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THE DISPLAY OF SPATIAL INFORMATION AND VISUALLY GUIDED BEHAVIOR

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INTRODUCTION

The basic informational elements of spatial orientation are attitude and position within a coordinate system. The problem that faces aeronautical designers is that a pilot must deal with several coordinate systems, sometimes simultaneously. The display must depict unambiguously not only position and attitude, but also designate the relevant coordinate system. If this is not done accurately what will occur is, at the minimum, spatial disorientation, at the worst, catastrophe. This paper explains the different coordinate systems used in aeronautical tasks and the problems that occur in the display of spatial information used by pilots for aircraft control.

Pilot tasks and information sources. In order to successfully complete a flight mission, pilots traditionally have been taught to:

First--
    Aviate,
Then--
    Navigate,
Then--
    Communicate.

Essentially, the first two of these are visually controlled tasks. The primary type of visual information used to accomplish these tasks will vary widely, depending on the task and the source of the information.

At one extreme, vehicle control tasks may be heavily dependent on visual information that is primarily sensory in nature. This might be the case if the primary goal of the control input is to regulate a specific aircraft state. Motion states are defined by a vehicle's three rotational (pitch, roll, and yaw) and three translational (longitudinal, lateral, and vertical) vectors. However, if the primary goal of a control input is ground track control (e.g., navigation), the pilot may rely primarily on cognitive synthesis of available visual information. The resulting knowledge may be in the form of perceptual or cognitive constructs. There are several other classes of visual information that are important to flight path guidance, but are related only secondarily to primary aircraft control and navigation. These include the display of radar weather returns, threat target locations, and traffic collision avoidance information.

Most of the non-visual sensory systems studied have been shown to have a significant impact on primary visual percepts. In the past, aeronautical display concepts typically have not taken advantage of the synergistic effects of polysensory inputs. This is the case despite the fact that polysensory displays may improve visual detection and recognition of optical events. Additionally, it may be that a given non-visual sensory system might more efficiently represent certain information. For example, it is possible that an auditory display may provide certain advantages in the display of spatial information. Accordingly, such displays merit systematic evaluation in an aeronautical setting.

SPATIAL INFORMATION DISPLAYS

As suggested by the aphorism presented earlier, the primary flight tasks are twofold: 1) control of translation and rotation of a craft, and 2) regulation of a craft's course. During flight through calm skies, these tasks apparently can be accomplished simultaneously. But, even the most novice of pilots soon learns that, during a flight, the mildest of winds can insidiously de-couple the control actions necessary to maintain orientation from those necessary to control the craft's course.

Decomposing these two tasks permits a relatively straightforward explanation of why, for the most part, a pilot has difficulty in performing them in parallel. The first task requires a reasonably solid understanding of aerodynamics, the science of the forces acting on a body in motion relative to air. The foundations of the second task lie in navigation, the science of determining position, course, and distance traveled. While pilots enjoy their amateur status as aerodynamicist and navigator, many find it nearly impossible to be both at the same time.

Spatial orientation and orienting usually refer to rather global tasks like determining attitude, position, and course. Early on in the history of flight, it was discovered that pilots are very poor at determining spatial orientation without the aid of reliable instrumentation. In fact, all of the primary flight displays were designed with only one purpose in mind: to maintain spatial orientation.

To be sure, certain flight tasks can be accomplished as accurately (or even better) by using the real world, perspective transformations as when the primary flight instruments are used. This statement is dependent, however, on the vehicle states. For example, at 100 feet there is a substantial amount of visual information generated by optical flow patterns. Such patterns can be used easily as visual cues. As a result, flight control based on the perspective transformations is possible. However, at 10,000 feet during straight and level flight there is little optical flow available; and, the pilot must rely on instruments for many flight control tasks.

The key to understanding the effectiveness of these displays is to realize how each of them supports the pilot in fulfilling the role of aerodynamicist or navigator. The key to the design of these displays is to understand how the information presented in each of them supports the pilot's ability to maintain spatial orientation.

