

Designing an Efficient Trajectory Clearance Information Format for Air Traffic Controllers' Displays

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ABSTRACT

Some of the air traffic control decision-support tools currently being developed require controllers to issue complex trajectory information as clearances to pilots. If traditional voice communication, instead of a data link, is to be used, the trajectory information must be presented to the controller in a way that facilitates accurate clearance reading. The trajectory information should also be as compact as possible so the chance of obstructing critical traffic information is minimized. The present study examined the effects of three trajectory-clearance information formats—A) most abbreviated text, B) less-abbreviated text, and C) graphical format—on controllers' clearance-reading performance. The results showed tradeoffs between clearance readability and the amount and type of displayed information. The results also indicated importance of training if more-abbreviated format is to be used.

INTRODUCTION

Recently, a number of new trajectory-based operation (TBO) tools have been proposed under the Next Generation Air Transportation System (NextGen) initiative to increase air-space capacity and reduce the environmental impacts of flights. Advanced computer technologies enable the TBO tools to calculate complex flight trajectories to achieve these goals. For such applications, a Controller-Pilot Data Link Communication system (henceforth *data link*) would be ideal for conveying the complex trajectory clearance to the pilot (FAA, 1995). However, if a TBO tool is to be deployed in the absence of a data link, the clearance would need to be issued via traditional voice communication by the human controller. Even if a data link is already available, if a transition period is expected, where there will be a mixture of data-link-equipped and -unequipped aircraft, or if the system needs to have a voice backup option, clearances will still need to be given occasionally through voice communication. If that is the case, care must be taken in designing the display of new TBO clearance information.

The controller's display for a busy sector is already very crowded. To lower the display clutter level and reduce the chances of obscuring critical traffic information, a compact format is desired for the clearance information. Yet, too much abbreviation or compression of the information could impede accurate and smooth reading of the clearance and/or increase the controller's cognitive workload.

Studies on the readability of abbreviated texts have been conducted in various domains, such as instant messaging (e.g., Kleen & Heinrichs, 2008). The current study differs from previous work by focusing on a specific air-traffic-control application, where an expert operator is required to quickly reconstruct the correct phraseology from the abbreviated information and read it accurately and smoothly under high-workload situations.

In an effort to identify efficient ways to present complex trajectory-clearance information to the controller, the present study compared three display formats: A) most abbreviated text, B) less-abbreviated text, and C) graphical format. The last format presents the trajectory clearance information directly on the map display. Some TBO tools depict the clearance route graphically on the map display. If all the other information associated with the clearance, such as speed, altitude, etc., is presented next to the graphical route, this may serve as the clearance display. Such a graphical format eliminates the need to present separate text information elsewhere, and thus helps to reduce display clutter. The added graphical information might also improve awareness of the cleared trajectory.

For the complex trajectory-clearance phraseology, the phraseology developed and used by one of NASA's proposed TBO tools—Efficient Descent Advisor (formerly, En Route Descent Advisor; EDA) (Coppenger, et al., 2004) was used. In this study, air-traffic controller participants were asked to read trajectory-clearance information presented in one of the three formats. No air-traffic management task was simulated. Instead, the participants were asked to perform a simple secondary task concurrently with the clearance-reading task.

METHODS

THREE CLEARANCE TYPES AND PHRASEOLOGY

To investigate the effects of the formats, the phraseologies for three EDA clearance types, denoted CT1 (descent speed), CT2 (cruise and descent speeds), and CT3 (path stretch), were used in this experiment. Examples are as follows:

- CT1 (descent speed): “American 123, EDA clearance, descend via the SHARK SIX arrival, transition at 260 knots in descent.”
- CT2 (cruise and descent speeds): “United 456, EDA clearance, maintain mach .81, descend via the LUNAR FIVE arrival, transition at 280 knots in descent.”
- CT3 (path stretch): “Continental 789, EDA clearance, maintain mach .77, revised routing when ready to copy,” “Continental 789, at Bowie (BOW), proceed direct to the HERON 146 bearing 108 mile fix, then direct HERON,” “Continental 789, descend via the SHARK SIX arrival, transition at 260 knots in descent.”

