# Simplified Approach Charts Improve Data Retrieval Performance

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The effectiveness of different instrument approach charts to deliver minimum visibility and altitude information during airport equipment outages was investigated. Eighteen pilots flew simulated instrument approaches in three conditions: (a) normal operations using a standard approach chart (*standard-normal*), (b) equipment outage conditions using a standard approach chart (*standard-outage*), and (c) equipment outage conditions using a prototype decluttered approach chart (*prototype-outage*). Errors and retrieval times in identifying minimum altitudes and visibilities were measured. The standard-outage condition produced significantly more errors and longer retrieval times versus the standard-normal condition. The prototype-outage condition had significantly fewer errors and shorter retrieval times than did the standard-outage condition. The prototype-outage condition produced significantly fewer errors but similar retrieval times when compared with the standard-normal condition. Thus, changing the presentation of minima may reduce risk and increase safety in instrument approaches, specifically with airport equipment outages.

**Keywords:** approach chart, aviation, complexity, distractions, errors, human in the loop simulation, methods, minima

Instrument approach procedures (IAPs) are precise flight paths that guide aircraft to land. Visual cues from the outside environment are normally required only for landing and rollout. As the aircraft progresses through the procedure, its boundaries narrow and funnel it to a position for the pilot to acquire the airport environment visually. Respecting the boundaries of the IAP are essential for safety because they guarantee obstacle clearance and navigational system performance.

In terms of error tolerance, the margins are tightest at the end of the IAP. Here, the lowest altitude is reached, and the pilot must either see the runway or climb away. Pilots need two things at this point: the correct altitude and enough visibility to land. These two values are called *minima* and are depicted on charts. Altitude minima are referred to either as a minimum descent altitude (MDA) or a decision altitude (DA). Minimum visibility is the lowest reported visibility authorized to execute the approach. If respected, it gives the pilot a good chance of seeing ground cues to land. Pilots must compare current visibility reported with the charted minimum value to determine the acceptability of the IAP. Visibility and altitude minima vary depending on many factors, including lighting systems, terrain, and navigation precision (Federal Aviation Administration [FAA], 1976).

## PREVIOUS RESEARCH

Due to the criticality of the information, charts must convey these minima effectively and efficiently. Charting has evolved over time mostly as a result of accident investigation reports from the National Transportation Safety Board (NTSB) and surveys of pilots (Hansman & Mykityshyn, 1990). The majority of changes have involved required content. That is, charting evolution has been in terms of the presence or absence of information, rather than how the information is delivered from a human performance standpoint (Hansman & Mykityshyn, 1990).

The two main producers of charts are the FAA's Aeronautical Navigation Products (AeroNav) and Jeppesen Sanderson (Mykityshyn,

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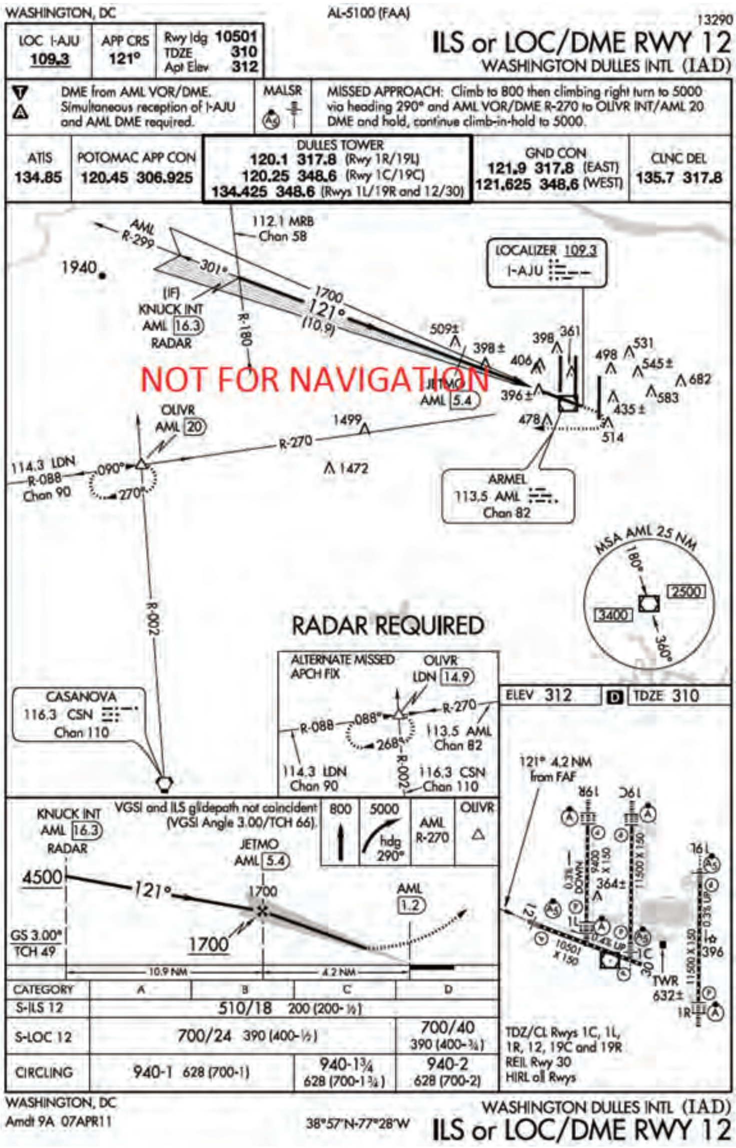


*Figure 1.* Approach plate example.

1991). IAPs are depicted on approach "plates" (charts), which are typically 5 3/8 by 8 1/2 inches, usually printed on paper or presented with an electronic interface (see Figure 1).

The combination of small physical size and high information content was identified as operationally problematic in earlier research (Hansman & Mykityshyn, 1990). Legibility of small text and symbols, as well as information density, creates an unreadable interface in low light and turbulent conditions (Mykityshyn, 1991). These general design deficiencies are thought to be the result of litigation and the necessity for charts to limit cockpit instrument occlusion when mounted on a control yoke (Hansman & Mykityshyn, 1990).

Apart from legibility limitations, other deficiencies have been identified: Pilot surveys, accident reports, and empirical research have revealed that identification of altitudes, navigational frequencies, approach minima, notes, missed approach instructions, and information density are also areas of possible error in information retrieval (Butchibabu & Hansman, 2012; Hansman & Mykityshyn, 1990; NTSB, 1975; Osborne, Huntley, Turner, & Donovan, 1995). With respect to navigational frequencies, the use of Morse code identifiers and the symbolic depiction of a given frequency can be very similar to the identifier and symbol of another frequency (Hansman & Mykityshyn, 1990). IAPs often use one frequency for primary navigation and another for identifying waypoints, missed approach courses, and/or distance-measuring equipment. Some identifiers may be identical except for a preceding "I" that denotes a frequency's status as a localizer. This similarity has led pilots to mistakenly choose one frequency in place of the other, effectively compromising the navigational capability of the aircraft, which has caused accidents (Hansman & Mykityshyn, 1990).

