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ABSTRACT

In recent years, many experiments have demonstrated that optic flow is sufficient for visually controlled action, with the suggestion that perceptual representations of 3-D space are superfluous. In contrast, recent research in our lab indicates that some visually controlled actions, including some thought to be based on optic flow, are indeed mediated by perceptual representations. For example, we have demonstrated that people are able to perform complex spatial behaviors, like walking, driving, and object interception, in virtual environments which are rendered visible solely by cyclopean stimulation (random-dot cinematograms). In such situations, the absence of any retinal optic flow that is correlated with the objects and surfaces within the virtual environment means that people are using stereo-based perceptual representations to perform the behavior. The fact that people can perform such behaviors without training suggests that the perceptual representations are likely the same as those used when retinal optic flow is present. Other research indicates that optic flow, whether retinal or a more abstract property of the perceptual representation, is not the basis for postural control, because postural instability is related to perceived relative motion between self and the visual surroundings rather than to optic flow, even in the abstract sense.

Keywords: perception/action, visual control of locomotion, postural control, optic flow, steering

1. INTRODUCTION

Two prominent theories of how vision is used to control action are optic-flow theory and perceptual representation theory (Figure 1). The optic-flow theory, conceived and initially developed by Gibson[1, 2, 3], asserts that changing visual perspective (optic flow) is the basis for much of controlled ongoing behaviors, like running, driving, and returning a tennis volley (as opposed to ballistic actions, like ball throwing); in such cases, perception of distance per se is not required. Within optic flow theory, models of visually controlled action do not posit internal representations of 3-D space. Instead, such models account for visually controlled action by "control laws" which specify how various aspects of optic flow (optical invariants) regulate the behaviors in question[4,5]. For example, global radial flow provides a basis

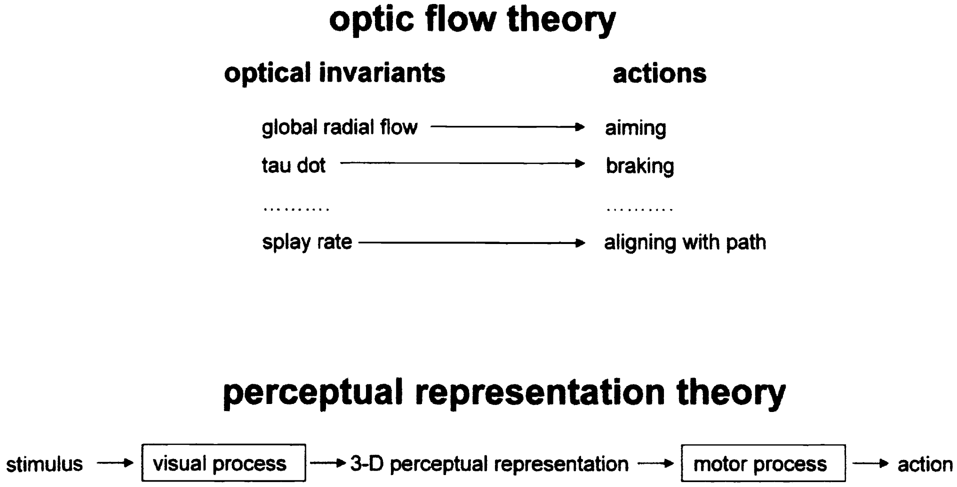

Figure 1. Two theories of visually controlled action

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for aiming toward a point on the ground even in the presence of laterally perturbing forces (like crosswinds)[6,7], tau dot (the temporal derivative of tau, which in turn is the instantaneous angular size of an object divided by its rate of optical expansion) provides a basis for braking short of an obstacle[8,9], and splay rate (rate of optical rotation) of a straight path on the ground plane provides a basis for turning into alignment with the path[10,11]. In recent years, an extensive literature has supported the idea of optic flow as the basis for visually controlled action, including postural control, visually controlled locomotion, and ball catching.

Perceptual representation theory is the classic one, more in line with the layperson's notion of how behavior is controlled. It asserts that action is guided by an internal (perceptual) representation of 3-D space—for example, we see where paths and obstacles are and guide our behavior with respect to these perceptual entities within 3-D space. Optic flow theory, based as it is on changing visual perspective, posits no explicit role for distance, except insofar as distance influences the translational flow field (e.g., flow magnitude decreases with environmental distance). Pictorial cues to distance (like texture and height in the field) and binocular cues, like disparity and disparity change, do not influence optic flow and thus play no role in controlling action. However, the evidence is growing that distance does influence visually controlled action, either through some direct effect of multiple distance cues or by the mediating effect of a perceptual representation (which is a usually a variable of lower-dimensionality reflecting the integrated effect of multiple cues). For example, in modeling visually guided movement through a field of obstacles, Warren and Fajen[5] explicitly include the distances of targets. More direct evidence for the role of distance perception comes from research on "visually directed action", much of it carried out by the first author and his colleagues. In tasks involving visually directed action, the observer 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[12,13,14]. A more complex response is to view a target and, then with eyes closed, walk along an indirect path to the target[15]. The fact that observers are able to perform these walking tasks well while viewing the target from a fixed position means that optic flow is not relevant and that a 3-D visual representation as well as a nonvisual representation of the target stored and updated in memory are involved. More recently, we have shown that a similar model is involved in steering a vehicle[16].

