REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-05-

0352

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
06/30/2005	Final	03/01/02 - 03/31/05

4. TITLE AND SUBTITLE

Visual Control of Locomotion

5a. CONTRACT NUMBER

5b. GRANT NUMBER

F49620-02-1-0145

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Loomis, Jack, M.

Beall, Andrew, C.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

The Regents of the University of California
Office of Research
3227 Cheadle Hall
Santa Barbara, CA 93106-2050

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

The Regents of the University of California
Accounting Services & Controls
Extramural Fund Accounting
Santa Barbara, CA 93106-2040

NL

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approve for Public Release: Distribution Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The accomplishments were threefold. First, a software tool for rendering virtual environments was developed, a tool useful for other researchers interested in visual perception and visual control of action. Second, an instrumented electric scooter was developed that allows a person to drive around in virtual reality while experiencing the normal inertial cues associated with physical motion. This type of research vehicle can be used to investigate the roles of visual and inertial cues in the control of locomotion. Third, a number of behavioral experiments were conducted in real and virtual environments. The principal research findings were these: (1) complex behaviors, like steering a curved path and ball catching, can be performed without the retinal motion associated with luminance-based stimulation, (2) visual control of posture depends on the sensed relative motion between self and environment instead of on "optic flow", (3) people can continue steering a vehicle after the loss of visual information, implicating an internal model of surrounding space, (4) a steering error observed while driving with visual information only is eliminated when inertial cues

15. SUBJECT TERMS

(continued from box 14 above) are made available, and (5) a flying study reveals the challenge airplane pilots face when pulling up from a dive toward terrain.

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Jack M. Loomis/ Andrew C. Beall
					19b. TELEPHONE NUMBER (Include area code) (805)893-2475

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

2. Objectives. The primary objective is to advance the understanding of how humans use vision to control their locomotion through space. The research deals with terrestrial locomotion (walking and driving) and aircraft piloting. The secondary objective is to contribute to improvements in driving and flight safety. The objectives are very close to those in the proposal of 2001, but the research was broadened to include postural control and interception tasks. This was done because interesting questions about these came up in the course of the research.

3. Status of effort. The accomplishments were threefold. First, a software tool for rendering virtual environments was developed, a tool useful for other researchers interested in visual perception and visual control of action. Second, an instrumented electric scooter was developed that allows a person to drive around in virtual reality while experiencing the normal inertial cues associated with physical motion. This type of research vehicle can be used to investigate the roles of visual and inertial cues in the control of locomotion. Third, a number of behavioral experiments were conducted in real and virtual environments. The principal research findings were these: (1) complex behaviors, like steering a curved path and ball catching, can be performed without the retinal motion associated with luminance-based stimulation, (2) visual control of posture depends on the sensed relative motion between self and environment instead of on "optic flow", (3) people can continue steering a vehicle after the loss of visual information, implicating an internal model of surrounding space, (4) a steering error observed while driving with visual information only is eliminated when inertial cues are made available, and (5) a flying study reveals the challenge airplane pilots face when pulling up from a dive toward terrain.

4. Accomplishments/New Findings

I. Development of software technique for presenting cyclopean stimuli.

In determining which visual information is used to control locomotion and other forms of action, a stimulus which contains only binocular depth information (i.e., no monocular information) is of value. This type of stimulus, referred to as a cyclopean stimulus, was first developed by Julesz in 1971. It consists of a rapid sequence of random dot stereograms, each lasting just one graphics frame. What appears to each eye as just a scintillating field of random dots of uniform spatial density appears to both eyes as a world of stationary and moving objects. Using the primitive computers of his time, Julesz (1971) showed that a subject viewing such a sequence could readily perceive smooth motion of a target in the frontoparallel plane. Gray and Regan (1996, 1998) reported research using special electronic hardware used in conjunction with a computer; this hardware made it possible to move a single target in real time using the same basic technique developed by Julesz. They showed that subjects can accurately judge direction of motion in depth as well as time to collision with an approaching object. Co-PI Andrew Beall has developed a software technique that can be used with any modern 3-D graphics accelerator card that uses OpenGL graphics functions. This means that any computer-graphics rendered 3-D object, objects, or complex scene, whether displayed on a standard desktop computer with 3-D graphics card or with a head-mounted display in immersive virtual can be presented as a purely binocular (cyclopean) stimulus. The co-PI made his software plug-in available for free to anyone who wishes it, by way of his Web site: http://www.recveb.ucsb.edu/stickydots.htm The software is simple to use; with a single keypress within a graphics program, a person can switch from normally rendered 3-D graphics to a cyclopean version.