As an example of the problems that approach charts may cause in flight, consider the crash of TWA 514 in 1974. Altitude depiction was considered one of three contributing factors in the accident (NTSB, 1975). Specifically, the aircraft descended to an incorrect altitude for the portion of the approach being flown. This resulted in a collision with Mount Weather, Virginia. Although the pilots retrieved the correct type of information from the chart, that information was incorrect for their current location. In fact, the pilots had a discussion regarding the altitude to fly during the descent (NTSB, 1975). Although incorrect training and air traffic control procedures were also involved in this accident, the chart's method of information delivery was a contributing factor. This type of error indicates a more complex problem than legibility. In survey research, 25% of pilot respondents stated that they had confusion with approach minima while using FAA charts (Hansman & Mykityshyn, 1990). Information density from including all user groups' information on a single chart creates the possibility of selecting incorrect values. In addition, notes that give exceptions to theses minima are often missed due to pilot perception of lesser importance (Hansman & Mykityshyn, 1990).

Butchibabu and Hansman (2012) investigated the effects of clutter, or information density, on pilot performance with respect to information retrieval. Pilots were given a chart on a computer and retrieved pieces of information from it (e.g., altitudes, distances). They investigated arrival, departure, and approach charts with multiple transition paths depicted together. In the decluttered condition, depictions of nonapplicable paths were removed. In the baseline condition, charts were presented in their original form. Because an aircraft can fly only one path, these researchers examined the effects of depicting one versus multiple paths on retrieval time and errors. The decluttered format significantly reduced information retrieval times. In some cases, a nearly 50% reduction was observed. Instrument approaches, over departures, yielded the largest reduction in retrieval times. Specifically, distances between waypoints and altitudes produced the largest time differences. This supports the idea that the depiction method of information has a direct impact on the user. However, there was no significant difference in errors between the two depictions due to a ceiling effect. One possible explanation of the lack of error could be the context of the experiment because it was performed without concurrent tasks. As one pilot noted in a study by Mykityshyn (1991), "there is an unquestionable difference between reading a chart at a well-lit desk versus using one in flight during bad weather at night." Simply put, the context of use makes a difference.

To address context and ecological validity, Osborne et al. (1995) investigated pictorial missed approach (rejected landing) icons and a briefing strip of pertinent approach information against textual descriptions of the procedure. Missed approach instructions require fast identification of information because of the proximity to terrain and immediate required climbs and turns. Also, accurate and timely retrieval of frequencies, courses, airport elevations, and so on were the motivation for the organized briefing strip (Osborne et al., 1995). The study required pilots to fly a real aircraft and perform several instrument approaches ending with missed approaches. Pilots answered information retrieval questions while flying; their accuracy and retrieval times were measured. Retrieval times were significantly reduced for both conditions when using the iconic missed approach depiction and the briefing strip. However, no differences were found in accuracy

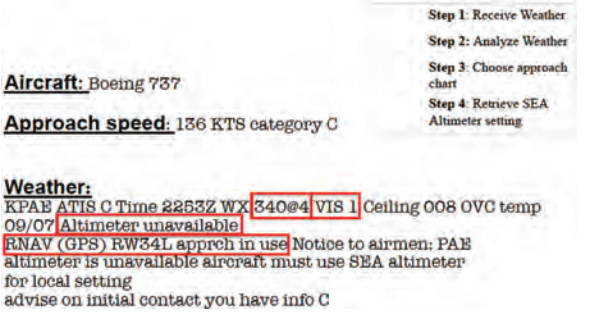


*Figure 2.* Sample scenario for determining minima.

between the conditions. This may have been due to the training that the participants received before data collection and possibly the simplistic nature of the information. The briefing strip and the iconic missed approach depiction are both found in today's approach charts.

## COMPLEXITY OF APPROACH MINIMA

Approach procedures must accommodate all possible users, so they are one-size-fits-all products. User-specific minima are embedded in the chart with other users' minima. As a result, approach charts contain information not pertaining to the specific operational situation. Current methods for deriving approach minima are dependent on airport equipment status, aircraft navigational capability, aircraft speed, weather, and, occasionally, pilot training (FAA, 2007a, 2013a, 2013b). Deriving minima includes not only sifting through unnecessary information but also referencing notes within the chart itself or noncollocated notices to airman (NOTAMs). Theses noncollocated notes are sometimes a factor in determining the value of a minimum altitude and/or visibility. For the purposes of this discussion, conditions of inoperative airport equipment are referred to as *outages*. For example, if the local altimeter setting was not available, there may be a note that states a value to add to the minima to compensate for the likely increase in altimeter error.

To illustrate this point, we use a fictitious example including weather, aircraft type, capability, and approach speed (see Figures 2–4). First, we determine the category of aircraft, which is decided by aircraft speed. For this example, we are dealing with a Category C aircraft (121–140 kts). Next, we narrow the field by ruling out approach minima for which our aircraft is not equipped. This sample aircraft has only lateral navigation, which rules out any minima including a DA, as this is a nonprecision capability. At this point, the first two rows and the A, B, and D columns are not applicable. Next, we determine if the wind at the airport allows a straight-in landing (i.e., without circling). In this example, the wind permits a straight-in landing. What these three steps have given us is the triangulated number on the bottom of the approach plate in Figure 3. Even though a number is located, it is not complete. Because the local altimeter setting is not available, the notes at the top of the page dictate the additional amount to add to our minimum to make it correct and legal (see Figure 4). In this case, that amount is 100 ft and 1⁄4 mi of visibility. Finally, the minimum altitude and visibility for our example are 1100 ft and 1 1⁄4 mi, respectively. Although this example is not routine, it demonstrates where steps become more complex requiring arithmetic and careful reading of text.

## RELEVANCE OF VISIBILITY REQUIREMENTS TO PILOTS

There are two main types of visibility reported to pilots: runway visual range (RVR) and statute miles (SM). RVR is the most accurate measurement and is reported in hundreds of feet (e.g., 1200 RVR). Statute miles and fractions thereof are reported by automated sensors or trained observers (FAA, 2007a). What this means to pilots is the amount of expected visual range they will experience when near the lowest altitude in the IAP. If the visibility is low and the minimum altitude is high, it can lead to a