Another line of research challenging the optic flow theory is recent work on the "visual direction" strategy. Rushton and his colleagues have shown that heading perception based on optic flow is not always used to control aiming toward a visible target—under some conditions, an observer samples the direction of the target relative to the body and then moves in that direction with the goal of keeping the bearing to the target constant[17,18] (also see work by Warren et al. [19]). Rushton and Harris[18] have argued that the egocentric direction strategy can be generalized to other steering behaviors besides aiming, such as moving along a corridor with turns. In a similar vein, others have argued that eye fixations are used to identify intermediate goals of locomotion and that subsequent steering is based on this targeting by the eyes[20,21].

In the years since Gibson developed his ideas about optic flow and its role in visually controlled action, many researchers have closely tied optic flow to retinal flow (see, for example, chapters in the volume by Vaina, Beardsley, and Rushton[22]). Gibson intended optic flow to be more distal than retinal flow; optic flow refers to the changing angular directions of environmental points produced by rotations and translations of the observer's head. Normally, for an eye stationary in the orbit, retinal flow mirrors optic flow (except for the limited retinal field of view and some subtleties relating to the geometry of the projection). When the eye rotates, the resulting retinal flow has a component of rotational flow superimposed on the optic flow. With and without eye rotations, optic flow usually entails first-order retinal motion ("Fourier motion"). Gibson's conception of optic flow made no commitment to there being first-order retinal motion. Thus, we may speak of abstract optic flow, which can be signaled by retinal flow or by purely binocular stimulation for which there is no retinal flow.

In the work reported below, we first provide evidence for visually controlled action that does not rely on retinal motion that is correlated with the behavior. This result is consistent with action that is controlled by abstract optic flow. We then present evidence of visually controlled action, specifically postural stability, which cannot be explained even by abstract optic flow, but instead requires a perceptual representation of a distal state of affairs, namely the relative motion between the observer and the environment.

2. REPORT OF RECENT RESEARCH

2.1. Visual control of action without retinal optic flow

We have recently shown that a wide variety of complex actions can be performed without retinal optic flow[23]. This research was made possible by a novel computer-graphics technique. The basic idea involved converting a conventional immersive virtual environment viewed while wearing a head-mounted display (HMD) into a cyclopean virtual environment which could be seen only with binocular vision. The type of cyclopean stimulus we used was developed years ago by Julesz for movie film[24] and adapted more recently by other researchers using special purpose computer graphics hardware[25,26]. With either method, an observer is stimulated with a different random-dot stereogram (RDS) every graphics frame. Each successive RDS conveys information about an event in 3-D space. Thus, what appears to each eye as a scintillating pattern of noise is for both eyes a readily perceivable event in binocular space, such as a stationary or moving object in visual space. The new computer-graphics technique we have developed is implemented in software and can render any conventional 3-D computer graphics. Specifically, we can use the cyclopean stimulus to render a fully immersive and interactive virtual environment. Visibility of the virtual environment, however, is limited by such factors as the spatial resolution of the display and the temporal and spatial bandwidths of cyclopean vision.

The important result of our recent research is that once participants begin to see the cyclopean virtual environment (which takes some observers up to tens of seconds), they can immediately begin moving about within the environment, walking toward objects of interest while avoiding obstacles[23]. We have demonstrated this in informal demonstrations with well over 30 different people. The fact that our observers can do so without any special training or practice means that cyclopean stimulation provides some of the same locomotion-related information afforded by conventional stimulation. With a smaller number of people, mostly lab personnel, we have demonstrated the ability to carry out even more complex actions, such as intercepting moving objects. Because the scintillating noise in each eye has no first-order retinal motion that is correlated with the events within the virtual environment, these demonstrations show that retinal optic flow need not be the basis for visually-guided action.

