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PERCEPTION AND CONTROL OF ROTORCRAFT FLIGHT

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Of the topics receiving attention during the workshop, three overlap with my areas of expertise and interests in application to rotorcraft flight. Therefore, in this report, I will concentrate on (a) the nature of visual information, (b) what visual information is informative about, and (c) the control of visual information. The first topic generated controversy concerning what I will call the anchorage of visual perception, i.e., is it the distribution of structure in the surrounding optical array or is it the distribution of optical structure over the retinal surface? The second topic provoked debate about whether the referent of visual event perception, and in turn control, is optical motion, kinetics, or dynamics. The third issue dealt with the interface of control theory and visual perception. The relationships among these problems will constitute the organization of my report.

STIMULUS THEORY

A brief foray into stimulus theory is necessary to clarify the informative properties of stimulation. In attempting to answer what he considered to be the fundamental question for perception, i.e., "Why do things look as they do?", Koffka (1935) distinguished the proximal stimulus (the distribution of excitations to which the light rays coming from an object give rise) from the distant stimulus (the object in the geographical environment). He was concerned with functional issues, because he believed that, "as a rule,...the looks of things tell us what to do with them" (p. 76). Because he was convinced of a lack of specificity between either stimulus and the world as perceived, Koffka rejected both proximal and distal descriptions of stimulation as useful in answering functional questions in favor of a self-organizing process of field organization. Proximal and distal psychophysics persist as experimental approaches, of course, with particular concern for retinal image variables in accounts of depth, distance, and motion perception, and a variety of mediational mechanisms have replaced the field forces of Gestalt theory. Self organization continues to be an intriguing notion, but current versions consider systems the unit of analysis rather than processes, a point to which this discussion will return.

J.J. Gibson devoted much of his effort to stimulus theory and came to the conclusion, for a variety of reasons, that perceiving is anchored to the structure in the medium between the surfaces of the environment and the sensory surface. If so, he argued, the appropriate description of visual stimulation is in terms of the variables and invariants of the ambient optic array (cf. Gibson, 1958, 1961, 1966, 1979). To complete Koffka's classification system, I will call this a medial description.

Gibson considered optic array structure to be informative to an individual about the environment and the individual's relation to the environment. He proposed that visual perception is ordinarily anchored to the ambient array and that properties of optic array transformation or flow are

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particularly important support for perceiving events, including motion of the self in the environment. (Note that the transformation in an array at a moving convergence point is not conceived as the difference between arrays at successive stationary convergence points, Gibson, 1966, p. 195-196.) After several attempts to answer Koffka's question, and partly as a result of defining and quantifying information in this fashion, Gibson reframed the fundamental question for perceptionists. He concluded that the primary function of perceiving is to support action, and that perceiving and acting have a reciprocal relationship. By acting, an individual produces transformations and invariants in the flow pattern that are informative about whether the actions are appropriate to achieve the intended goal. Perceiving is the active acquiring of information about which action strategy is appropriate and the relative success of behaving. Actions are initiated, modulated, and terminated in order to control the informative variables of stimulation (cf. Gibson, 1958, 1979). (An encompassing claim for this position is that phenomenal experience, nervous system activity, and performance all are anchored to the ambient optic array.) For Gibson, the problem with the highest priority is determining what properties of the ambient array are informative in each control situation.

It is important to note that optical variables are potentially informative until they are effectively informing, and that only then can they appropriately be called visual variables. As a case in point, two aircraft maintaining an invariant angle between their flight paths will collide, unless at least one of the pilots notices that the optical angle is constant over other optical transformations and initiates control adjustments to change it. The optical angle is there to be sampled; it is potentially informative about impending collision, but it is not a visual angle until a pilot samples it with a visual system, and only then is it informative.

