THE EFFECTS OF ADVANCED NAVIGATION AIDS ON CREW ROLES AND COMMUNICATION IN GROUND TAXI

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ABSTRACT

New technologies to help pilots navigate in low-visibility conditions were evaluated in a high-fidelity simulation. Navigation performance with a paper Jeppesen chart was compared with 1) an electronic moving map and 2) an electronic moving map plus a HUD. The impact of these new technologies on crew roles, procedures, and interactions is examined in this study. The debriefings suggest strategies for working with these new technologies.

INTRODUCTION

In an attempt to increase airport safety and efficiency, especially in low-visibility conditions, new technologies have been developed to aid pilots in ground taxi. Three types of navigational aids for taxiing in low visibility conditions were compared in a high-fidelity simulation of landing and taxiing at Chicago's O'Hare airport: the traditional paper Jeppesen chart, an electronic moving map (EMM), and the EMM plus a head-up display (HUD) for the captain. Pictures of these technologies can be seen elsewhere in these proceedings [1] and a complete description is in Reference 2. Sixteen highly experienced two-person flight crews from two major airlines navigated six routes in each condition. In general, it was found that pilots made more errors and taxied more slowly in the paper chart condition than in the EMM condition, and in the EMM condition than the EMM+HUD condition [2]. The purpose of the current study is to examine the differences in crew roles, procedures, and interactions in the three conditions.

The pilots were given a preferred turn-off at the beginning of each trial, 12 miles out, so that the trials would be comparable. In the conditions with the EMM, the pilots could each toggle their nav display to view a north-up airport overview showing their highlighted runway, turn-off, and cleared taxi route. At 500 feet altitude, airport traffic appeared on the airport overview. The pilots autolanded, turned off the runway, received a lengthy verbal clearance from ATC, and taxied to the concourse. In the EMM conditions, at weight-on-wheels the EMM display displaced the nav displays and showed a track-up airport map with the cleared route in magenta. Each pilot could select from 5 zoom levels. In the EMM+HUD conditions, the captain had in addition a HUD which began to depict route guidance at about 1,000 feet before the runway turn-off. Both the EMM and HUD had hold short symbology—a flashing line for the EMM and cross marks and a stop sign for the HUD. Traffic was shown on the EMM but not the HUD.

The following methods were used to ascertain crew roles, procedures, and interactions. 1) A jumpseat observer noted use of procedures and errors, and also rated crews on situational awareness, work load, and crew resource management (CRM) variables. 2) Crew communication was coded online with a field coding method, and selected trials were coded later from videotapes with a more detailed coding method. 3) Errors were analyzed. 4) Finally, pilots were debriefed after the simulation. The results from using each of the methods will be discussed in the sections that follow.

JUMPSEAT OBSERVER

A recently retired airline captain noted the following uses of procedures.

Writing Down the Clearance. The first officers wrote down the clearance in only about 59% of the trials in all conditions, even though it was a lengthy clearance. Six first officers usually did not write down the clearance. Although not related to navigation errors in this simulation, it was related to readback errors (see below).

Understanding the Clearance the First Time. The first officer did not understand the clearance the first time in 22% of the paper chart trials and in 10% of the trials when the EMM was present (Pearson's Chi Square = 7.7, df 1, p =.01). Hence, having the EMM reduced interactions with ATC at time of clearance. Of the 41 clearances that were not understood at first, 16 involved readback errors, and the other 25 involved the first officer asking further questions of ATC. Most of the questioning occurred in the paper

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condition (76%) and most of the readback errors occurred in the conditions with the EMM (88%), Pearson's Chi Square = 15.8, df 2, p<.001. Overall, more readback errors occurred when the first officers did not write down the clearance (10%) than when they did (3%) (Pearson Chi Square =5.41,df 1, p=.02), further justifying the practice of writing down clearances in busy airports when the readback is not given or corrected. In the EMM conditions, 10 of the 14 readback errors (71%) occurred when the first officers did not write down the clearance (Pearson's chi square = 4.5, df = 1, p = .03).[1]

Readbacks. Two of the sixteen first officers did not read back the clearances, even though they said it was their company's IFR procedures to do so. In the debriefing, pilots commented that in some airports there wasn't time to read back the clearance due to radio congestion. Not reading back the clearances saved seconds at a crucial time, when many errors in the simulation occurred. On the other hand, by not reading back a clearance, a first officer ran the risk of not having it corrected either by ground (who corrected 13 of the 252 readbacks in the simulation) or by the captain (who corrected 2). One readback error was not caught, resulting in a navigation error.