THE PILOT AS AERODYNAMICIST AND NAVIGATOR

Aerodynamicist. The fundamental issue that produces de-coupling of aerodynamic and navigational control is the term "relative motion." As was pointed out earlier, aerodynamics deals with the motion of a body not just through air (although that is implicit), but motion of a body relative to air motions (wind). Knowledge of ground speed (which is calculated relative to the surface and is a navigation term) is unnecessary for the aerodynamic control of an aircraft. What a pilot must regulate is the rate at which air molecules pass over the wings. This information is displayed to the pilot by means of a sensor and gauge called the air speed indicator. However, air speed only represents part of the information set that is necessary to determine the rotational and translational motions of an airframe relative to the air mass.

All of the primary flight displays are specifically designed to provide some information concerning the six basic motion states of the craft. What complicates the design problem is that, in some cases, these displays provide information about orientation with respect to different coordinate systems. For example, the inertially referenced attitude indicator provides accurate information concerning pitch and roll relative to an earth fixed coordinate system. On the other hand, the airspeed (ram air) and altitude (barometric) indicators are referenced to the air mass coordinate system.

Suffice it to say at this point that understanding the translation and rotational motions of the craft "relative" to the motions of the air is necessary to avoid catastrophe. It follows that control inputs should first meet aerodynamic requirements. In fact, many accidents have resulted from a pilot's control inputs that are intended for navigational control without regard to the aerodynamic consequences. An example of this is when a pilot commands a bank to initiate a course change without considering the loss in lift that inevitably results when the craft rolls. A second, more dramatic example occurs when a pilot is low on a final approach course. A pitch-up command might appear to the novice pilot the simplest way to intercept the glide slope, and avoid landing short. But, a low approach in conjunction with a pitch-up command can be a deadly combination, for it results in increased drag, loss of lift, and loss of altitude. The FAA accidents classify such events as "controlled collisions with the ground."

Navigator. Generally, navigation is based on a pilot's ability to understand and control craft motions relative to true or magnetic north. The primary flight displays that are designed for navigation provide specific, although not necessarily complete, angular information about position relative to magnetic north or relative to some ground location. The pilot must take this angular information, convert it to longitude and latitude coordinates, and then plot the position on a chart. The positions, plotted over time, will provide the information necessary for accurate navigation (location, course, and distance traveled).

In addition, navigation is often considered to be a two dimensional task. (After all, charts are two-dimensional.) But, in fact, aeronautical navigation is three-dimensional (longitude, latitude, and altitude). The charting of a vertical flight path is necessary in order to establish cruise or descent profiles used for for calculating ground speed. And, just as lateral flight profiles are important for obstacle avoidance, vertical flight profiles are important for air traffic separation.

But, as was stated earlier, a pilot must first understand and deal with the motions of his craft relative to the air. In windy conditions, this pilotage canon will necessarily complicate the task of navigation. The classic example of such a case is when crabbing is required to make a direct translation between two ground locations. In the no-wind condition the craft heading (direction of the nose) is co-planar with the craft course (ground track). To maintain a rectilinear course on a windy day, the pilot must yaw the longitudinal axis of the craft (change heading) out of the plane of translation. When a pilot does this, the craft is no longer pointing (heading) where it is going (course direction).

The five coordinate system problem. It is important to recognize that there are two fundamental tasks that pilots must perform. One concerns getting from one point to another in the world. The other deals with keeping the craft in the air. However, it is also the case that for proper flight control, there are, in fact, five coordinate systems with which a pilot must deal simultaneously. They include three earth centered systems: inertial, magnetic, and polar. A fourth coordinate system is generated by the three planes normal and orthogonal to the relative wind. (The term relative wind is defined by the flow of air parallel to the craft's translational vector.) The fifth system is based on the longitudinal, lateral, and vertical axes of the craft. The challenge that faces a pilot is understanding the relationships among these coordinate systems. For proper flight control, they must be able to specify the impact of a simple control action on a craft's orientation in each of the coordinate systems.

A frequent and simple solution to the problem, but also a most dangerous one, is to ignore the way in which a single control input will be transformed through the different coordinate systems. The training a pilot receives emphasizes that control inputs directed toward a navigational goal will not necessarily assure aerodynamic stability. Often, however, a pilot does not learn that primary flight displays will not automatically sort out the interrelationships among the various coordinate systems.

