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Visually Controlled Locomotion: Its Dependence on Optic Flow, Three-Dimensional Space Perception, and Cognition

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Gibson (1958/this issue) and his followers have emphasized the role of optic flow in the control of locomotion. In recent years much research has been devoted to the visual control of aiming and braking, mainly in connection with terrestrial locomotion. The goal of this article is to broaden the topic empirically and theoretically. At the empirical level, we argue that there are a number of visually controlled maneuvers that need to be addressed for their own sake, for they involve more than can be learned from research on aiming and braking. At the theoretical level, we argue that optic flow needs to be supplemented by other explanatory primitives, including the actor's perception of three-dimensional spatial layout and the actor's cognitive representations of the spatial envelope and plant dynamics of his or her body or vehicle.

Gibson's (1958/this issue) article, "Visually Controlled Locomotion and Visual Orientation in Animals," like many of his books and articles, was way ahead of its time Serious efforts to understand the visual control of locomotion are relatively recen and much remains to be done. In this landmark article, Gibson argued why th topic, neglected by his contemporaries in the field of visual perception, was worth

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of and amenable to scientific study, identified a number of functionally distinct behaviors under the general topic, and articulated some of the concepts, notably optic flow, that ultimately will constitute part of our understanding.

We have been greatly influenced by this and other works of Gibson (e.g., Gibson, 1950, 1966, 1979; Gibson, Olum, & Rosenblatt, 1955), as well as those of his followers (e.g., Lee, 1976; Lee & Lishman, 1977; Turvey & Remez, 1979; R. Warren, 1988; R. Warren & Wertheim, 1990; W. H. Warren, 1988; Yilmaz & Warren, 1995) that deal with the control of locomotion. In our article, however, we extend this body of work empirically and theoretically by broadening the range of behaviors needing analysis and by embracing a larger set of explanatory primitives than Gibson and his followers have posited.

In his article, Gibson acknowledged some of the special problems facing flying and water-dwelling organisms, but his primary focus was on terrestrial animals, including humans. In other work, Gibson (1950; Gibson et al., 1955) dealt with the control of descent during the landing approach in airplanes, and other researchers (e.g., Calvert, 1954; Flach, Warren, Garness, Kelly, & Stanard, 1997; Grosz et al., 1995; Johnson, Tsang, Bennett, & Phatak, 1989; Lintern & Walker, 1991; Owen & Warren, 1987; R. Warren, 1988; Zacharias, Caglayan, & Sinacori, 1985) have addressed this and other aspects of aircraft control. However, we do not believe that this work goes far enough in recognizing what is involved in the control of aircraft and watercraft. Because we are both airplane pilots and Andrew C. Beall, as well, is a sailor and diver, our experience motivates us to recognize a wider domain of locomotor behavior. Moreover, because so much of human travel is now accomplished by way of aircraft and watercraft, we feel that a broader treatment is essential if we wish to reduce the loss of life and property caused by accidents involving human error and to improve the selection of pilots of these craft.

At the theoretical level, Gibson and his followers have emphasized the role of optic flow in the control of locomotion; as a consequence, they have tended to focus on those aspects of locomotor control for which an optic flow analysis is sufficient. We believe that a proper understanding of visually controlled locomotion requires a multilevel analysis: optic flow rules for closed-loop regulation of certain aspects of locomotor behavior; perception of three-dimensional space for regulating other aspects of behavior and for short-term planning; and a variety of cognitive representations, both for short-term and long-term planning. For a similar view in the context of autonomous vehicles, see Dickmanns (1992).