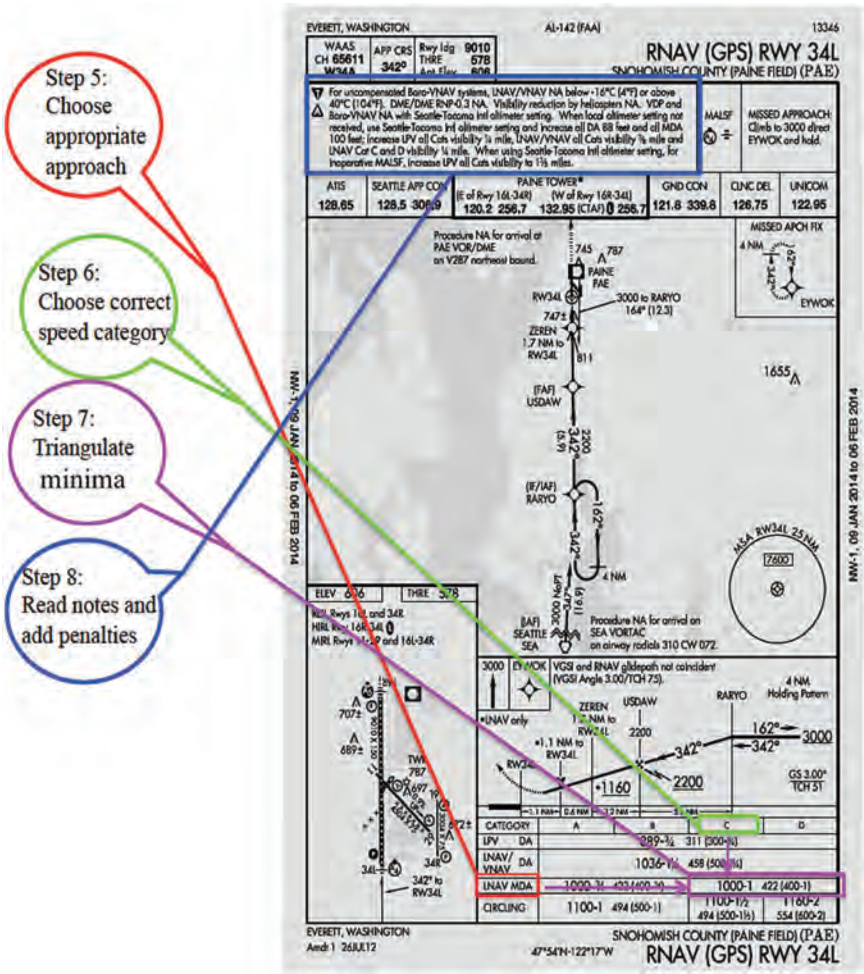


*Figure 3.* Steps to derive approach minima with notice-to-airman outage from scenario.

situation where the airplane is too high to safely land if visual cues are received late. Visibility requirements are established according to several variables, such as airport lighting systems, height of minimum altitudes, and runway alignment angles (FAA, 1976). For commercial operators (FAR Parts 121 and 135), these minimum visibilities are legally controlling. Operators are not permitted to initiate an IAP without at least the minimum visibility for the procedure being flown (FAA, 2007a).

Approach lighting systems have been developed to aid pilots in the visual acquisition of the runway and its relative alignment angle from the instrument portion of the flight (not requiring any outside reference; FAA, 2013a). This means that the visibility requirement for a specific approach utilizing an approach lighting system is contingent on that system's operation. If it is inoperative, the visibility requirement must be increased to compensate for the loss of guidance (FAA, 1976). For the purpose of this study, approach lighting system malfunctions were primarily used to test visibility adjustments.

## TRENDS IN CHARTING

Recently, charting has been migrating to electronic interfaces, which are free of printing costs. The popularity of this format has been made apparent by the FAA's creation of formal guidance to handle the use of electronic charting interfaces by pilots (FAA, 2007b). Popularity of the

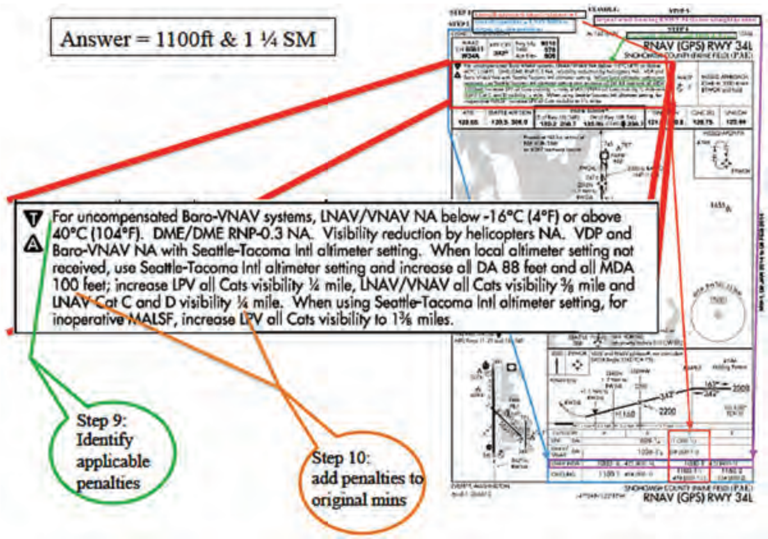


*Figure 4.* Steps to read notes and add penalties.

electronic format is also noted by its application in the air carrier world. Many U.S. carriers are in the process of transitioning to all electronic charts and manuals (Alaska Air Group, 2014; American Airlines, 2013; Delta Airlines, 2013). In addition, electronic charts have migrated into the consumer world as mobile applications that are downloadable to a tablet. ForeFlight is an example of an electronic charting application, and it accounts for 25% of general aviation chart use (Silva, Jensen, Emig, & Hansman, 2014). A driving factor for the present study was the idea that changes in aviation charting are necessary and currently possible with electronic interfaces. Future electronic charts should be free of unnecessary problems because the system affords plasticity. Rather than merely evolving the current medium of charting, there is a need to provide new content and structure to enhance safety and usability.

## TIME AND ATTENTION CONSTRAINTS IN APPROACH PREPARATION

Ideally, IAPs are reviewed prior to the descent phase of flight for effective retrieval of the information necessary to perform the approach (Ricks, Jonsson, & Barry, 1996). However, there are situations that require preparation to occur after that ideal portion of the flight has passed. This happens when the planned approach changes, for many reasons: wind shift, equipment outage, aircraft performance, traffic flow rates, and so on (Lohr, 2011). Timing of the reassignment may play a large factor in how detrimental the effect is. In addition, time-constrained approaches can result from diverting from an intended airport of landing to a secondary choice for unforeseen circumstances (e.g., weather or airport closure). This can result in a pilot having less time and more concurrent tasks while preparing for the approach.

Flying often requires a pilot to attend to multiple pieces of information and perform several tasks in close temporal proximity (e.g., monitoring the aircraft and reading a checklist). Concurrent task management has been explored in the context of aviation and many other domains. If concurrent tasks are not expected and interfere with the primary task, they become a distraction. Severity of the distraction involves its modality (e.g., visual or auditory), complexity, and duration, as well as the complexity of the previous task (Gillie & Broadbent, 1989). Complicated primary tasks are affected more by distractions than are simple tasks. Also, distractions based on the same modality as the primary task are more detrimental than distractions through another modality. Chart reading is a complex visual task, and complicated visual distractions are detrimental to many aspects of flying. Pilots are not trained on how to manage distractions: When faced with competing tasks, they often neglect one in favor of the other, and the hierarchy of tasks is not always consistent (Dismukes, 2006; Loukopoulos, Dismukes, & Barshi, 2003). We exploited these issues to show the limitations of current charting.

## ERROR CATEGORIES IN RETRIEVING MINIMA

After analyzing the context of use and design structure, we identified four broad categories and named them as possible causes for using incorrect minima: *arithmetic error, omitted procedure error, incorrect procedure error*, and *selection error*. Each error category has many possible examples within its scope. Additionally, the categories are not mutually exclusive, and descriptions of each are given.

### Arithmetic Error

Adjustments to minima typically require adding a penalty. This presents the possibility for error due to incorrect calculation of the arithmetic problem. In our previous example (see Figure 4), we needed to add 100 ft to the MDA. This illustrates the potential to arrive at the incorrect minimum altitude. However, the magnitude and directionality of the possible error are difficult to determine.