Besides these informal demonstrations, we have conducted formal research on two steering tasks (steering a curved path and steering a straight path in the presence of "crosswinds") and found that the root-mean-squared (rms) error was just slightly greater for the cyclopean stimuli than it was for the luminance stimuli[23]. Taken together, the demonstrations and formal experiments show that complex actions can be carried out visually without retinal optic flow. We note, however, that because some actions, like playing tennis and batting a baseball, involve optic flow of high angular velocities, cyclopean visual perception is surely inadequate given that its spatiotemporal bandwidth is lower than that of luminance-based vision[25].

In related research, we have conducted psychophysical experiments on heading perception without retinal optic flow[27]. Using the traditional paradigm for measuring the precision of heading perception (except that the observer wears a head-mounted display) and adjusting the luminance stimuli to be equal to the cyclopean stimuli in terms of motion visibility, we have found that heading thresholds for cyclopean stimuli are very nearly the same as those for luminance (optic flow) stimuli.

2.2 Research showing that optic flow, even in the abstract sense, is not the basis for postural control

While much research has been reported claiming that optic flow is the visual basis for postural control, there is an alternative hypothesis. It is that the observer perceives relative movement between self and the environment (while standing still) and makes appropriate postural adjustments. Usually, when the self is moving relative to the environment, there is corresponding optic flow, either in the abstract sense mentioned above or in the conventional sense, which involves retinal flow as well. To distinguish these, one can manipulate binocular cues, which can alter the perceived motion between self and environment without altering the optic flow. In research we have done on this topic[28], the observer was made unstable by having to standing on one foot. In one visual condition the visual stimulus was a rectangular box viewed binocularly in immersive virtual reality. This box appeared to be rigid and stationary as the person's head translated slightly (because of postural instability). It helped to stabilize the observer. The other condition was obtained simply by switching the images to the two eyes. Switching the eyes had no effect on the optic flow but dramatically changed the perception of the rectangular box in terms of 3-D perception. Now the box appeared as a truncated pyramid, which appeared to rotate and distort as the person's head moved in space. The apparent motion and non-rigidity of an object associated with head movement has been called "apparent concomitant motion" by Gogel, who has studied it extensively and provided a detailed explanation[29]. In our two experiments on this topic, we found that such a stimulus was significantly less effective in stabilizing the observers, causing postural sway to be about 25%-50% greater, depending on the condition. Because the optic flow was unchanged, this result indicates that optic flow is not the stimulus that controls posture. Rather, the postural control system is relying on the apparent relative motion between self and environment.

3. CONCLUSIONS

The first line of research reported above shows that complex spatial behaviors can be easily and accurately executed with cyclopean stimulation without prior training or practice. This means that retinal optic flow is not necessary for the performance of complex spatial behaviors. There are three ways of interpreting these results. The first is that the observer carries out the behavior using a full-blown 3-D perceptual representation, one suitable for continued "visually directed action" if the visual stimulation is unexpectedly terminated. The second is that the observer is relying only on the changing perspective (abstract optic flow) in the perceived environment conveyed by the cyclopean stimulus. Here the behavior would not depend explicitly on the perception of distance. The third is that the behavior is controlled not by the cyclopean perceptual representation (either 3-D or just its perspective) but by the binocular cues of convergence, disparity, and disparity change. Without the necessity for training or practice, the ability to perform a complex spatial behavior while relying only on low level binocular cues seems highly unlikely, not to mention that there is no obvious way to model complex behavior in terms of low-level cues. Thus, we are left with the first two interpretations, both of which assign a role to an internal (perceptual) representation in the control of action.

The second line of research, dealing with postural control, is even more decisive in ruling out optic flow, even abstract optic flow, and in implicating perceptual representations. This work is related to the psychophysical experiments by a number of researchers showing that manipulating perceived distance without altering optic flow has measurable effects on observers' judgments of heading[30] and time-to-contact[26,31]. The two lines of research reported here, along with other research mentioned in the introduction, show that optic flow does not have the exclusivity in the control of action that it was once thought to have.

REFERENCES

1. Gibson, J. J. (1950). *The perception of the visual world.* Boston: Houghton-Mifflin.

2. Gibson, J. J., Olum, P., & Rosenblatt, F. (1955). Parallax and perspective during aircraft landings. *American Journal of Psychology*, 68, 372-385.

3. Gibson, J. J. (1958). Visually controlled locomotion and visual orientation in animals. *British Journal of Psychology*, 49, 182-194.

4. Warren, W. H. (1998). Visually controlled locomotion: 40 years later. *Ecological Psychology, 10*, 177-219.

5. Warren, W. H. & Fajen, B. R. (2004). From optic flow to laws of control. In L. Vaina, S. Beardsley, and S. Rushton (Eds.). *Optic Flow and Beyond* (pp. 307-337). Boston: Kluwer Academic Publishers.