TERMINOLOGY

The instantaneous velocity of an actor is specified by its direction in three-dimensional space and its magnitude or "speed." For terrestrial motion over the surface plane, velocity direction can be specified by one parameter, which is commonly referred to as *course* and is usually measured with respect to a reference direction, such as true or magnetic north; *relative course* is defined with respect to a visible target. There are two other important directional variables characterizing the moving actor. The first of these is the three-dimensional orientation (*attitude*) of the actor's head, body, or vehicle; in the case of terrestrial travel over the horizontal plane, orientation can be specified by one parameter, which is commonly referred to as *heading*. Heading and course are generally different for aircraft and watercraft because of crosswinds and currents, respectively. The second directional variable is the direction of the thrust vector of the actor's body or vehicle. For a person who is walking sideways, heading and the direction of the thrust vector are 90° out of alignment, but the latter is aligned with course. In contrast, because a helicopter can orient its thrust vector in any horizontal direction independently of its heading, this means that heading, course, and the thrust vector direction can all be different in the presence of a crosswind.

Other important terms relate to the directions of locations from the actor's position. *Bearing* refers to the direction of a landmark, measured with respect to a reference direction (e.g., true north). *Heading-relative bearing* or *relative bearing* refers to the direction of a landmark, measured with respect to the actor's heading, whereas *course-relative bearing* refers to the direction of a landmark, measured with respect to the actor's course (Beall & Loomis, 1996). Finally, *relative course* is the direction of travel with respect to an identifiable location in the environment and is equivalent to course-relative bearing. An actor wishing to proceed directly toward a visible landmark needs only to null relative course (or course-relative bearing).

TOWARD A MORE ENCOMPASSING THEORY OF VISUALLY CONTROLLED LOCOMOTION

For an actor who has already decided on some action requiring visually controlled locomotion, one can identify three levels of control (Dickmanns, 1992; Lee & Lishman, 1977; McRuer, Allan, Weir, & Klein, 1977), which correspond roughly with three different time scales. The first and highest level of control involves formulating a general plan for completing the action. For example, an actor wishing to travel to some remote and unseen location uses knowledge of the environment or an external map to plan a route. Once underway, forced or inadvertent deviations from the route result in attempts to regain the route or reformulation of a new route. This level of control involves both visual perception and cognition, such as accessing internal representations ("cognitive maps") of the environment. The second and next lower level of control involves assessing the spatial layout of the immediate environment, planning a detailed path through the environment, and then attempting to follow that path, subject to additional constraints (e.g., appearance of potential collision targets). This level involves both three-dimensional visual space perception and a variety of cognitive representations, to be mentioned shortly. Gibson and Crooks (1938) presented an analysis for this level of control employing the notion of the *field* *of safe travel,* an internal representation of the open space in front of the driver that is momentarily suitable for forward progress. The third and lowest level, which operates on the shortest time scale, is the regulation of speed and direction necessary for staying within the selected path. It involves both three-dimensional space perception and optic flow rules. Our focus in this article is on the lower two levels of control, with greater emphasis on the latter.

Other than a brief discussion of spatial orientation, Gibson's (1958/this issue) article was largely concerned with optic flow rules that might be employed to regulate simple aiming and braking behaviors. Most of the basic research literature on visually controlled locomotion has taken his lead by focusing on one-dimensional aiming behavior and braking, often by way of discrete-trial tasks on the corresponding perceptual judgments of "heading" (course) (e.g., Crowell & Banks, 1993; Cutting, 1986; Cutting, Springer, Braren, & Johnson, 1992; Cutting, Vishton, & Braren, 1995; Royden, Crowell, & Banks, 1994; W. H. Warren & Hannon, 1990; W. H. Warren, Morris, & Kalish, 1988) and time-to-contact (e.g., Kaiser & Mowafy, 1993; Schiff & Detwiler, 1979; Tresilian, 1991) but more recently by way of active control tasks (Yilmaz & Warren, 1995; W. H. Warren & Kay, 1997). These and related studies are important in demonstrating that optic flow rules (or "laws of control;" W. Warren, 1988) are often sufficient for explaining the regulation of speed and direction and for revealing much about the mechanisms involved. In our treatment, the optic flow rules we have in mind are rules for action that are tied directly to measurements of optic flow and its first and second derivatives. We thus exclude computations of three-dimensional spatial layout based on optic flow. We note, however, that some optic flow rules rely on subsidiary information that is nonvisual (e.g., vestibular).

