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A Comparison of the Effects of Navigational Display Formats and Memory Aids on Pilot Performance

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16. Abstract

A great deal of effort has been invested in examining integrated instrumentation for advanced cockpits, but little comparable effort has been directed toward the greatest number of aircraft presently flying - those in the general aviation environment. This series of studies examined the benefits of a simple and widely available integrated instrument, the horizontal situation indicator (HSI), in the performance of simple navigational and orientational tasks by private pilots and instructor pilots. Tested in the context of the multiple-processor Basic General Aviation Research Simulator (BGARS), the private pilots exhibited significantly fewer navigational reversals and orientational errors when using the HSI (in comparison with their performances when using the traditional VOR and directional gyro combination). These results were consistent with but even more definitive than those obtained for the instructor pilots. Similar benefits in procedural error reduction were also found when instrument index markers, or "bugs," were used as short-term memory aids.

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FOREWORD

This series of studies was conducted as a part of the Civil Aeromedical Institute (CAMI) general aviation (GA) human factors research program which incorporates both near-term and far-term objectives. The following mission statement guides the overall effort:

> Conduct applied human factors research in the laboratory and in the field on carefully selected GA problems, to obtain objective, scientifically derived data which will aid in identifying affordable options for reducing the risk exposure, and number of incidents and accidents in the general aviation community, and which will serve to enhance GA pilot performance under non-routine flying conditions.

This report resulted from a FY'94-95 effort to consider affordable GA cockpit innovations that would provide a more-or-less immediate enhancement of GA pilot performance.

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- Dr. Thomas McCloy and Dr. Ronald Simmons, Human Factors Division (AAR-100) of the Office of Aviation Research, provided Human Factors Program coordination.
- Mr. Bruce Landsberg, from the Aircraft Owners and Pilots Association and representing the General Aviation Coalition, assisted in the selection of the research focus.
- Dr. Robert E. Blanchard managed the GA program within CAMI.

A Comparison of the Effects of Navigational Display Formats and Memory Aids on Pilot Performance

INTRODUCTION

Problem

The separated presentation of navigational data to the pilot has long been recognized as imposing additional integration demands. Numerous schemes have been devised and implemented to integrate data within a common reference frame. One such instrument, the Horizontal Situation Indicator (HSI), has seen considerable use and combines the functions of the very-high-frequency omni range (VOR) and directional gyro (DG) indicators within a single instrument (a design suggested by Walter Grether; see Williams, 1949, as reprinted in Roscoe, 1971). There has been little doubt that the HSI simplifies the pilot's task of integrating the various pieces of data with some attendant gains in the performance of tracking and orienting tasks. The issue at hand was the cost/benefit tradeoff: Did the associated performance enhancements justify the expense of acquiring and installing such an instrument in comparatively inexpensive general aviation aircraft? The cost of a HSI head ranges from $3200 for a rebuilt nonslaved unit to $4500 for a new slaved unit. Installation is potentially in the area of $750. A VOR/DG configuration will cost approximately $1000 and is reasonably standard equipment.

A second question was whether the use of inexpensive memory aids in the form of instrument "bugs" (adjustable indices on the display faces) could be used effectively to counter the occasional altitude or heading overshoot or reference loss. Add-on altimeter bugs can be purchased for as little as $10. A heading bug, however, can add $150 to $200 to the cost of a DG or HSI (HSIs associated with autopilots can be expected to have one). These options are more economical than altitude and heading preselect systems as found in an autopilot, something not likely to be present in most single-engined simplex training aircraft.

A third question addressed in this series of studies was how effective a moderate-fidelity flight simulation would be in providing a task context for this type of experimentation. The use of personal-computer-based flight simulation has been and is continuing to be addressed in the realm of *training* (Moroney, Hampton, Biers and Kirton, 1994; Williams and Blanchard, 1995), with additional studies on transfer of training using PC-based devices currently under way. Requirements for effective use of these devices for training are also presently under examination (Williams and Blanchard, 1995).

