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14. ABSTRACT

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Abstract

Pilots' mental resources can be overburdened by the information presented in cockpit displays. Previous research found that presenting information in a 3D perspective, or *virtual*, head-up display (HUD) can lessen information overload. The current research examined whether extending virtual HUDs into the visual periphery will further reduce the mental workload associated with spatial orientation processes such as perception and control of the heading direction and speed of self-motion (egospeed). It found that: a) heading control based on peripheral vision is equivalent to that based on central vision if informative areas of optical flow are visible; b) control of heading requires only a limited amount of attentional resources; and c) the complex motion created by transparently superimposing optical flow in a display can lead to systematic heading errors. Additional research found that perception and control of egospeed is based primarily on the mean image velocity of the display, but that texture density and motion parallax produce small but consistent biases. Further research found better flight-path and speed control performance with a peripherally-located virtual speed-error HUD as compared to the MIL-STD-1787B HUD airspeed indicator. Taken as a whole, these results suggest that peripheral virtual HUDs have significant potential for conveying spatial orientation with fewer resource demands than conventional HUDs.

Background and Research Objectives

To successfully complete their missions, pilots must quickly perceive and analyze a vast amount of information. Increasingly complex aircraft, weapon systems, and mission requirements combine to create a level of workload that may overwhelm the perceptual and cognitive resources of pilots, thereby reducing pilot performance and increasing the risk of accidents. Modern cockpit displays that present navigational and tactical information in an integrated, 3D perspective, head-up display (HUD) format—what we will subsequently refer to as a *virtual HUD*—have been shown to moderate workload while simultaneously increasing performance and reducing the risk of accidents (cf. Hettinger, Brickman, Roe, Nelson, & Haas, 1996).

However, because these advanced displays present information to the central visual field only, some problems remain. For example, the superposition of HUD or helmet-mounted display (HMD) symbology over the pilot's view of the outside world can lead to cognitive capture and the potential that important information, either within the HUD or outside the window may be obscured (Boston & Braun, 1996; Becklen & Cervone, 1984). Furthermore, competition within central vision among tasks requiring focused attention, such as target acquisition and flight systems monitoring, may interfere with pilots' spatial orientation—the zero- and higher-order time derivatives of a pilot's position and orientation in space—leading to reduced situation awareness.

One potential solution to these problems is to present selected visual information to the pilot with displays located in the visual periphery and thus take advantage of the relatively underused peripheral visual field (Roscoe, 1980). Some tasks may be especially well suited for peripheral displays. For example, psychophysical research has shown that the peripheral visual field can provide superior performance on tasks related to spatial orientation (Brandt, Dichgans, & Koenig, 1973; Dichgans, Held, Young, & Brandt, 1972; Dichgans & Brandt, 1974; Held, Dichgans, & Bauer, 1975; Lestienne, Soechting, & Berthoz, 1977; Stoffregen, 1985). This report summarizes further research that examined the potential of peripheral visual displays for spatial orientation during vehicular control, including experiments conducted within an ecologically valid dual-task context where attentional and central visual field resources are demanded by other tasks.

There were three general objectives of this research. The first objective was to develop the technical capacity for examining human visual performance in the context of active control. Due to the novelty of this research area, much of the software necessary to display interactive simulations with precise measurement and analysis needed to be developed. A second objective was to determine the relative capability, information basis, and resource demands of perception and control of spatial orientation as a function of visual field. Two aspects of spatial orientation were examined: a) perception of *egospeed*, the speed of self-motion; and b) perception of *heading*, the direction of self-motion. A third objective was to determine the optimal format for peripherally-located virtual HUDs and to test these displays against currently-used display formats. Based on design principles derived from psychophysical research on perceived egospeed, a peripherally-located speed-error display was developed and compared to the military standard (MIL-STD-1787B) speed display in a dual-task environment in which observers controlled both their flight-path and speed.

Technical Summary of Significant Work Accomplished

Research Software Development

ViEWER (Virtual Environment Workbench for Education and Research). An initial objective was to develop the software necessary to produce the visual simulations to be used in experiments involving closed-loop control of locomotion through virtual environments. To achieve this objective, *ViEWER*, an extension of the OpenGL graphics-library, was developed. *ViEWER* supports the design and presentation of simulations for the scientific study of human interactions with virtual environments. In contrast to existing commercial software packages for developing virtual environments, *ViEWER* was specifically designed for research, combining flexible simulation of many types of virtual environments, precise timing of animation, and the ability to precisely measure human performance within virtual environments. *ViEWER* v1.03 has a number of important features. First, since it is based on Silicon Graphics' OpenGL graphics library, it can potentially be used on graphics workstations running either Microsoft Windows (95, 98, me, NT4, or 2000) or UNIX (IRIX, AIX, HP UX, Solarix, or Linux) operating systems. Second, the software allows precise control of timing and animation, making it ideal for research applications that depend on precise temporal control and measurement. Third, the software supports the development of a variety of virtual environments, both realistic (e.g., flight simulation) and abstract (e.g., dot displays used in typical experiments in vision science). Fourth, the software allows users to specify what types of measures will be recorded. These measures currently include tracking of participant movements through the virtual environment, user inputs from controls such as joysticks and footpedals, and physiological measurements such as eye and head movements. Presently, *ViEWER* v1.03 is usable by those with modest C++ programming knowledge, allowing researchers to develop virtual environments in a fraction of the time needed to program these environments from scratch.

FUSE (Front-end Utility for Setting-up Experiments). FUSE is an easy-to-use utility that allows researchers to design experiments that make use of the interactive virtual environments developed with *ViEWER.* With *FUSE* an experimenter can set the order and features of experimental conditions (blocks and trials) to be used for data collection, and can specify parameters to control *ViEWER*-generated simulations, such as the data to be collected or external disturbances.

Automated NASA-TLX Subjective Workload Scale. This program implements the widely used NASA-TLX Subjective Workload Scale (Hart & Staveland, 1999) in an easy-to-use software tool that automates data collection and analysis.

Time-Series Analysis Tool (CLAnalyzer). This program allows researchers to quickly derive useful measures from the time-series data produced by ViEWER simulations for further inferential analysis with standard statistical programs.

Research on Heading Perception

An important component of dynamic spatial orientation is the perception of the direction of observer motion (the heading direction). An accurate perception of the heading direction is particularly important for visually demanding flight missions such as terrain-following or nap-of-the-earth (NOE) flight, in which pilots are required to fly at low altitudes at relatively high speeds (R. Warren, 1988; Kleiss & Hubbard, 1993), and where serious consequences may result from misperceptions of heading. Currently, pilots rely primarily on alpha-numeric displays and visual information available "out-the-window" for determining heading in these circumstances (R. Warren, 1988). However, accurate control of heading could be enhanced through the use of a peripherally-located virtual display comprised of flowing elements that cue the direction of heading in a natural manner. Understanding the visual mechanisms underlying perception of heading is thus an important basic perceptual problem that has potential application to virtual display design.

Three aspects of heading perception are particularly relevant to the design and use of peripherally-located virtual displays as aids for spatial orientation and visual navigation: 1) the capability of the peripheral visual field for supporting control of heading, 2) the attentional demands of heading control, and 3) the effect on heading perception of superimposing moving symbols in a virtual HUD or HMD over the directly-viewed scene. Research examining these three issues is summarized below. For more detailed information, please refer to the theses and articles listed in the section titled, "Publications Stemming from the Research Effort."

Peripheral Vision and Heading Performance. Previous studies examining the contributions of central and peripheral vision (also referred to as retinal eccentricity) to heading perception did not assess the task of heading perception in its most common everyday form: Where an observer is free to look over a large field of view while controlling their locomotion over periods of minutes to hours (e.g., Atchley & Andersen, 1997; Crowell & Banks, 1993; Warren & Kurtz, 1992). Rather, these studies required observers to fixate their gaze on a stationary object while viewing brief and small displays simulating self-motion (e.g., lasting less than 1 s in duration and presented on a 21" computer monitor subtending perhaps 10-40 degrees of visual angle) and then respond with a verbal judgment of their perceived direction of heading. Our understanding of the contribution of the central and peripheral visual fields to heading perception is thus limited to the special case of an observer with no control—in effect a passenger—whose eyes are fixed in a particular direction, viewing the world through a small window for a brief time period and then making a verbal judgment. Clearly, the general conclusion found by this previous research, that the central visual field is necessary and sufficient for optimal heading performance, does not necessarily apply to the more common and relevant case of an observer engaged in closed-loop control (i.e., a pilot), who is freely looking throughout a

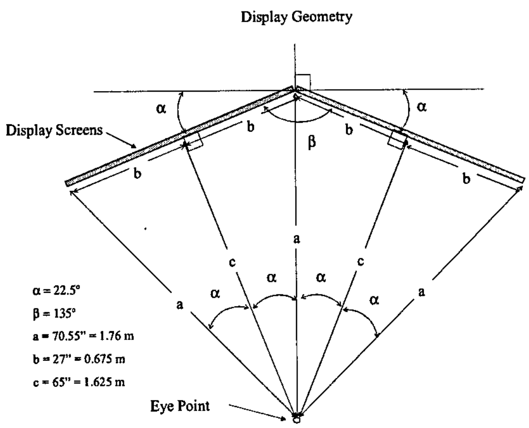


Figure 1. Pictorial representation (top-down view) of the display geometry used to present the 90 x 34 degree (H x V) field of view.