There are other aspects of visually controlled locomotion that require the actor to perceive the three-dimensional layout of the environment, both for choosing an optimal detailed path (subject to obstacles, hazards, and capabilities of the actor or vehicle) and for regulating locomotion along that path. It is the belief of many visual space perception researchers that the visual process results in a perceptual representation of the surrounding environment, a representation that exists independently of any of the actions that it participates in controlling. A multiplicity of visual cues, including optic flow, together with internal constraints within the nervous system, determine the perceptual representation of the environment at any given moment (Loomis, in press; Philbeck, Loomis, & Beall, 1997). This perceptual representation is not determined by any single information source, but is jointly determined by the many cues and internal constraints involved. (For example, a change in the value in relative optic flow specifying the slant of a surface might be compensated for by changes in binocular disparity, such that the perceived slant remains constant.) Moreover, this representation often exhibits distortion with respect to the physical environment, even under full cue conditions (e.g., Loomis & Philbeck, in press; Proffitt, Bhalla, Gossweiler, & Midgett, 1995). It is the view of many researchers that this perceptual representation is a major determinant of action. Thus, in this view, visual information is not directly linked to action but instead partly determines the perceptual representation, which in turn serves as one of the causes of action. Some of the strongest support for such a representation comes from work on *visually directed action.* In tasks involving visually directed action, the actor views a target from a fixed vantage point, and then attempts to carry out some locomotor response in relation to the target without receiving further perceptual information about its location. The simplest response is blind walking to the target location (e.g., Loomis, Da Silva, Fujita, & Fukusima, 1992; Philbeck & Loomis, 1997; Rieser, Ashmead, Talor, & Youngquist, 1990; Thomson, 1983), but more complex "triangulation" responses have been studied as well (e.g., Fukusima, Loomis, & DaSilva, 1997; Philbeck & Loomis, 1997; Philbeck et al., 1997). The fact that actors are able to perform these tasks well while viewing the target from a fixed position means that optic flow is not relevant and that a visually based perceptual representation and a nonvisual representation stored and updated in memory are involved.

We believe that optic flow rules and three-dimensional perceptual representations together are still not sufficient to explain the control of locomotion, for a number of cognitive representations are also implicated. For us, these memory-based representations are not specific to the current environmental circumstances, such as a mental image of the current scene, but are instead general and thus deployable across a variety of circumstances. One type of cognitive representation is that of the spatial envelope of one's body or vehicle. When one is attempting to negotiate a narrow passageway, one must take into account the size of one's body and its accoutrements (e.g., hat or helmet, backpack, etc.). Similarly, when controlling a car, one needs to take into account the locations of the wheels relative to the road, the locations of the bumpers and fenders, and the presence of any accessories, such as luggage rack, when negotiating a narrow space. While the body representation has innate determinants, learning is also clearly involved, as indicated by recalibration associated with changes in the physical body during development, weight gain, and loss of limb (e.g., Simmel, 1966). Similarly, knowledge of the spatial envelope of one's car develops over time with the result that one gradually gains confidence in parking and in passing through narrow openings.

Another important cognitive representation is that of the plant dynamics When we locomote under our own power or within a vehicle, our locomotion is constrained by the plant dynamics of our body or vehicle. The plant dynamics connect the control inputs to the resulting body or vehicle kinematics. A model of the plant dynamics of a vehicle, for example, can be used to predict the linear and rotary accelerations, thence the linear and rotary velocities, and thence the position and orientation of the vehicle in the absence of external perturbations. Such perturbations cause position and orientation to diverge from the model predictions. A human actor often needs a crude model of the plant dynamics to predict the state variables of the body or vehicle into the near future, for the actor needs to know in advance whether a particular action can proceed safely. For example, an automo bile driver deciding whether to pass a vehicle ahead on a two-lane road must assess whether his or her vehicle can accelerate quickly enough to pass clear before colliding with an oncoming vehicle. Similarly, an airplane pilot diving toward the ground needs a model of the aircraft dynamics to know the minimum altitude at which a pullup maneuver can be safely accomplished, for if begun too late, the optic flow will simply inform the pilot that the inevitable is about to occur. Finally, the pilot of a large vessel needs to have a model of its dynamics to know when to initiate a docking maneuver tens of seconds before arriving at the dock.