CURRENT CONCEPTS IN SPATIAL INFORMATION DISPLAYS

Currently, there are two basic approaches to the graphical and numeric presentation of spatial information in a cockpit. One group, the primary flight displays, are the ones with which most people are familiar. The basic characteristic of such displays is that they present spatial information in an abstract format; for example, translational speed is displayed in the form of air speed or vertical velocity. The second general approach is called the contact analog display. It is designed to present a perspective, naturalistic representation of the crafts' motions that could then be easily related to abstract information in the primary flight displays. Typically, such a display will represent the craft moving over a ground plane.

The information that these displays present is very explicit concerning various vehicle states. However, the information in a given display is not necessarily specific to a coordinate system. The problems generated by this lack of specificity is discussed in the following sections.

Primary Flight Displays

Typically, primary flight displays present information about single aircraft states. Examples are air speed and vertical velocity indicators (translational rate displays), and the magnetic compass and directional gyroscope (rotational position displays). It should be noted, however, that some indicators, such as the turn coordinator, combine information about two states (yaw information and roll rate information).

Navigation-related displays also normally present a single dimension of guidance information [e.g., the VHF Omni Range (VOR) indicator presents bearing to a specific ground location relative to magnetic north, and the Automatic Direction Finder (ADF) presents this bearing relative to the nose of the craft]. However, like the turn coordinator, the localizer/glide slope display used for an instrument landing (ILS) combines information about two states (vertical and horizontal angular position). Although these displays primarily provide navigation information, they also provide indirectly attitude information that is used actively by the pilot. For example, if the pilot is monitoring heading by means of the directional gyroscope, any movement in the indicator specifies changes in roll and/or yaw.

Finally, since a pilot observes a display over time, the temporal dimension is present implicitly in all displays. While the time dimension is implicit, pilots explicitly use it to determine velocity or acceleration information (what pilots refer to as "trend" information).

Contact Analog Displays

The origin of the term contact display has its roots in the term contact flight. The latter has been given a specific usage by the FAA. It makes reference to a pilot's ability to fly and navigate by visual reference to the surface.

In the strictest sense, a contact flight display incorporates the perspective projection of a three dimensional model onto a picture plane. Typically, these displays represent a ground plane and a command path for a pilot to follow. In practice, the definition of a contact display is quite loose; examples of such displays have ranged from video displays to head-up-displays (HUD's).

The intent of contact flight displays was to take advantage of the eye's natural ability to sense and perceive motion in a perspective projection. Early in the history of these displays, questions arose concerning the design criteria for the field-of-view (FOV), field-of-regard (FOR), and resolution requirements. Little, if any, attention was directed to specifying surface texture element criteria.

Several studies have suggested that, for "normal" flight conditions, there are few differences in pilot control responses due to using contact or primary flight displays. Other studies suggest, that when the pilot is "stressed," performance with the contact analog display is better. However, caution should be exercised in generalizing from such studies due to the inadequate operational definition of the "stressor" variables.

What apparently draws engineers and designers to contact displays is the intuitive notion that if a naturalistic representation of the outside world can be presented to the pilot, performance will be enhanced. This point of view is based on the assumption that a pilot can extract the information in a multi-dimensional perspective representation more efficiently than from a traditional single dimensional state variable display. It is assumed that a pilot can fly more accurately using dynamic perspective cues than using abstract informational displays. However, the conditions under which such assumptions may be true have yet to be defined.

Primary and Contact Flight Display Tradeoffs

The potential amount of information content in each of these two classes of displays is vastly different. As a result, the cost to the pilot in using them may also be very different. As indicated, a typical primary flight display presents a single dimensional state of the vehicle (e.g., airspeed). This display format has the benefit of being simple to read and interpret; but, several displays have to be read and integrated to acquire information concerning the overall state of the vehicle. This may not be a problem if the time required to use several single-state displays is minimal. Though it has not been well documented, experienced pilots can reportedly "read" an instrument panel at a glance, in a fashion analogous to someone who is learning to play chess. It has been argued that as one progresses from chess novice to chess expert, the essential skill that is acquired is the ability to perceive general patterns and the possible trends that might emerge. Apparently (and emphasis should be placed on the word apparently) pilots can perceive and determine multiple vehicle states with a single glance. It should be emphasized that this ability has not been demonstrated. It may well be that experienced pilots, particularly instrument-rated pilots, merely have a more disciplined and efficient instrument scan.