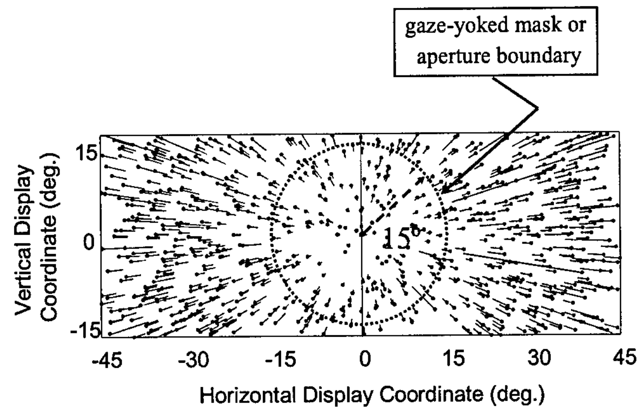


Figure 2. Pictorial representation of the optical flow fields used to examine the relationship between heading performance and retinal field of view. Each arrow represents the velocity of a moving dot. Note: the mask or aperture was centered on the gaze direction and moved with it across the displays.

large field of view as they control their direction of motion over a more extended time period.

The experiments reported here extend our understanding of the relationship between retinal eccentricity and heading perception to the more ecologically relevant task of active control of heading. The method used in these experiments was to present observers 30 s simulations of flight on a straight path through a field of moving points (a star field). Simulated wind gusts (defined by a sum of sine waves at five prime frequencies) rotated the observer's viewpoint about either: a) the vertical (yaw) axis passing directly through their eye, as if the observer was seated in a turning swivel chair, or b) the horizontal (pitch) axis passing from left to right through their eye, as if the observer was seated in a rocking chair. The simulations were presented on a large, 90 x 34 degree (H x V) display formed by placing two rear-projection screens side-by-side at an angle of 135 degrees (see Figure 1). The observer's task was to control their direction of yaw or pitch so that they countered the simulated wind disturbances and maintained their perceived direction of heading straight-ahead toward the center of the display screens.

Two variables were of primary interest: a) the field of view stimulated, and b) the axis of heading perception and control. Field of view was varied on three levels: a) central—within a 15 degree radius circle centered on the direction of gaze; b) peripheral—outside a 15 degree radius circle centered on the direction of gaze; and c) full-field—the entire 90 x 34 degree display (see Figure 2). Unlike previous studies, this manipulation of visual field did not require observers to fixate their direction of gaze on a particular point or object in the display. Rather, observers were free to look anywhere in the display and wore an eye-head tracking apparatus that allowed their direction of gaze to be monitored in real-time. Using this measurement of gaze direction, the graphics computer generating the displays yoked a mask or aperture to the gaze direction, which constrained the moving dots to appear only in the central or peripheral visual fields. In effect, this simulated blindness in different parts of the visual field. The dimensions of the central and peripheral display conditions were chosen based on the cortical magnification factor (Rovamo & Virsu, 1979) such that the volumes of primary visual cortex stimulated by either the central or peripheral displays were approximately equal and one-half the volume stimulated by the full-field display. This choice balanced the volume of primary visual cortex stimulated by the central and peripheral displays.

Observers controlled their simulated rotation about one of two axes oriented orthogonally to their direction of motion: a) the vertical (yaw) axis, or b) the horizontal (pitch) axis. Because the displays were confined to a 90 x34 degree (H x V) field of view, the manipulation the of axis of rotational control resulted in the presentation of different regions of optical flow to the observer, allowing independent manipulation of visual field and optical flow structure.

Optical flow is a quantitative description of the dynamic pattern of light projected onto a point of observation, such as the human eye. Information carried by the structure of optical flow underlies visual guidance of locomotion (Gibson, 1950; Gibson, Olum, & Rosenblat, 1955). For example, movement straight-ahead through the environment results in a radial pattern of optical flow diverging from a common locus, called the *focus of expansion (FOE)*. The location of the focus of expansion coincides with the heading direction. In principle, an ideal observer could determine their direction of heading by finding the focus of expansion in optical flow through a process of vector triangulation (W.H. Warren, 1998). However, *heading precision*, the precision with which the heading direction can be triangulated, depends on which regions of optical flow are visible to the observer. Formal analyses of optical flow structure (Crowell & Banks, 1996;

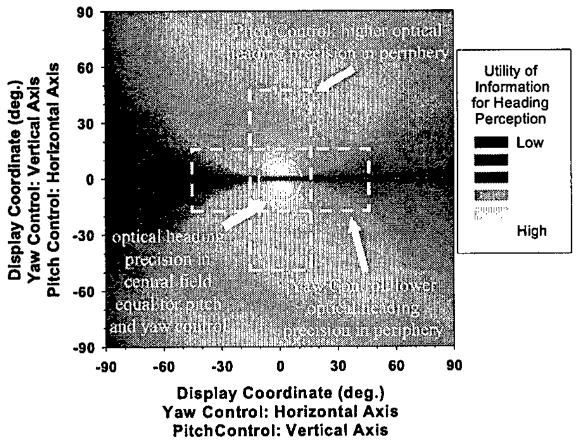


Figure 3. Plot of heading precision (see text) as a function of the horizontal and vertical display coordinates, assuming that the observer is headed toward the origin (0, 0) of the displays. The shading at each location indicates the precision with which heading can be recovered by an ideal observer based on an analysis of image element trajectories at that location. Note that a) the horizontal axis represents the heading axis (see text) for both pitch- and yaw-control, and b) for pitch-control the figure is rotated 90 degrees relative to the actual orientation of the display used in the experiment, where the longer axis was horizontal and the heading axis was vertical.

Dyre, Morrow, & Richman, 2001) indicate that the regions of optical flow with the worst heading precision are located along the axis over which the heading direction is changing (what will subsequently be referred to as the *heading axis*), while regions of high heading precision are located adjacent to the heading direction but orthogonal to the heading axis (see Figure 3). To illustrate, imagine the task of driving a car. Automobile driving requires that we control our heading direction along a horizontal (left-right) axis, so the most informative regions of optical flow for determining our direction of heading would extend vertically above and below the current heading direction.

Ironically, the displays used in previous studies of heading performance and retinal field (Atchley & Andersen, 1999; Crowell & Banks, 1993; Warren & Kurtz, 1992) presented only those areas of optical flow falling near the heading axis. Regions of higher heading precision located orthogonal to the heading axis were not displayed. To reproduce a similar pattern of optical flow the present study used a yaw-control task where the heading axis passed horizontally through the midline of a 90 degree wide display. Vertically, the display subtended only 34 degrees of visual angle, so informative areas of optical flow above and below the heading axis were truncated by the top and bottom of the display. The present study also examined heading performance with displays that included these areas of higher heading precision by using a pitch-control task. For pitch-control the heading direction varies along a vertical axis. The more informative regions of optical flow located orthogonal to the heading axis were thus visible within the 90 degree horizontal extent of the displays. As a result, the pitch-control task presented regions of optical flow with greater heading precision than the yaw-control task, regions of flow that have not been examined in previous experiments on the relative contribution of central and peripheral vision to heading perception.

The primary results of this research are presented in Figure 4, which shows errors in heading control as a function of visual field (central, peripheral, or full field) and control axis (yaw vs. pitch). Results for the yaw control task confirmed the results of previous research (Crowell & Banks, 1993; Warren & Kurtz, 1992): the central visual field was necessary and sufficient for optimal heading performance. This result was not entirely surprising given that, like these previous studies, the informative areas of optical flow above and below the heading axis were not visible. The results for pitch control show a remarkably different pattern: equivalent heading performance for central and peripheral vision. Analysis of the gaze patterns of observers suggest that this difference in performance for the two tasks is not due to differences in scanning behavior. In both tasks observers generally focused their gaze at or near the center of the display (see Figure 5).

What are the implications of these results for the potential use of peripheral displays for supporting perception of heading? Most importantly, these results suggest that observers are capable of accurate control of their heading direction using only peripheral vision, but only if critical regions of optical flow orthogonal to the heading axis are visible. Hence, peripherally-located displays supporting heading control must be located orthogonal to the primary axis of heading control. For piloting a surface vehicle where the axis of heading control is defined by the horizon, these

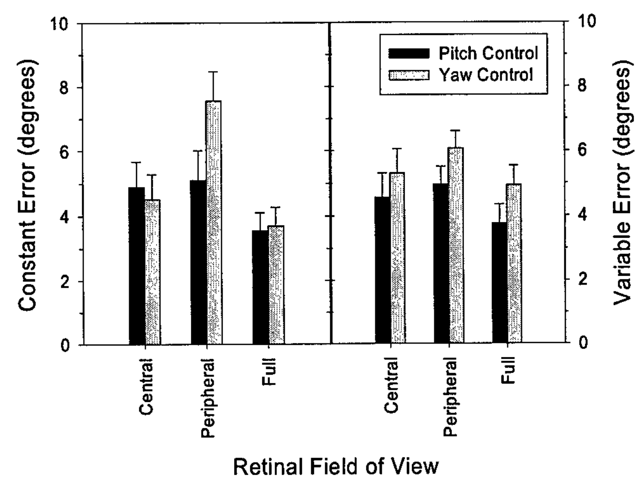


Figure 4. Constant and variable errors for pitch and yaw control across three conditions of retinal stimulation (central, peripheral, and full; see text for details). Error bars represent standard errors of the mean.