One sign of a novice operator of any complex vehicle is the tendency to overcontrol—using unnecessarily large control inputs with moderate to high intermittency. At the other extreme, a highly skilled operator can accomplish the desired maneuvering with a minimum of control inputs. Especially in airplanes, for example, where change of course is the second integral of control yoke input, a very small yoke input can result in very large course changes over time. Thus, a highly skilled pilot can align an airplane with the runway with almost indiscernible yoke inputs provided that they are made at just the right time. It is fair to say that those pilots who have minimal root-mean-squared values of their control inputs during some specific maneuver, such as the landing approach, are those with the best internal model of the aircraft dynamics. Such pilots are using model-based feedforward control rather than pure feedback control based on a comparison of the desired and observed optic flow values.

To illustrate the aforementioned multilevel analysis, we consider the situation of an airplane pilot wishing to cross a mountain range at a minimum altitude to proceed to a destination on the other side. Using an external or cognitive map of the environment, the pilot chooses a course roughly aligned with the bearing to the unseen destination. Prior to crossing the range, the pilot uses three-dimensional visual perception to assess the spatial layout of the visible terrain to select the approximate route through the mountain range that satisfies the desired constraints, such as minimum number of turns and minimum changes in absolute altitude while keeping close to the surface. Once the traverse begins, the pilot alternately uses optic flow rules and three-dimensional space perception coupled with a representation of the aircraft dynamics to track the terrain. If the aircraft approaches steeply rising terrain, the pilot must use three-dimensional perception to assess its inclination (see Proffitt et al., 1995) and compare it with the modeled dynamics of the aircraft to know how long to delay initiation of the climb. Between such critical decision points, optic flow is often going to be sufficient for closed-loop tracking of the terrain.

We note that visually controlled locomotion often is accomplished with supplementary nonvisual information about the actor's motions. Vestibular and somatosensory signals provide the operator of a vehicle with information about vehicle accelerations (Gillingham & Wolfe, 1986) and, in the case of flying at night, provide information about aircraft orientation when lights on the ground are sparse and not easily differentiable from the stars. Vestibular information also plays a role in judging alignment with a straight path on the ground when only the path is visible (Beall & Loomis, 1997; Calvert, 1954). Vestibular information is also important to divers for maintaining orientation under minimal lighting conditions. Finally, kinesthetic information, including efference copy, is important for perceiving self-motion propelled by the body, both on land and in the water.

Finally, we note that there is an alternative to our hypothesizing the existence of explicit representations of spatial envelope and plant dynamics. In this alternative view, there is not some form of mental comparison between internal representation and current environmental values, but simply a detection of the fit between properties of the actor and properties of the environment (Gibson, 1979; Lee & Thomson, 1982; W. H. Warren, 1984; W. H. Warren & Whang, 1987). In this view, the actor and the environment constitute a tightly coupled ecosystem. Advocates of this view explain adjustment of the actor to changes in body size, muscle strength, and so forth, in terms of recalibration of the "control laws" intervening between environmental stimulation and the motor efference underlying action, based on recent successful and unsuccessful behavior within the environment. Thus, learning is involved but there is no explicit internal representation of spatial envelope or of plant dynamics.