### Omitted Procedure Error

Adjusting minima is a procedure. Therefore, pilots must be aware of the need to apply the appropriate procedure if the situation requires it. If a pilot is unaware or mistakenly omits the procedure, the penalty will not be respected.

### Incorrect Procedure Error

Minima adjustment procedures vary. If a nonstandard penalty replaces the inoperative components table but the pilot applies the inoperative components table, which would be standard, he or she would be performing an incorrect procedure (see Figure 5).

### Selection Error

Because the approach chart is a tool designed for all user groups, its information content is high, and its interface real estate is low. This density creates a situation in which more than one possibility is presented, thereby increasing the possibility of making an incorrect selection. Number, spacing, units, and typography may all play a factor in the likelihood of a selection error.

## PROTOTYPE APPROACH PLATE DESIGN

The primary goal of the prototype approach plate used in this study was to design out as much possibility for error as feasible and then mitigate the remaining amount (see Figure 6). Nonapplicable aircraft approach categories and minima were eliminated. This lowered the possibility of choosing the incorrect minimum as the result of a selection error. Next, because the present chart design does not label any of the numbers in the minima section, unit-type differentiation and proper selection are the product of declarative knowledge. Therefore, we added labels to denote units for minima (e.g., RVR, SM, and AGL), to reduce the memorization requirements, and to increase selection accuracy of visibility values and minimum altitudes.

Minimum altitudes and visibilities were set in bold, underlined font to increase salience and perceived importance. This was motivated by research investigating methods of directing attention to specific information in maps (Wickens, Ambinder, & Alexander, 2004). To differentiate height-above-ground-level from altitude, we added parentheses and in regular nonbold font a unit labeled "AGL" next to it. A dark magenta label was added to the top of the minima box to denote the category and type of approach in use (e.g., Category A ILS). Color was used to be unique and associated with a specific piece of information. In addition, color was used to connect associated information. For example, NOTAMs that affected the minimum altitude were boxed in red dashes, as was the modified minimum altitude. This was a way to show that the two were connected and the reason for the amended minimum. Blue solid boxes were used for visibility. The use of color to guide the user was indirectly motivated by the salience methods of Wickens et al. (2004). Because the procedure designer preconceives visibility and altitude penalties, all arithmetic was automatically

INOP COMPONENTS
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INOPERATIVE COMPONENTS OR VISUAL AIDS TABLE

Landing minimums published on instrument approach procedure charts are based upon full operation of all components and visual aids associated with the particular instrument approach chart being used. Higher minimums are required with inoperative components or visual aids as indicated below. If more than one component is inoperative, each minimum is raised to the highest minimum required by any single component that is inoperative. ILS glide slope inoperative minimums are published on the instrument approach charts as localizer minimums. This table may be amended by notes on the approach chart. Such notes apply only to the particular approach category(ies) as stated. See legend page for description of components indicated below.

(1) ILS, MLS, PAR and RNAV (LPV line of minima)

| Inoperative Component or Aid | Approach Category | Increase Visibility |
|---|---|---|
| ALSF 1 & 2, MALSR, & SSALR | ABCD | ¼ mile |

(2) ILS with visibility minimum of 1,800 RVR

| | | |
|---|---|---|
| ALSF 1 & 2, MALSR, & SSALR | ABCD | To 4000 RVR |
| TDZI RCLS | ABCD | To 2400 RVR |
| RVR | ABCD | To ½ mile |

(3) VOR, VOR/DME, TACAN, LOC, LOC/DME, LDA, LDA/DME, SDF, SDF/DME, GPS, ASR and RNAV (LNAV/VNAV and LNAV line of minima)

| Inoperative Visual Aid | Approach Category | Increase Visibility |
|---|---|---|
| ALSF 1 & 2, MALSR, & SSALR | ABCD | ½ mile |
| SSALS,MALS, & ODALS | ABC | ¼ mile |

(4) NDB

| | | |
|---|---|---|
| ALSF 1 & 2, MALSR, & SSALR | C | ½ mile |
| | ABD | ¼ mile |
| MALS, SSALS, ODALS | ABC | ¼ mile |

CORRECTIONS, COMMENTS AND/OR PROCUREMENT

FOR CHANGES, ADDITIONS, OR RECOMMENDATIONS ON PROCEDURAL ASPECTS CONTACT:

FAA, Aeronautical Information Services, ATO-R
800 Independence Avenue, SW
Washington, DC 20591
Telephone 1-866-295-8236

FOR CHARTING ERRORS CONTACT:

FAA, National Aeronautical Charting Office, ATO-W
SSMC-4, Sta. #2335
1305 East West Highway
Silver Spring, MD 20910-3281
Telephone 1-800-626-3677
Email 9-AMC-Aerochart@faa.gov

FOR PROCUREMENT CONTACT:

FAA, National Aeronautical Charting Office
Distribution Division, ATO-W
10201 Good Luck Road
Glenn Dale, MD 20769-9700
Online at www.naco.faa.gov
Email 9-AMC-Chartsales@faa.gov
Telephone 1-800-638-8972
Fax 301-436-6829
or any authorized chart agent

Frequently asked questions (FAQ) are answered on our website at www.naco.faa.gov. See the FAQs prior to contact via toll free number or email.
Request for the creation or revisions to Airport Diagrams should be in accordance with FAA Order 7910.4.

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*Figure 5.* Inoperative components or visual aids table.

applied when necessary. The purpose of this was to eliminate the possibility of making arithmetic errors and to delete the notes section of the plate. Although the main purpose of this study was not to reinvent the approach plate, it was necessary to eliminate the issues thought to be problematic with the current design for a reasonable comparison. It is also well understood that implementing a system for reliable dynamic charts would require extensive research and effort.

## PURPOSE

The purpose of the present study was to investigate whether approach plate minima presentation can be improved to reduce or remove