STRUCTURE IN THE MEDIUM

In the case of self motion, the referent of perceiving is not a distant surface, but rather the relation between the moving individual and the distant surfaces. What kinds of optical support are there for detecting and controlling this relation? Three types of potentially informative medial properties can be distinguished: (a) local, (b) regional, and (c) global.

Local flow structure. Some properties of the flow pattern are available only in specific directions in the optic array. The foci of expansion and contraction are examples, and their usefulness has been controversial. Local optical density, local flow velocity, and local optical discontinuity rate are all specifiable in every location, but their regional and global gradients appear to be more informative.

Regionally distributed flow structure. Regions of the optic array are structured by (a) environmental differences and (b) visible parts of the self. The region in the direction of movement is characterized by flow expansion, the lateral regions by nearly lamilar flow, and the region opposite to the direction of movement by flow contraction. The horizon is a regional optical structure which provides an anchor for the pitch and roll dimensions of rotational self motion. The horizon also provides a referent for the optical displacement of places and objects below the horizon (the subtense or "dip" angle) and for eyeheight and change in eyeheight relative to objects extending above the horizon (the horizon ratio, cf Langewiesche, 1944; Sedgwick, 1973, 1980).

Since both optical density and optical flow velocity vary with the distance of surfaces from the path of motion of the eye, regions or sectors of the array structured by surfaces at different distances will reveal differences in both variables. Driving through a tunnel provides a suitably constrained case, as the regional density and regional flow velocity will vary with the distance to each of the four surrounding surfaces. Change in flow velocity, optical density, and perspectival "splay" angle (Wolpert, Owen, & Warren, 1983) all occur with change in the distance from the eye to a regional surface, so the regional character of each surface is multiply specified. Differential motion parallax arising from movement of the eye past surfaces with vertical extent is also regional (cf Cutting, 1986). By fixating a flowing optical discontinuity, the pilot is able to isolate useful flow structure in a particular region of the transforming array, and control it to achieve a goal, e.g., determining the current direction of heading or determining whether current heading is in the direction desired.

Environmental surfaces structure different regions of the optic array in different ways, but the different regional transformations and invariants can specify the same property of self motion. For example, during change in altitude, perspectival splay change is structured by ground surface texture elements, whereas change in horizon ratio and change in dip angle below the horizon are structured by surfaces with vertical extent. Since both types of surfaces are usually available during low-level flight, it is would be useful to know whether it is better to learn with redundant information, or better to learn to detect and control the various types of information separately before they are introduced in concert.

Regions of the optic array are also differentially structured by surfaces that travel in concert with the eye. These include the orbit of the eye, the side of the nose, other parts of the body which extend into the visual field, and parts of the extended ego encompassed by a moving vehicle (windscreen frame or sections of the aircraft). In the case of pure egorotation about the center of the eye, there would be no change at all in the ambient array other than that resulting from progressive occlusion of sectors of the array by the body.

Globally distributed flow structure. The defining characteristic of a global optical description is that it is independent of optical position, i.e., it is the same for every locus (Warren, 1982) and, it follows, for every region. Therefore, global array properties can be used to compare two arrays or, more commonly, to detect change in an array over time. They are especially useful and reliable because they are the same wherever the individual looks, as long as there are optical discontinuities to convey them. Some hold for both frozen and transforming arrays, and some occur only with motion. Global optical texture density, global optical flow velocity, and global optical discontinuity rate will be used as examples, since they form a linked set and have received extensive empirical attention.

Global optical texture density is defined as the number of surface texture units that can be spanned by the eyeheight of the individual (Warren, 1982). The metric is ground units per eyeheight. Since texture units are nested, a referent must be chosen for any case where more than one grain is available, e.g., fields at higher altitudes, rocks and clumps of vegetation at lower altitudes. For detection of changes in both speed and altitude, density has an optimal level, and appears to provide contextual support for other linked variables (Owen, 1989).