The Gray and Regan hardware was not portable and, consequently, few people have been able to use this type of stimulus in their research. There are many interesting questions concerning visual perception, visual cognition, and visually controlled action to be pursued using this new stimulus. Thus, this new software technique is a valuable resource for other researchers.

II. Development of an instrumented vehicle for use in an immersive virtual environment

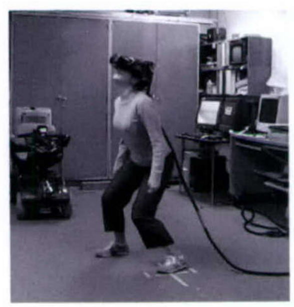
A new research tool has been developed in accordance with the project proposal of 2001. It involves an electric scooter of the kind used by disabled and elderly people (see figure). The vehicle can move at up to 5 mph and make tight turns while being virtually impossible to tip over. This means that the subject is kept safe while being exposed to suprathreshold inertial cues signaling motion. All of the electronic and computer equipment for tracking the position and orientation of the vehicle and for implementing virtual reality is carried at the rear of the vehicle.

The subject is immersed within a fully interactive virtual environment (wearing a head-mounted display) while moving about within a large physical space. The vehicle has been instrumented with a potentiometer attached to the steering, an AD/DC converter to sense the speed control, an optical encoder that senses wheel turning, and a high quality GPS receiver to track the vehicle's location out of doors A software Kalman filter integrates the various inputs to give an accurate and precise measurement of the vehicle's position and orientation at all times, even when GPS signals are weak. By mounting the vehicle on a stationary platform, the subject can visually drive the vehicle through the virtual environment without physically moving. By comparing performance in the stationary and moving conditions, the vehicle can be used to determine the contribution of inertial cues to visual control of vehicle, both with concurrent visual input and with visual input temporarily eliminated. The idea of using a moving ground vehicle as the platform for immersive virtual reality is unique and has several advantages over motion-base simulators for studying the role of inertial cues in vehicle control. Because of this, other researchers have expressed interest in the vehicle developed for this project.

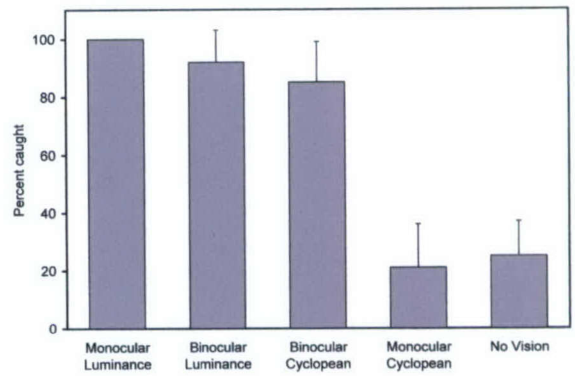
III. Visual perception and visually controlled behaviors without retinal optic flow

Much research over the years has shown the importance of optic flow in the visual control of locomotion and, more generally, action. Optic flow (changes in angular positions of environmental points) produced by self-motion gives rise to corresponding retinal flow, except that eye rotations cause additional retinal flow that is superimposed on that produced by optic flow. Using the software technique described above, research has been conducted on three issues relating to the visual control of action. This research shows that a more abstract form of optic flow produced by cyclopean stimulation results in visual perception and visually based action similar to those resulting from the more conventional luminance-based optic flow, which has retinal motion ("Fourier motion" or "motion energy").

A. Visual control of action without retinal optic flow. In three publications (Loomis & Beall, 2004; Loomis et al., 2005; Loomis et al., in press), the research team has shown that a wide variety of complex actions can be performed using cyclopean stimulation (i.e., without retinal optic flow) about as well as using conventional luminance stimulation (monocular or binocular). For these, the subject wears a head-mounted display and moves through the cyclopean version of a virtual environment. These actions include walking to a goal through a field of obstacles, ball catching, steering a curving path, and steering a straight path in the presence of lateral perturbing forces. The figure to the right shows a subject catching a ball in virtual reality.

