A HUMAN FACTORS APPROACH TO USE OF GPS RECEIVERS

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Introduction

> On August 17, 1995, a pilot took off from Fort McMurray, Alberta in his company Cessna U206G on a VFR flight to Uranium City, Saskatchewan. His plan was to spend the evening there with his wife and son and fly the next day to an important business meeting in Hay River. He took the *direct* route to his destination through high terrain because, reportedly, he had flown it a number of times using his GPS receiver, and preferred it to the longer one over low terrain along the Athabasca River. Alas, GPS receivers do not provide the kind of information needed when high terrain is obscured by low ceilings and visibility is down to 1/2 mile in rain and fog. The 340-ft trail of aircraft wreckage was found on a ridge about 2,000 ft asl. From the TSB report of this accident, it is clear that the pilot needed more recent instrument flying experience, and that he might have been helped by a weather briefing updated from information he had obtained apparently too far in advance of departure. What is only implicit in the report is that the pilot, like many of his flying counterparts, may have placed undue reliance on his GPS receiver. Tragically, the family could be re-united only at graveside.

Few would argue that, since introduction of ATC radar in the 1950s, no technological innovation has had a more dramatic impact on the world of aviation than has GPS. This fascinating technology - which promises to increase the efficiency of flying en route, nonprecision approaches and, eventually, through wide area augmentation systems (WAAS), even precision approaches - is now greatly changing the task and, hence, the art and craft of flying. It will continue to do so for at least another decade. Technological change of such magnitude can scarcely be expected not to bring with it a number of snags and snarls that disappear only as the new system grows and adapts. Certainly this seems true of the GPS receiver, a device that, under the drive of competing manufacturers, has exploded onto the aviation scene in a plethora of models, and at a pace that left governments unprepared to deal with standards of design and operation. Resulting difficulties leave little room for over-confidence in connection with operation of either the small portable VFR units used for en route navigation, or the more complex units designed for IFR and approach navigation, whether panel-mounted or interfaced with the FMS. The purpose of this paper is to put forth an ergonomics/human factors perspective of these problems.

Working co-operatively with the FAA's Satellite Operational Implementation Team (SOIT), members of the Aircraft Certification Directorate of Transport Canada Aviation (TCA) have carefully collected, studied, organized, and documented an immense body of relevant information. The intention of the present authors is not to present an exhaustive account of this material, but rather to highlight some of the more significant issues, so that those affected by them - pilots, trainers, operators, and others - may be enlightened with respect to their safety implications and, thereby, better prepared to deal with them, both now and as future developments take place.

So that the relevant topics may be understood within an ergonomics framework, the paper begins with a brief description of a rudimentary model of human-information processing and an explanation of its relation to pilot workload. In the next section, this framework is applied in the treatment of difficulties observed in connection with use of GPS receivers. The general thrust of this section will be toward use of GPS as a navigation system for IFR approach operations, since it is under these conditions that human factors deficiencies are likely to have their greatest impact. The paper concludes with a summary and suggestions for the aviation community.

An Ergonomics Framework

As an introduction to this section, the authors emphasize that they make no distinction between ergonomics and human factors as a practice. The former term is used more frequently in this paper partly because its theoretical underpinnings are perhaps more formalized, but also because it can more easily be converted to adjectival and adverbial forms. The basic theoretical model underlying this discipline takes a systems perspective, holding that operator and machine (a pilot and an aircraft in this case) are parts of a closed loop system in constant exchanges of information. Figure 1 depicts the process: the pilot makes control responses on the basis of information obtained through the senses from the aircraft (i.e. from both the interface displays

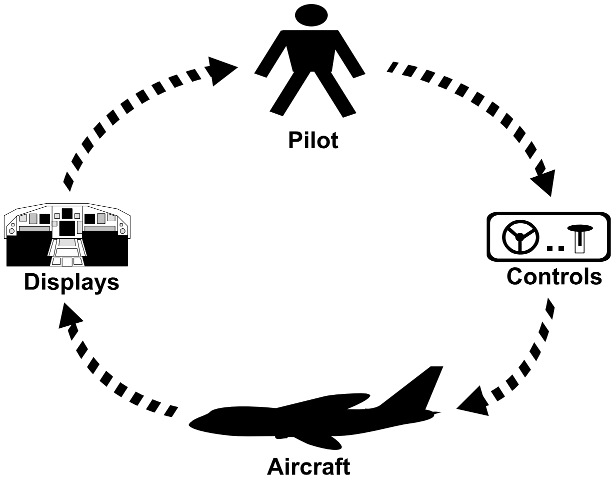

Figure 1. Information exchange in the closed loop pilot/aircraft system.

and the behaviour of the aircraft), as well as from its environment; the resulting changes in the aircraft's behaviour are fed back to the pilot, and the cycle begins again. Input to the pilot, of course, goes far beyond feedback from the aircraft and its environment. Information is also received from many external sources, and *all* relevant input must then be processed in the brain in a way that enables the pilot to operate the aircraft in a safe and efficient manner. Clearly, a requisite for this outcome is that feedback from the machine be swift and accurate.