Global optical flow velocity is indexed by the common multiplier of path speed divided by eyeheight applied to every locus in the transforming array (Gibson, Olum, & Rosenblatt, 1955; Warren, 1982). (Note that global flow velocity in eyeheights per second is equal to local flow velocity in radians per second directly below the eye.) Since global flow velocity varies with change in either speed or altitude, but not necessarily with simultaneous change in both, it is not an unequivocal specifier of either self-motion variable. Warren (1982) partitioned global optical flow acceleration into a vertical component (change in eyeheight divided by current eyeheight, i.e., fractional change in altitude) and the multiplier indexing change in flow velocity as function of change in path speed. This partitioning had two empirical consequences: (a) It was found that flow acceleration is not functionally informative about approach to the ground surface, and it in fact interferes with detection of descent (Hettinger, Owen, & Warren, 1985). (b) Fractional (as opposed to absolute) loss in altitude was found to be a functional event variable, leading to a search for functional optical variables.

Optical discontinuity rate. Optical discontinuities result from differences in surface reflectance, refraction, or emission of light. Discontinuities can be structured by elements of surface texture (e.g., rocks, trees, buildings, or dots in a schematic simulation) or by borders (e.g., edges of fields or stripes across a roadway). Discontinuity rate indexes the number of discontinuities crossing a given optical locus per unit time (Warren, 1982). Global discontinuity rate is indexed by the ratio of path speed to distance between surface discontinuities. Therefore, it depends on both egospeed and the spacing of elements or borders on the environing surfaces, but is independent of the distance of the eye from the surfaces. The role of edge rate has been studied extensively in the contexts of perceiving and controlling speed (Larish & Flach, in press) and change in speed (Awe, Johnson,& Schmitz, 1989; Denton, 1980; Owen, Wolpert, & Warren, 1984; Warren, Owen, & Hettinger, 1982; Zaff & Owen, 1987)

Fractional change. Fractional change in global flow- pattern variables have consistently proved to be the information attended to and controlled in experiments concerned with change in the direction or speed of flight. The metric is percent per second change in the variable describing the self-motion event, as well as its optical specifier. Whereas the lower-order global variables are indexed by a common multiplier on varying local properties, fractional changes are optically privileged in the global sense in that they change at the same rate at all loci. This fact may be of particular relevance to an explanation of their general salience and usefulness. Summaries of the experiments isolating the variable described above and testing their usefulness, as well as relevant references, can be found in reviews by Owen and Warren (1987) and Owen (1989).

WHAT DOES THE RETINA DO?

The relation between sensitivity to and control of the ambient flow field points toward a different conceptualization of the retina, the brain, and the rest of the nervous system than arises from mediational theories of perception and information processing theories of cognition and action in general. Most vision theorists and researchers are concerned with how the visual system recovers the nature of the visible world from retinal stimulation. If vision is instead anchored to the ambient optic array, what is the role of the retina? Gibson proposed that light is a stimulus for a rod or a cone, but not for a visual system, therefore, visual stimulation does not consist of stimuli (Gibson, 1979). Kugler and

Turvey (1987) argue that during the perceiving of an event there is a flow pattern in the nervous system. The variables and invariants of that flow are assumed to be specific to the variables and invariants of the flow pattern in stimulation.

What function does the retina have in this formulation? If the function of the entire system is specificational, then the retina must specify something about light. It would seem to have only two tasks: to specify (a) what direction the light came from and (b) what the nature of the light is. The direction from which the light comes is maintained in the curvature of the retinal surface itself. The nature of the light (frequency variation) is maintained by the selective broad-band sensitivities of the differently pigmented cells. If the retina "registers" anything, it must be these properties, but it cannot register optical flow. If the primary adaptation of the nervous system is to deal with flow fields, then it is more appropriate to consider the nervous system a medium than a processor. The retina, then, is a transducing interface between two media that support flow patterns. Is the concept of information equally at home in either flow pattern? Perhaps, but it may be more appropriate to limit informing to optical flow and consider the role of nervous system to be that of testing for reduction of uncertainty and confirming or disconfirming relative to the intended flow pattern, discrepancy from which leads to control actions modulating flow.