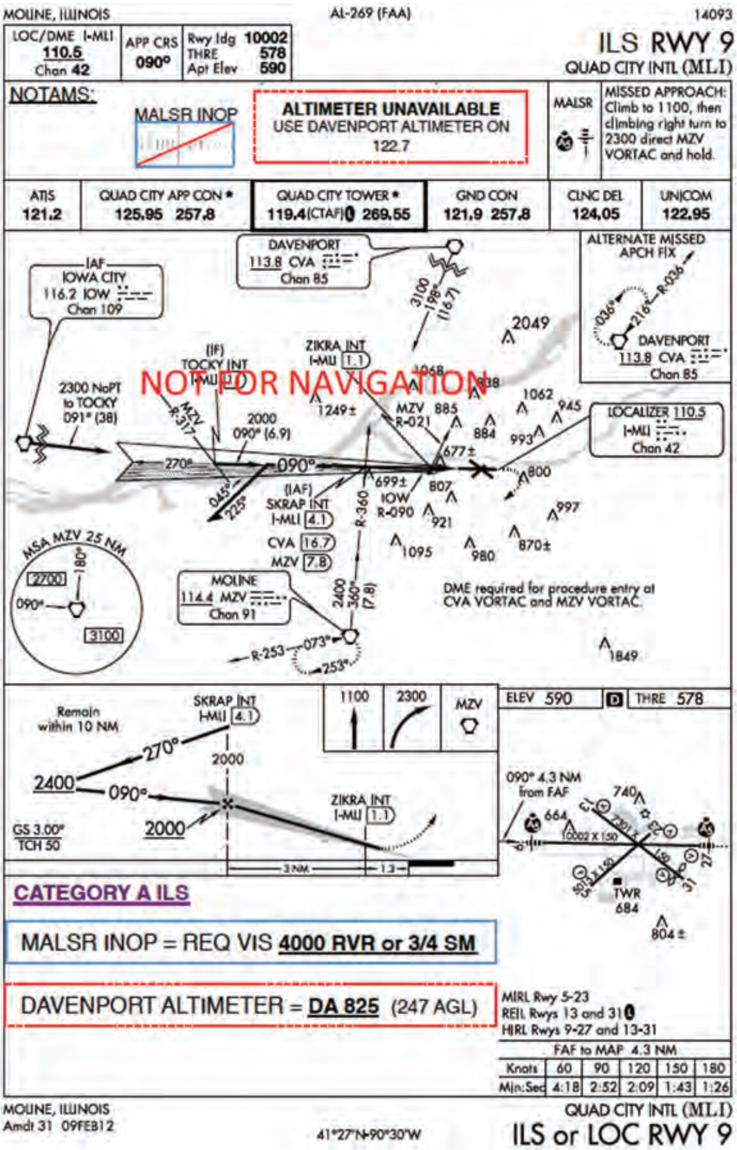


*Figure 6.* Prototype approach plate design example.

errors and decrease time when used during time-compressed instrument approaches. Specifically, this study compared a prototype method of prederived minima designed to relieve the pilot of workload during any use case. Because charting is migrating to an electronic format (Alaska Air Group, 2014; Delta Airlines, 2013; FAA, 2007b), the feasibility of creating a more dynamic and tailored approach plate is high.

Approaches with outages added to the minima pose a complex visual distraction. Charts must be robust to all use cases and aid the pilot as an effective work tool. Current approach plate design may be problematic if used concurrently with other tasks requiring attention. Late approach preparation was explored to identify how the chart works as a real-time tool with distractions. Furthermore, using a flight simulator, we duplicated flight tasks associated with the descent-and-approach phase of flight, making the demands on the pilot as realistic as possible without endangering people by testing in a real aircraft. The simulator requires many similar visual scanning requirements as compared with an airplane, increasing validity.

## HYPOTHESES

The process of identifying approach minima can range from retrieving one number from a small group of numbers to a multistep process involving other information sources and mental calculation. We hypothesized that the number of errors in identifying the correct visibility and minimum altitude from the chart would increase as NOTAM outages were added to the charted minima (e.g., approach lights out of service). When no noted outages were added to the minima, we expected that the number of errors would be very low. Error rates from the prototype chart were expected to be comparable to the standard chart without noted outages. Retrieval times were expected to increase due to the addition of procedural steps as outages to the minima were applied. When no outages were added to the minima, retrieval times were expected to be the shortest due to the task requiring the fewest steps. Outages from the prototype chart were expected to yield similar retrieval times as the standard chart without any outages.

## METHOD

### Participants

We recruited 18 pilot participants: 2 women and 16 men, aged 21 to 84 years ($M$ = 38, $Mdn$ = 29, $SD$ = 19.01) from the NASA Ames Research Center pilot participant pool. Recruitment consisted of fliers and emails sent to potential recruits. Participants were required to hold at least a private pilot's certificate with instrument-airplane rating. We did not control for age, gender, education, or ethnicity. Participant flight experience ranged from 198 hours to 10,000 hours ($M$ = 1,292, $Mdn$ = 775, $SD$ = 2,223). The sample included a diverse set of pilot qualifications, including seven private instrument pilots, seven commercial pilots, one flight instructor, one instrument instructor, and two airline transport pilots also certified as instrument instructors. Compensation for participating was US$20 per hour. Data from questionnaires were kept secure by de-identifying the participant's name and replacing it with a number. One participant's data were excluded from analysis due to a communication between the participant and a previous participant, and that participant was replaced.

### Materials and Apparatus

All sessions took place in a simulator room. The certified desktop simulator used was a personal computer–aided training device with radio navigation and a color monitor. Precision Flight Controls, Inc., of Rancho Cordova, California, manufactured the Cirrus II model flight controls and the Digital Avionics Standard radio stack. Checklists were custom made for the simulation and supported only the descent-and-approach portion of flight.

Computerized surveys were used for both the pre- and poststudy surveys. Excel spreadsheet software was utilized for recording participant retrieval times measured by a stopwatch. Approach plates were printed with a high-quality color printer to remain faithful to the original design. Prototype charts were AeroNav charts modified with PowerPoint to create the revised depiction of the notes and minima sections (see Figure 6). All plates used were current and downloaded from the FAA's terminal procedures publication service: http://www.faa.gov/air_traffic/flight_info/aeronav/digital_products/dtpp/.

### Procedure

Participants read and signed the informed consent form, then were given the prestudy demographic questionnaire on a laptop computer. Next, they received a verbal briefing of the experiment (e.g., how many approaches they would fly, what was expected). Participants were instructed how to operate the simulator; autopilot and flight director use was demonstrated prior to the beginning of the practice session. Participants were then given one practice approach and coached on operational issues with the simulator. Autopilot or flight director use was required during the final approach portion of the flight. This was required so that all pilots could utilize the "RVR 1800 authorized with use of (autopilot; flight director; head-up

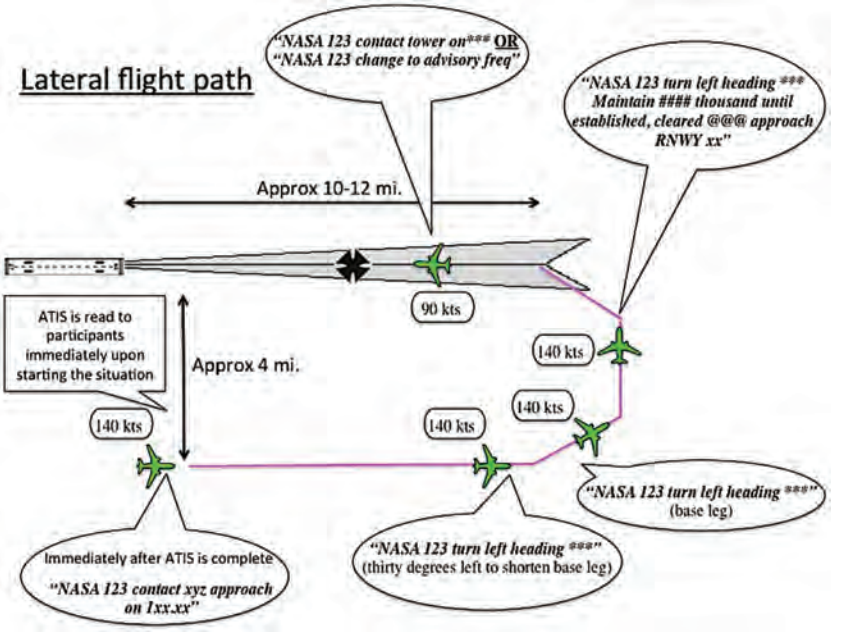


*Figure 7.* Lateral flight path flown by participants with air traffic control communications, speeds, and context notes.

