the surfaces and objects of the earth. But not only solidity is specified in the array; the slants and slopes and the facings of this arrangement of surfaces are specified by gradients of the optical texture (Gibson, 1950, chap. 6). The edges are specified by steps of the texture variables, and convexities or concavities are specified by changes of gradient. In short, the lay of the land, the jumping-off places, the
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interspaces, barriers and obstacles, as well as the level stretches, are given by the geometry of the optic array. Depending on the locomotor capacities of the animal, this terrain provides definite possibilities or impossibilities for crawling, walking, climbing and the like. And if the animal can discriminate the textural variables it can discriminate among potential paths for locomotion. A potential path is a stretch of surface extending away from the animal which affords the kind of locomotion for which the animal is equipped. A barrier or obstacle is a surface which does not afford locomotion. There are transitional cases between path and barrier, to be sure, and a cliff or vertical edge is a special type of barrier, but the definitions will serve well enough for theoretical purposes. (The responses of rats to a ‘visual cliff’ have recently been studied under laboratory conditions—Walk, Gibson & Tighe, 1957—and they show the kind of aversion predicted by this theory.) A terrestrial animal is always encircled, then, by a radiating set of paths or barriers. Each angular sector of the optic array specifies the possibility of locomotion in that direction. A level path of unlimited distance is given by a gradual increase of textural density up the array to the horizon. A barrier is given by a region over which density remains constant, and its distance by the point at which the change in the density gradient begins. A falling-off place is given by an abrupt increase in density upward in the array. A margin between land and water (a barrier for a non-swimmer) is given by a change in the kind and rigidity of texture together with a change in colour. Confinement consists of barriers in all directions; freedom consists of paths in all directions. To the extent that the animal can respond to these variables of the encircling optic array, we may now conclude, he has locomotor orientation to his environment. He perceives the possibilities of locomotion surrounding him. And this is probably what should be meant by asserting that an animal has visual space perception.

(iii) Orientation to the environment outside the range of vision

The visible environment may be limited by enclosing surfaces such as those of a laboratory maze, and even in an open medium it is limited by the acuity of the eye, the clearness of the medium, and the level of the illumination. An animal, nevertheless, can learn in some degree to go to places and objects outside of these limits (Rabaud, 1928; Thorpe, 1956) just as a man can learn to find his way about a house, the streets of a city, or the highways of a state. How is this behaviour to be accounted for, and in what sense is it visually determined? It is not explained by the unchanging pattern of an optic array to a single position. Consider, however, the transformations of pattern of an optic array to a moving position, as described in the seventh and eighth postulates. We have assumed that a family of continuous transformations is itself an optical stimulus, and that the properties which remain invariant under transformations also remain stimuli during such flux. The former specifies the particular path of locomotion taken; the latter specify the permanent arrangement of surfaces. An animal that explores its environment in the course of time moves from each of many places to each of many other places and, just as each place corresponds to a unique pattern, so each movement corresponds to a unique transformation. The visual flux of a locomotor animal, as it goes about its business, consists of a sequence of transformation families interspersed with periods of non-transformation. Since these families each begin where the preceding one ended, they are linked. The entire life of the animal is co-extensive, in fact, with a single grand family of optical transformations which specify the history of its travels and explorations. This fact should
be taken into consideration in any theory of maze learning or, more generally, of how an animal learns its way about. The successive patterns of the optic array are not a series of discrete pictures like a series of nonsense syllables which have to be associated; they are parts of a continuous transformation with a temporal pattern of its own. The nature of this temporal pattern—the direction of the change of the momentary patterns—is probably something which an animal can sense and, if so, we do not have to postulate the conditioning of a series of responses to a series of discrete stimuli as Hull (1952) does in his theory of the goal-gradient and the habit-family. Hull chops a temporal pattern into a set of static patterns and is then faced with the problem of integration. The integration of behaviour is partly explainable in terms of the pre-existing integrity of stimulation, and by the hypothesis that an animal learns to respond to it. If maze learning is to be explained in S-R terms we must recognize that the stimuli to which responses are made change as well as the responses themselves (Gibson & Gibson, 1955). In the course of learning, a whole temporal pattern may become the effective stimulus for a single integrated act.

The controversy over ‘response learning’ and ‘place learning’ has now reached major proportions in psychology (Woodworth & Schlosberg, 1954, chap. 21; Thorpe, 1956, chap. 5), but neither side has troubled to analyse the optical stimulation. Hull’s theory of maze learning asserts that it is the acquiring of a sequence of movements. Tolman’s theory asserts that it is the acquiring of a cognitive map of the maze (Tolman, 1948). If Hull’s theory could profit by utilizing the notion of continuous transformation, Tolman’s theory could profit by the notion of invariant variables of stimulation under transformation. The perceiving of the possibilities of locomotion surrounding an animal does not, as Tolman assumes, require a theory of sign learning or the interpretation of sensory cues. Space perception can be explained with greater parsimony by kinds of stimulation hitherto neglected in sensory physiology. Knowing the possibilities of locomotion outside the limits of momentary vision, that is to say the cognitive mapping of the extended environment, can be explained in part by the recurrent, constant, or invariant properties of such stimulation which are discovered during exploratory behaviour.

(iv) The learning of visual orientation by exploration

Animals learn to get about the environment and they also learn about the environment. The first kind of learning is called behavioural and the second cognitive, but nothing prevents us from making both assertions. If an animal goes to where something is we can infer that he knows where it is. In either case the experimental evidence suggests that the learning depends on exploratory activity. Artificial environments such as mazes have provided much of the evidence, but the conclusion holds for natural environments as well, the evidence coming from work on homing and foraging (Thorpe, 1956). No other kind of stimulation is as informative about the environment as light when it is many-times reflected in a medium. The best means of exploring an environment is (a) to point the eyes in various directions, and (b) to plant them at various station points. It seems probable that eyes are sensitive to the transitions between visual patterns as well as the patterns themselves. Certainly locomotion is guided thus. A transformation may be more significant than a form, in fact, since it carries all the information that a form does plus that carried by the kind of transition. There are families and superfamilies of such information in focusable light. The more of it an animal can react to the more efficiently and
quickly he can go from place to place in his environment, and the more he can learn what the arrangement of his environment is. This kind of learning is by no means the only kind, to be sure, but it is an important one.

REFERENCES


(Manuscript received 28 June 1957)