Numerous research efforts using high-fidelity simulation systems have been reported over several decades and some studies using elaborate networks of PCs have appeared recently (Hettinger, Nelson & Haas, 1994, for example, report a combat aircraft research simulation using a network of *23* 80486 microcomputers), but few studies have reported on the efficacy of moderate-fidelity *PC-based* flight simulations for investigating flight manipulation and navigation tasks (Thornton, Braun, Bowers and Morgan, 1992; Beringer, 1994; Beringer and Harris, 1995). Some efforts have been reported that use single-computer simulations of an aircraft (Kramer, Than, Konrad, Wickens, Lintern, Marsh, Fox, and Merwin, 1994; Bowers, Deaton, Oser, Prince and Kolb, 1995), but it is usually not possible to determine either the fidelity of the flight model or the development investment from the published accounts. One is usually left to compare simulator performance with published handbook performance for the aircraft in question and/or rely upon the opinions of subject matter experts (SMEs) rated in the specific aircraft.

The first study of this series had demonstrated that some differences in performance could be detected for primarily instrument-referenced flight tasks when using a moderate-fidelity flight simulation, assembled and integrated from off-the-shelf hardware and software, that reasonably well approximated the performance of the aircraft being simulated (by handbook reference and SME opinion). However, the task environment did not capitalize on the capability of the simulator to support visually referenced maneuvers nor did it produce data that were pertinent to use by low-experience-level private pilots. The latter studies reported here extended the examination of flight instrument formats to the private pilot population and examined their performance in the context of a positive-control scenario requiring flight by minimal reference to instruments (altitude and VOR track).

Integrated Display Format

These studies were the second and third in a series designed to measure the differences in performance obtainable with both the VOR/DG configuration and the HSI, as well as memory aids. The first study (Beringer, 1994) examined the performance of instructor pilots. The second and third studies examined the same displays and memory aids using samples of relatively inexperienced pilots. We anticipated that these pilots would exhibit greater differences in performance between the integrated (HSI) and separated (VOR/DG) display conditions than had the previous sample of experienced flight instructors, a number of whom had experience with both the VOR/DG instrumentation and the HSI. The principal effects were expected to be in orienting to the radial to be intercepted and determining in which direction to turn for the intercept.

The differences between instrument indications are shown in Figure 1 for the worst possible case where the pilot is instructed to "fly to" the station on the 180 radial, and sets the VOR head with 180 at the top, rather than at the bottom, of the instrument. This all-too-common error produces reversed depiction in the VOR head where the right deviation of the needle on the instrument is actually a left deviation relative to