display; decision altitude) AP, FD or HUD to DA" note for some approaches. Each participant flew 15 approaches under three conditions (five approaches each). The *standard-outage* condition involved five approaches using standard FAA charts with outages affecting the charted minima (i.e., airport equipment outages). The *standard-normal* condition required five approaches using standard FAA charts without outages. The *prototype-outage* condition involved five approaches using the prototype charts with analogous outages to the standard-outage condition. Each equipment outage condition was replicated between the standard plate and the prototype plate, but no specific approaches were repeated to avoid memorizing the criteria. Charts were categorized into three conditions: A = prototype-outage, B = standard-outage, and C = standard-normal. The order of conditions was counterbalanced so that each chart condition could be tested first. The condition sequence was ABC, CBA, BAC, with participants randomly assigned to each condition group. Participants started in the air before the initial descent had begun and were radar vectored to the approach by the researcher, based on a predetermined route, with scripted air traffic control instructions (see Figures 7 and 8). Participants were asked to write down the visibility requirement, primary navigation aid frequency, missed approach altitude, and the DA or MDA as applicable. The responses written down were compared with the correct answers after data collection. Feedback was not given to the participants on answer accuracy. Errors were analyzed and placed into their appropriate category or categories. *Omitted procedure error* was identified when a participant would select the appropriate minimum but not add a penalty. *Incorrect procedure error* was identified when a participant would add a penalty that was not appropriate for the condition. *Selection error* was identified when a participant chose a value listed on the chart that was not appropriate for the condition. The participant's notes revealed *arithmetic error* when an addition error on the scratch paper was obvious. When errors were not identifiable, they were designated as *other.*

## Design

This study was based on a repeated measures experimental design that compared the three

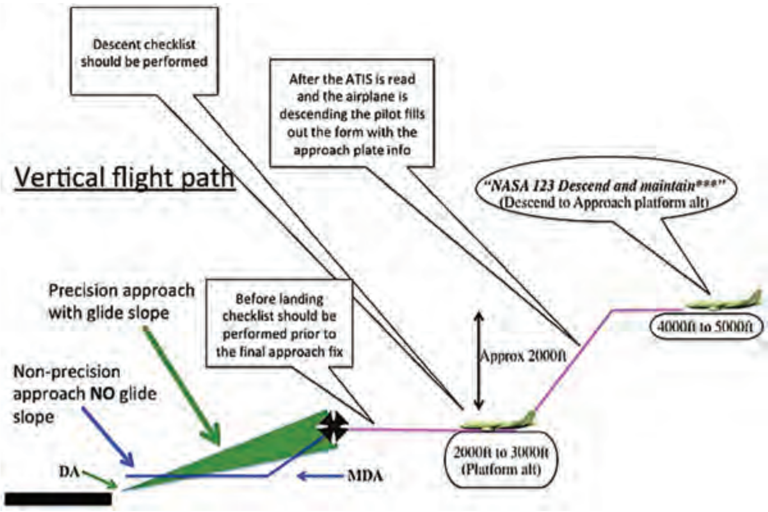


*Figure 8.* Vertical flight path flown by participants with air traffic control communications, speeds, and context notes.

conditions (standard-outage, standard-normal, and prototype-outage). Dependent variables were consistent among all conditions: correct or incorrect minimum altitude and minimum visibility identification (i.e., errors) and retrieval times for identifying minima. Mean error rates and retrieval times were analyzed through a repeated measures analysis of variance (ANOVA) to determine if differences existed among conditions. Mauchly's test of sphericity was performed to test the assumption of uniform levels of variance. A Huynh-Feldt correction was applied when this assumption was violated. Degrees of freedom were rounded down to the nearest whole number and reported in the event that a Huynh-Feldt correction was applied. Post hoc pairwise comparisons were made with the Fisher-Hayter test for repeated measures data (Huitema, 2011). For pairwise comparisons, effect size was measured with Cohen's *d*. Pearson correlation coefficients were calculated to identify correlations between the number of errors and numerical participant demographic data. Due to outliers in age (84 years) and flight time (10,000 hours), correlational tests were performed with and without the outliers to gauge their influence. Participants were randomly assigned to three groups, which dictated the order of approaches they received. This measured if the preceding chart type led the participant into a different level of performance. A one-way ANOVA was performed to test for differences among the counterbalanced groups' error rates and retrieval times. All tests were performed at a .05 level of significance.

## RESULTS

### Effects of Counterbalancing Order on Errors and Retrieval Times

To assess the effect of chart presentation order on errors, a one-way ANOVA was performed. This compared each of the three chart orders (ABC, BAC, CBA) against the errors in each chart type: A, B, and C. There was no significant difference in mean errors across presentation order. Because retrieval time was also a dependent variable and therefore subjected to the same counterbalancing system, a second one-way ANOVA was performed. This assessed the counterbalancing system's effect on retrieval times. No significant mean differences were found to exist across presentation order. Because no effects of the counterbalancing order were found, all of the data were grouped for subsequent analyses.

### Errors

The hypotheses that error rates would be greater due to outages affecting the minima, as well as relatively low when used during normal

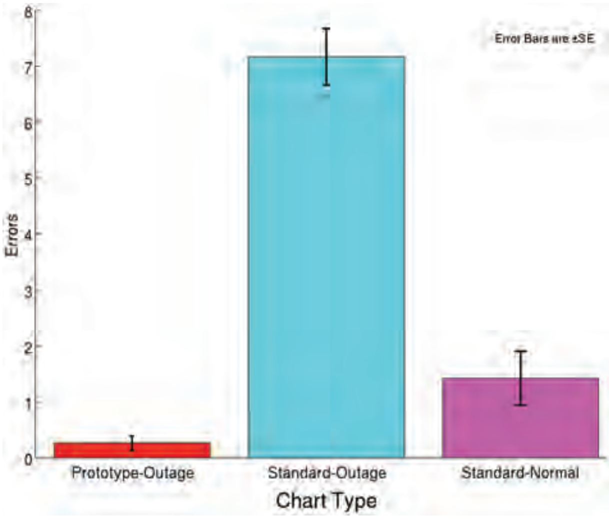


*Figure 9.* Mean error rates for each chart condition.

operations, were both confirmed. When outages were added to the standard chart's minima, mean errors were 7.28 (*SD* = 2.14). When the standard chart was used in normal conditions, mean errors were 1.39 (*SD* = 2.09). Furthermore, the hypothesis that an alternative prototype depiction of the minima would reduce errors when outages were added was also confirmed. Mean errors were 0.28 (*SD* = 0.57; see Figure 9). These mean differences were statistically significant, $F(2, 34) = 116.23$, $p < .001$. Three Fisher-Hayter tests were performed to test all pairwise comparisons. All three tests revealed significant mean differences. The standard chart with outages produced significantly more errors than did the prototype chart, *q*F-H(34) = 20.06, $p < .001$, $d = 4.73$. Surprising, the prototype chart with outages had a significantly lower mean number of errors than did the standard chart used during normal conditions, *q*F-H(34) = 3.19, $p = .031$, $d = 0.75$. Finally, the standard chart during normal conditions produced significantly fewer mean errors than did the standard with outages, *q*F-H(34) = 5.89, $p < .001$, $d = 3.98$.