Although consideration of information from external sources adds a measure of complexity to the model shown in Figure 1, this model is still far too simplistic to cover a system that includes a GPS receiver. The receiver can be thought of as a subsystem that adds another closed loop, complete with controls and displays, that interacts with the basic one, as shown in Figure 2. The process involves activation of control keys by the pilot, this resulting in a change in

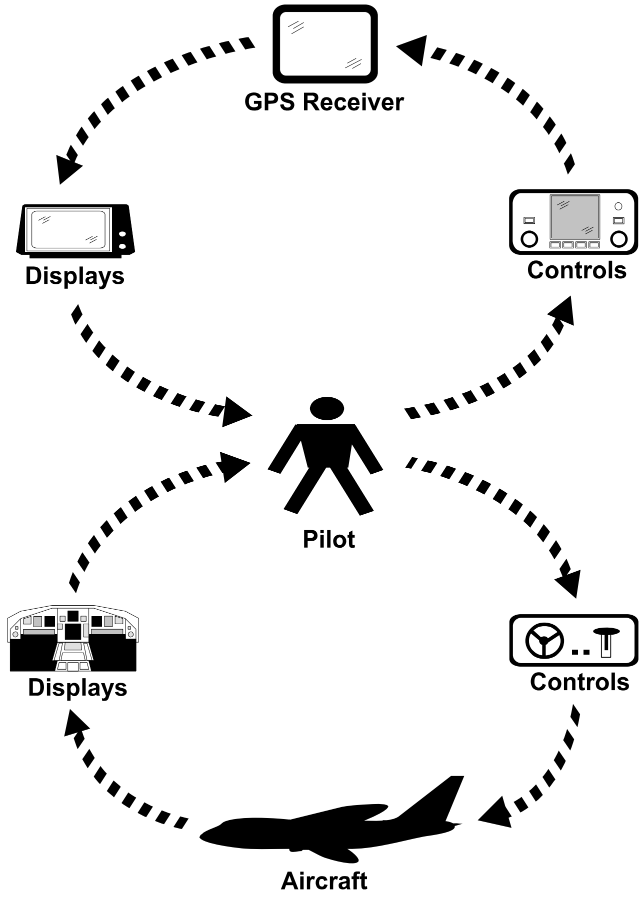

Figure 2. Operation of the GPS adds another closed loop to the pilot/aircraft system.

the status of the receiver system, which is fed back to the pilot on the system's displays. The pilot then uses this information, along with information obtained through the major loop, to control the aircraft. This model would hold also for a pilot/aircraft system with a GPS receiver interfaced with an FMS, in which case the FMS, rather than the receiver, would be regarded as the machine part of the closed loop subsystem.

A very simplified model of how the pilot accomplishes the information-processing necessary to fly the aircraft appears in Figure 3. The process begins with input to some sensory organ, say, the eye. The data are held very briefly in a sensory store for processes of attention and detection and, possibly, subsequent storage in short-term memory (STM). Pattern discrimination and recognition occur as a result of comparison of the transformed input with engrams in long-term memory (LTM), and this perceptual activity is complete when meaning has been assigned to the stimuli. Decision-making involves further interaction with LTM in order to effect an integration of the perceptual detail with other relevant information stored there. Motor cells must then be marshalled in preparation for an overt response, whereupon the response is executed. The described components of processing must be executed in the brain in an incredibly short time if the control response is to be effective.

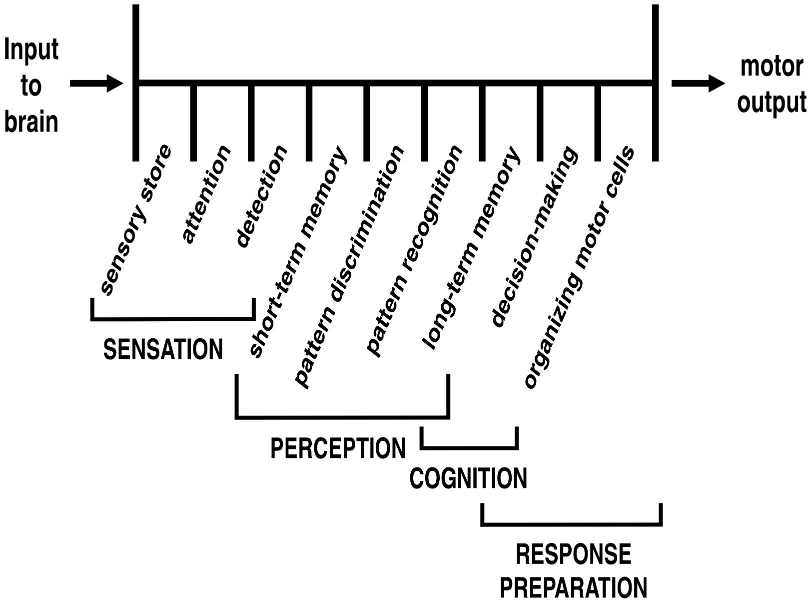

Figure 3. The information processing time line.