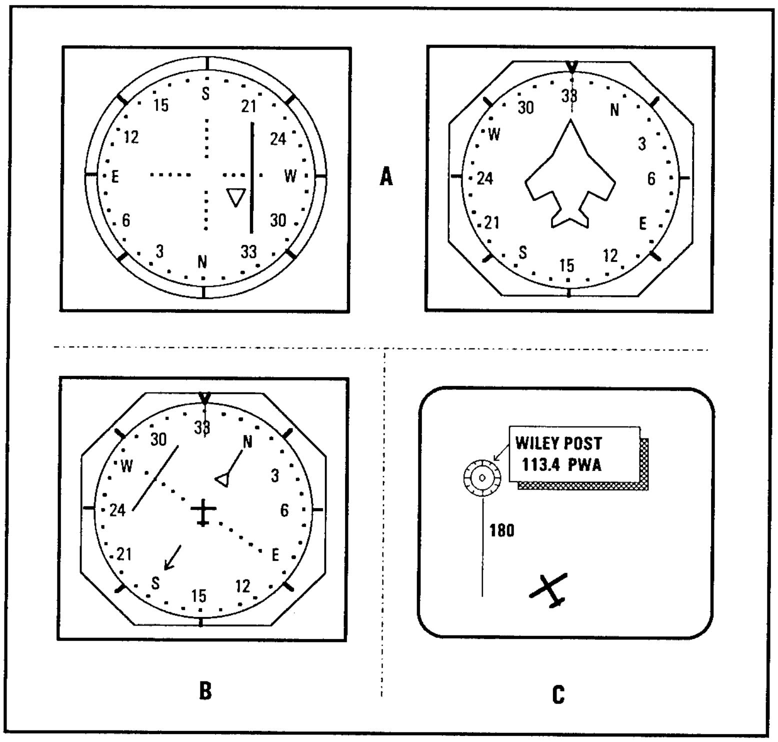

Figure 1. (A) VOR/DG and (B) HSI instruments depicting indications for relative position of aircraft (C) with the inbound radial selected rather than heading, producing a left-right reversal similar to that found for a south heading on a north-up map.

present heading of the aircraft (the same type of problem as found in flying south on a north-up map display). The HSI, however, continues to depict the appropriate left-right orientation, as the data are mapped onto the rotating compass card.

METHOD

Design

The experimental approach selected was a single-factor within-subject design using navigation display type (VOR/DG; HSI) as the independent variable in Sample 2. Sample 3 substituted heading and altitude bugs (present/absent) as the primary independent variable. We selected the repeated measures design because we expected high between-subject variability in the performance of the flight navigation tracking tasks, particularly with the private pilots. Order of administration of conditions was counterbalanced across subjects for samples 2 and 3.

Subjects

Participants were obtained through a contractor operating a local fixed-base training operation. Private pilots with less than 200 hours of flight time and less than 100 hours in the last 6 months were selected for both samples (12 each). These individuals ranged in age from 18 to 30 years and were all males. Total flight experience ranged from 41 to 309 hours (mean = 117.1, sd = 72.8) with 3 to 80 hours (mean = 46.6, sd = 27.1) having been flown in the previous 90 days. Pilots of this experience level were selected because they were expected to benefit most from the display integration and because they would provide the greatest contrast with the instructor pilots examined previously.

Apparatus

The Basic General Aviation Research Simulator (BGARS), described in detail by Beringer (1994; 1995) and Beringer and Harris (1995), was used as the simulation platform. It was configured as a Beech Sundowner for the second and third studies. Participants in the first study flew the simulation as a Beech A-36 Bonanza (only the Aero models differed; displays and controls were identical).

Procedures/Tasks

All pilots participated in two 2-hour sessions, one each at the same time on consecutive days. The first session consisted of familiarization and training. Preparation for the familiarization flight included the reading of a manual explaining the operation of the simulator, focusing on the flight instruments and the radio interface panel. Subsequent flight familiarization included traffic patterns, constant-altitude standard-rate turns, and VOR radial interception and tracking. The second flight scenario, recorded as baseline performance, included simulated ATC communications and crosswinds. These two flights were conducted using the VOR/DG instrumentation.

The second day was used for instruction in the use of the HSI (sample 2) or instrument bugs (sample 3) and for collecting performance data in the two display conditions (samples 2 & 3). Two 35- to 45-minute courses were used for collecting both tracking and turn-and-intercept data. Pilots flew both simplified four-leg positive-control scenarios requiring tracking VOR radials inbound and outbound, a 270-degree turn, ATC-provided vectors, and a visual approach (optional ILS approach). Use of the localizer was recommended to the private pilots for initial alignment with the runway. The courses were flown with full simulated radio communications and involved maneuvers and procedures similar to those used in the practice scenario. Instructions were given to the participants one course leg at a time, e.g., "Track inbound to the Tinker VOR on the two one zero radial. Report crossing the VOR." Subjects received a turn instruction to intercept another radial outbound upon reporting the VOR. Thus, pilots were not required to process or copy a procedure that represented the entire course. All turns and vector instructions to intercept courselines were provided by the "controller" at the appropriate times.