AFFORDANCE SPECIFICATION?

Affordances are what an individual's environment provides to support actions that result in the achievement of desirable consequences or the avoidance of undesirable consequences (Gibson, 1977, 1979). An effectivity is a set of action properties taken with reference to a set of properties of the environment which can be acted upon (Shaw & McIntyre, 1974). Gibson proposed that affordances are perceived directly on the basis of action-scaled information in the light. This concept embodies an approach to understanding what went wrong when an error is made, since it is assumed that errors are made relative to affordances. Action is scored relative to the availability of an appropriate affordance. Perception is scored correct or in correct relative to the availability of appropriate information specifying an affordance.

Affordances have consequences due to dynamics, and effectivities are also describable in terms of dynamics. A surface that affords landing upon must support the mass of the rotorcraft. To avoid colliding with the ground or objects protruding from the ground, the pilot must manage the forces under his control. These are the effectivity properties of the person-vehicle system. The argument that affordances are directly perceivable, then must entail the assumption that dynamic properties of events are perceivable. Gibson argued for a chain of specificities that links ambient-array variables with kinetics, i.e., relative motions among surfaces. Runeson extended the chain by proposing that the variables of kinematics are specific to the variables of dynamics, and conducted a series of perception experiments to support his claim that dynamics are perceivable (cf Runeson & Fryckholm, 1983, for a review). Kugler and Turvey (1987) conclude that "any flow morphology that can be defined reliably on a low energy field...is potentially a source of information about the dynamics that gave rise to it (p. 104)." Proffitt (1989a, b), in contrast, argues from the results of a series of experiments, that dynamics are not perceptually penetrable and that problems involving dynamics are solved by using unidimensional heuristics.

The experiments reported by Runeson and Proffitt have involved judgments of discrete events based on abstract knowledge. Rotorcraft flight, in contrast, involves closed- loop coupling of perception and control actions with continuous feedback from which a pilot could develop procedural knowledge. In actual flight, the pilot must deal with multidimensional dynamics, involving control, flight, and wind dynamics. If the chain of specificities is sufficiently "tight" under active control conditions, a person may learn to perceive dynamics. This learning is likely to be self organizing in that feedback is intrinsic to the extended event, so that with exploratory actions and practice, a trainee could learn without feedback from an extrinsic agent (e.g., either an instructor or a computer). If learning to fly a rotorcraft is of this type, then questions should be raised concerning how best to support self organization of the necessary skills, perhaps instead of instruction. These are problems that deserve experimental attention, and may benefit from the kind of physical theory explored by Kugler and Turvey (1987). The fact that different optical variables may be linked to the same change in dynamics might provide the needed wedge to open this issue to investigation.

CONTROL OF OPTICAL VARIABLES

The preceding discussion emphasizes the linkages among optical variables. Controlling self motion involves maintaining intended conditions of speed and direction of flight, as well as self orientation, relative to environmental surfaces. In the process, variables are linked and unlinked as speed and direction change. With knowledge of the relevance of the different kinds of information to different kinds of flight tasks, the variables and their linkages can be controlled to achieve intended goals. The same ambient array properties which were independent variables in passive judgment experiments can be recorded as dependent variables in the study of active control. This is possible for both performatory actions initiated to achieve goals or avoid problems (e.g., an undesirable collision) and exploratory actions, which may allow the individual to discover or confirm functional relationships (Flach, 1989).

"Smart" mechanisms for perception and control. It might be supposed that other flying animals have "smart" perceptual mechanisms (Runeson, 1977) for acquiring information that maps directly onto an action system specialized for controlling flight. In contrast, human flight must be mediated by a vehicle. Whereas the human's perceptual mechanisms may be sufficiently smart to pick up the relevant information, manipulation of the control surfaces is apt to be quite foreign to an animal whose effectivities and prior experiences involve adaptation to terrestrial locomotion.