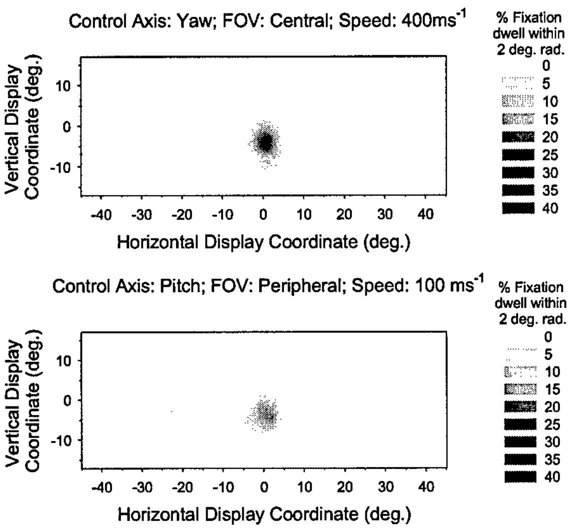


Figure 5. Typical gaze distributions (fixation dwell times) for the yaw (top) and pitch (bottom) control tasks. The shading indicates the percentage of time the gaze dwelled within a 2 degree radius of a particular display coordinate.

displays would ideally be located above and below the horizon line. For piloting flying vehicles, the primary axis of heading control varies depending on the phase of flight. Control of glide-path during landing, for example, requires dual-axis control of pitch and yaw. Displays located in the left and right peripheral visual fields would serve control of pitch quite effectively, but not yaw. Similarly, displays located in the upper and lower peripheral visual fields would serve control of yaw quite effectively, but not pitch.

The Role of Attention in Heading Control. A second issue relevant to the potential of peripheral visual displays for controlling heading concerns the degree of attentional or mental workload demanded by the task of heading control. Because attention is a mental resource with limited capacity, one can only perceive and respond to a limited amount of information at a time. The potential utility of peripheral displays for heading depends largely on their ability to support accurate heading control with low attentional demand, so that maximal mental resources are available for pilots to devote to other tasks. Past research indicates that attention modulates perception of movement (Cavanah, 1992; Chaudhuri, 1990; Lankheet & Verstraten, 1995; Rees, Frith & Lavie, 1997).

Previous studies of attention and heading judgments (Royden & Hildreth, 1999; Wann, Swapp & Rushton, 2000) produced mixed results suggesting that attention plays little or no role in perceiving heading. However, these studies did not examine continuous manual control of heading. Instead, they used traditional psychophysical techniques that required observers to make a heading judgment after viewing a very brief display of optical flow. Further, in these studies attentional demand was manipulated with changes in the visual information present in the display. It is thus difficult to assess whether changes in heading performance were due to changes in attentional load, memory load (because responses were delayed until after the displays terminated), or simply due to changes in the information presented in the displays. In sum, whether heading control is adversely affected when attention is directed to other information or tasks remains unclear.

The purpose of the present study was to more precisely assess the attentional demand of heading control. Observers continuously controlled heading in response to yaw disturbances while simultaneously identifying targets in a rapid serial visual presentation (RSVP) of arrays of numbers and letters (Schneider & Shiffrin, 1977). This *dual-task method* differs from previous research in a number of important ways. First, the method used here is more sensitive to small changes in attentional demand because both tasks required continuous monitoring to be performed well. Second, performance on each task was measured while the tasks were actually being performed, rather than with a delayed response, which eliminates post-display memory demands as a potential confounding factor. Third, heading performance was measured in the context of continuous control, rather than a verbal judgment, which more accurately reflects perception of heading while piloting a vehicle. Finally, by varying target mapping and target set size to manipulate attentional demand of the RSVP task, perceptual factors were held constant—all displays consisted of alpha-numeric RSVP arrays superimposed over the optical flow field.

The yaw-control task was similar to the full visual field condition used in the study of field-of-view and heading control discussed previously. The heading displays simulated linear translation through a star field combined with a sum-of-sines disturbance about the yaw axis. Over a 60 s period, observers controlled yaw to maintain their perceived direction of heading straight ahead toward the center of the displays. For the search task, the RSVP arrays were superimposed over the optical flow pattern and yoked to the observer's gaze direction in real-time using an eye-head tracking system (see Figure 6). This allowed observers to look wherever they

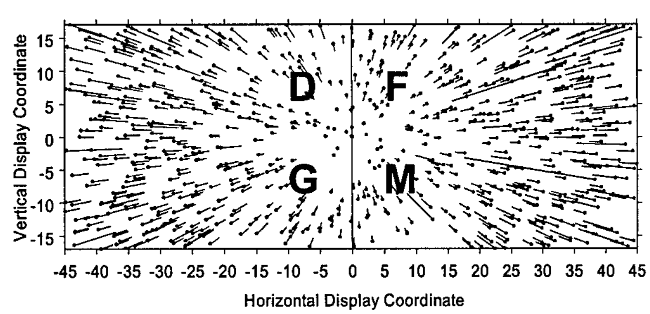


Figure 6. Pictorial representation of the optical flow fields used to examine the influence of attention on heading performance. Each arrow represents the velocity of a moving dot. The array of letters was centered on the gaze direction and moved with it across the displays.

needed to best perform the heading control task, while maintaining the visibility of the RSVP task. The RSVP arrays consisted of four letters or numbers that changed identities every 200 ms, spaced equally at the corners of a virtual square centered on the gaze direction. Prior to the onset of each RSVP sequence, a set of either one or four targets was presented to the observer. If any of these targets was detected in the subsequent RSVP sequence, observers responded by pressing a button on the same joystick used to control heading. Observers were instructed to attend and respond to a) the heading display only (single-task heading), the search display only (single-task search), or both displays (dual task).

To manipulate the attentional demand of the RSVP task, two target mappings were used: a) *consistent mapping* or *CM*, where target and distracter items were selected from unique sets (e.g., letter targets among digit distracters), and b) *varied mapping* or *VM*, where target and distracter items were selected from the same set (targets for a given trial could serve as distracters on other trials). Target set size was also

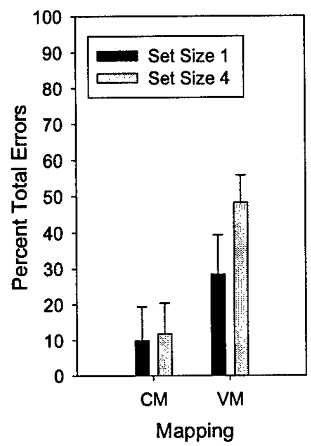


Figure 7. Search Task Errors as a function of type of mapping, consistent (CM) vs. variable (VM), and set size (1 or 4). These data are averaged across all other experimental factors, which showed no reliable effects. Error bars represent standard errors of the mean.

assumed to manipulate attentional demand since greater set sizes would place greater demands on working memory. Schneider and Shffirin (1977) showed that with training, target set size does not influence target detection accuracy in the CM search, which demands little attention and can be carried out in parallel. In contrast, even after extensive training, target detection errors increase as set size increases for VM search, which demands greater attention and requires a serial search of the RSVP array. Note that the CM and VM search conditions both require search of an RSVP sequence, thus the visual conditions were equated for conditions of low (CM) and high (VM) attentional demand.

If heading perception demands attentional resources, one of two outcomes could occur depending on the priority given to the heading and search tasks by participants. If the search task receives higher priority, then attention to the heading-control task will be reduced and heading errors will increase, particularly when the heading task is paired with the more attentionally-demanding VM search task. If, on the other hand, the heading-control task receives higher priority, heading performance might remain constant and the effect of increased attentional demand for the dual task will be evident in an interaction between task (search alone vs. dual task) and target mapping (VM vs. CM) on *search errors*, with greater single-to-dual-task increases in error for the more attentionally-demanding VM search task as compared to the lower attentionally-demanding CM search task. In addition to these performance measures, observers completed the NASA Task-Load Index (TLX) questionnaire for each unique combination of search mapping, search set size, and task (single vs. dual) so that the subjective mental workload demanded by the various display conditions could be assessed.

In general, the RSVP search results for both single- and dual-task conditions showed the typical pattern found in previous research. The number of errors was greater for VM as compared to CM search, particularly for set size 4 (see

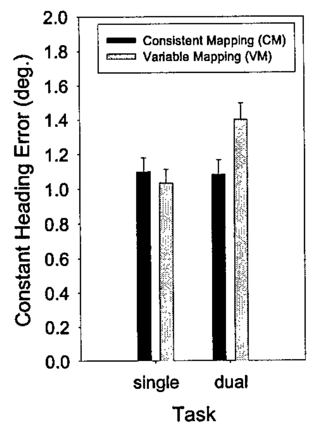


Figure 8. Constant heading errors as a function of type of task, single vs. dual, and mapping, consistent (CM) vs. variable (VM). Error bars represent standard errors of the mean.

Figure 7). These results confirm that VM search and larger set sizes demand more attention than CM search. Further, the consistency of this pattern across single- and dual-task conditions suggests that participants did not reduce the attentional resources allocated to the search task when it was paired with the heading control task. This result is not surprising given that explicit feedback was provided for search performance but not heading performance. The subjective workload ratings calculated from the NASA-TLX were consistent with the search data: VM search produced higher subjective workload than CM search, particularly for set size 4.

Participants also reported higher subjective workload on the NASA-TLX when the heading and search tasks were paired together as compared to performing either task independently. This result suggests that participants perceived both tasks to demand mental resources. Performance on the heading control task was consistent with this perception. As illustrated in Figure 8, constant errors in heading control were increased by approximately 40% when the heading task was paired with the VM search task relative to the heading task alone or when it was paired with the CM search task. This increase in heading error for only VM searches suggests that participants shifted attentional resources from the heading control task to the attentionally-demanding VM search task to maintain search performance.

This result conclusively demonstrates that visual control of heading from optical flow demands at least some attentional resources, and by extension, pilots would need to allocate attentional resources to process virtual displays designed to support heading control. However, the amount of attentional resources demanded by the heading task appears to be relatively modest, as the average increase in heading error for the VM search condition was only 0.4 degrees. Whether this small increase in error is operationally significant is difficult to assess, but it seems reasonable to expect that inattention to the alpha-numeric display symbology currently used to specify heading would result in a much greater degree of error. Further research is needed to empirically test this hypothesis. However, the current results strongly suggest that virtual displays using optical flow may convey heading information in a manner that requires only a very small amount of attentional resources. Indeed, the attentional effects on heading performance found here were only evident due to the strong attentional demand of the VM search and high sensitivity of the measure of heading performance. Previous research with less attentionally-demanding tasks and less sensitive measures failed to find that heading performance was attention-limited (Royden & Hildrith, 1999).