Note that CT3 clearance is issued via three separate radio transmissions and is the longest and most complex clearance of the three types. The pilot’s read back was not included in this study. All waypoints and Standard Terminal Arrival (STAR) names used in the experiment were fictional.

DISPLAY FORMATS

Format A is the most abbreviated text format, containing the bare minimum text information necessary to reconstruct the required phraseology. Figure 1 shows an example of a CT3 clearance in format A. (The purpose of the CLOSE button will be explained in the Tasks section.) The “C/” and “D/” indicate the cruise speed and the descent speed, respectively.

Format B, the less-abbreviated text format, presents more textual information than format A. If format A resulted in degraded clearance-reading performance compared to format B, that implies that the aggressive text abbreviation comes at a cost. Figure 2 shows the same CT3 clearance example in format B. Each line corresponds to a single radio transmission. The title bar shows “EDA CLEARANCE,” allowing the participant to simply read it following the aircraft ID.

Format C is a graphical format. Figure 3 shows the same CT3 clearance example in format C. The diamond represents the aircraft, the circle represents the navigation aid, and the crosses represent the waypoints. The cleared routes are shown in cyan color. The amount of text information in format C is exactly the same as in format A. The intention was to measure the effects of the graphical information by comparing formats A and C.

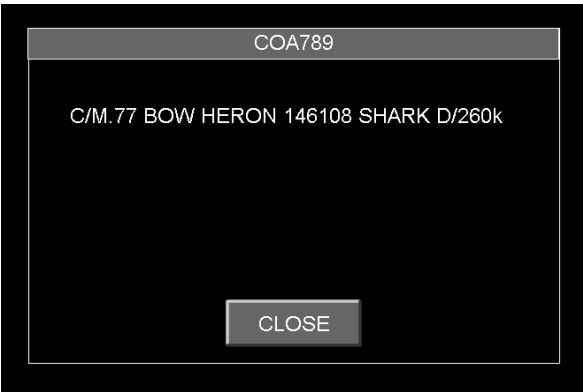


FIGURE 1 Example of CT3 clearance in format A. (Window size: 7" x 4.5")



FIGURE 2 Example of CT3 clearance in format B. (Window size: 7" x 4.5")

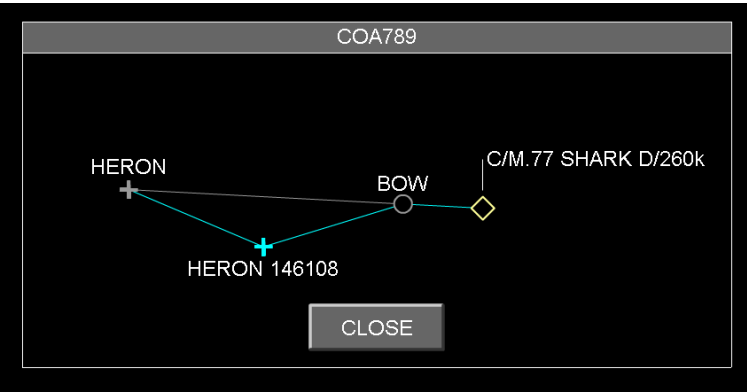


FIGURE 3 Example of CT3 clearance in format C. (Window size: 9" x 4.5")

PARTICIPANTS

Five retired and one current en-route air traffic controller participated in the study. All of the retired controllers retired within the past five years. Two were female and four were male. The ages ranged from 32 to 62 (mean: 51, std: 11), and their en-route-sector control experience ranged from five to 33 years (mean: 18, std: 11). All demonstrated sufficient visual acuity to view the displayed information used in this experiment (some used glasses).

APPARATUS

A 15-inch laptop computer was placed in front of the participant to present the clearance information. A mouse was provided on the right-hand side of the laptop for the participant's use. Another 15-inch laptop computer was placed on the left-hand side of the first laptop angled to face the participant to present the secondary-task visual stimuli. Both the clearance-information displays and the secondary-task visual stimuli were generated using ActionScript 2.0.