Guidance of flight can be cast in terms of control of musculature or it can be described as control of the path and speed of the eyes. The latter description is equally appropriate to unmediated flight and flight mediated by a vehicle. In performing a maneuver, the pilot cycles between sampling the information available and performing control adjustments to reduce deviations from desired optical conditions, repeating the perception-action cycle until satisfactory visual conditions have been achieved. As a consequence, the information acquired by perceiving and the information controlled by acting must be the same. This linkage allows recovery of the intention of a pilot by determining the properties of the flow pattern that were invariant over segments of the flight path with which the pilot was satisfied for some duration. Control systems for vehicles have been designed primarily around engineering constraints, including those of cables, levers, and hydraulic systems. The development of electronic and optical systems communicating between controls and control subsystems, including power, allows for the implementation of "smart" control systems designed to provide a match between the sensitivity of the human perceptual system and the effectivities of the human-vehicle action system. Smart action systems can evolve to support flight control by other flying animals, but for human control of flight they must be developed and tested. The flight environment demands that the principles be the same. In the sections which follow, those principles will be elaborated.

Direct or "natural" control. Using the cyclic and collective, helicopter pilots currently make an average of 50 control adjustments per minute during an approach to hover above a place on the ground. Pilots are instructed to keep "visual streaming" constant at the rate of a brisk walk during an approach to hover. Traditional controls usually operate mechanical linkages or hydraulically actuated systems to change an effector (control surface or power source). Recent fly-by-wire and fly-by-light technology allows interfacing a computer between the control and the effector. The computer can take inputs from the control and sensors (e.g., radar altimeter, forward-looking radar, a signal transmitted from the ground or a ship) and make adjustments in speed and direction that match the differences in event properties perceived or intended by the pilot. For approach to the ground or to surfaces with vertical extent, a fractional rate controller can reduce speed in the same proportion as distance to the surface is decreased. The pilot selects a fractional rate which matches the task demands, e.g., a high rate when time is critical, a low rate when accuracy is important. A second mode of control is appropriate for path angle. Whereas magnitude controllers vary the numerator or denominator of the ratio of vertical speed to ground speed, a path-slope controller varies the ratio directly. Since path slope equals the "dip" angle of the point of optical expansion below the horizon, the path-slope controller gives the pilot control over what he intends to achieve visually. Similar ratio modes could be developed for rotational control.

A control system designed around perception-action compatibility should reduce flight-control demands, freeing the pilot's attention for other workload. Maneuvers under difficult conditions should be simplified. Given that control is scaled in units of distance to the ground, fractional-rate control is particularly appropriate to low-level contour and terrain following. A design criterion for some new aircraft is that "trainability" be taken into account during development of the aircraft itself. Ratio controllers are relevant to this criterion, since training should be considerably simplified with a high compatibility system having independent modes of control, as compared to the current system involving complicated and sometimes arbitrary relationships between control adjustments and visual stimulation as well as interdependent relationships between the controls themselves. The proposed modes of control should also greatly simplify training and increase safety at low altitudes in cluttered environments and under difficult conditions, e.g., high work load or stress. Although experienced helicopter pilots have shown no sign of negative transfer, having a computer in the control loop means that traditional modes of control could be selected by a pilot who was trained with those modes.

It is important to emphasize at this point that the entire system should be the unit of analysis, rather than studying perception and control separately. A particular mode of control may be best given a particular kind of optical information, so that the adequacy of a control mode may vary with task and environmental conditions. The relevant interactions cannot be investigated without simultaneously varying kinds and distributions of surface texture, information acquisition strategies, and modes of control. These variables may also affect transfer of training and transfer of research findings from simulation to actual flight by interacting with types of simulation, i.e., a window on the head (head mounted display), a window on the vehicle, or a window on the world (dome display representing a sector of the ambient array).

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