The words "time line" in the title of Figure 3, "The information-processing time line", refer to the fact that the process as a whole can be very roughly divided into sensory, perceptual, cognitive, and response preparation phases. However, numerous feedback and feedforward loops render it far from linear. Moreover, the simplified model described above scarcely begins to capture the activity involved in even the lowest level of pilot workload. Something of the complexity of it may perhaps be grasped when it is considered that a pilot simultaneously receives inputs from a *number* of sensory modalities - eg. visual, auditory, tactile, kinaesthetic - and that each of these involves four dimensions, three of space and one of time. The addition of the GPS receiver subsystem adds to the complexity with its separate loop of information processing and its output of information that must be integrated with that occurring in the major loop. Highest workload occurs when parallel input to the brain is at or near its zenith - that is, during the approach and landing phases of flight, especially if, under direction from the ATC, the pilot must re-program the approach for landing at a different runway. During this time, the pilot is carrying out advanced multitasking that calls for allocation to lower brain levels of highly practised and, ultimately, programmed parts of the task (eg. operation of controls), thereby leaving the upper brain levels available for cognitive processing of the kind required during decision-making and communication with the ATC and crew.

It will be appreciated that, just as there are limits to how far an arm can reach or how much air the lungs can take in, so are there limits to how much information the brain can process in a given unit of time, or how effective a response can be if input is not in a form that can be readily processed. In different words, there is a limit to how much sensory/perceptual/cognitive workload the brain can take on. Loading - which can occur at any stage of processing - may relate to information that arrives too slowly, too quickly, or simultaneously in too many channels, as well as to information that is inaccurate, incomplete, misleading, ambiguous, irrelevant, or degraded, and to information that requires too difficult or too complex a response.

A striking example of the limitation of human information-processing is provided by the May 1995 Sioux Lookout mid-air collision between Bearskin's Fairchild Metro 23 and Air Sandy's Piper Navajo PA-31, the former inbound, the latter outbound, both guided by GPS receivers on virtually the same track. Details of this occurrence leave uncertain just how much information processing the pilots of these aircraft were able to accomplish before the crash. Perhaps each had completed the sensory, or even the perceptual phases of information processing. In different words, perhaps each detected the other aircraft or even perceived the meaning of the image. Each may even have reached the decision stage with respect to the appropriate evasive action. Just how much processing took place can never be determined precisely. What is certain, however, is that neither pilot could mobilize motor units in time to execute the satisfactory reponse of collision avoidance.

While, clearly, the pilot has a responsibility to apply the highest level of skill to operation of the aircraft, the ergonomist sees the pilot as operating in a system environment and, therefore, unable to perform optimally without the ‘co-operation’ of the many other parts of the system. This view will be recognized as running counter to simple notions of causality that invoke ‘pilot error’ as an explanation of incidents or accidents which, rather - and because in a system all parts are interrelated - tend to be regarded as indications of system inefficiency. An important aspect of the ergonomics approach to system efficiency and, hence, to accident/incident prevention relates to ensuring that systems are designed so as to avoid violation of any human limitations, whether these be sensory, perceptual, cognitive, motor, psychological, physiological, or whatever. The section to follow examines design features of today’s GPS IFR receivers from this perspective, utilizing the information-processing concepts described above.

Design Deficiencies of Current IFR GPS Receivers

System Archictecture

Whether installed as a stand-alone panel-mounted system or interfaced with the FMS, the IFR GPS receiver is part of the overall interface between the aircraft and the pilot. In any ergonomics assessment of its efficiency, questions will arise as to how the task of operating the unit is integrated with the task of flying the aircraft or, more specifically, how the pilot operates the GPS receiver so as to obtain information, and how this information is used for decision-making concerning control of the aircraft. Attempts to cast light on these questions can begin with a brief look at the basic architecture of these receiver systems which, by and large, will be comparable to that appearing in Figure 4. It will be clear from the diagram in this figure that information is organized around a number of modes such as Nav, Database, Flight Plan, and so on. It will be clear also that a given mode has a number of pages each of which relates to a specific topic within the mode: for example, From, To, Next Wpt is the eighth page under NAV; Nav Info is the first page under SYS; and Nearest 20 NDB is the third page under EMG. Some pages may have sub-pages. The modes are accessed by pressing the labelled buttons, the pages by turning the large knob. Sub-pages, the availability of which is indicated by a flashing diamond in the bottom right-hand corner of a page, are accessed by turning the small knob. Sel (Select), Ent (Enter), and -D-> (Direct To) buttons are also available.

Human Factors of System Operation

With some understanding of the architecture in place, attention can be turned to aspects of the pilot’s operational task. These are presented under select sub-headings and related briefly to the systems/information-processing models outlined earlier.