VISUALLY CONTROLLED MANEUVERS

In the analysis of visually controlled locomotion, one hopes to identify a set of locomotor primitives (maneuvers), out of which all other locomotor behaviors are composed. The following maneuvers are a subset of the candidate primitives discussed by Loomis (in press); these are presented in the spirit of similar analyses by Gibson (1958/this issue, 1979) and Turvey and Remez (1979).

Aiming Toward a Stationary Target

For locomotion through air or through water, aiming is two-dimensional, whereas for travel over a flat surface, it is one-dimensional. A special one-dimensional case occurs in connection with landing an airplane. A pilot of an airplane that is already aligned with the runway controls the descent to touch down on the runway near the approach end. The aim point, which is the intersection of the current motion vector with the ground, is specified by the optic flow field. The pilot regulates the descent rate so that the aim point coincides with the desired touchdown location. Gibson (1950; Gibson, Olum, & Rosenblatt, 1955) was the first to articulate and formalize the relevant optic flow concepts for this aspect of the landing approach.

For travel over a horizontal surface, controlling aim point is equivalent to aligning one's course with the bearing to some visible target or nulling one's relative course. In the last 10 years, a great deal of empirical research has been devoted to the perception of relative course (or heading, as it has been referred to in this literature; e.g., Crowell & Banks, 1993; Cutting, 1986; Cutting et al., 1992; Cutting et al., 1995; Royden et al., 1994; W. H. Warren & Hannon, 1990; W. H. Warren et al., 1988). Under a wide variety of conditions, the perception of course is accurate to within 1°. More recently, research has begun on the active control of aiming (W. H. Warren & Kay, 1997).

Negotiating an Aperture or Passageway

Closely related to aiming is control of one's motion through an aperture. Unlike simple aiming, one also needs to take into account the frontal extent of one's body or vehicle in relation to the size of the aperture. W. H. Warren and Whang (1987) conducted research on the judgment of aperture width in relation to the perceiver's body dimensions and showed that participants are very accurate in discriminating the passability of apertures. When one is traveling through a narrow twisting passageway, one also needs to take into account surface friction and plant dynamics.

Steering a Straight Path on the Ground Plane

Steering a straight path on the horizontal plane in the presence of lateral perturbing forces might be thought to depend on a succession of aiming responses, with aiming depending on the sensing of relative course. However, Beall and Loomis (1996) noted that when the straight path is defined solely by continuous visible markers at its boundaries and no other ground features are visible, course is specified only to within 180°, because the component of motion parallel to the path is indeterminate. Yet, under these conditions, Beall and Loomis found that participants were able to steer a straight path with the same accuracy as when course information was made available by the presence of point features. Thus, it would appear that steering a straight path need not depend on the sensing of relative course. Beall and Loomis reasoned that participants must have been steering using splay and splay rate of each lane marker. (*Splay* is the spherical angle between the optical projection of the lane marker and the environmental vertical; *splay rate* is its time derivative.) Riemersma (1981) argued earlier that these optical variables could be used in straight path steering. However, more than optic flow is involved. Because a driver is usually off to one side in an automobile, a car that is centered within the lane presents different values of splay magnitude (with opposite sign) to the driver. Thus, a driver keeping the car centered must be comparing the current values of splay with command values stored in memory.

Turning Into Alignment With a Straight Path

Turning into alignment with a straight path, like steering a straight path, can be accomplished without course information. A special case of this maneuver is that of an airplane turning into alignment with the runway during the landing approach. Calvert (1954) proposed that pilots use splay and splay rate of the runway boundaries, along with vestibular information, to control the turn into alignment. Beall and Loomis (1997) extended this work by proposing several optic flow rules based on splay and splay rate, one of which is to guide the aircraft along a curving trajectory toward the runway such that splay rate remains constant or nearly so. They also studied this maneuver in pilots making day and night landing approaches in an airplane and found support for the idea that pilots do employ a variant of the constant splay rate rule. Subsequent research performed in the laboratory with pilots flying a flight simulator provided additional support for the idea (Beall, 1998).