Conversely, it may not be most efficient to present multiple vehicle states simultaneously, as is done in contact analog displays. The notion here is that because a contact display is a representation of the real world, pilots would be able to use the information in the display as efficiently as they use the information in the real world.

There are three assumptions implicit in the supposition that the contact analog display format is more effective. The first is that we can in fact use efficiently the information in the real world. But, unfortunately, there are many ambiguities in the world scene that make motion sensing difficult. It may be that single dimensional primary flight displays are less ambiguous, and, thus, can be used more accurately. The second assumption is that pilots are sensitive to the graphical elements that are used to depict the real world. However, little research is available that specifies the visual cues in a graphical scene used by a pilot to control his virtual motion, and, more importantly, whether they are the same visual cues he would use in directly viewing the real world. A third assumption is that pilots rely on perspective cues to control translation and rotation. Under certain flight conditions, a pilot may simply rely on the two-dimensional information in a scene (e.g., image size).

Integrated Primary/Contact Flight Display

An alternative display concept is to integrate features of primary flight and contact analog displays into a single instrument. However, the benefits gained from such integration may be lost due to the added complexity.

Attempts to incorporate positional/rate information (in analog format) into contact flight displays have been limited. Examples of such attempts include "tunnel-in-the-sky" displays developed a decade ago. In such a display, a pictorial representation of changes in vehicle states are represented by simultaneously displaying slightly altered images of the same object, as if you were observing a cube from successively different viewing angles. This is akin to presenting sequential cartoon images closely in time, that are then assembled by the observer into a coherent motion percept.

Just as there have been attempts to integrate specific position/rate information into a contact display, there have been attempts to display plan-view navigation information into contact displays. Boeing is currently testing several of these displays. Other approaches have attempted to employ a "God's-eye-view" display of the craft's position.

However, trying to integrate features of these two display types will necessarily result in embedding even more information into the display. Whether this will facilitate information extraction by the pilot is another matter.

Cartesian versus Polar Coordinate Display Strategies

In developing display concepts, the designer has the freedom to specify the coordinate system (e.g., inertial) in which the information is presented. Freedom is also permitted in selecting the mathematical coordinate transformations used to specify position. The nature of the coordinate transformation depicted may influence the control strategy used by the pilot. Additionally, the designer is permitted freedom to "condition" the displayed information by a wide variety of filtering and lead/lag algorithms. Such techniques, while critical to design criteria for aeronautical information displays, will not be dealt with in this paper.

Cartesian coordinates. The assumption implicit in the design of most of the displays discussed is that the pilot has an internal representation of his motion through a Cartesian coordinate system. This assumes that pilots represent their space as if it has three intersecting planes which are orthogonal to each other.

This space is specified by three axes (x, y, and z) which provide distance metrics. A change in position is represented by a change in x, y, and z locations. To specify changes in rates of a vehicle, it is necessary to specify change in position over time in each of the three axes independently. While this may seem a bit obvious, the implication is that a single term cannot be used to describe something even as simple as approach speed on a glide slope because forward velocity must be computed independently of vertical velocity.

One potential problem a Cartesian based coordinate system display may generate is that it would direct the pilot to the "one-up-two-over" control strategy. That is, the display may lead the pilot to consider it is most efficient to control motions in different planes independently. For example, the standard ILS display in current cockpits shows angular deviation from the approach course and glide slope (horizontal and vertical planes). This causes many pilots to sequentially control either position on the approach course or glide slope. Such a response strategy may be contrasted to one in which a single control action is used to correct deviations in both approach course and glide slope.

Polar coordinates. Space also may be defined in terms of a polar coordinate system. Location in this space depends upon a single vector term [which is defined by its slant angle (a combined azimuth and elevation term) and the distance between the origin of the sphere and the reference point]. Changes in flight path angle and heading only require changes in a single value (slant angle). Changes in rate only require changes in the magnitude of the vector. Such a display may generate a ballistic control strategy based on craft dynamics.