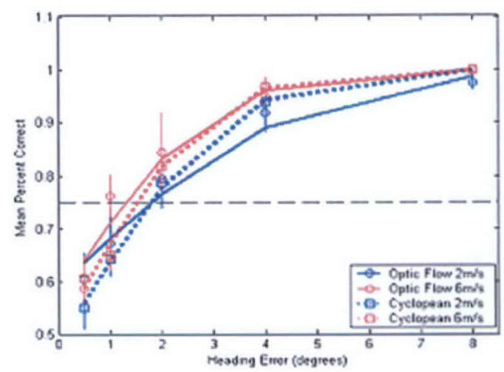


The data figure on the right shows the results for ball catching with different visual stimuli. Ball catching performance (percent caught) was almost as good with the purely binocular (cyclopean) stimulus as with conventional luminance stimuli (both binocular and monocular); no vision and a single eye view of the cyclopean stimulus led to the same poor performance. (For the latter two conditions, the relatively high proportion of successful "catches" occurred because the landing region of the ball was quite small and a successful catch was registered when the subject was within some critical radius of the ball).

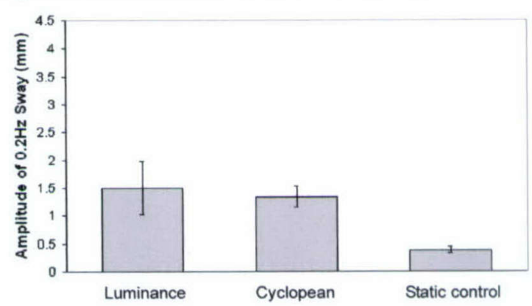


The results for other visually guided actions were similar in showing that cyclopean stimulation allows almost the same level of performance as conventional luminance stimulation, which contains informative retinal motion. This work shows that complex actions can be carried out visually using a more abstract form of optic flow that does not involve retinal motion. However, because some actions, like playing tennis and batting a baseball, involve optic flow of high angular velocities, cyclopean visual perception is probably inadequate for these given that its spatiotemporal bandwidth is lower than that of luminance-based vision.

B. Heading perception without retinal optic flow. Many psychophysical studies in the 1990's investigated "heading perception" with optic flow presented on computer displays. Project personnel have conducted research on heading perception without retinal optic flow. Using the traditional paradigm for measuring the precision of heading perception (except that the subject wears a head-mounted display) and adjusting the luminance stimuli to be equal to the cyclopean stimuli in terms of motion visibility, it was found that heading thresholds for cyclopean stimuli were nearly the same as those for luminance ("optic flow") stimuli; in the accompanying figure, the thresholds (corresponding to 75% percent correct performance) were just slightly larger for the two observer speeds studied (Macuga et al., submitted).



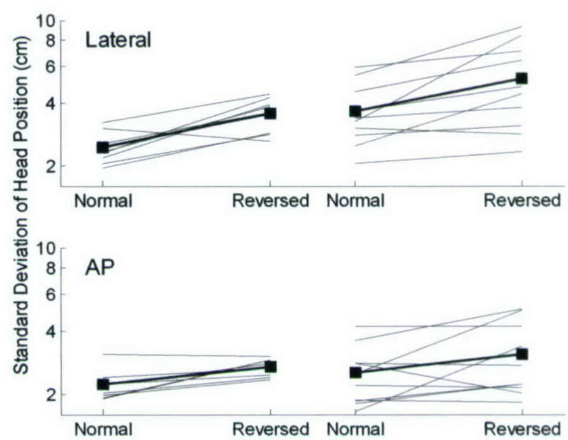
C. **Postural control without retinal optic flow.** Prior research has demonstrated that postural sway can be induced by optic flow, as for example, when a swinging room surrounds a person (Lee & Lishman, 1975). Project personnel conducted research to determine whether such optic flow needs to involve retinal flow or can be more abstract, like that produced by cyclopean stimulation. In this research, the subject stood upright wearing a head-mounted display. The goal was to move as little as possible, while a large cross moved sinusoidally toward and away from the subject. Its motion was conveyed by cyclopean or luminance stimuli; in the latter case, the stimulus was biocular (identical for the two eyes). When adjusting the luminance stimuli to match the cyclopean stimuli in terms of motion visibility, similar (but small) amounts of body sway were observed (see figure at the right). Both were greater than the amount of sway measured when the subject was asked to stand still while



viewing a stationary stimulus defined by luminance. This work shows that the optic flow inducing postural sway need not have associated retinal flow.