In conclusion, the current research demonstrates that virtual displays using optical flow for specifying heading demand relatively little attention and may be especially useful for supporting precise heading control under conditions of high mental workload, such as landings. However, further research is needed to determine more precisely the potential of virtual displays for such tasks.

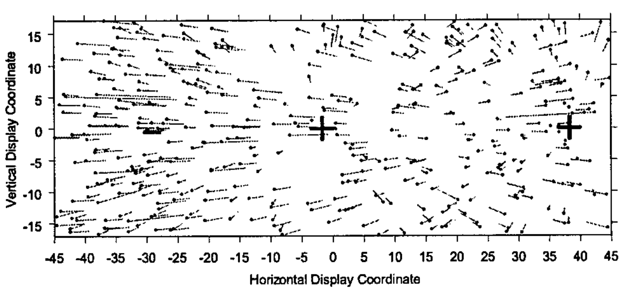


Figure 9. Pictorial representation of the optical flow fields used to examine the influence of motion transparency on heading performance. Each arrow represents the velocity of a moving dot. The crosshairs indicate the heading directions specified by the two transparently overlaid flow fields. These crosshairs were not included in the displays used in the experiments.

Motion Transparency, Attention, and Heading Perception. There are, however, some potential drawbacks in transparently superimposing a virtual HUD containing optical flow over a pilot's view of the environment. For example, studies of heading perception in the context of moving transparent objects (Warren & Saunders, 1995; Royden & Hildreth, 1996) found that moving display elements specifying heading may be perceptually integrated with the motion of objects, and this integration can result in inaccuracies in heading perception, particularly if the optical flows of the moving object and background specify different heading directions.

To further examine this phenomenon a series of experiments was conducted that examined heading judgments and control in the context of transparently superimposed optical flow, such as that produced by using a HUD to overlay a virtual optical flow display on the optical flow directly projected from the environment through the windscreen. The purpose of this research was to determine the effect on heading accuracy of misalignments between the optical flow presented in a HUD and that projected by real-world objects. Misalignments like these are common, for example, in night-warfare settings where infrared sensor imagery is projected onto a HUD or HMD. Generally, the sensor producing the imagery is not aligned with the pilot's eye, so the optical flow of the sensor imagery is not exactly aligned with the optical flow of the environment viewed directly through the windscreen. This misalignment could result in misperception of the direction of heading and compromise safe and effective flight control.

The general method used in these experiments was to present participants with simulations of observer movement through two overlapping, but independently moving, star-fields similar to those used in the experiments previously described, except that each flow field specified a unique heading direction (see Figure 9). Participants judged how many distinct heading directions they perceived and estimated the heading direction specified by one of the two flow fields. The effects of motion transparency on heading performance were assessed by examining the errors in these judgments as a function of angular separation between the heading directions.

The direction of errors in heading perception were coded as either *attraction errors*—the judged heading direction lay between the two actual heading directions—or *repulsion errors*—the judged heading direction lay outside the area between the two actual heading directions, in other words, the perceived heading direction of the judged flow field was repulsed away from the non-judged flow field. Typical results are shown in Figure 10. Note that significant errors in perception of heading occur in response to misaligned transparent optical flow. For small misalignments, observers perceive the two flow fields as one coherent flow field and errors of attraction occur that suggest the visual system is averaging the flow vectors to estimate the heading direction. However, as angular separation increases, observers more

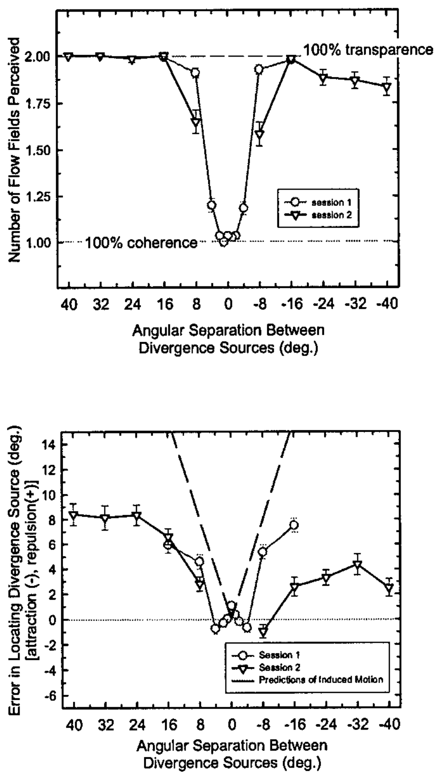


Figure 10. Number of flow fields perceived (top) and errors in perceived heading direction (bottom) as a function of angular separation between the heading directions simulated by the two flow fields. Error bars represent standard errors of the mean.

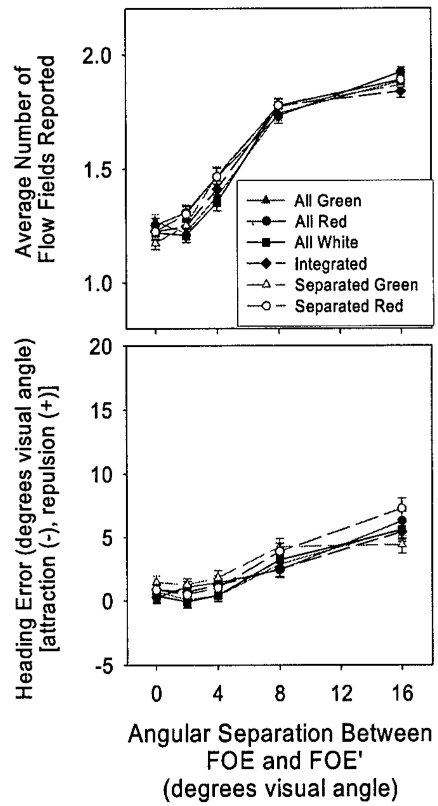


Figure 11. Number of flow fields perceived (top) and errors in perceived heading direction (bottom) as a function of angular separation between the heading directions simulated by the two flow fields and color coding of the dots in each flow field. Error bars represent standard errors of the mean.

likely perceive two distinct flow fields (motion transparency) and repulsion errors generally increase.

This pattern of errors is consistent with a *motion contrast* effect (Marshak & Sekuler, 1979) that would result if neural units tuned to detect heading in different directions, such as those proposed by Perrone and Stone (1994, 1998), mutually inhibit one another. Such inhibitory interactions between neural units are common in the visual system, affecting, for example, perception of orientation and linear motion direction (Marshak & Sekuler, 1979). Hence, it is reasonable to expect that higher level cortical motion mechanisms involved in heading perception may also exhibit mutual inhibition.

An alternative explanation for the repulsion errors is that they result from *induced motion*: the illusory perception of foreground motion resulting from movement of the background. The repulsion errors found in this experiment are consistent with the errors predicted by induced motion of the judged flow-field (perceived as foreground) relative to the non-judged flow field (perceived as background). Hence, it is unclear whether the repulsion errors observed in these experiments result from motion contrast or induced motion. Regardless of the underlying cause, the results indicate that operationally significant heading errors can be induced by misaligned transparent motion of two optical flow fields composed of homogenous elements.

Further experiments examined whether pre-attentive and attentional selection of flow components based on a non-motion attribute, color, modulates the heading errors associated with transparent flow. This could happen, for example, when a pilot attentively selects the uniquely-colored optical flow presented within a virtual HUD for processing and ignores the optical flow projected from the real-world environment through the windscreen. This attentional selection could, in principle, reduce or eliminate errors in heading perception resulting from misaligned flow by reducing the saliency of optical flow information in the non-judged flow field. Alternatively, attentional selection of one flow component could increase errors in heading perception by enhancing segregation of foreground and background, and hence, an induced motion effect.

To test these competing hypotheses, further motion transparency experiments were conducted with the two flow components coded in distinct colors. Figure 11 shows heading errors with these displays (labeled "separated red" and

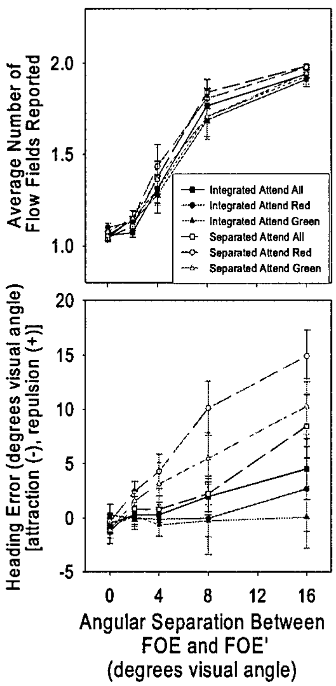


Figure 12. Number of flow fields perceived (top) and errors in perceived heading direction (bottom) as a function of angular separation between the heading directions simulated by the two flow fields, color coding of the dots, and attentional instructions. Error bars represent standard errors of the mean.

"separated green") as compared to either homogeneously-colored displays (labeled "all green", "all red", or "all white"), or displays where all colors were equally integrated across both flow components ("integrated"). For these data, participants were unaware of the color-coding manipulation and no attentional instructions were given. Therefore, any effect of color coding was presumed to result from pre-attentive processes. As can be seen in Figure 11, no reliable effects of color coding were found, which suggests that simply distinguishing optical flow components by color does not alter the effects of motion transparency.