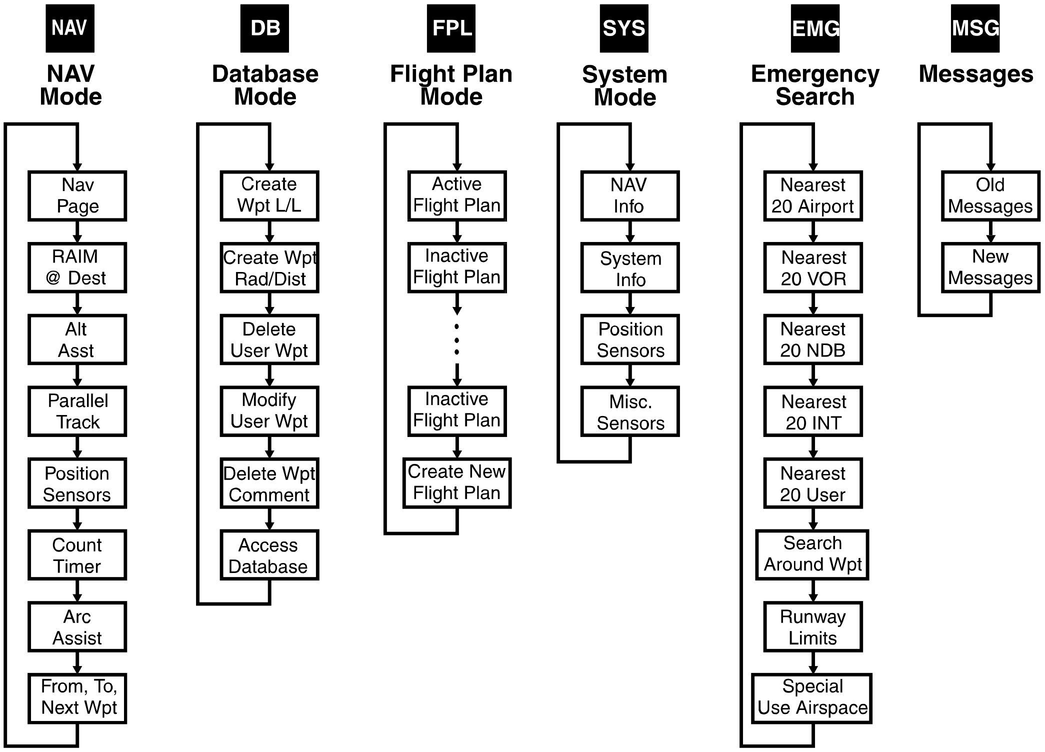

Figure 4. Architecture of a typical GPS receiver system.

Keystrike problems. On one model, the projecting contour of keys invites inadvertent activation. Moreover, because the keys lack both auditory and tactile feedback (the latter being the more important in the noisy aircraft environment), the user was, until recently, often left to wonder what on earth had happened and how to get back to the left-off point. Even if the pilot did indeed realize that an irrelevant key had been struck, he/she still had trouble getting back to the left-off point because, like most models, there is no “undo” button to nullify the error. Contrariwise, the lack of key-strike feedback also had potential for leading to uncertainty about whether a key the operator *intended* to strike had indeed been struck. On those occasions when the operator thought the intended key *had* been struck but in fact it had *not* been, puzzlement as to why nothing happened inevitably followed. The situation was particularly aggravating with respect to those procedures requiring *two* presses of the same button, in which cases the pilot could not be sure whether an intended process, or for that matter an unintended one, had been initiated. A later model provides a compensatory modification in the form of screen feedback for key strikes. However this visual form of information will not be as efficient as that in tactile mode, as it travels to the brain via a less immediate pathway, and could in fact result in certain confusions. In turbulence, of course, it is extremely difficult to make correct inputs to keys of *any* model. Outcomes such as these, requiring time-consuming re-initiation of the entire program as they usually do, will result in enormous frustration. Pilots using the earlier model in approach mode may also be plagued by the fact that certain keystrokes will precipitate a lock-up of the system followed by the incredibly insensitive and frustrating message “Contact Factory.” While this problem has been removed in the newer model, the fact that it existed in the first place reflects the extent to which the designs of most of these systems have proceeded without the guidance of ergonomics expertise, and even without a common-sense understanding of what the pilot experiences in the cockpit.

Needless to say, the uncertainty associated with any of the events mentioned above would slow down processing in the subsystem loop in Figure 2, so that the pilot is unable to access quickly the information needed for decision-making in the main loop associated with actual control of the aircraft. When frustration is added to the picture, efficiency is decreased further, and effects could then completely disrupt the complex information processing required when multitasking begins to peak, as it does during preparation for the approach phase of flight. Characteristically, the pilot engages in head-down time while struggling to gain control over the receiver, with loss of situation awareness being the risky consequent.

Load on memory. Operation of virtually any GPS receiver model of today places undue load on memory. To understand something of the extent of the problem, consider the following task elements required by one unit to load a nonprecision approach:

- press FPL to access Flight Plan Mode
- turn the large knob to display the desired destination waypoint
- press SEL
- press ENT to prepare to load approach waypoints
- turn the small knob to display the available approach choices
- press ENT to select the displayed approach path
- turn the small knob to display the approach legs
- press NAV to return to Navigation Mode

Not counting the number of clicks of the large and small knobs, this operation requires eight steps, a very large number for an activity that may need to be carried out at a time when workload is already high. However eight inputs seems minuscule when compared with the *30* or more required by some GPS receivers for the same operation! Although some receivers come with prompts that provide some step-by-step guidance, in most models each step must be remembered with respect to both function and order. Such a requirement leads to frequent input error, a costly mishap that, because of the difficulty of getting back to the last valid input, usually requires re-initiation of the entire program.

Not uncommonly, memory difficulty is compounded by the fact that one or more knobs may have multiple functions. The left and right knobs of a currently used receiver serve to illustrate the point: each has different functions depending on whether the cursor is on or off, and whether the inner knob is in or out. Load on memory is increased further when, as is true for another unit, the user must remember that certain successive clicks do not change the display.

The effects of load on memory are very similar to those described earlier with respect to keystroke problems. When memory fails, the pilot becomes literally unable to gain efficient control with respect to the GPS receiver. With reference to Figure 2, information processing in the GPS subsystem loop is then greatly retarded, thereby preventing efficient processing in the main loop of the pilot/aircraft system. Again, head-down time, with potential for loss of situation awareness, is the undesirable result.