Currently a vector display has been fielded for the control of hover location. In this case, there is a two dimensional vector (only x and y information is represented) that presents which direction and how fast the helicopter is moving away from a designated location depending upon the magnitude of its components.

An application of a Cartesian coordinate strategy to the same problem would present a surface with a dot moving around a specific reference location. Rate information would not be directly displayed, as it is in a polar coordinate display, but would have to be derived over time by the pilot.

Control strategies. The mathematical strategy that a designer uses to represent space may influence the nature of the control strategies a pilot uses. It may well be that different displays and/or control strategies may result in optimum performance depending upon the task. For example, when ballistic motions relative to the current location are sufficient (e.g., the hover-hold task), then a polar coordinate display may be optimal. On the other hand, when a pilot is flying close to the surface and needs to consider obstacle avoidance, a Cartesian-based coordinate display may be optimal.

SPATIAL INFORMATION DISPLAY CONCEPTS AND VISUAL ATTENTION

In any given display, there are often several sources of information. One goal of the display designer is to make it easier for the user to extract the information that is most highly correlated with an optimal response. Perhaps one of the most frustrating outcomes of display design is that the observer attends to information in the display that results in sub-optimal performance. This may occur because the "secondary" source of information is more compelling, or because the observer is more sensitive to it. For example, a perspective scene is generated to simulate translation over the real world. However, a pilot may not attend to the three-dimensional perspective transformations (which provide the mathematically optimal solution), but to two-dimensional motions of the surface texture elements against the edge of the screen.

One display design strategy is to physically co-locate information on the display surface (or even overlay information) so that the pilot can "simultaneously" assimilate both information domains. A classic example of this approach is the HUD. The intent, in part, was to overlay symbolic information on the real world scene, thereby reducing the amount of time it would take a pilot to integrate both information sources.

Several suppositions were made when this design strategy was conceived. One was that, because two information sources are proximally located, assimilation time would be reduced. This would be the case if the critical path component was movement of the eyes from one spot to another, and not the time it took to sense and perceive the data source. A second assumption was one of "simultaneous assimilation." However, data existed even at the time when HUD's were first designed that suggested that parallel processing of diverse visual information may occur only under fairly limited circumstances.

The psychological literature is replete with studies on position perception. But, even now, little is known about how well an observer can perceive and control the motion of an object in three-dimensional space. Does the observer control motions in the x, y, and z planes in a serial fashion? Or, does the observer make a ballistic move between two locations, and only then check the error in the x, y, and z planes? Another way to state the question is the following: Does the observer treat each plane as a separate information dimension? An even more difficult question is how to tell which strategy a pilot is using.

This question illustrates one of the major issues in the design of visual displays; and it concerns the capacity of the visual system to parallel process (or, at least, multiplex) separate channels of multi-dimensional display. The problem of visual attention and display of spatial information often reduces to one of two issues. One concerns "tunneling" of visual attention. That is, information presented just a few degrees eccentric to the line-of-sight (LOS) may or may not be visually perceived. The other concerns the overlaying of visual information (the HUD strategy). What is not clear is whether or not a pilot can parallel process visual information that is overlaid, but is in two different planes. Stated in a more operational form, the question is: Can a pilot actually see and use information on the HUD while simultaneously attending to ground features?

NAVIGATION AND SPATIAL INFORMATION DISPLAYS

Typically, navigation displays are developed in isolation from the design of aerodynamic control displays because it is assumed that control and navigation displays are unrelated. Nothing could be farther from the truth. Unfortunately, designers have made this mistake; and, tragically, some pilots have made this same error and have killed themselves and their passengers. The following section describes the problem and discusses ongoing research efforts that address it.

Orientation and Multi-Coordinate System Registration

Relative wind and earth-relative coordinates. It was pointed out earlier that pilots are taught to attend to their aerodynamic tasks before attempting to solve their navigational problems. It was also described that, at times, a control movement made to solve one flight task is incompatible with solving the other. How a display might represent the impact of a control input on vehicle states in the different coordinate systems has received little attention.

Earlier, it was pointed out that the conventional wisdom of novice pilots often results in a pitch-up control input when his aircraft is low on a final approach course. The lack of understanding concerning the motion requirements for safely "navigating" in an air mass versus the motion requirements for navigating relative to a fixed earth position has unnerved many flight instructors.