However, color coding was found to affect heading errors resulting from motion transparency when observers were explicitly instructed to attend only display elements of a particular color. Figure 12 shows the results of an experiment with color-coded flow fields where participants were explicitly instructed to attend "all the dots," "only the red dots," or "only the green dots." The magnitude of repulsion errors increased when observers attended one flow field and ignored the other (the lines labeled "attend red" or "attend green" in Figure 12). These results are consistent with attentional enhancement of induced motion. An important practical implication of these results is that color coding optical flow in virtual HUDs will not reduce heading errors that result from motion transparency, and may actually increase these errors, if pilots are instructed to attentionally select the moving HUD symbology.

Summary and Conclusions of Research on Heading Perception and Control. Several practical conclusions can be drawn from this body of research on heading perception. First, this research suggests that the heading direction can be accurately perceived from optical flow processed in the peripheral visual fields if informative regions of optical flow structure are visible. These informative areas of optical flow lie in directions orthogonal to the heading axis, adjacent to the current heading direction, which suggests that for tasks such as yaw-control, where the heading axis is horizontal, peripheral visual displays should be located directly above or below the most-likely direction of heading. Moreover, the research on attentional demands of heading perception suggests that errors in heading control do not increase dramatically even when attention is directed to a demanding secondary task. Together, these results indicate that heading control during periods of high mental workload could potentially benefit from peripherally-located virtual optical flow displays. One important caveat, however, comes from the research on motion transparency and heading perception: Overlaying optical flow from a HUD on the scene viewed through the windscreen can produce systematic errors in heading perception if the heading directions specified by each optical flow pattern are significantly misaligned.

Research on Egospeed Perception and Control

The importance of accurate perception of the speed of self-motion, or *egospeed*, for successful vehicular control is evidenced by the prominence of airspeed indicators in aviation cockpits and speedometers on automobile dashboards. These highly-symbolic displays of speed information augment the optical flow visible through the windscreen and significantly increase precision in speed control, particularly when fog or other optical conditions might produce speed illusions (Snowden, Stimpson, & Ruddle, 1998). However, the symbols used in airspeed indicators and speedometers require direct visual fixation, visual attention, and other cognitive processes to perceive and interpret—resources that might be scarce during difficult aviation operations such as landing or threat-evasion. Controlling speed under these circumstances might be enhanced by speed information displayed as optical flow in a virtual HUD, a speed indicator that could potentially be processed pre-attentively by the visual periphery with less cognitive intervention, thereby freeing mental resources and reducing workload. To gain an understanding of the potential of such displays and how they might best be designed, it is first necessary to understand how egospeed is visually perceived and controlled.

The research summarized below examined three issues: 1) the influence of texture density on perceived egospeed and whether this influence varies as a function of visual field, 2) the influence of texture density on egospeed control, and 3) the misperception of changes in egospeed from changes in image speed variability due to motion parallax. For more detailed information please refer to the theses and other publications listed in the section titled, "Publications Stemming from the Research Effort."

Texture Density Effects on Egospeed Perception. Owen, Wolpert, and Warren (1984) identified *discontinuity rate* and *global optical flow rate* as two sources of information that specify egospeed. Discontinuity rate, which is determined by counting the number of texture elements passing a fixed visual reference per unit time (temporal frequency), is dependent on egospeed and texture density, and is generally expressed in units of discontinuities/s or Hz . Global optical flow rate is the rate of egospeed scaled in altitude units. It is generally expressed in units such as eyeheights/s, where one eyeheight equals the altitude of the observer's eye above a ground plane. Usually, these two information sources redundantly specify egospeed; however, sometimes they can conflict. For example, global optical flow rate will change if an observer changes altitude, and discontinuity rate will change with variations in texture density, such as the increase in the density of flora while approaching a river passing through a desert.

The majority of egospeed research has shown that while both discontinuity rate and global optical flow rate contribute to the perception of egospeed, discontinuity rate dominates (Denton, 1980; Owen et al., 1984), perhaps reflecting the involvement of cognitive processes such as edge counting (Larish & Flach, 1990). Other research (Dyre, 1997) found the exact opposite result: acceleration judgments were dominated by global optical flow rate. Indeed, its effect was 72 times stronger than the effect of discontinuity rate, which suggests that effects of discontinuity rate on egospeed might reflect the effects of temporal frequency on motion sensing (Watamaniuk, Grzywacz, & Yuille, 1993). A number of

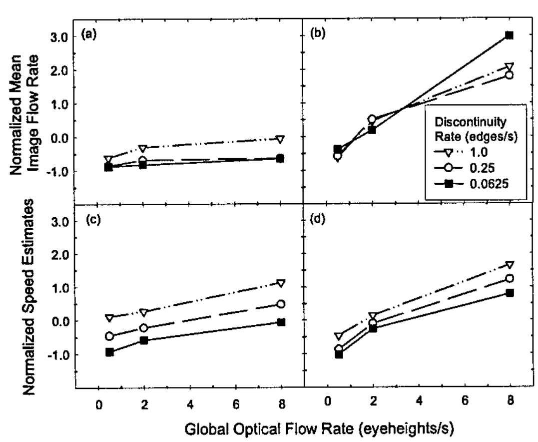


Figure 13. Normalized mean image flow rate and egospeed estimates plotted as a function of global optical flow rate and discontinuity rate. Panel (a) shows normalized image flow rates calculated for displays replicating those of Larish & Flach (1990). Note that mean image flow rate is more correlated with discontinuity rate than global optical flow rate. Panel (b) shows normalized image flow rates calculated for displays where mean image flow rate was more correlated with global optical flow rate. Panels (c) and (d) show normalized egospeed estimates for these displays.

methodological differences between these studies may account for these conflicting results. The present study aimed to determine which factors produced these contradictory results, and identify the most relevant information for perceiving egospeed. To this end, experiments were conducted with a variety of displays and experimental tasks that bridged the differences between these previous studies, examining issues such as frame-update rate, field of view, and optical flow structure. The overall results of these experiments suggested that one methodological factor in particular appeared to best account for the conflicting results: covariation of mean image flow rate with the experimental manipulations of discontinuity rate or global optical flow rate.

Mean image flow rate is the average angular rate at which the images corresponding to environmental objects move in optical flow projected onto an image surface. Because mean image flow rate is a description of optical speed, it is closely related to global optical flow rate, although it is expressed in angular units of degrees per second rather than environmental units such as eyeheights/s. As a result, mean image flow rate and global optical flow rate are highly correlated. In contrast, mean image flow rate and discontinuity rate are conceptually distinct. The former is a description of speed, the latter a description of temporal frequency. For regular or uniformly random distributions of texture in the environment, discontinuity rate and mean image flow rate are independent.

Unfortunately, the manipulations of discontinuity rate used in previous studies (Denton, 1980; Larish & Flach, 1990; Owen et al., 1984) resulted in large, statistically reliable, correlations between discontinuity rate and mean image flow rate, which may in part explain the relatively large discontinuity rate effects found. For example, consider the data presented in Figure 13. This figure shows the relationship between mean image flow rate and egospeed estimates for displays simulating straight-ahead observer movement over a groundplane, where global optical flow rate and discontinuity rate were manipulated by varying altitude and texture density, respectively. The left column of panels corresponds to displays similar to those used by Larish and Flach (1990). For these displays, mean image flow rate was more correlated with discontinuity rate than global optical flow rate and discontinuity rate dominated egospeed estimates. The right column of panels corresponds to displays where mean image flow rate was more correlated with global optical flow rate than discontinuity rate. For these displays, global optical flow rate dominated egospeed estimates. Geometric analysis of the displays used by Denton (1980), Dyre (1997), Larish and Flach (1990), and Owen et al. (1984) revealed the same pattern: the cue that dominated perceived egospeed was always more strongly correlated with mean image flow rate.

Although these results suggest that mean image speed rather than discontinuity rate per se dominates perceived egospeed, they do not completely rule out any influence of texture density and temporal frequency. Indeed, manipulations of texture density and temporal frequency independent of mean image speed have been shown to influence the perceived speed of 2D linear object motion

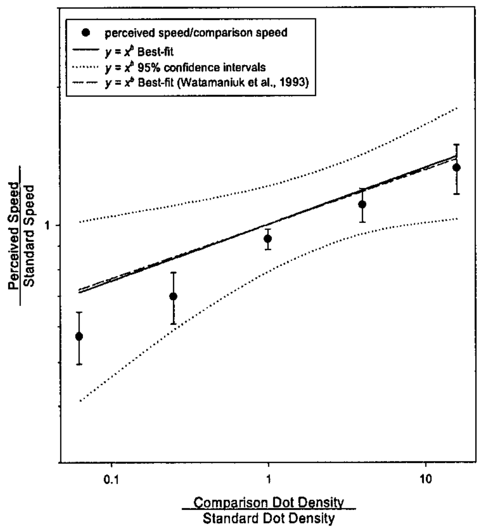


Figure 14. Ratio of perceived speed to standard speed plotted as a function of the ratio of the comparison dot density to the standard dot density. The solid circles represent standardized perceived speeds calculated from the proportion of "faster" judgments for each stimulus. Error bars represent standard errors of the mean. The solid line represents the best fit power function of the form

$$\frac{\textit{perceived speed}}{\textit{standard speed}} = \left(\frac{\textit{comparison dot density}}{\textit{standard dot density}}\right)^b,$$

where the exponent ($b = 0.123$) is the slope of the linear increase (in log-log space) of perceived speed with increasing dot density. The dotted lines represent 95% confidence intervals for the best-fit power function described above. The dashed line represents the predicted perceived speed based on the exponent ($b = 0.118$) found by Watamaniuk et al. (1993) for 2-D frontal parallel motion.