TASKS

The primary task was reading the trajectory clearance. Clearance information was presented on the monitor in front of the participant in one of the three formats. The participant reconstructed the proper phraseology and read it aloud. When the reading was complete, the participant clicked the CLOSE button using the mouse. The next clearance information then appeared. The process was repeated.

In addition, a secondary task was administered to assess the participant's spare attention level. The side monitor presented a yellow vertical bar whose height reduced at a constant speed. The participant was asked to press the space bar as soon as he/she noticed that the top of the bar had reached the bottom. This task mimicked monitoring for another flight to attain a certain point or altitude at a known speed. The bar size was 1.25×4 inches at its full height. The bar speed was randomly chosen from three values: 6.8, 8.5, and 10.3 cycles per minute. If the space bar was pressed prematurely, it was inactivated for two seconds and the vertical bar turned red. The participants were instructed that they should perform both tasks well, but if maintaining the dual tasks became difficult, the secondary task could be unattended temporarily.

PROCEDURE

Prior to the experiment date, an information packet was sent to the participants, and they were asked to read it and memorize the phraseology, the waypoint names, and the STAR names. On the experiment date, a briefing was held to review the

information in the packet, and was followed by a practice session. Once the participant and the experimenter both felt comfortable, the data collection started.

The same format was used within a single trial. Each participant performed nine trials, containing three trials for each of the three formats. The orders of the formats were counterbalanced within and among the participants. Each trial consisted of four CT1, four CT2, and nine CT3 clearances (thus, 17 clearances in total), presented in a balanced order.

The data collected were the audio recording of the clearance reading and the timestamps of the participants' presses of the CLOSE button and the space bar. After completion of all the nine trials, the participants filled out a questionnaire that asked questions regarding their subjective preferences and comments.

RESULTS

SPEED OF CLEARANCE READING

The clearance reading times, measured as the time between the opening of new clearance information and the pressing of the CLOSE button, were analyzed with a four-way mixed-model analysis of variance (ANOVA). The main effects were Participant, Trial Block (the first three, second three, and the third three trials), Format (A, B, and C), and Clearance Type (CT3 and others). The Participant was treated as a random effect (Lindman, 1974), which led to more conservative statistical-inference results. The results showed statistically significant effects of the Participant ($F_{5, 810} = 157.5, p < 0.01$), Format ($F_{2, 10} = 6.5, p = 0.02$), Clearance Type ($F_{1, 5} = 409.8, p < 0.01$), Participant \times Trial Block ($F_{10, 810} = 9.1, p < 0.01$), Participant \times Format ($F_{10, 810} = 2.13, p = 0.02$), Participant \times Clearance Type ($F_{5, 810} = 31.1, p < 0.01$), Trial Block \times Clearance Type ($F_{2, 10} = 4.43, p = 0.04$), and Participant \times Trial Block \times Format ($F_{20, 810} = 2.21, p < 0.01$).

To visualize the Format effects, Figure 4 plots the means and standard errors of each format. Format B resulted in the fastest clearance reading, and format C resulted in the slowest. Planned comparisons showed a statistically significant difference between formats A and C ($F_{1, 10} = 4.80, p = 0.05$), but not between A and B. For the formats B and C, a more-conservative Fisher's *post hoc* comparison was applied since testing this pair was not planned originally: The results showed a statistically significant difference between these two formats ($F_{1, 10} = 13.4, p = 0.01$).

Figure 5 plots the means of clearance-reading times for each combination of the trial blocks and formats. It shows large learning effects in formats A and C, but not in format B. Later in the trials, format A resulted in even faster clearance reading than format B. However, the Trial Block \times Format effect did not result in a significant difference in the above ANOVA, mainly due to the presence of the random effect. Instead, the Participant \times Trial Block \times Format effect was found to be statistically significant. That implies the impacts of the Trial Block \times Format

effects depend on the individual participant.