Relative wind and magnetic north. A similar flight control problem was described concerning polar or magnetic transformations. The directional gyroscope has a compass rose that rotates as the aircraft yaws, while the number at the top of the display represents the magnetic heading. Due to the design of the display (it looks like a compass rose on a chart), and its dynamic characteristics (its motions are similar, but opposite, to the magnetic compass), a natural response is to treat the directional gyroscope as a navigation display. Unfortunately motions in this instrument also indirectly indicate vehicle yaw and/or roll in the air mass. In fact, during partial panel emergencies, pilots are taught to use the directional gyroscope as a substitute source for information that is normally displayed by the attitude indicator.

Again, a pilot must sort out the different coordinate systems. However, there is only one condition when the directional gyroscope provides accurate information about orientation in the relative wind coordinate system: when the two coordinate systems are in registration (aligned). Under many conditions the two coordinate systems are aligned closely enough that pilots can disregard the differences in the two coordinate systems. However, this is not the case in high performance aircraft. A separate instrument was designed to provide information about major changes in orientation of the craft in the relative wind coordinate system that may not be clearly represented in displays more closely related to the other coordinate systems. The instrument is called the angle-of-attack meter; and it has saved many lives.

Part of the point of presenting these two examples is to show that design problems associated with classical navigational questions should not be considered in isolation. Unfortunately there is very little information available concerning how a pilot might confuse motion information in a navigation display with motion information necessary for aerodynamic control.

Magnetic north and true north. There is another classic problem that falls into this multi-coordinate system problem; and, it has plagued display designers for years. It is the non-registration of the polar (north/south) and magnetic coordinate systems. Proper pre-flight planning will minimize problems a pilot might have in conceptualizing the relationships between these two coordinate systems. But, the fact remains that because of the difficulty in bringing these systems into registration conceptually during flight, that the unpracticed and unprepared pilot will avoid using the magnetic compass except in dire emergencies. (The problem is not only that the two norths are misaligned, but that the planes that form the magnetic axes are curvilinear.)

Orientation Within the Navigational Coordinate Systems

Plan versus perspective view. The display of position location is fundamental to navigation. To accomplish this accurately and unambiguously is the challenge of the designer. There are several issues that are important to the design of navigation displays, but will not be dealt with here in detail. These issues are primarily related to the iconic representation of the world and its features. But it is understood that such factors will undoubtedly influence the "cognitive display" of the world that the pilot generates.

The traditional approach to navigation display design has been to present a plan-view of the world as seen from above. In addition, there are some plan-view navigation displays that present a side view of the scene. This is often done when accurate altitude control is critical. An example of such a navigational display is the standard instrument approach plate.

With the advent of high-speed, high-powered, small sized graphics displays (and terrain data bases), came the possibility of presenting three-dimensional representations of the terrain. But, as long as the position information is presented graphically, virtually the same questions remain for three-dimensional navigation displays as there were for the two-dimensional plan-view representations. What viewing angle should be shown? How should the surface be depicted? What is the best way to represent cultural and vegetative features?

Coordinate transformation. Determining exact position location on a chart from the world scene and the information in the navigation displays is another critical navigation task. The pilot must take the real world scene, match it with some graphical representation in the display (or chart), and determine its associated coordinates. The task of determining the graphical/navigational metric values is a constant source of problems for the pilot. It is created by the fact that all of the typical charts available to the pilot provide location information in degrees of longitude and latitude. However, in the cockpit, the information about position location is typically presented in relative angular units (degrees).

This transformation problem is not simply solved by cockpit displays which provide longitude and latitude coordinates of the craft's current location. The pilot still must look out the cockpit wind screen, identify an object, determine its relative angular bearing to his craft (remember there are no longitude and latitude lines in the real world), then compute the object's location (in degrees longitude and latitude) based on his present coordinate location.

Design Criteria and the Display of Spatial Information for Navigation

Examples have been presented which show how navigation display design can influence the use of spatial information, particularly as a pilot controls his orientation in the other coordinate systems. This problem must not be disregarded if an accurate, as well as safe, display is to be designed.