An additional loading task was included that required the pilot to engage the IDENT function on the transponder when requested by ATC. Transponder IDENT was used as a probe reaction time task; transponder code, mode, and response time were recorded for each event. ATC-pseudopilot communications occurred during transition segments to introduce memory interference. All procedures were conducted in unlimited-visibility VFR conditions.

Sixteen data variables were collected at 0.5 Hz, including latitude, longitude, altitude, airspeed, heading, magnetic variation, cross-track error, glide-slope altitude, DME, and status of marker beacons, gear, flaps, and experimenter-entered event marks. Procedural errors were noted by the experimenter and simultaneously recorded on videotape. Each pilot was debriefed at the conclusion of the session concerning the purpose of the experiment.

RESULTS

Procedural/discrete Errors

Procedural errors were defined for the study as those related to the navigation/orientation problem and those related to memory of heading and altitudes or elements of the verbally issued ATC instructions. Navigation/orientation errors included inappropriate setting of the omni bearing selector (OBS), flying through radials without any corrective action, and turning in the wrong direction for an intercept. Memory errors included callbacks for heading, altitude, or radial, failure to recall present assigned altitude, and failure to report VOR and middle-marker crossings.

The tabled data could not be directly analyzed as frequency data using standard distribution-free tests, due to dependence of the data both between and within cells. Thus, the number of errors committed per individual per condition was tabulated and used as an error score; these scores being submitted to analysis of variance (ANOVA). Table 1 contains frequencies of procedural errors by error type, display, and sample types, including data from the first study (Beringer and Harris, 1995). On the average, pilots committed 5.3 errors per flight when using the VOR/DG, as opposed to 2.8 when using the HSI [$F(1,11) = 5.8$; $p=.035$]. The categories that appeared to contribute most were *turned past heading* (3:1 ratio), *heading recall* (4:1), and *OBS setting incorrect* (7:1). These results suggest that the effect is largely one restricted to setting and interpretation of the navigation instrumentation, as evidenced by the large difference in the number of errors between displays for OBS setting and turning past the desired heading for an intercept.

Table 1. Procedural errors by display type and error category for three samples

	Error Type *								
	OBS setting Incorrect	Failed to Report	Altitude Recall	Heading Recall	Radial Recall	Turned past heading	Flew through radial	Other	Total
					Private Pilots (12) *(Sample 2)*				
Displays									
VOR/DG	**14**	**19**	**1**	**4**	**7**	**23**	**nd**	**nd**	**68**
HSI	**2**	**8**	**0**	**1**	**3**	**8**	**nd**	**nd**	**24**
					Private Pilots (11) *(Sample 3)*				
Displays									
No Bugs	**8**	**18**	**2**	**5**	**2**	**4**	**9**	**25**	**73**
BUGS	**3**	**7**	**0**	**1**	**2**	**0**	**2**	**7**	**22**
					Instructors (11) *(Beringer and Harris, 1995)*				
Displays									
VOR/DG	**14**	**3**	**3**	**0**	**2**	**nd**	**nd**	**nd**	**22**
HSI	**5**	**0**	**2**	**3**	**1**	**nd**	**nd**	**nd**	**11**

**(Data omitted for initial wrong intercept turn direction and frequency select errors)*

It is also evident that the workload and additional monitoring activity required by the separated instrumentation produced over twice the number of failures to report in the VOR/DG condition, as compared with the HSI condition. Although the other categorical differences all evidenced trends in the same direction, the differences were small. It is noteworthy that these differences were obtained despite the fact that training in the use of the HSI was comparatively short and did not involve any actual flight with the instrument.

Use of instrument bugs also produced a significant overall reduction in procedural errors with an average of 5.8 errors committed during flights without bugs and 1.9 committed in flights with bugs [$F(1,10) = 84.05$, $p<.001$]. This effect was a decided contrast with the no-difference finding for the use of bugs by the instructor pilots. The instructors regularly used the heading bug but largely ignored the altimeter bug. The private pilots were instructed to always use both bugs and were reminded (in the bugs condition) if they failed to do so. Although part of the difference may be attributable to this procedure, the categorical examination of errors does not support the hypothesis that memory errors were more likely with the instructors.