6. Lappe, M., Bremmer, F. & van den Berg, A. V. (1999). Perception of self motion from visual flow. *Trends in Cognitive Sciences*, 3, 329-336.

7. Warren, W. H., Morris, M. W., & Kalish, M. (1988). Perception of translational heading from optical flow. *Journal of Experimental Psychology: Human Perception and Performance*, *17*, 28-43.

8. Lee, D. N. (1976). A theory of visual control of braking based on information about time-to-collision. *Perception*, 5, 437-459.

9. Yilmaz, E. H. & Warren, W. H. (1995). Visual control of braking: a test of the tau-dot hypothesis. *Journal of Experimental Psychology: Human Perception and Performance*, 21, 996-1014.

10. Beall, A. C. & Loomis, J. M. (1996). Visual control of steering without course information. *Perception*, 25, 481-494.

11. Calvert, E. S. (1954). Visual judgments in motion. *Journal of the Institute of Navigation*, 7, 233-251.

12. Thomson, J. A. (1983). Is continuous visual monitoring necessary in visually guided locomotion? *Journal of Experimental Psychology: Human Perception and Performance*, 9, 427-443.

13. Loomis, J. M., Da Silva, J.A., Fujita, N., & Fukusima, S. S. (1992) Visual space perception and visually directed action. *Journal of Experimental Psychology: Human Perception and Performance*, 18, 906-921.

14. Philbeck, J. W. & Loomis, J. M. (1997). Comparison of two indicators of visually perceived egocentric distance under full-cue and reduced-cue conditions. *Journal of Experimental Psychology: Human Perception and Performance*, 23, 72-85.

15. Philbeck, J. W., Loomis, J. M., & Beall, A. C. (1997). Visually perceived location is an invariant in the control of action. *Perception & Psychophysics*, 59, 601-612.

16. Macuga, K. L., Beall, A. C., Loomis, J. M., & Smith, R. (submitted). Visual control of steering along a curving path.

17. Rushton, S. K., Harris, J. M., Lloyd, M. R. & Wann, J. P. (1998). Guidance locomotion on foot uses perceived target location rather than optic flow. *Current Biology*, 21, 1191-1194.

18. Rushton, S. K. & Harris, J. M. (2004). The utility of not changing direction and the visual guidance of locomotion. In L. Vaina, S. Beardsley, & S. Rushton (Eds.). *Optic flow and beyond* (pp. 363-381). Boston: Kluwer Academic Publishers.

19. Warren, W. H., Kay, B. A., Zosh, W. D., Duchon, A. P., & Sahuc, S. (2001). Optic flow is used to control human walking. *Nature Neuroscience*, 4, 213-216.

20. Patla, A. E. (2004). Gaze behaviors during adaptive human locomotion: Insights into how vision is used to regulate locomotion. In L. Vaina, S. Beardsley, & S. Rushton (Eds.). *Optic flow and beyond* (pp. 383-399). Boston: Kluwer Academic Publishers.

21. Wann, J. P. & Wilkie, R. M. (2004). How do we control high speed steering? In L. Vaina, S. Beardsley, & S. Rushton (Eds.). *Optic flow and beyond* (pp. 401-420). Boston: Kluwer Academic Publishers.

22. Vaina, L., Beardsley, S. & Rushton, S. (2004) . *Optic flow and beyond* (pp. 401-420). Boston: Kluwer Academic Publishers.

23. Loomis, J. M. & Beall, A. C. (submitted). Visual control of action without retinal optic flow.

24. Julesz, B. (1971). *Foundations of cyclopean perception.* (Chicago: University of Chicago Press)

25. Patterson, R. (1999). Stereoscopic (cyclopean) motion sensing. *Vision Research*, 39, 3329-3345.

26. Gray, R. & Regan, D. (1998). Accuracy of estimating time to collision using binocular and monocular information. *Vision Research*, 38, 499-512.

27. Macuga, K. L., Loomis, J. M., Beall, A. C., & Kelly, J. W. (submitted). Perception of heading without optic flow.

28. Kelly, J. W., Loomis, J. M. & Beall, A. C. (in press). The importance of perceived relative motion in the control of posture. *Experimental Brain Research.*

29. Gogel, W. C. (1990). A theory of phenomenal geometry and its applications. *Perception & Psychophysics*, 48, 105-123.

30. Beusmans, J. M. H. (1998). Perceived object shape affects the perceived direction of self-movement. *Perception, 27*, 1079-1085.

31. DeLucia, P. R, Kaiser, M. K., Bush, J. M., Meyer, L. E., & Sweet, B. T. (2003). Information integration in judgments of time to contact. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology*, 56, 1165-1189.

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