Effect of nonintuitive logic on memory load. A characteristic of GPS receivers that significantly undermines ability of the user to remember their operational complexities is the nonintuitive logic underlying system operation. To illustrate, labels that are misleading or run counter to what ergonomists call the “population stereotype” (a term roughly translatable as “what the majority would expect”) are nonintuitive and, thus, have no power as mnemonics. Without power of labels to act as cues to assist memory, load on memory is greatly increased. A compelling example of violation of a population stereotype is one unit’s requirement of pressing a button labelled “Select” in order to *exit* the flight plan mode; the violation lies in the fact that the meaning most if not all people attach to the word “Select” in no way equates with or even suggests the action of exiting, and so there is no immediate understanding of why the Select button should be pressed. Another example is one model’s requirement of striking the Direct To button twice to activate the flight plan, an operation that, inasmuch as the Direct To label is commonly associated with simple from-A-to-B navigation, makes no sense at all in the context of a full-blown flight plan. In the newer version, the function of the Direct To button has been redefined, this now being to change the flight path of the aircraft; also, prompts have been added, requesting repeated selections of this key to enable a desired flight path change. While these modifications alleviate somewhat the potential for confusion apparent in the earlier model, they scarcely represent an ergonomically ideal solution.

The Hold button on some receivers is troublesome to pilots. First, the pilot must remember that, when such a receiver is in the Hold mode during a nonprecision approach, the heading displayed on the receiver is not, as might be expected, the heading to the next waypoint; rather it is the heading selected on the HSI. Moreover the meaning of the Hold button (viz. suspend the flight plan) conflicts with the meaning of the word when used by the ATC during an approach (viz.

go into a holding pattern). If directed by the ATC to hold at the Missed Approach Holding Waypoint (MAHWP), the receiver must be put into the Hold function to prevent it from sequencing to the next approach waypoint. Conversely, when released by ATC from the holding pattern, the pilot must not forget that proceeding to the next waypoint will be impossible unless the unit is taken *out* of the Hold function. These rules would undoubtedly be remembered by the GPS-trained pilot immediately they are brought to attention *after the fact*; but their incompatibility with the past experience of the pilot using traditional navaids may well render the rules irretrievable from memory when in the midst of the high multitasking workload situation of flying a GPS nonprecision approach. Potential for a similar type of memory lapse was pointed out to the senior author by Aircraft Services Training Director, Bruce Russell, during a demonstration of GPS/FMS operation in Transport Canada's Citation simulator at Ottawa Airport. The track for the loaded overlay approach to Ottawa proceeded south through YOW to Visol waypoints, and then northeast to the FAF, Oscar. However, the FMS manufacturer's software is such that, at this point, the GPS sensor is deselected from the four available and must be reselected manually before a GPS/FMS approach can be completed. The tendency to forget this fact is understandable because, again, the expectation is that the approach will continue, and the fact that it requires an additional operation at the FAF is counterintuitive. The software is now being modified to prevent the deselection of the GPS sensor at the FAF. However, this brief account of the incident illustrates how software idiosyncrasies can introduce human factors problems into the flying task.

Briefly, the point to be underscored regarding the examples cited above is that, in operating today's GPS receivers, not only does the requirement for numerous control responses place an undue load on memory, but also the pattern and nature of these responses are, in many cases, such that they *increase* that load because they violate the normal expectations of the pilot.

Effects of nonstandardization. TSO C129, developed by the FAA and accepted by Canada, is the Technical Standard Order for certification of IFR GPS receivers as being suitable for installation. Additionally, Canadian approval requires satisfaction of features specified in various FAR paragraphs, the one most frequently failed being No. 2x.1301 specifying that the unit must perform its intended function. Clearly, however, neither TSO C129 nor requisites within the FARs are restrictive enough to have prevented manufacturers from following their own fancies with respect to the design of architecture, labels, controls, displays, operational logic, database codification procedures, or operating manuals. This freedom enjoyed by the manufacturers has far-reaching human factors effects for pilots, trainers, ATCs and others. Consider, for example, a pilot who has been trained and has become as well practised in flight as possible with one model, say A. That pilot will almost certainly experience negative transfer if, for whatever reason, he/she must fly a different aircraft in which a different GPS receiver, say model B, has been installed. More explicitly, model B will be more difficult to learn and remember because of interference from what has been learned about model A. Moreover, even after model B's complicated operational steps have indeed been learned, these steps might well fall away from memory in confusion with those of model A, under conditions of fatigue, stress, or emergency. Further, if that same pilot were required to go back to flying the aircraft with the model A receiver, interference from model B might well manifest itself, such that what was originally learned with respect to A now becomes less well defined in long-term memory (LTM). One hesitates to contemplate the situation in which the pilot is trying not only to keep operations for *several* different models clearly distinguishable in memory, but also to be efficient in obtaining information from the relevant one while flying an overlay approach. To be brief, under such circumstances, lack of standardization would have harmful effects on memory processes, this making for very high information-processing workload, perhaps too high under certain conditions to avoid confusion and error.