The examination of responses to the transponder IDENT task indicated no significant differences in response times by instrument condition. Observation of the pilots during the simulations indicated that the task was performed much as one would expect it to be in the actual flight environment: without any particular sense of urgency and often with a transmitted confirmation of the request prior to the IDENT action. This task has limits as to the number of times it can be used legitimately during a scenario (at sector crossings or hand-offs) without arousing the suspicion of the pilot because instructions to perform the task with more immediacy would be contrary to the usual practice. Thus, this task may not be useful for workload inference without some modification or the use of procedures that are somewhat artificial.

Tracking/Controlling Task Errors

On the second issue, the problem of *measuring real-time pilot performance of tracking and controlling tasks,* examination of the track plots indicated consistent loss of orientation for many of the pilots when flying with the VOR/DG configuration, particularly during the 270-degree turn. Flying past/through intercepts was also a regular occurrence. Examples of actual ground tracks relative to desired paths are shown in Figures 2A & B for one pilot to compare the HSI course tracking with the VOR/DG course tracking. It is evident that better acquisition and tracking performance was obtained using the HSI, consistent with

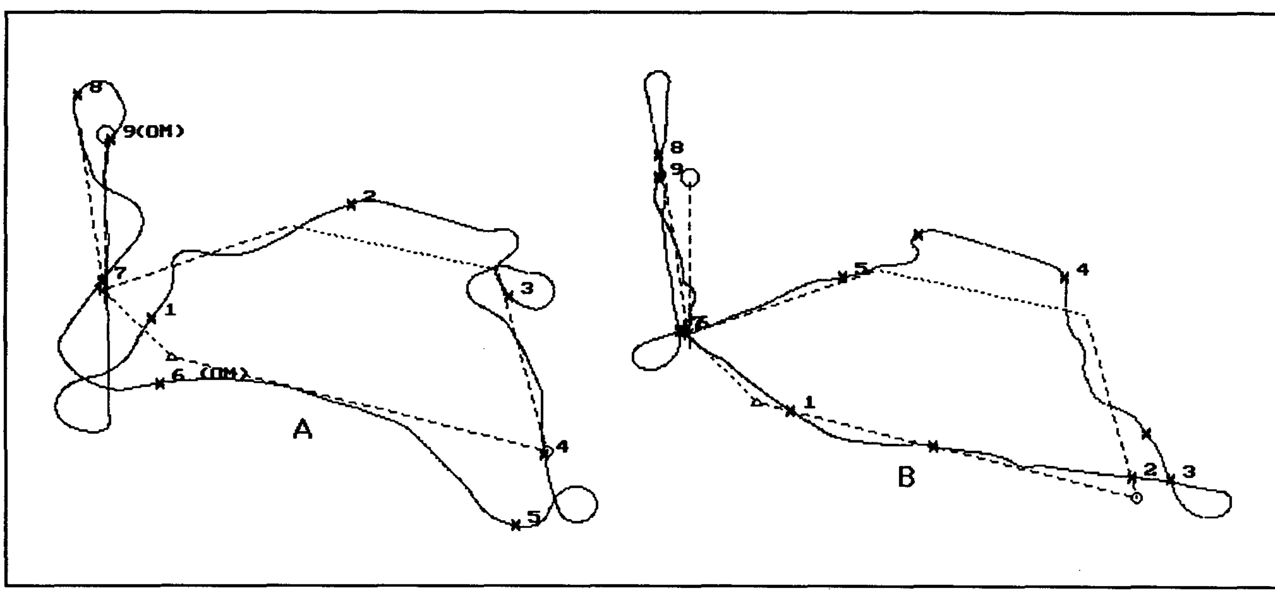

Figure 2. Performance with (A) VOR/DG and (B) HSI. Broken lines represent desired tracks.

the procedural data previously mentioned. Analyses of continuous performance data supported this observation, with significantly greater root-mean-square errors (RMSE) in cross-track and altitude for the VOR/DG condition than for the HSI condition. Analyses of continuous performance data for Sample 3 (bugs/no bugs) showed no significant main effects for RMS errors. This is consistent with the use of bugs as procedural and memory aids, and not as an aid to course or altitude tracking, except to fix the reference point.