Steering Along a Curving Path

One of the more ubiquitous locomotor behaviors in modern life is steering a car along a curving path. Despite its ubiquity, this maneuver has received scant attention by researchers as a basic research problem. This is beginning to change with the publication of several recent studies by Land and his colleagues (Land & Horwood, 1995; Land & Lee, 1994). Land and Lee examined the eye fixation patterns of drivers negotiating a winding road and found that at critical moments prior to entering a curve, drivers allocated much of their fixation to the tangent point, the point where the image of the inside lane marker folds back on itself (i.e., the point where the tangent to the lane marker's image is vertical). Their optic flow analysis revealed that the tangent point is predictive of the curvature of the upcoming curve. A model linking the tangent point to control inputs for steering, however, is too simple. Land and Horwood conducted a simulated driving task in which the various portions of the forward field of view were windowed by apertures. They found that different parts of the road ahead are used to control different aspects of steering; the more distant portion provides advance information about road curvature up ahead, whereas the near portion provides feedback for keeping within the lane.

Maintaining a Constant Altitude Above the Ground

A number of experimental studies using flight simulators have addressed the type of optic flow information used in maintaining constant altitude above flat terrain (e.g., Flach et al., 1997; Johnson et at. 1989; R. Warren, 1988). In these studies, participants attempted to maintain constant altitude in the presence of various disturbances (e.g., forward, lateral, and vertical). The research indicates that participants use a variety of optic flow cues, such as the splay rates of visible line segments.

Maintenance of constant altitude above the ground during forward flight is far more demanding when the terrain is undulating (Zacharias et al., 1985), especially in "nap of the earth" flight where the aircraft remains close to the surface and high G-load maneuvering is often required. As argued in connection with the earlier example of crossing mountainous terrain, it is likely that understanding of nap-of-the earth flight requires three-dimensional space perception for sensing the layout of the terrain ahead, cognitive modeling of the aircraft's plant dynamics, and optic flow for closed-loop regulation; moreover, the heavier the aircraft and the less power available, the more critical is the need for predictive control based on three-dimensional space perception and modeling of the plant dynamics.

Regulation of Braking, Docking, and Vertical Landing

A common maneuver is slowing one's motion relative to an object or extended surface so that one either makes gentle contact with the surface or stops just short of it. In driving, the driver typically brakes his or her car to stop just short of an obstacle or stationary car up ahead. In the landing of a vertical-flight aircraft, such as a helicopter or airship, the pilot reduces the descent rate so as to make gentle contact with the surface. A docking maneuver by spacecraft or watercraft is even more challenging, for the actor also has to steer while attempting to make gentle contact.

Lee (1976) proposed a theory of braking that applies to these behaviors. It is based on the optical variable, tau, which is the ratio of the angular extent of the object ahead divided by its time derivative, the rate of optical expansion. The optimal control strategy is to decelerate in such a way as to maintain the derivative of tau at a value greater than or equal to –0.5. Yilmaz and Warren (1995) provided support for the theory by showing that actors employed a strategy close to the optimal one and that manipulating the availability of distance cues had little effect on performance. However, Flach, Stanard, and Smith (in press) have cast doubt on this interpretation by providing data and an analysis suggesting that actors are regulating their stopping behavior using the optical expansion rate itself.

Moving Into Tangency With a Surface

Related to the preceding maneuver is reducing one's closing velocity to a surface so as to move into tangency with it. This maneuver is different in that there is also a significant component of motion parallel to the surface. A common example is the landing of an airplane. In this case, the pilot wishes to expedite gentle contact with the ground (to minimize the ground run) while still moving with a significant horizontal velocity. Grosz et al. (1995) found evidence for the role of optical tau in controlling the landing flare, by which the pilot of an airplane decelerates to level flight just prior to touchdown. However, the fact that pilots landing on unusually wide runways tend to level out too high (Gillingham & Wolfe, 1986; Lintern & Walker, 1991) indicates that they are comparing the current perspective view (what pilots call the "sight picture") with a stored representation of the average runway instead of just using the optic flow field.