Effects of reliance on memory. All the features mentioned so far, and others too numerous to mention, add up to a formidable memory problem, and training and/or frequent practice may not be totally effective as safeguards against effects of underlying ergonomically deficient designs. The fact is that there is a distinction between recognition and retrieval memory processes such that, although overlearned and practised material may be readily *recognized* when presented to the eye or ear, it may nevertheless not be *retrievable* from LTM in the absence of appropriate cues. This type of memory failure, widely experienced among the general population, appears to have been reported after an absence from flying duty of only a few weeks by pilots who had been well trained and practised with GPS receivers. A significant feature of inability to retrieve items from LTM is that it is very apt to occur when an individual is experiencing stress, fatigue, or high workload. Because of nonstandardization of GPS receivers, the memory problem becomes more complex when the pilot must operate with different models. In these cases, *both* recognition and retrieval processes may be insecure because of the disorganizing effect the acquisition of various models would have on memory storage.

Since LTM is involved in a high degree of interaction with other data the brain is handling during the perceptual and decision-making phases of information processing, any overload of the brain's capacity in this respect carries with it the risk of seriously disrupting these processes and, thereby, of increasing the probability of navigation error. As mentioned earlier, the pilot's experience is that of confusion, followed by frustration and perilous loss of situational awareness because of head-down time required to re-program or otherwise gain control over operation of the receiver. Two January 1994 occurrences point up the problem. In the first case, a pilot trying to make an emergency landing on Timmins runway 28 landed 800 ft short of the runway because he had become preoccupied with his GPS receiver and had flown a half hour over his fuel-on-board time. Although the pilot escaped injury, his newly constructed Pulsar was seriously damaged.

The second of the two occurrences referred to above involved two aircraft - a Dornier that had just departed Winnipeg, and a B727 inbound to Winnipeg from Hamilton via Sioux Lookout, and due to cross over the Dornier 15 to 20 nm east of Winnipeg. Crew of the Dornier had been advised by ATC to climb to a maximum of 6,000 ft, that of the B727 to descend to 7,000 ft. However the ATC noted that the Dornier was climbing beyond the specified altitude and advised the pilot to descend. In an area where 1,000 ft vertical and 3 nm horizontal separation are required, the pilot had climbed to 6,500 ft and was only 1.25 nm horizontally distant from the B727 before descending to 6,000 ft. The explanation of this dangerous incident was that the GPS unit used by the Dornier crew had “broken down”, and the pilot’s attention had been diverted to provide assistance to the co-pilot who was having difficulty re-programming it. Confusion in operating the GPS receiver translated into head-down time of the pilot not flying and distraction of the pilot flying. The result for both was loss of situation awareness that, had it not been for the ATC’s observation, might have led to disastrous consequences.

Database problems. One of the important features of TSO C129 is its requirement for GPS receivers to have Receiver Autonomous Integrity Monitoring (RAIM). If erroneous satellite signals are identified, or if there are two few signals in the right geometry for RAIM to operate, then a RAIM alert is provided, and the pilot must carry on with traditional navigation aids. However, while the pilot is protected in this way against *position* errors, there is nothing in GPS receivers to protect the pilot against errors, omissions, or other troubling features within their databases. Errors in co-ordinates have been reported, due likely to the fact that the software used to reformat databases provided to receiver manufacturers by suppliers is peculiar to the receiver. Keeping the database current is the pilot’s responsibility; however there is no guarantee that the updating process, to be carried out every 28 days, will leave the receiver database with the same degree of accuracy on each transition. Again, the onus is on the pilot to verify waypoint co-ordinates *before* the approach is flown. However full verification of the integrity of what is in the database is far from straightforward, requiring as it does reference to various types of information. Moreover, data automatically entered into the FMS by the manufacturer are not changeable.

TSO C129 requires also that the database of a GPS receiver contain co-ordinates for all waypoints of overlay approaches approved for GPS nonprecision approach operation in Canada, in the same order as the relevant NDBs or VORs are shown on the approach plates, and under the existing approach’s name. However co-ordinates for some of the relevant waypoints, and in some cases even the entire navaid record, may be missing from some databases. Conversely, some databases may contain co-ordinates for waypoints *not* on existing approach plates, thus leaving the pilot to make inferences regarding their sites in order to be in harmony with the unit’s autosequencing.

Another database difficulty, and the confusion it can engender, find an illustration in the CFIT accident of American Airlines' Boeing 757 near Cali, Columbia, in December 1995. Tracking south and having been cleared by ATC to land straight in on Runway 19, the pilot flying (the FO) input the letter R for the relevant NDB, Rozo. However, although the approach plates identify this NDB as R, the database supplier had excluded it from the 12 names listed under this letter because of procedures dictated by ARINC 424 and entered it instead as ROZO. (It is important to point out here that standards for ARINC 424 are set only by industry without any regulated government involvement.) The name that came up as the NDB nearest the B757's position was Romeo. Following the indicated track on the map and directed by the FMS, the aircraft turned approximately 90^0 left and maintained this eastward direction away from the approach track for almost 87 sec before the crew disengaged LNAV and turned to the right. From the CVR and FMS readout, it appears that the crew, confused after the left turn, had then made the right turn intending to go direct to Rozo. It is notable that the *same* incorrect selection, R, had been made. Ironically, though, the aircraft did not re-direct to Romeo because LNAV had been disengaged. In any case, it was too late. The B757 impacted a mountain at 8,900 ft asl. When this accident is considered from an ergonomics perspective, the crew's action of pressing R a second time in order to get Rozo is scarcely surprising. Actually, that behaviour provides another example of human reaction being to what would normally be expected, rather than to what was actually there. The crew, of course did not know that Rozo had arbitrarily been excluded from the list of fixes entered into the database under the single letter R. And, as they would *expect* Rozo to be on the R list, they would likely attribute their deviation from track to be the result of some *other* type of error that they themselves had made. Pressing R when opportunity arose again was likely done with determination not to mess up a second time. Because ARINC procedures have limited Canada to one approach per single-letter identifier, similar types of anomalies (which are known to be associated with human error) may well be prevalent in databases for this country's overlay approaches - for 46 of which there is at least one other approach with the same single-letter identifier.