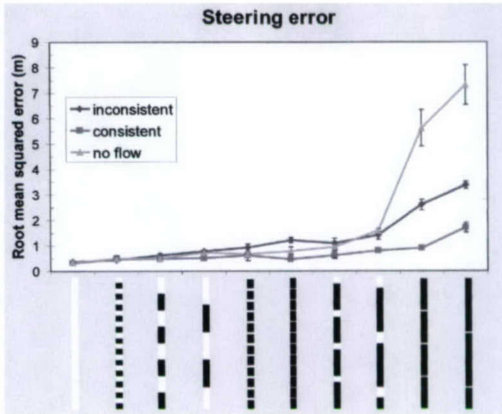
IV. Research showing that optic flow, even in the abstract sense, is not the basis for postural control.

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 subject 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 the research on this topic (Kelly, Loomis, & Beall, 2005), the subject 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 appears to be rigid and stationary as the person's head translates slightly (because of postural instability). The other condition was obtained simply by switching the images to the two eyes. Switching the eyes has no effect on the optic flow but dramatically changes the perception of the rectangular box in terms of 3-D perception. Now the box appears as a truncated pyramid, which appears to rotate and distort as the person's head moves 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 (Gogel, 1990). In two experiments on this, it was found that such a stimulus was much less effective in stabilizing the subjects (mean and individual data are shown in the accompanying figure; for the two experiments, amount of head instability is plotted as a function of visual condition and axis of movement, either lateral or anterior/posterior). 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. This finding is an important challenge to researchers who attempt to interpret visual control of action solely in terms of optic flow (whether abstract or involving retinal flow).



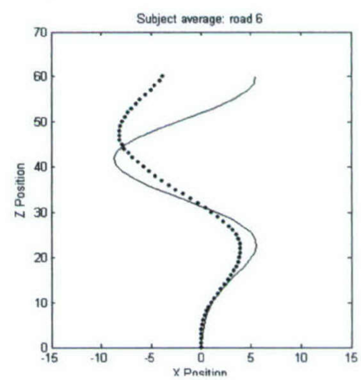
V. Visual control of steering.

A. Open-loop steering. In line with the 2001 proposal and with ideas presented in the chapter by Loomis and Beall (2004), research has been conducted on the roles of both optic flow and a perceptual model of the path being steered (Macuga, Beall et al, in preparation). The experiment involved steering a curved path defined by smooth lane markers. A driving simulator with wide projection screen was used. An important manipulation was intermittent presentation of the path, ranging from continuously present to one video frame every couple of seconds. In the accompanying figure on the next page, the different conditions of intermittency over time are presented using black and white symbols, with the white representing the period of visibility. Each symbol represents 2.5 sec. There were three conditions of optic flow in the experiment: In the CONSISTENT FLOW condition, the optic flow produced by ground texture was consistent with the path being steered. In the INCONSISTENT FLOW condition, the optic flow had two components. One component corresponded to motion over a separate "ghost" path. The other component was the rotational flow associated with the subject's actual steering inputs. Because the changes in optic flow were partially correlated with the steering inputs, the subject could use the changes in flow to gauge turn rate. The third and final flow condition was NO FLOW. In this condition, flow was consistent but it disappeared when the path disappeared.