(Watamaniuk et al, 1993) and Dyre (1997) found weak but reliable texture density effects on the perception of accelerating egospeed. To further examine this issue, the present study varied texture density independently of mean image speed using displays that manipulated discontinuity rate and global optical flow rate in a manner similar to Dyre (1997) and measured their effects on perceived speed using a standard-comparison discrimination technique similar to Watamaniuk et al. (1993). The results are presented in Figure 14. Variations in texture density produced small but statistically reliable effects on perceived egospeed (e.g., a 1000% increase in density resulted in a 10% increase in perceived egospeed). The magnitude of the texture density effect on perceived egospeed was strikingly similar to the magnitude of the texture density effect on the perceived speed of 2D linear object motion found by Watamaniuk et al. (1993). This result suggests that texture density most likely affects representations of speed early in the 2D motion sensing process and this effect filters through to higher-level 3D motion processing underlying phenomenon such as perception of egospeed.

This conclusion is confirmed by further experiments conducted to assess how the influence of discontinuity rate and global optical flow rate may change as a function of field-of-view. Similar to the research on visual field and heading described above, visual field was manipulated by yoking a moving mask (or aperture) to the gaze direction measured in real-time within a large 90 x 34 deg. (H x V) field of view display by an eye-head tracking apparatus. Seven different fields of view were examined, including small circular apertures (7 deg. radius) centered on the gaze direction, large field peripheral displays spanning 30-40 degrees, and the full 90 x 34 deg. field of view. No matter the visual field condition, both discontinuity rate and global optical flow rate had consistently-sized effects on egospeed estimates. There was no evidence suggesting that the mechanism by which texture density affects egospeed perception varies as a function of visual field, an observation that is easier to reconcile with the hypothesis that texture density effects on speed occur during early motion sensing, rather than being part of higher-level cognitive processing.

Texture Density and Control of Speed. Experiments were also conducted to examine the influence of discontinuity rate and global optical flow rate on the control of egospeed. Previous studies all measured open-loop magnitude estimations or discriminations of perceived egospeed. However, discontinuity rate might have less of a biasing effect on perception of egospeed when a pilot is engaged in closed-loop control, where continuous visual-motor feedback might serve to disambiguate true changes in egospeed from the illusory effects of discontinuity rate. Similar to the experiments on control of yaw discussed previously in this report, observers were shown displays simulating straight-ahead movement over a groundplane defined by dots. The displays lasted 40 s and filled a field of view spanning 90 x 34 deg. (H x V). Observers attempted to maintain a constant speed in response to a simulated head-wind disturbance defined by a sum-of-sines function. Independent changes in

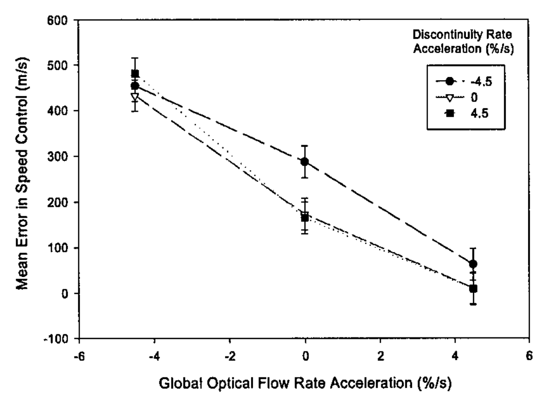


Figure 15. Mean errors in egospeed control as functions of global optical flow rate and discontinuity rate. Error bars represent standard errors of the mean.

discontinuity rate and global optical flow rate were introduced by exponentially increasing or decreasing the density of visible dots, or the simulated altitude over the plane, respectively. The mean errors in speed control computed for each combination of discontinuity rate and global optical flow rate are shown in Figure 15. Two results in particular are of note.

First, discontinuity rate had no reliable effect on control of egospeed, while global optical flow rate had a large, reliable effect. This result is consistent with the relatively small effect of discontinuity rate found by the experiments described above that measured speed estimations or discriminations, but directly contradicts previous research that found egospeed control to be profoundly influenced by discontinuity rate (Denton, 1980). Again, the critical factor that explains the difference in results is whether discontinuity rate is correlated with changes in mean image speed, as in Denton's study, or, as in this study, discontinuity rate was uncorrelated with mean image speed. Mean image speed appears to be the critical factor not only for visually perceiving egospeed, but also for controlling egospeed.

Second, participants tended to increase speed (positive errors) over the trial duration for almost every type of display examined, including those in which global optical flow rate and discontinuity rate were perfectly correlated with changes in egospeed. The greatest increases in error occurred for displays in which altitude increased exponentially resulting in a concomitant decrease in global optical flow rate. The decreasing optical flow rate for these displays most likely resulted in the perception of slower egospeed and observers compensated by speeding up. In comparison, little or no error occurred for displays in which altitude decreased, causing global optical flow rate to increase. The relatively constant speed maintained in these conditions suggests that observers perceived speed to be unchanging despite the increase in global optical flow rate.

An additional experiment that examined the effect of texture density on the precision of speed control replicated this "speeding-up" phenomenon. Unlike the experiments discussed previously, which examined how variations in texture density might bias estimates and control of egospeed, this experiment attempted to determine which constant level of display density provided optimal speed control performance. It used methods and displays similar to those used in the experiments on speed control described previously, except that a) texture density and altitude were constant for the duration of the display and b) the number of display elements (texture density) was varied across displays. Observers attempted to maintain constant speed in response to a simulated headwind disturbance defined by a sum-of-sines function. Like the previously described study of egospeed control, control of egospeed was actually quite poor; observers exhibited positive speed errors for all the display densities examined (i.e., they sped up over the course of each trial), although the increase in speed was minimized at moderate display densities (see Figure 16).

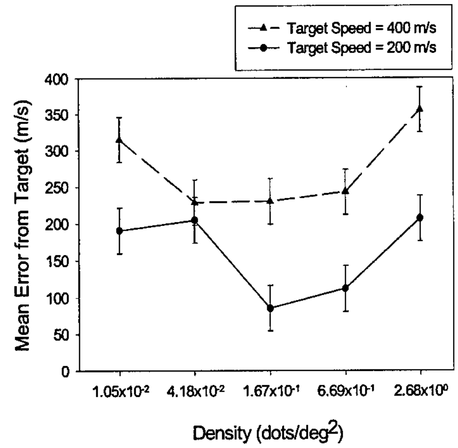


Figure 16. Mean errors in egospeed control as functions of texture density and target egospeed. Error bars represent standard errors of the mean.

How can this consistent increase in egospeed be explained? One possibility is that observers sped up to compensate for perceptual adaptation to the optical flow over time, which could lead to decreased motion sensitivity and a perception of slower egospeed. A second possibility is that observers simply could not maintain a precise memory representation of their initial egospeed, and over time their egospeed drifted upward, perhaps to alleviate boredom with the experimental task. Either way, it is clear that observers were unable to maintain constant egospeed based on optical flow alone and further, were unaware of significant increases in egospeed over the course of a trial—sometimes greater than 40%. This gross insensitivity to visually accelerating self-motion is consistent with previous psychophysical research that found observers to be relatively insensitive in discriminating constant velocity from accelerating self-motion based solely on visual stimulation (Dyre, 1997) and is an important design consideration for virtual displays of egospeed. Clearly, designers cannot expect pilots to accurately control egospeed by maintaining the absolute speed perceived from an optical flow display. A better solution might be to use virtual displays of optical flow to convey deviations in egospeed from a target speed (egospeed-error). Because displays like this would have zero movement when observers are moving at the target speed, motion adaptation effects would be eliminated. The use of optical flow for conveying errors in speed will be discussed in more detail in the section titled, "Research on virtual HUDs for speed control."

Motion Parallax and Biases in Speed Perception. Factors other than variations in display density can also lead to misperceptions or illusions of speed and egospeed. For example, observers have been shown to mistake changes in the variability of image speed as changes in mean speed (Atchley & Andersen, 1995). Variability in image speed occurs whenever an observer moves through an environment

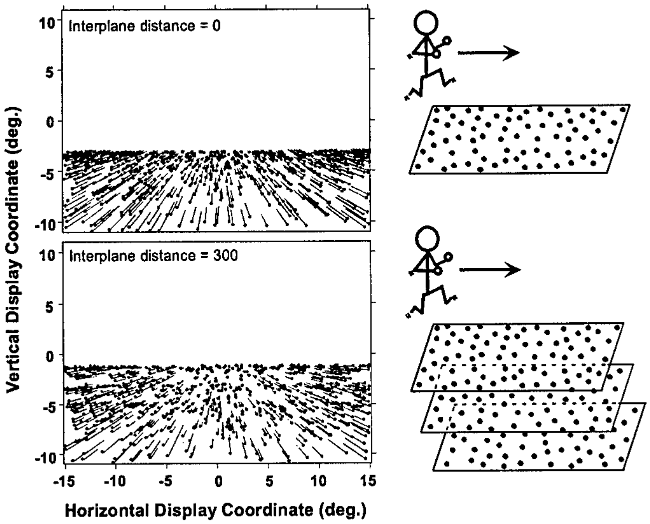


Figure 17. Pictorial representation of the stimuli used to examine the relationship between perceived egospeed and degree of motion parallax. *Left Panels:* The optical flow fields presented. Each arrow represents the velocity of a moving dot. *Right Panels:* The interplane distances used to manipulate the degree of motion parallax corresponding to the optical flows shown in the left panels.