In sum, various types of GPS receiver database irregularities manifest themselves from time to time. They inevitably result in loss of both time and situation awareness not only because of the pilot's quandary as to whether he/she has operated the unit incorrectly or has missed some explanatory detail, but also because of consequent head-down time during efforts to solve the problem. Thus, again, the impaired information processing with respect to the pilot/GPS loop translates into a disruptive effect on the information processing that must be carried out in the pilot/aircraft loop in order that the aircraft is operated in a safe manner.

Display properties

To be ergonomically sound in the sense of being such that information processing by the operator will be as efficient as possible, signals must be both detectible (i.e. be seen by the observer) and recognizable (i.e. have meaning for the observer). However annunciator lights are reportedly not readily detectible in some GPS receiver models, a feature that could be attributable to any one or more of the following possibilities: (i) the absolute level of the signal's brightness is not great enough, (ii) the brightness contrast is not great enough, (iii) the size of the light is too small, (iv) the light is too displaced from the pilot's working range of view, or (v) the colour of the signal is not effective. The last of these would apply mainly when it is not possible to have high signal/background contrast, in which case red would be the best choice of colour, or perhaps green, with yellow or white being the worst.

In some cases, pilots have been reported as having "ignored" important annunciator lights. A possible explanation for this lack of reaction is that distraction by after-the-fact activation of signals (eg. a "set altimeter" signal occurring after the altimeter has been set) prevented detection of important signals. Another is that the missed signals were detected by the pilots in question, but not recognized - i.e. that their *meanings* were either forgotten or never understood in the first place. Of course it is possible, too, that detection was prevented by brief visual dimming arising from over-stimulation of the retina due to glare from the screen or to visual noise or dazzle from the interface and other sources.

Ergonomics acceptability for alphanumeric characters presented on a screen requires that they have the three properties set out below:

- *detectibility*, the ability of a character to be seen as a separate figure against its background; dependent on many factors including illumination, and brightness and colour contrast;

- *recognizability*, the ability of a character to be discriminated from others; dependent on typographic features such as font, stroke width, and width/height ratio, as well as on illumination, and brightness and colour contrast; and

- *readability,* the ability of groups of characters to be recognized as meaningful words or groups of words so that, together, they convey meaningingful information; dependent on the spacing of groups of characters, and on the spacing between lines.

Specific standards for these properties, drawn up in the 50s and 60s by U. S. military researchers, can be found in almost any good ergonomics text. Yet, examination of GPS receiver displays, largely with respect to the perceptual domain, suggests that manufacturers have not availed themselves of this information. While the limited numbers of scan lines and pixels available undoubtedly create challenges in attempts to achieve recognizability of characters and readability of text, the space factor does not appear to be the sole basis for the shortcomings in question. A receiver preferred by many airplane manufacturers is one having a high resolution six-line deep CRT that can be divided into left and right portions, thus allowing for six lines of readout. Nevertheless the high screen density resulting from such a screen division compromises text readability, especially when a map is called up to one side of the screen, thus forcing important navigation information, such as time, speed, distance, and track detail, into the remaining space. Use of capitals for all letters, especially in a light green shade that irradiates into a dark background making the strokes look thicker than they actually are, reduces character recognizability and, accordingly, readability. Using lower-case letters wherever possible and particularly for expressions such as “KT” and “NM”, along with reducing the thickness of strokes, would tend to reduce screen density somewhat, while increasing discriminability among groups of characters. Character recognizability and, hence, text readability are particularly poor if the screen must be viewed from a downward angle.

Run-together letters is a technique often used to overcome the paucity of available pixels, but never advisedly, as the following prompt display illustrates:

CREATEUSERWPT
BY LAT/LON
PRESSENT

A moving map undoubtedly enhances situation awareness by its graphic representation of track and waypoints, especially if it can be rotated to heading-up, north-up, or track-up positions. At the same time, pilots’ reports of difficulties in attempting to extract quickly the information they need indicate that the resulting high screen density and, hence, low screen readability, is an important concern, especially since it is one that will exist until the straight-in approaches under WAAS remove the data complexity associated with existing overlay approaches.

In sum, the displays of present-day GPS receivers leave much to be desired in terms of the three properties mentioned earlier and, therefore, in terms of ergonomic acceptability. More explicitly, even if correct control responses have been made with respect to the receiver, the processing of the resulting output displayed on the screen is likely to be delayed or disrupted at either or both the sensory and perceptual stages of the information-processing relevant to the unit. As a consequence, the pilot will have difficulty integrating this output with that on other displays in the aircraft, and this will translate into difficulty with decision-making and response execution with respect to the flying task.