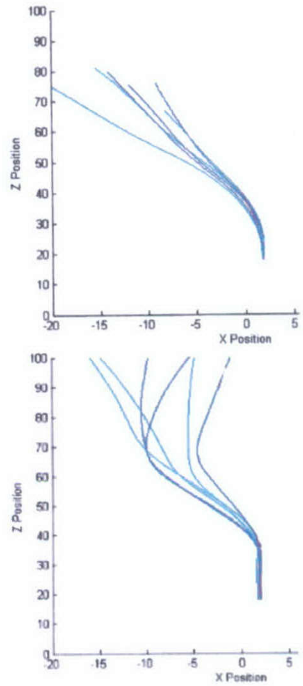


The results of the three conditions were quite revealing. For continuous viewing of the path, there was little effect of whether flow is consistent or inconsistent. For intermittent viewing, CONSISTENT FLOW led to best steering performance, as expected. What was surprising is that the NO FLOW condition was much worse than INCONSISTENT FLOW. This means that although the INCONSISTENT FLOW does not specify the vehicle's absolute heading, the changing flow (which is partly determined by the subject's steering inputs) specifies the turn rate of the vehicle, which can be used by the subject for steering. These results are interpreted in the following way. Subjects are using path information that is continuously or intermittently present to form a 3-D or perspective representation of the path. Subjects steer with respect to the perceptual path when possible, but are able to mentally update with respect to the imagined path when it is not present. The optic flow serves to provide information about the speed and turns of the vehicle even when absolute information about heading is provided by optic flow.

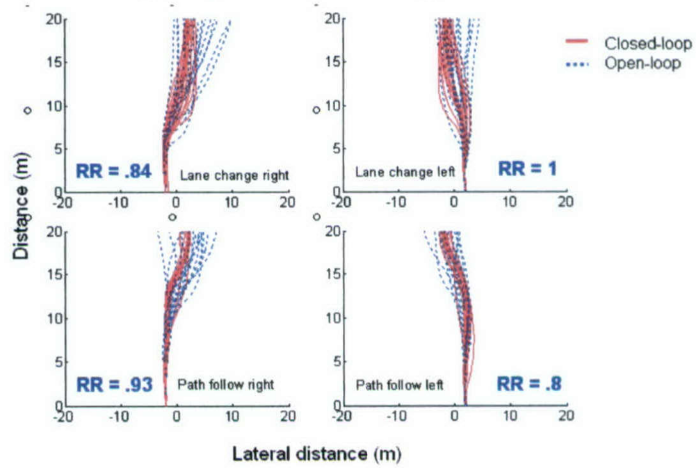
If subjects are indeed updating with respect to the imagined path when it is not perceptually present, they should make several successive steering inputs in accord with the changing heading of the path, even when they cannot see the path. In recent work, this has been confirmed (Macuga, Loomis et al., in preparation). The accompanying figure depicts a planview of a curved path (solid line)t. The dashed line is the average of 8 steering trajectories (4 subjects twice each) performed without vision. The subjects moved along a straight segment while viewing the path ahead and just as they entered the curved path, the path disappeared, leaving only optic flow of ground texture. The beginning of the average steering trajectory is at the bottom. This figure is just one of 7 different paths. This and figures for the other paths show that although subjects are not steering with perfect accuracy, they are making multiple steering inputs at appropriate times to maintain an average path that is quite similar to the actual path. This is evidence of imaginal updating with respect to a mental representation of the path.



These new results also contrast with those of several experiments by Wallis et al. (2002), in which they found that subjects making a lane change on a driving simulator, make a steering input to move toward the next lane but fail to make the opposite steering input to realign with the path. From this result they have concluded that people are unable to perform open loop steering, in part because of their having a poor representation of the steering dynamics of a vehicle. The results above challenge the generality of their result and their interpretation of it. However, because the paths in the above study were curved, it was necessary to investigate open loop steering in a task more like theirs. In recent research, subjects had to perform several steering tasks, of which just two are mentioned here. One was a lane change maneuver like that of Wallis et al. (2002). Subjects were moving down a two lane road and, on command, were instructed to change over into the adjacent lane. At the moment of the command, the path disappeared. In the other condition, subjects viewed a path consisting of 3 linear segments (corresponding approximately to a lane change maneuver). As the approached the path, it disappeared. The accompanying figure gives results of multiple attempts by one subject for the two conditions (lane change is above). The results of 9 subjects are similar in showing that when subjects make a lane change, they show the absence of a "return phase" in accord with the results of Wallis et al. (2002) but when there is an explicit path depicted, subjects are able to perform open loop steering that is qualitatively correct.