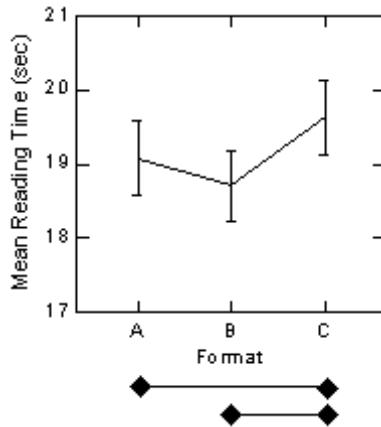


FIGURE 4 Format effects on clearance-reading time. Pairs of diamonds indicate statistically significant differences.

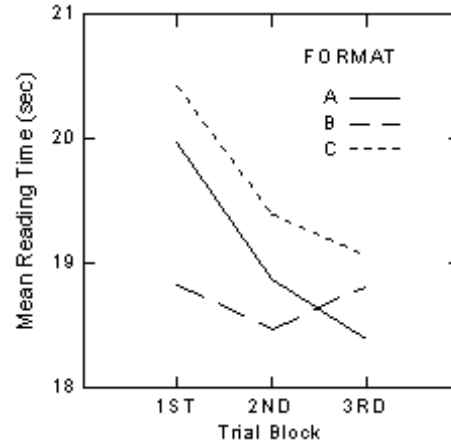


FIGURE 5 Trial Block \times Format effects on clearance-reading time.

ACCURACY OF CLEARANCE READING

Errors made in clearance reading were categorized as *format neutral* or *format dependent*. The format-neutral errors were those related to the information either displayed in an identical form in all of the formats (i.e., the aircraft ID, numbers, and units) or not displayed in any format (e.g., “descent,” “arrival”). The remaining errors were categorized as *format dependent*. Then, the format-dependent errors were analyzed in a three-way mixed-model ANOVA with Participant, Trial Block, and Format as the main effects. No interaction effect was included as there was only one frequency data per cell. The results showed a statistically significant Participant effect ($F_{5, 44} = 4.52, p < 0.01$) and a marginally significant Format effect ($F_{2, 10} = 3.55, p = 0.07$). A planned comparison of the Format effects revealed a marginally significant difference between formats A and B ($F_{1, 10} = 4.70, p = 0.06$).

Table 1 lists the frequencies of the format-dependent errors corrected and not corrected by the participants in each format. In the table, these errors were further divided into two groups: omission or wrong-word errors. A chi-square test was applied to a 2×2 table that was generated by adding the three 2×2 tables in Table 1. The test resulted in a statistically significant difference ($\chi^2_1 = 22.1, p < 0.01$). That means the omission errors were significantly harder to detect and correct than the wrong-word errors.

The format-neutral errors included 76 aircraft-ID errors (about 4% of all of the

aircraft IDs called in this experiment; of which 35 were corrected), 41 number errors (i.e., wrong, transposed, or missing digits, excluding the aircraft-ID and the STAR numbers; 22 corrected), 33 unit errors (such as “miles” vs. “knots”; 23 corrected), and 13 noun errors (such as “descent,” “arrival”; 10 corrected).

Table 1 Frequencies of format-dependent errors in clearance reading

	Format A		Format B		Format C	
	Corrected	Not Corrected	Corrected	Not Corrected	Corrected	Not Corrected
Omission	4	30	0	1	7	11
Wrong Word	22	10	8	2	29	26

RESPONSE DELAYS IN THE BAR-MONITORING TASK

The response delay in the bar-monitoring task was analyzed in the same four-way mixed-model ANOVA as in the clearance-reading task performance. However, no noteworthy effect of Format or Trial Block was found.

QUESTIONNAIRE RESULTS

Head-to-head comparison results on each pair of formats showed that the participants preferred format B the most, format A second, and format C the least. Five out of six participants remarked that they liked format B presenting each radio transmission on a separate line. However two commented that format B may be too much on the air-traffic controller’s display. Three commented that they liked format A for its brevity. One participant commented that she liked format B first, but later, as she got more used to the clearances, format A became her preference. Five participants remarked that they did not think adding graphical information helped reading the clearance. One participant commented that she did not like format C because the sequence of the information was different from that in the phraseology, which forced her to look back and forth.