A related behavior that requires predicting aircraft behavior further into the future is initiating a pullup maneuver following a rapid descent toward the ground. An aerobatic pilot performing this maneuver needs to know at any moment whether the current upward acceleration is sufficient to avoid ground collision, and if not, to increase the acceleration (subject to the design limits of the aircraft). A possible optic flow rule is that the current trajectory will pass clear of the horizontal surface plane if the aim point is accelerating toward the horizon (in units measured along the surface); for example, if the ground surface consists of uniform texture and the aim point is accelerating in terms of texture elements, the aircraft will not collide. Even if an optic flow rule represents a possible control strategy, however, avoiding collision with a surface, in the general case, must involve more. The pilot of a diving aircraft needs to take into account the plant dynamics and design limits of the aircraft to know how late a pullup maneuver can begin.

Intercepting or Avoiding Collision With Other Moving Objects

An actor moving with constant velocity (speed and direction) is on a collision course with another person or vehicle, also moving with constant velocity, if and only if the other has a constant optical position and is increasing in its angular size (Cutting et al., 1995). Thus, in three dimensions, the pilot of an aircraft who observes another aircraft increasing in angular size while at a fixed optical direction (e.g., above and to the right) needs to take evasive action. Similarly, in two dimensions, one ship is on a collision course with another if the two are approaching each other with constant course-relative bearings. In contrast, if either actor moves with accelerated motion (i.e., changing speed and/or direction), this optic flow rule no longer applies. For instance, if one actor is moving with constant velocity while another actor is moving along an intersecting circular path, collision is possible even though the mutual course-relative bearings are constantly changing. Consequently, interception and collision avoidance in this and other cases of accelerated motion involve more than the sensing of optic flow. A common occurrence is that of a driver waiting to cross a heavily traveled highway. In addition to the oncoming vehicles, the driver must take into account road traction as well as the acceleration dynamics and spatial envelope of his or her vehicle in judging when it is safe to cross Even more challenging is the maneuvering of a high-performance aircraft that is engaged in combat with another aircraft. Here, each pilot needs to consider the consider the altitude, kinetic energy, orientation with respect to gravity, and performance capabilities of each aircraft in judging how best to maneuver to intercept the other.

Orbiting Stationary or Moving Objects With a Constant Radius

If the object to be orbited and the travel medium are both stationary, maintenance of the orbit, once attained, can be accomplished using the following optic flow rule: Keep the object in a constant angular position with respect to the fixed axes of the body or vehicle by increasing or decreasing the turn radius. If the object to be orbited is stationary with respect to a uniformly moving travel medium (e.g., a raft floating in a river or a balloon floating in a moving airmass) and the actor is moving with respect to the medium, the same rule applies, for the frame of reference is now simply that associated with the travel medium.

If the target to be orbited and the actor no longer share the same medium (e.g., the target is on the ground, and an airplane is circling it within a moving airmass), maintaining a constant radius orbit involves much more than regulating turn using changes in heading-relative bearing, course-relative bearing, or the optical size of the target. Indeed, during primary flight training, airplane pilots require specialized instruction on rules for regulating turn rate during the orbiting of a ground target in the presence of a constant wind, rules that amount to feedforward control rather than simple feedback control based on the aforementioned variables.

SUMMARY

The goal of our article has been to broaden the topic of visually controlled locomotion both empirically and theoretically. At the empirical level, we have argued that there are a number of visually controlled maneuvers that need to be addressed for their own sake, for they are not reducible to a succession of more primitive aiming and braking behaviors. At the theoretical level, we have argued that optic flow needs to be supplemented by other explanatory primitives, including the actor's perception of three-dimensional spatial layout and the actor's cognitive representations of the spatial envelope and plant dynamics of his or her body or vehicle.

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