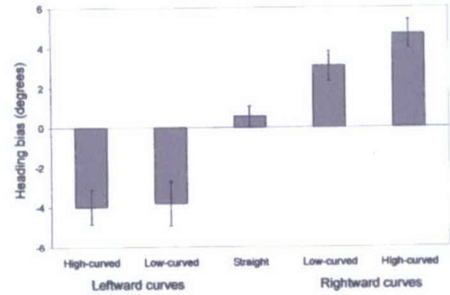


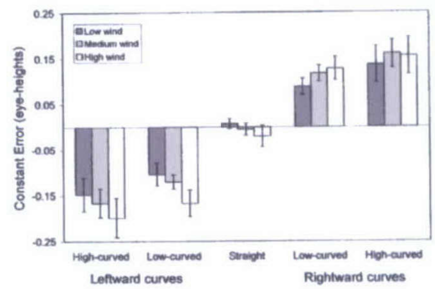
In the most recent research on this topic, subjects performed steering tasks on the instrumented electric scooter mentioned earlier out of doors. Subjects wore a head-mounted display and saw paths depicted in a virtual environment. While at a standing start, they saw either a two lane straight path ahead or an explicit path of 3 linear segments. When ready, the subjects accelerated and attempted to make a lane change or steer the path they had seen. On some trials the display was turned off while they were moving (open loop). The results are shown at the right. The solid lines are closed-loop control (with concurrent visual information). Subjects correctly performed the return phase for both steering tasks and for both open- and closed-loop control. The results show that the inertial cues provided while moving in a real vehicle are sufficient to induce the subjects to make the return phase, thus eliminating the steering error observed by Wallis et al.

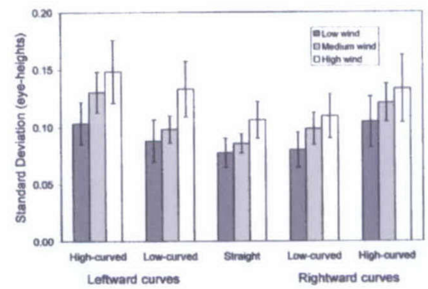


B. Simultaneous measurement of heading perception and steering performance

Notwithstanding the extensive literature from the 1990's on heading perception, a number of researchers have expressed skepticism that people use perceived heading based on optic flow to perform various steering behaviors, including aiming toward a point, steering a straight path in the presence of laterally perturbing forces, and turning into alignment with a straight path (Beall & Loomis, 1996, 1997; Loomis & Beall, 1998; Wann & Wilkie, 2004; Rushton & Harris, 2004). To address the issue of whether perceived heading is involved in steering a curved path, an experiment was conducted in which subjects steered along curved paths within an immersive virtual environment (implemented with a head-mounted display) while periodically being asked to make judgments of instantaneous heading using the standard probe technique. The paths consisted of concatenated segments that were straight, of low curvature, or of high curvature. Also manipulated was the magnitude of crosswinds. Steering performance was measured for the different path segments in terms of bias (constant lateral error) and variability (standard deviation of lateral error). Errors in perceived heading were measured in the conventional way. The results for the 8 subjects are shown in the accompanying figure. Heading bias (which could only be measured by collapsing across crosswind magnitude) varied systematically with the direction and magnitude of the path curvature. Steering bias was affected in a very similar fashion. The high correlation between heading bias and steering bias is quite surprising and seems to support the hypothesis that perceived heading is involved in steering a curved path. However, there are alternative hypotheses that might account for such a correlation. Ultimately, what is needed is a theory connecting the two.