Summary and Conclusion

The previous section pointed to certain design features of currently marketed GPS IFR receivers that give rise to human factors problems that have implications for aviation safety. In particular, adverse key-strike properties, load on memory, nonintuitive logic, nonstandardization of models, database irregularities, and difficult-to-read displays were cited. Each of these problems has disruptive effects at one or more stages of information processing in the brain so that, in sum, all stages are affected - sensory, perceptual, cognitive, and response preparation. The overall effect is increased processing workload. Moreover, this increased workload with respect to the *receiver* spills over to greatly increase workload with respect to controlling the *aircraft*. Information-processing workload is known to be at its highest during navigation of a nonprecision approach, representing as it does a complex multitasking situation during which the brain has so much to handle even at the best of times that it must allocate part of the task to its lower levels. The additional load arising from use of a poorly designed GPS receiver could readily make the total close to excessive, especially if the ATC calls for a landing at a different runway, thus necessitating a reprogramming of the entire approach. The situation could become serious if the pilot is stressed or fatigued or is faced with an emergency. The confusion arising from the disruption of information processing, and leading to head-down time and consequent loss of situation awareness, already appears manifest in certain accidents and incidents.

In conclusion, it can be said that the situation with respect to GPS receivers today is somewhat reminiscent of the forties when psychologists Paul Fitts and Richard Jones analyzed 460 “pilot errors” at Wright Patterson Air Force Base. They used quotes around the term “pilot errors” to indicate its inappropriateness in explaining the 460 examined incidents and accidents which they found to be due to design deficiencies rather than to pilot behaviour. Results of the Fitts and Jones study led to the conclusion that technology had gone beyond pilots’ capacities to use it - or, more explicitly, that it had resulted in interface designs that exceeded pilots’ information-processing limits. Although their findings led to the birth of ergonomics as a formal discipline and, subsequently, to the emergence of hundreds of well trained human factors specialists, alas, practitioners in this field were not in a position to influence the design of GPS receivers. And so, again, technology seems to have been at the head of the parade.

As explained earlier, the haste with which manufacturers got their GPS receivers to market caught governments short regarding ergonomics standards. Although TSO C129 and certain FAR paragraphs introduced some measure of control, their provisions fall far short of what is necessary to render this equipment ergonomically acceptable. Standardization of architecture, labels, controls, and operations is, of course, only one aspect of ergonomics acceptability; determining the best design for standardizing each of these system components is the extremely important other aspect. However a high level of ergonomics design efficiency is possible only if human factors specialists are on the scene working with the design engineers during all stages of system development.

Nevertheless, as part of the already mentioned co-operative effort between members of TCA's Aircraft Certification Directorate and the FAA SOIT group, important and impressive after-the-fact-measures are now being taken with respect to the use of GPS receivers. First and foremost, an enormous amount of human factors information is being carefully documented and communicated to the aviation community. Apart from this, an extensive set of bench tests for evaluating receivers has been developed. This protocol, virtually tantamount to output from a thoroughgoing task analysis, probes exhaustively for ergonomics deficiencies and, accordingly, could well form the basis of revision to TSO C129, if that were possible. If every new model were to be evaluated with this instrument as a prerequisite to certification for GPS IFR navigation, it would not be long before systems on the market would be such that pilots could fly with them with a much stronger feeling of confidence and safety.

Equally detailed and carefully formatted is the Flight Instructor Guide for GPS Training, prepared by Transport Canada. This manual covers use of receivers for preflight preparation; preparation for departure; en route, holding, approach, and missed approach procedures; diverting to an alternate; handling system malfunctions; and post flight procedures. From a human factors perspective, GPS receivers as they are today need thoroughgoing design modification based on ergonomics principles. Without this step being taken, training is then one of the best ways of dealing with many of the problems mentioned in this paper, especially if it is supplemented with practice (preferably with a simulator) before flight is undertaken. Because of the lack of standardization, such training is indicated for each different model with which a pilot is required to fly, with a refresher course being highly advisable when switching back to a once familiar model. It must be remembered, though, that training does not provide a fail-safe solution - that there are limits to human capacity to store information in and retrieve it from memory, and that technologies that push against these limits invite inefficiency and safety risks. In brief, training should not be relied upon to compensate for design deficiencies.

The Aircraft Certification group has also prepared a detailed account of the serious problems relevant to the integrity of aircraft on-board navigation data, drawing attention to the role of commercial database suppliers, and calling for some sort of quality control of data after being supplied to these companies by Canadian national authorities. Examples of discrepancies between FMS detail and, in turn, published procedures, altitude restrictions, waypoint identifications, and vertical navigation ‘pseudo’ glide path detail are provided, along with well drawn up solutions to the problems. The document will serve as a basis for highlighting information communicated to operators.

In sum, although there are many human factors difficulties associated with the use of GPS receivers, much is being done through Canada/U.S. co-operative activity to offset their effects in the short term and to remove them in the long term. Thus, in due time, the dream of the much greater efficiency this exciting technology can bring to the airspace system will undoubtedly be realized. Meanwhile, the purpose of this paper will have been served if it has alerted those in the aviation community to the implications of today's systems and, thereby, contributed even in some small way to greater safety in the air.

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