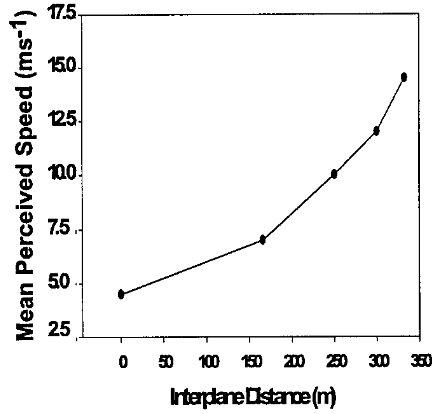


Figure 18. Mean perceived egospeed as a function of interplane distance (degree of motion parallax). Note: the mean image flow rate of the displays was constant across all interplane distances.

with objects located at different distances. Discounting the effects of eye movements, objects nearest the observer project the highest image velocities and objects located increasingly further from the observer project increasingly slower image velocities. This variability in image velocity is commonly known as *motion parallax* and provides information about the distance to objects in the environment. Motion parallax can also serve as a source of information regarding the direction of heading (Cutting, Springer, Braren, & Johnson, 1992).

Changes in the magnitude of motion parallax or image speed variability may also serve as an important cue for estimating egospeed. For the sort of everyday environments our visual system has evolved to perceive, changes in egospeed result in changes in both the mean and variability of image speed. As a result, egospeed could, in principle, be estimated from either of these statistical moments of image speed. Indeed, as shown by the experiments discussed previously, mean image speed is an important factor underlying perception of egospeed. However, the influence of image speed variability has not been systematically assessed. Why might image speed variability be important? One reason is that, unlike mean image speed, variability in image speed is unaffected by eye movements and thus could be used to perceive egospeed even when observers are moving their eyes to track objects during observer movement (McDevitt, Eggleston, & Dyre, 1999).

A series of experiments was conducted to more fully understand the influence of motion parallax on perceived egospeed. These experiments measured judgments of egospeed based on displays in which the variability in image speed due to motion parallax was manipulated independently of the mean image speed of the display. This dissociation between mean image speed and variability of image speed was achieved by simulating observer movement parallel to a set of three parallel planes of dots. Constant mean image speed was obtained by maintaining a constant distance between the eye point and the center plane of the three planes and keeping the distances between the center plane and each of the two outer planes equal (see Figure 17). Variability in image speed was manipulated by varying the distance between the two outer planes and the center plane, what will subsequently be referred to as the *interplane distance.* Increasing interplane distance increases the variability in image speed without affecting mean image speed. The series of experiments used one of two methods to assess the influence of interplane distance on egospeed estimates. Some experiments required observers to make magnitude estimates of egospeed in response to the displays. Other experiments serially presented a pair of two displays: a *standard* display with a constant speed and interplane distance, and a *comparison* display where speed and interplane distance varied. Observers then indicated which display produced a perception of faster egospeed.

The general result found with both methods was that increases in interplane distance, and hence increases in variability in image speed, increased judgments of perceived egospeed, even when the mean image speed of the displays remained constant (see Figure 18). Similar to the effects of texture density on perceived speed, the increase in perceived speed due to increased variability was modest compared to the effect of increasing mean image speed. However, perceived speed was found to be affected by changes in image speed variability regardless of whether observers freely scanned the displays or fixated a stationary cross-hair located in the center of the displays. The effect of image speed variability was also found with non-planar environments where objects were continuously distributed between the upper and lower planes (a volume of dots); hence it appears that these effects cannot be explained by observers tracking only the closest plane, either with the eye or an attentional focus. The results taken as a whole suggest that variability in image velocity affects the integration of a speed signal, perhaps in a manner related to the decreased thresholds for relative as compared to absolute motion (Gogel & McNulty, 1983).

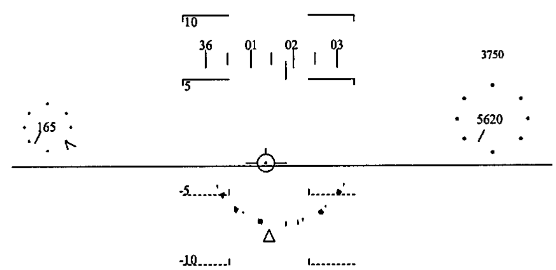
This phenomenon has important consequences for the design of virtual displays that use optical flow to convey egospeed information. Designers could, for example, use motion parallax to increase the perceived speed of a display, or to provide speed information that is invariant during eye movements. In the following section research on a virtual display for egospeed based on these principles is described.

Summary and Conclusions of Research on Egospeed Perception and Control. What are the implications of the research on egospeed perception described above? First, this research suggests that perception of egospeed is based primarily on the mean image speed presented in a display, although it may also be influenced by other factors such as texture density and the magnitude of motion parallax. These factors would need to be carefully considered when designing virtual displays that use optical flow to convey speed information.

Second, this research suggests that maintaining a constant egospeed based on the speed of optical flow is, at best difficult, at worst impossible. Observers tasked with maintaining constant speed in response to a simulated headwind disturbance performed poorly, and increased their egospeed over time, sometimes by as much as 80% over a one-minute trial. This difficulty in maintaining constant speed could result from a combination of perceptual adaptation, memory drift, and the general human insensitivity to visual accelerations. Regardless of the cause, this result severely limits the utility of virtual displays that code absolute egospeed by the absolute speed of optical flow, because over time egospeed will increasingly be misperceived. This does not mean, however, that virtual displays using optical flow cannot benefit speed control. Virtual displays that code the deviation of egospeed from a target speed could be potentially useful, because they would limit perceptual adaptation (no movement would be visible when the pilot is at the target speed), and provide a memorable target speed, zero flow. The following section describes research that compared such a display to the speed indicator specified by the military standard MIL-STD-1787B.

Research on Virtual HUDs for speed control

To more directly test the potential of peripherally-located virtual displays, two experiments were conducted that



MIL-STD-1787B HUD

Figure 19. Military standard HUD based on MIL-STD-1787B used as a baseline of comparison for the virtual HUD (see Figure 20). The dial on the left indicates airspeed. The dial on the right indicates altitude. A heading indicator, pitch ladder, bank indicator, flight path indicator and artificial horizon are also included.

compared a peripherally-located virtual display that codes speed error using optical flow to the speed indicator specified by the HUD MIL-STD-1787B (see Figure 19). The design of the virtual speed indicator (shown in Figure 20) was based on the general principles of egospeed perception discovered in the course of the basic research described above. Unlike the military standard HUD speed indicator, which requires direct fixation of gaze, focal attention, and higher cognitive resources to read and interpret, the virtual speed error indicator was designed to be processed by peripheral vision, with little or no attentional allocation or interpretation required. In theory, this type of display should provide better speed control while the pilot is under high mental workload, because it provides pilots with speed information in a ecological format compatible with naturally-evolved orienting and motion coding processes that do not demand large pools of attentional resources.

How should such a display be designed to best take advantage of human visual processing? The virtual speed indicator tested here consisted of optical flow fields defined by moving arrows presented to large areas (25 x 34 degrees, H x V) of the left and right peripheral visual fields (see Figure 20). The peripheral visual system is particularly well-suited for sensing motion distributed over a wide area (Tanaka, 1998) and can dominate processes of spatial orientation (Brandt et al., 1973). Further, peripheral vision is relatively underused by current display systems that are typically confined to the central 20 degrees of the visual field. Because speed control is generally independent of flight-path control (Haskell & Wickens, 1993), locating speed information in a peripheral display that is spatially removed from displays supporting flight-path control (such as the artificial horizon and heading display) is compatible with the proximity-compatibility principle (Carswell & Wickens, 1987), which states that

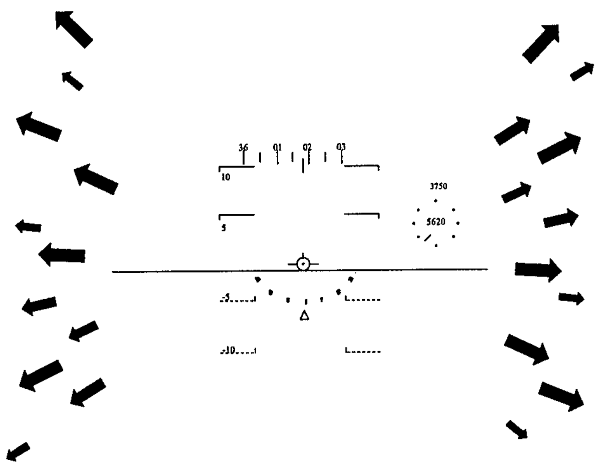


Figure 20. Virtual HUD based on MIL-STD-1787B in which the airspeed indicator dial has been replaced by the virtual speed-error display represented by the peripherally-located moving arrows. All other display elements were identical to the HUD shown in Figure 19.

displays supporting independent tasks should be separated while those supporting interdependent tasks should be integrated.

The size, speed, orientation, and direction of the moving arrows represented the magnitude and direction of egospeed error in the virtual HUD. The direction of error (above or below target speed) was coded in the orientation and movement direction of the arrows. Positive egospeed errors corresponding to pilots moving faster than their target speeds were represented by moving the arrows in depth along trajectories parallel to the line of sight, with the orientation of the arrow aligned with the direction of movement, i.e., aimed toward the observer. The arrows thus created an expanding pattern of optical flow radiating outward from a direction straight ahead. For negative speed errors (egospeed below the target speed) these directions were reversed: the motion and orientation of the arrows were directed away from the observer, which created a contracting pattern of optical flow converging on the straight-ahead direction. For both positive and negative speed errors, the direction indicated by the orientation and movement of the arrows was consistent with the direction of throttle movement necessary to correct the error. This stimulus-response compatibility takes advantage of natural perceptual-motor mappings (Wickens & Hollands, 1999), and should minimize the mental workload associated with mapping the appropriate control movement to the information presented in the display.