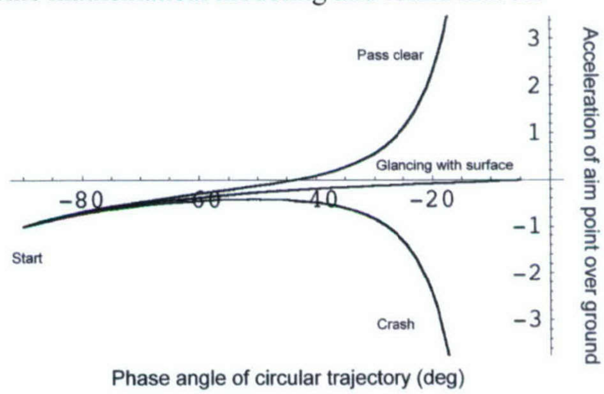




VI. Sensitivity to visual information during pullup from a vertical dive

One of the most complex visually controlled maneuvers is that of pulling up from a dive in an airplane. Failure to perform this correctly is the cause of occasional accidents at airshows, including one in 2003 by the solo pilot of the USAF Thunderbirds (http://www.f-16.net/f-16_news_article968.html). The precipitating cause of the accident was the pilot's briefing for the wrong field elevation, but his failure to quickly realize his error during the pullup shows how difficult the maneuver is; he safely ejected less than 1 sec before the aircraft crashed.

There is no instantaneous visual information (in the form of optic flow or distance cues) that informs the pilot as to whether collision with the ground will occur. Loomis and Beall (1998) speculated that one basis for judging involved changes over time of the aim point, as specified by optic flow. In particular, it was hypothesized that the aircraft would pass clear if and only if the aim point accelerated positively over the ground surface. Project member, Professor Roy Smith, did some mathematical modeling and found that the hypothesis is not quite correct. The accompanying figure shows the acceleration of the aim point as a function of the angle in a circular dive trajectory (when the aircraft is diving vertically at the start, the angle is -90°). Trajectories that collide always have negative accelerations. Trajectories that will pass clear initially have negative accelerations, but eventually the aim point switches to a positive acceleration. The diagnostic information occurs late in the trajectory, which may be only a few seconds, depending upon the rate of pullup.



Starting in February 2004, a control theory student from Delft University, Sebastiaan de Stigter, served as a research intern in the lab for 3 months. Besides giving tutorials on control theory, he conducted experimental research on the pullup maneuver. Although the data have yet to be thoroughly analyzed, the results confirm the difficulty of judging whether the trajectory will pass clear and reveal an important bias associated with the pitch of the aircraft, suggesting that people have difficulty distinguishing between the pointing direction of the aircraft and its instantaneous travel direction. This result may have implications for pilot training.

5. Personnel supported by or associated with project

Jack Loomis	Professor of Psychology; Principal Investigator
Andrew Beall	Project scientist; co-Principal Investigator
Roy Smith	Professor of Electrical and Computer Engineering; Senior Personnel
Jerome Tietz	Computer programmer
Jonathan Kelly	Graduate student researcher
Kristen Macuga	Graduate student researcher
Sebastiaan de Stigter	Undergraduate intern from Delft University, The Netherlands
Thomas Cook	Undergraduate engineering student from UCSB

6. Publications and manuscripts deriving from AFOSR support during the grant period

Loomis, J. M. & Beall, A. C. (2004). Model-based control of perception/action. In L. Vaina, S. Beardsley, and S. Rushton (Eds.). *Optic Flow and Beyond* (pp. 421-441). Boston: Kluwer Academic Publishers.

Kelly, J. W., Loomis, J. M., & Beall, A. C. (2004). Judgments of exocentric direction in large-scale space. *Perception*, 33, 443-454. (also supported by Office of Naval Research)

Kelly, J.W., Loomis, J.M., & Beall, A.C. (2005). The importance of perceived relative motion in the control of posture. *Experimental Brain Research*, 161, 285-292.

Loomis, J. M., Beall, A. C., Kelly, J. W., & Macuga, K. L. (2005). Importance of perceptual representation in the visual control of action. *Proceedings of the IS&T/SPIE's 17th Annual Symposium on Electronics* (pp. 356-361), January 16-20, 2005, San Jose CA.

Loomis, J. M., Beall, A. C., Macuga, K. L., Kelly, J. W. & Smith, R. (in press). Visual control of action without retinal optic flow. *Psychological Science*.

Macuga, K. L., Loomis, J. M., Beall, A. C., & Kelly, J. W. (under revision; acceptance expected). Perception of heading without optic flow. *Perception & Psychophysics*.