These results were, again, in contrast to those for the instructors (Sample 1), who showed no significant differences in tracking behaviors across the various display conditions. It should be noted that the private pilots were given slightly more opportunity to detect and correct their errors. In the case of the earlier sample of instructors, errors were detected and logged, and the pilots were instructed to take corrective actions after their errors were noted. This was done with the intent of separating decision making and track acquisition from actual course tracking.

Pilot Subjective Reports

Responses on the post-test questionnaire indicated that pilots perceived the HSI as easier to use than the VOR/DG configuration. On a scale of 1 (very difficult) to 6 (very easy), the group (Sample 2) rated the VOR/DG as 3.0 (sd = 1.13), whereas they rated the HSI as 4.5 (sd = 0.7) [$F(1,9)=10.87$, $p<.01$]. Instrument bugs (markers) were also perceived to decrease flight task difficulty. Rating of task difficulty with and without bugs (Sample 3) averaged 4.36 (sd = 1.45) and 2.99 (sd = .83) respectively [$F(1,10) = 9.3$, $p = .012$]. Pilots generally reported that the experimental scenarios were more challenging than usual flying, presenting a significant workload. This, of course, was a positive finding, as the intent was to load the pilots sufficiently to detect performance decrements. There were a few complaints from the private pilots regarding the degree of "instrument" flying required.

DISCUSSION

The primary benefits derived from the use of the HSI were evidenced in tasks requiring the pilot to determine the orientation of the aircraft relative to the radial to be tracked, and in simplifying the task of setting the VOR head for inbound tracking. Any accompanying differences in tracking performance appeared to accrue from reduced scanning requirements. The private pilots' attention was often focused on maintaining altitude and heading, to the exclusion of monitoring track deviation, often resulting in "flying through" the target radial. This behavior was greatly reduced or eliminated with the HSI. It is clear from the performance data and the subjective ratings that both a decided performance benefit and a perceived reduction in workload can be achieved by using the HSI display format. The only disadvantages are (1) the relative expense of the device and (2) the need to set the HSI for runway heading during an ILS approach to obtain proper left-right needle deviations, an action not required by the conventional VOR head.

The benefits of using instrument bugs appear to be largely procedural, as expected, and these benefits appear to accrue to a number of tasks across the board in the form of workload and memory-requirement reduction, evidenced by the categorical distribution of errors by type. Analyses of performance by segment type (inbound, outbound, transition) support this view.

Both the HSI and instrument bugs could be the short-term key to reducing pilot errors if manufacturers can be convinced to produce affordable hardware. The passage of time increases this likelihood as display-technology and microprocessor advances make possible increasingly flexible and affordable intelligent display systems. This immediate solution to navigation problems in the general aviation environment should be followed up by application of the appropriate design principles to longer-term display solutions for future GA aircraft that may employ electronic flight instrumentation systems (EFIS) and multi-function displays. The principles of integration and memory aiding must continue to be intelligently and diligently applied as we move into more advanced and flexible means of displaying data in the general aviation cockpit.

This series of studies demonstrates that moderate-fidelity PC-based simulation can be used to assess pilot behavior in task scenarios of this type. Performances obtained were comparable to those noted for more conventional simulators using similar error measures (e.g., Kraus, 1973). However, this simulator is, ultimately, "...a box sitting on the ground." (Hopkins, 1975). "How much should you pay for that box?" To answer that, we must determine how faithful a representation in simulation is necessary to produce acceptable generalization of results to the operational environment (Williams and Blanchard, 1995). The data suggest that devices of the class used in this study can produce and support task scenarios that generate reasonably representative data.

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