ATC Contacts en Route. Pilots contacted ATAC for clarification en route in 19% of the paper chart trials and in only 5% of the trials with the EMM present (Pearson Chi Square = 10.02, df 1, p =.002). (There was no difference between the EMM and EMM+HUD conditions in this regard.) Hence having the EMM reduced ATC interaction both at time of clearance and en route.

COMMUNICATION

Field Coding

Method. An online field coding method was used in all 288 trials to code the number of communication acts on three major dimensions shown to be important in group research [3]. From this, it was possible to ascertain the number of total communication acts of captain and first officer in each condition. It was also possible to ascertain the number of questions (e.g., "Is this Alpha?") and acts of uncertainty (e.g., "I'm not sure if we turn here") from captain to first officer in the three conditions. Another observer later watched and heard the videotapes and counted these acts and total acts in 21 randomly chosen trials. The correlation with the field coding method was r=.97, p <.001 on total communication acts and .88, p<.001 on number of captain's questions and statements of uncertainty.

Results. A two-way mixed-effects ANOVA with condition and crew as factors showed that there were more communication acts in the paper chart condition than in the EMM, and in the EMM than in the EMM+HUD conditions, as can be seen in Table 1.

Table 1
Number and Average Number
of Communication Acts* in Each Condition
by Captain, First Officer, and Crew,
From Weight on Wheels to Arrival at Destination

	Paper Chart	EMM	EMM+ HUD	Total	ANOVA F (2,30)
CA	991 (10.3)	503 (5.2)	390 (4.1)	1884 (6.5)	68.9 p <.001
FO	1291 (13.5)	746 (7.8)	595 (6.2)	2632 (9.1)	59.0 p<.001
Crew	2282 (23.8)	1249 (13.0)	985 (10.3)	4516 (15.7)	89.5 p<.001

*Excludes radio communication & runway callout speeds. (All intercomparisons are significant at .01 except between the EMM & EMM+HUD conditions which are significant at .05.)

Also, the captain asked more questions and made more statements of uncertainty in the paper condition than with the advanced technologies: an average of 2.3 in the paper condition, .41 in the EMM condition, and .13 in the EMM+HUD condition, F(2,30)=55, p=.001. Planned comparisons showed that the conditions all differed significantly from each other: the paper from the EMM, F(1,30)=70, p<.001, the paper from the EMM+HUD, F(1,30)=93, p .001, and the EMM from the EMM+HUD condition, F(1,15)=16.5, p <.001. The need for verbally communicating location and navigation in the paper chart condition appeared to be replaced by visual input from the technologies.

Comparison Between Conditions on More Difficult Routes

Method. We randomly picked two trials from each of the three conditions on 14 more difficult routes (which had at least one error on them). This yielded 84 trials, approximately 29% of the larger sample. (The proportion of errors in each of the three conditions was similar to that of the entire sample.) The videotapes of these trials were then coded by two different observers to determine whether the content of the acts was navigation or traffic related, and in addition, whether the acts were questions, statements

[1] It is possible that these first officers were trying to read back the clearances using the graphics on the EMM, which was difficult, according to some in the debriefing. Many pilots suggested a text list of the route on the EMM. This has now been provided for further testing.

which contained information, conveyed uncertainty, or were acknowledgements or answers. Interrater reliability was determined by a point-by-point agreement method (which takes into account both the number of agreements and disagreement), a more conservative method than those based on frequencies alone. On the measures listed above, the reliability was .73.

Results. A two-way fixed-effects ANOVA with condition and route as factors confirmed the results of the field coding in terms of relative numbers and distribution of both (1) total acts and (2) number of captains' questions and statements of uncertainty in the three conditions. In addition, there were the following findings.

ATC Communication. There were an average of 8 communication acts to and from ATC in the paper condition, and 6.7 and 6.3 in the EMM and EM+HUD conditions respectively, $F(2,42)=4.3$, $p<.025$. The difference between the conditions with the EMM and the paper conditions was significant at $<.01$, $F(1,42)=8.0$. Hence, the presence of the EMM in the cockpit reduced the calls to and from ATC by over one act per trial in this sample, a substantial number if transferable to the operational world.

Traffic Communication Acts by Crew. The content of the acts was coded as either navigation or traffic related. Having the EMM showing traffic in the cockpit increased the number of traffic related statements over the number in the paper condition in this sample. There were an average of 2 traffic statements per trial in the paper condition and an average of 4 in the conditions with the EMM, $F(2,42)=3.2$, $p=.05$; comparison $F(1,42)=5.8$, $p<.025$. This substantiates the jumpseat observer's ratings of the crews' traffic awareness being higher in the conditions with the EMM.