Kelly, J. W., Beall, A. C., Loomis, J. M., Smith, R. S., & Macuga, K. L. (under revision; acceptance expected). Simultaneous measurement of steering performance and perceived heading on a curving path. *ACM Transactions on Applied Perception.*

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

Macuga, K. L., Loomis, J. M., Beall, A. C., Smith, R. S., & Kelly, J.W. (in preparation). In steering without visual feedback, subjects can properly initiate the return phase of a "lane change" maneuver.

de Stigter, S., Loomis, J. M., Smith, R., & Beall, A. C. (in preparation). Psychophysical investigation of sensitivity to visual information during pullup from a vertical dive.

Kelly, J. W., Beall, A. C., Loomis, J. M., & Macuga, K. L. (in preparation). Postural control without retinal optic flow.

7. Interactions/Transitions

a. Talks and posters relating to AFOSR funding (in chronological order)

Beall. A. Creating virtual environments. Thematic Interdisciplinary School on Virtual Reality and Behavioral Science. Marseille France, May 2003.

Loomis, J. Using virtual reality to study visual space perception, action and spatial cognition. Thematic Interdisciplinary School on Virtual Reality and Behavioral Science. Marseille France, May 2003.

Kelly, J., Beall, A., & Loomis, J. (2003). Postural control without optic flow. Vision Sciences Society meeting, Sarasota, FL, 2003.

Loomis, J & Beall, A. (2003). Visual control of locomotion without optic flow. Vision Sciences Society meeting, Sarasota, FL, May 2003.

Macuga, K., Loomis, J. & Beall, A. (2003). Perception of heading without optic flow. Vision Sciences Society meeting, Sarasota, FL., 2003

Loomis, J. Visual control of locomotion. Colloquium, Schepens Eye Research Institute, Boston, MA, July, 2003.

Loomis, J. Perceiving and acting in space. Short course, International Spatial Cognition Institute, Bad Zwischenahn, Germany, September 2003.

Loomis, J. Perceiving and acting in real and virtual environments. Colloquium, Department of Neurosciences, School of Medicine, Erasmus University, Rotterdam, The Netherlands, September 2003.

Loomis, J. Visual control of locomotion. Colloquium, Faculty of Aerospace Engineering, Delft University of Technology, Delft, The Netherlands, September 2003.

Kelly, J. Postural control without optic flow. Colloquium, Max-Planck Institute, Tübingen, Germany, September 2003

Loomis, J. Perceiving and acting in space. Colloquium, Dept. of Psychological and Brain Sciences, Johns Hopkins University, Baltimore, MD, October 2003.

Loomis, J. M. (2004). Visual control of flight. Aerospace Lighting Institute, Los Angeles, CA, February 2004.

Kelly, J.W. (2004). Perception and action without optic flow. Colloquium, University of Texas at Austin.

Kelly, J.W., Beall, A.C., & Loomis, J.M. (2004). Accurate steering performance with large heading errors on a curving path. Vision Sciences Society Annual Meeting, Sarasota, FL.

Macuga, K. L., Loomis, J. M., & Beall, A. C. (2004). Two processes in the visual control of steering along a curving path: sensing turns and updating with respect to the path. Vision Science Society Annual Meeting, Sarasota, FL., 2004.

Loomis, J. M. Recent research on spatial hearing inspired by working with blind people. Colloquium, Auditory Research Group, Wright-Patterson Air Force Base, Dayton, OH, October 2004.

Loomis, J. Perceiving and acting in space. Colloquium, Dept. of Psychology, Wright State University, Dayton, OH, October 2004.

Loomis, J. Perceiving and acting in space. Colloquium, Dept. of Psychology, Rutgers University, Newark, NJ, December 2004.

Macuga, K. L., Loomis, J. M., Beall, A. C., Smith, R., & Kelly, J.W. (2005). In steering without visual feedback, subjects can properly execute return phase of a "lane change" maneuver. Journal of Vision. Presented at Vision Science Society Annual Meeting, Sarasota, FL, May 6-11, 2005.

b. Consultative and advisory functions to Air Force laboratories

In October, 2004, the PI, Jack Loomis, traveled to Wright-Patterson Air Force Base and spent the day with the Auditory Research Group, where he gave a talk and discussing with various personnel there possible new directions for research in the area of spatial hearing.

c. Transitions None

8. New inventions

Instrumented electric scooter that permits a user to be perceptually immersed in a virtual environment while driving around in real space.

9. Awards None