To accomplish the above, the designer must realize that display principles that seem quite appropriate on the ground, where a controller has to deal with only two axes, may not be appropriate in the air, where there is not only another axis to deal with, but also additional coordinate systems. The challenge here is to track the impact of control actions in all five of the coordinate systems, and to avoid displaying those orientation changes which will lead a pilot astray, while he is acting as an aerodynamicist or as a navigator.

VFR/IFR TRANSITIONS: A MODEL FOR DISPLAY EVALUATION

Operational definitions versus operational relevance. In the preceding discussion, some of the aerodynamic and navigational tasks that face a pilot were outlined. These problems were presented in terms of the coordinate systems with which a pilot must deal, and some of the characteristics of current spatial information displays. The development of a coherent design criteria for the display of spatial information is an imposing challenge to the perceptual scientist. To accomplish this, both the nature of spatial information, as well as vehicle control strategies must be better described. Such questions as the following need to be asked: How are points in space localized? Are different "mathematical" strategies used by pilots to specify translation and rotation in space? For that matter, how are vehicle dynamics understood by the pilot? In what manner are vehicle dynamics used by the novice pilot versus the veteran captain?

To formalize these questions for empirical scrutiny necessitates abstraction of the basic perceptual principles utilized during flight. The danger that lies in this process is that the resulting "operational definitions" (from an experimental methodology perspective) will not be "operationally" relevant from an aeronautical perspective. In an effort to minimize the problems that might occur during the transition from laboratory to cockpit, the following operational problem is parsed to clarify some of the relationships among perceptual constructs and pilot tasks.

Experimental model. Transitions between Visual Flight Rules (VFR) and Instrument Flight Rules (IFR) flight are considered to be some of the more formidable flight tasks. However, the specific nature of the difficulty is unclear. In the case when a pilot must transition from Instrument Meteorological Conditions (IMC) to Visual Meteorological Conditions (VMC), several sensory, perceptual, and cognitive tasks must be accomplished. While flying in IMC, the information from several one dimensional craft state displays must be integrated into a cognitive representation of position and attitude in space. This cognitive representation must include world features that will be encountered as the weather transition is made. Problems in disorientation may develop if the cognitive representation of the world does not match with that actually encountered.

Additionally, spatial disorientation (misperception of orientation and position in at least one coordinate system) may occur as the result of loss of the perception of vection. As a pilot transitions into the clouds, optical flow cues, which normally produce a sensation of vection, may not be present. The two-dimensional primary flight displays do not generate a sensation of vection. As a result, control inputs, which were associated with vection while flying in VMC, are suddenly dissociated from typical visual motion cues.

As the craft motions take it into VMC during an approach, the pilot will look out the cockpit window and his control motions will be influenced by the perspective transformations that are taking place in the world. The gain of the information in the world may be different than the gain of the primary flight displays. The pilot must adjust to differences in scale, format, and information content. Due to the total perspective transformation taking place, vection may be experienced. The pilot must adjust to this as well. As the pilot begins to recognize cultural and topographic features in the world, comparisons to the cognitive map he made during IMC flight will be made. These differences must be accommodated as well, and usually in a very short time period.

The most important problem that faces the pilot at these transitions are the extraction of position and attitude from uni-dimensional displays and the rapid mapping to the multi-dimensional world "display." Understanding the VMC/IMC transition process may well serve as a model for understanding the differences in performance when using primary flight displays versus contact analog displays. In addition, it may aid in the development of design strategies for representing different coordinate systems. And, perhaps most importantly, a model such as this may serve as the basis the development of a design criteria for spatial information displays in aircraft.

SUMMARY

Visually guided control of an aircraft is dependent upon a pilot's understanding of his location in any one of several coordinate systems. Such coordinate systems may be relative to the earth, the craft, or the pilot himself. To control an aircraft within these systems, the pilot must understand their spatial relationships to one another, as well as the control laws and craft dynamics which may be specific to a given coordinate system.

To develop spatial information displays for a pilot, a designer must consider the (1) aerodynamic and navigational coordinate systems within which a pilot must control his aircraft, (2) the control task required of the pilot, (3) the mental model that defines the control space, and (4) how the pilot transitions from one coordinate system to another.