Because participants made such a large number of errors when outages were added to the standard charts, Pearson correlations were performed between error rates and participant demographic data in an attempt to explain some of this effect. Total flight time, flight time in the last 3 months, number of instrument approaches in an airplane in the last 3 months, number of instrument approaches in a simulator in the last 3 months, and age were compared with error rates (see Table 1). The only significant correlation with errors was with the number of instrument approaches flown in an airplane in the last three months, $r(16) = -.576$, $p = .012$, two-tailed, $r^2 = .332$. Interestingly, instrument approaches in a simulator revealed nonsignificant results with another very low *r* value. Tests performed without the two outliers revealed similar results.

Errors were identified and categorized by type, then graphed to illustrate their respective proportion of the total errors (see Figure 10). Omitted procedure error and selection error were the two most common and constituted 44% and 34% of the total errors, respectively. Unexplainable errors that did not have an identifiable cause accounted for 6% of the total errors.

## Retrieval Times

The hypotheses that outages affecting the minima would increase retrieval times and that the prototype would reduce retrieval times given the same conditions were confirmed. Mean retrieval times (in seconds) increased when outages were added to the standard chart ($M = 57.19$, $SD = 27.82$) versus the standard chart in normal operations ($M = 34.90$, $SD = 12.30$). In addition, the prototype chart with outages yielded shorter

**TABLE 1:** Pearson Correlations of Mean Error Rates and Demographic Information

| | Mean Error[a] |
|---|---|
| Age | .147 |
| Total flight time | .055 |
| Flight time last 3 months | .087 |
| Instrument approaches last 3 months | |
| Simulator | –.091 |
| Plane | –.576* |

[a]Aeronautical Navigation Products with exceptions.
*$p < .05$.

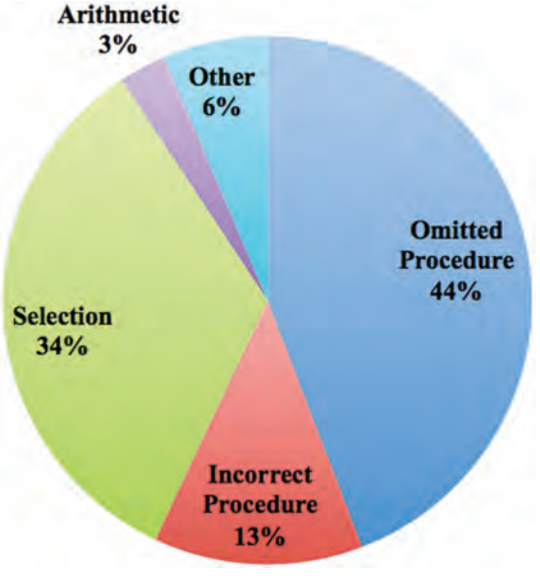


*Figure 10.* Error proportions by type.

mean retrieval times than the standard chart with outages ($M = 42.04$, $SD = 12.00$; see Figure 11). These mean differences (based on Huynh-Feldt correction) were significantly different, $F(1, 18) = 11.75$, $p = .002$. Three Fisher-Hayter tests were performed to test all pairwise comparisons. Results comparing the standard chart with outages against the standard chart during normal operations were significant, $q$F-H(2, 34) = 5.00, $p = .002$, $d = 1.18$. Results comparing the prototype chart with outages against the standard chart with outages were also significant, $q$F-H(2, 34) = 3.39, $p = .028$, $d = 0.80$. Retrieval time

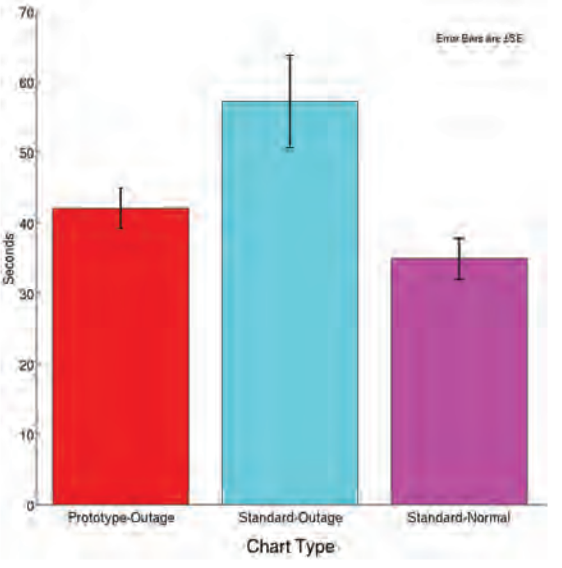


*Figure 11.* Mean retrieval times.

differences between the prototype with outages and the standard chart during normal operations were similar and nonsignificant. Three Pearson correlations were also performed to determine if there was a relationship between number of errors in each condition and length of time to retrieve the answers. None of the results were significant. Visual analyses of the scatterplots revealed no noticeable relationships. With the prototype chart and the standard chart during normal operations, there were simply too few data points to see any systematic relationship. Pearson $r$ values were as follows: $r(16) = –.043$, $p = .865$, two-tailed, and $r(16) = .185$, $p = .463$, two-tailed, respectively. The standard chart with outages had many data points but was completely unsystematic, $r(16) = –.103$, $p = .684$, two-tailed.

## Subjective Survey Responses

Responses to the poststudy survey revealed that 12 of 18 (66%) participants reported that a part or parts of the standard approach plates are confusing. Of those 12, 50% ($n = 6$) said that the minima section was confusing; another 50% ($n = 6$) said that the briefing and notes section was confusing. Approximately 16% ($n = 3$) of participants believed that there was information on the charts that was unnecessary. Forty-four percent ($n$ = 8) believed there was information missing from the chart that would have been beneficial. In addition to simple yes/no questions, participants were asked to explain the specific issues that they thought were confusing. Several participant quotes explain the issues:

- "Minimums increase are specified separately for ceiling and visibility, so you have to compute both separately. A unified minimum would be clearer."
- "Text often very dense especially when explaining many nonstandard variations (effects of inop components or missing equipment)."
- "I don't like NOAA plates where you have to go to a separate place (the INOP table) to figure out alternate minimums when approach equipment is INOP. I like Jeppesen plates where all the info is on the plate you are using."
- "If I haven't flown for awhile I often forget what is what in the minima area until I review it, and the same goes for the profile and plan views as well. There's a lot of information and often repeating information in parenthesis does not always help to simplify things."
- "The LDA approach minima were confusing as to which minima I had to use."

## DISCUSSION

### Expected and Unexpected Performance

We investigated the effects of minima depiction and airport equipment outages on errors and retrieval times. Our goal was to identify and assess different problems with charted minima as they pertain to human performance limitations. In addition, we analyzed a possible mitigation strategy by comparing a prototype approach chart to the current approach charts. Lower error rates were observed with the prototype chart versus the standard chart when outages affected the minima. In fact, mean errors were approximately 26 times less with the prototype chart. Error rates were also approximately 5 times less with the standard chart during normal operations as compared with the standard chart with outages affecting the minima. These results were generally in line with our hypotheses. In contrast, the prototype chart with outages yielded approximately 5 times fewer errors than the standard chart in normal operations. This finding was unexpected, as the two chart types were hypothesized to be comparable in all performance aspects.