The magnitude of speed error was coded by arrow size and speed of movement. The speed of the moving arrows increased linearly with the magnitude of speed error. The size of the moving arrows increased in discrete steps as the magnitude of speed error increased. When egospeed equaled the target speed, the arrows had zero size and moved at zero velocity; in effect, the arrows disappeared from view. As speed error increased from zero beyond a threshold value, a field of slowly moving arrows would suddenly appear. This *sudden onset* briefly captures attention and informs the pilot that the speed error is too large. If the pilot reacts swiftly to the motion and orientation of the arrows and reduces the speed error below the threshold value, the arrows would once again disappear. If, on the other hand, the pilot does not immediately respond and speed errors continue to increase (as might happen during maneuvers in which attentional load is high), the arrows move progressively faster and step upward in size. The progressively faster arrow movement and additional sudden onsets associated with each step increase in size increase the probability that attention will be briefly captured by the display and appropriate control responses made. Hence, the saliency of the display adapts to the severity of the error in egospeed control. Large errors produce an extremely salient display that is difficult to ignore, while small errors result in the display disappearing entirely.

To evaluate this display, two experiments were conducted that measured the precision of egospeed and flight-path control during simulated flight. Two types of speed indicators were examined: the Mil-Standard (MIL-STD-1787B) airspeed indicator and the virtual speed-error indicator described above (see Figures 19 and 20, respectively). Participants with no flight experience other than video games flew a simulated aircraft with simplified control dynamics through a simulated environment. The simulated environment consisted of two flat planes consisting of green, yellow, and brown squares, separated in elevation by a cliff composed of grey squares of varying shades. To provide additional texture in the environment, each plane was covered with simulated trees, scattered randomly across the planes. Fog effects were used to enrich perceived depth in the displays through an aerial perspective cue. A flight-path was defined by waypoints consisting of wireframe squares floating above the planes. A target speed and altitude for each leg of the flight path was defined for each waypoint and displayed in the HUDs. The location of the waypoints, as well as the speed and altitude targets they defined, varied randomly from trial to trial around two general flight paths. Participants were instructed to attain the target speeds and altitudes defined by each waypoint as soon as possible, and maintain them until they had passed through the next waypoint. To induce participants to make continuous corrective control input, simulated wind disturbances defined by sum-of-sine functions continuously changed forward speed, altitude, pitch, yaw, and roll.

Participants controlled their movement through the environment by moving a joystick with their right hand, a throttle with their left hand, and rudder pedals with their feet. Forward-backward movements of the joystick controlled the angular velocity of changes in pitch, while side-to-side movements controlled the angular velocity of changes in roll. Movement of the rudder pedals controlled the velocity of yaw rotations, and movement of the throttle controlled the acceleration of forward movement. These control movements were recorded and analyzed, together with the simulated

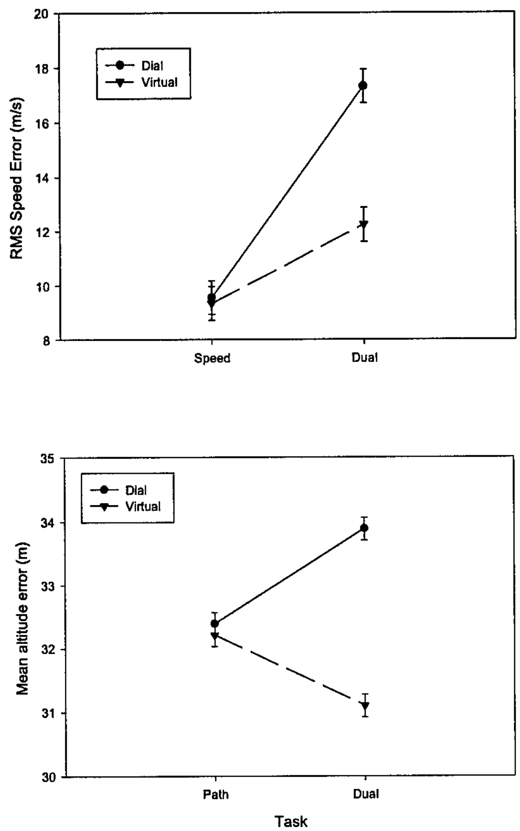


Figure 21. RMS speed error (top) and mean altitude error (bottom) for single and dual task control with HUDs containing either the MIL-STD-1787B dial airspeed indicator or the virtual speed-error indicator. Error bars represent standard errors of the mean.

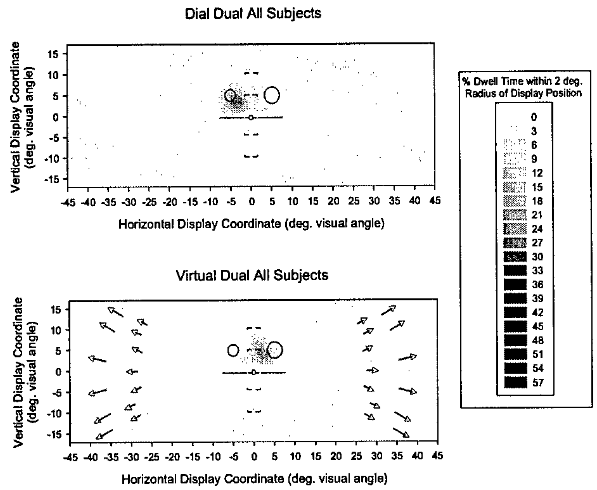


Figure 22. Gaze distributions (fixation dwell times) averaged across all subjects and trials for the dual control task with the MIL-STD-1787B airspeed dial (top) and the virtual speed-error indicator (bottom). The shading indicates the percentage of time gaze dwelled within a 2 degree radius of a particular display coordinate.

aircraft's location, altitude, and speed as well as the target speeds and altitudes set by the waypoints. In addition to the performance measures, these experiments also measured subjective mental workload using the NASA-TLX and gaze direction using an eye-head tracking system.

To compare the relative difficulty and mental workload of controlling speed and altitude with the Mil-standard and virtual HUDs, performance, workload, and gaze direction were measured for both single- and dual-task conditions. For single-task egospeed-control trials, participants needed only to control egospeed with the throttle while an autopilot controlled pitch, yaw, and roll to maintain the target flight path and altitude. For single-task flight-path control trials, participants controlled pitch, yaw, and roll with the joystick and rudder pedals to guide themselves along the proper flight path, but the autopilot controlled the throttle governing egospeed. For dual-task trials, participants used all the input devices to control both flight path and egospeed. The virtual speed-error display was expected to provide the largest performance benefit for the dual-task conditions, because successful performance of the dual-task requires participants to divide their attention between egospeed control and flight-path control. In contrast, for the single-task conditions participants could devote all their mental resources to controlling speed or flight-path, providing an estimate of the optimal performance attainable with a given display.

The results of this study show that the virtual speed-error HUD did indeed reduce mental workload and increase the precision of egospeed and altitude control relative to the mil-standard airspeed indicator. The speed and altitude control results are presented in the top and bottom panels of Figure 21, respectively. Note that for single-task conditions, altitude and speed control were equivalent for the two displays, which suggests that both types of HUD can provide adequate speed information when attention is fully devoted to processing the display. However, for dual-task conditions, altitude and speed control were more accurate with the virtual speed-error HUD. Estimates of subjective mental workload were consistent with the performance data, participants rated the virtual speed error indicator as inducing less mental workload than the military standard speed indicator.

The gaze patterns associated with each display confirm the difference in visual resources demanded by each display (see Figure 22). Participants did indeed process the virtual

HUD with peripheral vision, which enabled them to direct a greater proportion of their gaze time to information important for controlling flight-path as compared to the mil-standard HUD, which required direct fixation of gaze to read.

Taken together, the performance and gaze distribution results show that for untrained observers flying a simplified flight simulation, speed and flight-path control is better served by peripherally located virtual displays that take advantage of the natural orienting processes in which peripheral vision excels.

These results have important implications for the design of future HUDs. Clearly, the peripheral visual fields are an important visual resource that is underused with current HUDs and may be a particularly valuable resource for processing flight parameters related to spatial orientation, like control of airspeed. Virtual displays of these parameters may provide pilots with information in a natural manner that minimizes the impact on pilot workload and central visual field processing, thereby freeing resources for processing other flight information and increasing flight safety. Whether these advantages hold for experienced pilots in real flight situations needs to be evaluated with further research.

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Personnel Involved in the Research Effort

The following personnel were supported during portions of the period spanning July 1, 1998 to December 31, 2001.

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John Grimes, Research Programmer/Analyst (1-1-01 to 12-31-01)

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Dyre, B. P., Ballard, T. G., & McDevitt, J. R. *Perceiving the Speed of Self-motion from Optical and Image Flow.* (In Revision for *Journal of Experimental Psychology: Human Perception & Performance*).

Dyre, B. P., Cox, E., Morrow, F. J, & Schaudt, W. A. *Comparative analysis of a virtual-flow airspeed error indicator.*

Dyre, B. P., McDevitt, J. R., & Schaudt, W. A. *Motion parallax in divergence flow affects perceived speed but not sensitivity to acceleration.* (To be submitted to *Vision Research*).

Dyre, B. P., Fournier, L. R., Richman, J. B., & McDevitt, J. R. *Is heading perception during yaw control attention limited?* (To be submitted to *Journal of Experimental Psychology: Applied*).

Dyre, B. P., Richman, J. B., & Fournier, L. R. *Direction repulsion, motion coherency, and motion transparency of divergence flow fields.* (To be submitted to *Vision Research*).

Dyre, B. P., Morrow, F. J., & Richman, J. B. *Heading Performance is Retinally Invariant When Peripheral Optical Flow is Displayed Off the Axis of Judgment.* (To be submitted to *Perception and Psychophysics*).