Length of Time the Captain Waited for Answers. We measured the length of time the captain waited for the first officer to answer his questions and statements of uncertainty. The average length of time was 2.5 seconds in the paper chart trials, 1.2 seconds in the EMM trials, and .54 seconds in the EMM+HUD trials; $F(2,42)=10.3$, $p<.01$. The paper chart condition was significantly different both from the EMM condition, $F(1,42)=7.8$, $p<.01$, and the EMM+HUD condition, $F(1,42)=20$, $p<.01$. Although these differences are not large, the captain asked more questions in the paper condition, resulting in more total time he was waiting for information in that condition.

ERRORS

Determining Errors. Errors were determined based on (1) data from the jumpseat observer, (2) the proportion of time the aircraft was over 11 meters away from the centerline in either direction, and (3) inspection of the video tapes. Errors were further classified into major and minor errors. Major errors were defined as making a wrong turn or failing to make a turn, or making an error with possible operational consequences (e.g., busted hold short). In these cases, we infer that pilots lacked situational awareness to identify the error quickly and/or could not recover quickly. Minor errors were defined as those where crews began to make an error such as overshooting a turn, but identified the error quickly, corrected it, and continued on route.

Location of Errors. The error types/locations are given in Table 2. It can be seen that most of the errors occurred in the first third of the taxiway.

Table 2
Error Type/Location in 37 Error Trials
and Number of Major Errors in Each Location

	# of Errors	# of Major Errors	% of Total Errors
Missed Runway Turn-off	3	(3)	8.1
Overshot Turn-off	4	(1)	10.8
Hold Short	5	(5)	13.5
1st Third of Taxiway	19	(12)	51.4
Rest of Taxiway	6	(5)	16.2
Total	37	(26)	100.0

Twenty-eight of the errors were in the paper condition. Of the 8 errors in the EMM condition, 1 was a missed turn off (major), 1 an overshot turn-off (minor) and 6 were in the 1st third of the taxiway (3 major). The one error in the EMM+HUD condition was an overshot turn-off (minor).

Recognition of the Error. Of the 37 errors, 9 of them did not appear to be realized by the crew (24.3%). Seven of these were major errors. All 9 were in the paper condition This was marginally significant (Pearson Chi square = 3.43, df = 1, $p=.06$) due to the small number of EMM errors, but it suggests that if the pilots did make an error in the EMM condition, the EMM helped the pilots recognize it.

Length of Time to Realize the Error. In the 27 cases where the error *was* recognized (19 in the paper, 8 in the EMM and 1 in the EMM+HUD condition), it took a mean of 23.4 seconds for the pilots to recognize it in the paper chart condition vs. 9 seconds in the EMM condition (equal variances not assumed, t = 2.1, df = 21.4, p <.05). Hence, when errors were made, it took significantly less time for the pilots to recognize their errors in the EMM than in the paper condition.

Length of time to Rejoin the Route After the Error. Not considering the five hold short errors (which did not involve leaving the route), and the one crew in the paper condition who never did rejoin the route (ending up in a different destination), it took an average of 83 seconds for crews in the paper condition to rejoin the route compared with 46 seconds in the EMM condition. (This was marginally significant at p =.06; equal variances not assumed, t=1.9, df=25.6). Hence even if the crew got off course in the EMM condition, they rejoined the route faster than those crews without the EMM.

ATC Workload. Examination of the video tapes indicated that a crew member's preoccupation with communication to or from ATC contributed to 51% of the errors in the error trials, and to 84% of the errors in the first third of the taxiway, as seen in Table 3. ATC workload also played a role in 2 of the 4 overshot turn-offs. (Just before turn-off, tower reminds the first officer to contact ground and the first officer acknowledges it.)

Table 3
Error Location and ATC Workload

ErrorType/Location	ATC Distracted	Of Total	% of Error Type
Missed Runway Turn-Off	0	3	0%
Overshot Turn-Off	2	4	50%
Hold Short	0	5	0%
1st Third of Taxiway	16	19	84%
Rest of Taxiway	1	6	17%
Total	19	37	51%

Comparing Error and Non-Error Trials on Communication Variables

Method. Each of the 37 error trials was matched with a randomly chosen comparable non-error trial on the same route and in the same condition. We did not include 9 error trials since there were no error-free paper trials to compare with them. (Excluded trials were 1 missed exit, 4 hold shorts, and 4 in the 1st third of taxiway.) We determined the location on the route where the error had been made from the EMM. We then matched this location to the tape time of the non-error comparison trial at the same location.