The errors observed during normal operations with the standard chart may be attributed to several factors, but one explanation could be the inconsistent spacing of rows and columns between different approach configurations. For example, the ILS 01R in Washington Dulles and the ILS Z 16R at Paine Field are north/south runways, using more longitudinal space of the chart and compression of other parts. In this case, the result is an instrument landing system (ILS) minima row that is half the height of the others. Several participants chose second-row minima when they should have selected from Row 1. Numbers are also centered in the column they occupy. If the minima are applicable to all categories of aircraft (e.g., ABCD), the information will not be aligned with the row below it and will have a large blank area to the left, which is generally where people start reading. Furthermore, the presence of noncivilian information, distinguished by parentheses, caused errors for participants using the standard chart in normal conditions. Participants would choose the wrong (military) number as their visibility minimum. These issues might be the result of a learned habit as they quickly retrieve information. Jeppesen uses parentheses to depict height above ground level, which is applicable to the civilian user. If users are exposed to both government and Jeppesen formats, there is a possibility of negative transfer with respect to the meaning of parentheses. This unexpected result may indicate that the lack of unit labeling and selection error possibilities are problematic.

### Time Pressure

Every trial was intentionally time constrained to simulate an approach change near the airport and to add realism. This forced the participants to use the chart as a real-time work tool, which required its use to be mixed with primary flight tasks, such as monitoring aircraft parameters, navigating, and communicating with air traffic control. When the chart was used simply as a data extraction interface (i.e., search and identify), flight interference was relatively low, as was chart use interference. Pilots were able to make quick transitions between monitoring the aircraft and extracting pieces of information from the chart. In contrast, when the chart required multiple steps (i.e., when outages were added), the primary task of flying the airplane was sometimes neglected. Speed, checklists, and navigation frequency identification were common tasks that were discarded when the chart required abnormal amounts of attention. One participant wrote in the poststudy survey, "Most charts are simple, but some charts have an impenetrable wall of text that can require a great deal of decision making."

Conversely, there were times when the flying tasks would take priority over the intricate steps of the chart. This caused the chart to be revisited multiple times, eventually leading to some very complicated retrieval errors. For example, one participant knew about a required procedure but was simply unable to concentrate on it long enough to arrive at the correct answer. This resulted in an arithmetic error, a selection error, and an incorrect procedure error in a single case. Throughout the entire study, no participants asked for a delay to prepare for the approach. At no time was it said that delays were not allowed. This was a fascinating occurrence, as there were many approaches that were not set up completely, yet the pilot elected to continue. It is unclear if this phenomenon was an artifact of flying in a simulator or if pilots felt compelled to continue for some other reason.

## Errors and Retrieval Times

Our data showed no relationship between correct answers and retrieval times for any of the three chart types. This has different meaning depending on which chart type is discussed. Omitted procedure error, incorrect procedure error, and arithmetic error differed in the amount of time that it took to get to the wrong answer. Incorrect procedure errors and arithmetic errors exhibited longer retrieval times and incorrect answers, whereas omitted procedure errors were shorter. Therefore, the retrieval times could be fast and inaccurate or slow and inaccurate. In addition, omitted procedure errors as a result of not using the inoperative components or visual aids table were particularly interesting. Several participants did not use the table even though it was attached to a clipboard in front of then. In reality, it would be more difficult to access and not co-located with the charts in use. This may indicate that pilots are not familiar with its purpose or usage. Furthermore, if pilots do not use this table when it is given to them, it is unlikely that they use it in reality. Last, the prototype-outage chart's lack of correlation with time and errors is not meaningful due to the lack of data points.

Error rates were most likely high in the standard chart, with outages due to the complexity of the procedural steps in combination with the complexity of the task of flying. Additionally, pilot knowledge and training of how to handle these issues appeared to be highly variable, as indicated by the observed differences in errors and retrieval times. This combination was enough to render the information presentation ineffective in certain cases. Overall retrieval times were in line with the hypothesis, as well as similar to Butchibabu and Hansman's (2012) decluttering results with information retrieval from approach procedures. When unnecessary information is removed, it reduces complexity and allows for faster identification of important information. Average retrieval times were reduced by approximately 28% with the prototype chart as compared with the standard chart with outages affecting the minima. Furthermore, this increase in speed did not come at the cost of increased error. During high-workload phases of flight, reducing retrieval times is undoubtedly a positive outcome. Limiting the duration of cockpit distractions allows for more resources to be applied to understanding the current situation.

## Implications

This study provided empirical support for identifying the limitations of standard approach minima depiction in delivering information to pilots in time-compressed situations with equipment outages. These findings in and of themselves should not be mistaken for an overall evaluation of the standard approach plate but rather a small subset of unusual use cases. Mostly, these findings, along with others preceding them, should be taken as a cue that aviation charting could be improved. Prior limiting factors, such as printing costs, color ink, and paper thickness, are no longer issues. High-resolution screens and automatic dependent surveillance–broadcast connectivity could allow the user to update data in real time and display them on an electronic interface. Initial charting design for any procedure should incorporate known human perceptual and cognitive limitations, with special consideration for the context of use, environmental as well as situational.

### Limitations

Generalizability of this study may be limited to AeroNav charts because Jeppesen utilizes an alternative method of depicting approach minima. However, certain notes and NOTAM changes would be similar in the Jeppesen format. Utilizing a simulator may have produced different behavior than that seen in actual flight. This study focused on realism but undoubtedly fell short in several areas. Because this study was performed as a single-pilot operation, there may be differences in the way that two-crew operators handle situations with instrument approaches. It was beyond the scope of this project to address these issues.

### Future Research

This research required long data collection sessions; therefore, it was limited in scope. Many separate yet closely associated areas are still in need of exploration. First, comparing Jeppesen approach plates with the same procedures and study design is a logical next step in fully understanding performance limitations in approach minima depiction. Second, exploring two-crew operations would address areas that this study could not. Effects of crew coordination, crosschecking, and briefing would be further areas to examine. Third, NOTAM depiction as it pertains to other aspects of charting will need to be explored. Because NOTAMs can affect other parts of the chart besides the minima section, a comprehensive investigation is required to gauge their impact on operational safety. Finally, the impact of time pressure as an independent variable during abnormal and normal operations would be useful in determining exactly how detrimental it is to performance.

## CONCLUSIONS

This study provides support for the previous studies on approach plate decluttering and information depiction. In comparison with Butchibabu and Hansman (2012) and Osborne et al. (1995), we also noticed a significant reduction in time spent extracting information from approach charts. However, unlike previous studies, we believe that flying tasks, abnormal conditions, and time pressure created by our simulated scenarios were able to exploit further issues. In high-workload situations complicated by airport equipment outages, we noticed a large increase in errors identifying correct approach minima. In addition, our prototype method of depiction appeared to be very effective at mitigating errors in all use cases and should be explored further for possible use. By automating many of the charting procedures and changing the depiction of information, we believe that aviation safety could be improved.

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