DISCUSSION

The results showed that controllers can read the trajectory clearance faster with the text formats (formats A and B) than with the graphical format (format C). Between the two text formats, format B (the less-abbreviated text format) generally yielded a faster reading completion time than format A (the most abbreviated text format), though the difference was not statistically significant. Format B tended to incur the fewest format-dependent errors, and therefore the least amount of time used to

correct them. This explains the resulting faster reading speed using format B. The participants may also have needed to pose and recall the subsequent words least frequently with format B. Format B was also the most preferred format among the participants, though some were concerned that the large footprint of format B may be too much for the controller's display.

Large learning effects in the clearance-reading speeds were observed with formats A (the most abbreviated text format) and C (the graphical format), but not format B (the less-abbreviated text format). Note that all participants received about the same amount of training for each format before the data collection session. That means the controllers need additional training to be fluent in more-abbreviated formats, such as formats A and C. The amount of initial and recurring training required for these more-abbreviated formats may vary largely by individual controller (based on the large Participant \times Trial Block \times Format effect observed in the reading speed). Moreover, the format-dependent error counts suggest that omissions were particularly hard to detect and correct. Hence, the instructor may want to emphasize preventing omission of critical words.

After a sufficient amount of (on-the-trial) training with format A, the participants performed as well as, or in some cases even better than, they did with format B. Format A requires smaller footprint than format B. One way to take advantage of both formats while also reducing the need for controller training is to design the display so that the controller can select either format A or B. If the controller is relatively new to the TBO tool or has not been using the tool for a while, the complex trajectory-clearance information is shown in format B. Once he/she becomes used to reading the information, the display can be switched back to format A.

Even after some (on-the-trial) training with format C, the participants did not achieve the performance level attained with formats A and B. The graphical information of the path-stretch route offered little help in clearance reading (though it may be helpful for the purpose of route planning). Thus, display designers should not depend on graphical information of the cleared trajectory. However, the route graphics was merely added information, which the participants could have ignored if they wanted. The real disadvantage of format C appeared to be the text information being displayed out of sequence. Thus, if graphical format is to be used, the display designer needs to devise a way to present the text information in an order consistent with the phraseology.

The study found a number of format-neutral errors along the way. For instance, about 4% of all of the aircraft IDs were misspoken. (In reality, many such errors are quickly corrected by either the controller or the pilot. This still takes up precious radio time, however.) What this tells us is that no matter how much displays are improved, errors in spoken words will never completely disappear. It is still important for us to make every effort to assist the controller by designing better displays. However, the ultimate solution may be a data link.

Lastly, in this experiment, the bar-monitoring secondary task did not indicate any obvious performance interference caused by the Format or Trial Block effects. Instead, the interference appeared in the primary task performance. It seemed that

all the participants managed to perform the secondary task very well. If a researcher wishes to make the secondary task a more sensitive measure of the workload level, he/she may need to raise the task intensity (e.g., faster bar speed) or select a task that requires mental resources similar to those required for the clearance-reading task, such as text search or mental arithmetic.

CONCLUSION

The study provided empirical evidence of the tradeoffs between readability and the level of abbreviation when the air traffic controllers (i.e., experts) needed to reconstruct the correct phraseology for a TBO clearance from the abbreviated information and read it aloud. The results showed that displaying the information in the less-abbreviated text format (format B) yielded the fewest clearance-reading errors and the fastest clearance-reading speed. This format was also preferred most by the participants; yet, the larger footprint required for its display may be a concern for this format. The more abbreviated and more compact text format (format A) could attain similar performance as format B (or even better performance than format B) with sufficient controller training. An idea for possible adaptive display design was discussed. This design would allow the controller to switch between formats A and B at will, to take advantage of the different levels of abbreviation without increasing the need for controller training. The graphical format (format C) caused the slowest reading-completion time as well as the greatest number of reading errors, probably due to the text information being arranged inconsistently with the clearance phraseology. Though the experiment used the phraseology for a particular TBO tool, the results obtained in this experiment are generic enough to be applied to other TBO tools' trajectory-clearance information display designs as well.

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