Error Communication Differences. The captains of the non-error crews communicated significantly more about navigation and traffic matters before the error than did the captains of the error crews: an average of 5.8 vs. 4.2 (t = -2.2, df 27, p =.04). The non-error captains had more acts containing information about navigation and traffic (2.5 vs. 1.6, t = -2.2, df = 27, p = .04) and also more acknowledgements (1.6 vs. .68, t = -2.5, df = 27, p= .02). Both the non-error captain and the first officer made more acknowledgements than did the error crews before the error (2.9 vs. 1.4, t =-2.2, df 27, p =.04).

These findings held for both paper and EMM conditions. Hence, even though there was more communication in the paper condition, and also more errors, *within* each condition, more communication was associated with fewer errors. This adds to a long line of aviation research showing that more communication is associated with fewer errors. Unfortunately, as we find out next, it appears that the crews in the error trials may have been prevented from talking in a large percentage of the error trials, the ones made on the first third of the taxiway.

Errors in the First Third of the Taxiway

Crew Behavior. Errors in the first third of the taxiway were the most common in the simulation, and hence most important to understand. In the five seconds before the error, fewer of the first officers in the error trials were talking to the captain (13% vs. 53%, t=2.4, df 14, p =.03). Further, observers of the videotape noted whether the crew discussed the route after it was given to them and also whether they had time to discuss the route. Only 33% of the crews in the error trial had time to discuss the route just after it was given compared to 73% of the non-error crews t=3.1, df=14, p =.01). It is not surprising, therefore, that only 27% of the error crews did discuss the route compared to 73% of the non-error crews (t = 3.0, df =14, p <.01). We examined in more detail why the crews in the error trials were so pressed for time. We compared the location of their aircraft with that of the non-error crews *after* they finished receiving ground clearance. We measured the distance from the turn-off on the videotape EMM display using grids matched to the EMM magnification level. The crews that made errors on the first third of the taxiway were an average of 5 grid marks (each roughly an airplane length) past the turn-off and the non-error crews were an average of 2 grid marks (t=2.7, df=14, p = .02). How far an aircraft is past the turn-off at this point is important since many times it is necessary to make turns within the first few grid marks after a turn-off. There was also a difference in the number of seconds the crews were from the turn-off when they were finished with the clearance. The crews in the error trials were an average of 22 seconds past the turn-off compared to just 16 seconds for the non-error crews ($t=2.0, df\ 14, p=.06$). Hence the crews that made the errors were delayed in both location and in time in their completion of clearance. It would often be too late to discuss the route, because the mean time of error after the turn-off was 21 seconds—one second before the average clearance was finished for the error crews. To see if taxi speed contributed to the error, we measured how long it took the non-error crew to taxi the same distance to the error location, and it was 22 seconds—almost identical. This indicated that the error and non-error captains were taxiing at the same speeds at this juncture.

We examined the events leading up to this point in both error and non-error crews. Tower told the crews to contact ground at significantly different times before the turn-off (the non-error earlier than the error), but the crews did not do so, either in time or distance from the turn-off. Ground started the clearance very near the turn-off in both cases, and the clearance did not vary significantly in length (6 vs. 7 seconds for error vs. non-error crews). A difference between the error crews and non-error crews was the longer average length of first officer readback in the error trials—12.6 vs. 7 seconds ($t=1.9, df\ 14, p=.07$).

It can be seen how compressed events are at this juncture and how differences in seconds can contribute to errors. If a crew were able to finish the clearance by 16 seconds after the turn-off, the average for the non-error crews, it would in many cases give them time to discuss the route and enable the first officer to help the captain before the average error location of 21 seconds past turn-off.

One can also note that if route information could be transmitted accurately without verbal clearance and readback, it would save an average of 14 seconds (the average clearance plus readback time), in addition to the time it takes to reach ground, and that would likely reduce errors. Even with the necessity to hear and read back clearances, the EMM and EMM+HUD reduced errors at this juncture: in the whole sample, the paper condition had 13 errors, the EMM had 6, and the EMM+HUD had none. In the six errors trials in the EMM condition, the crew seemed to forget temporarily that they had the EMM and focused only on the verbal clearance. The visuals on the HUD may have prevented this from happening.

DEBRIEFING

In general, the pilots were pleased with the technologies. They were enthusiastic about the ability to see traffic on the runway from the air on the EMM display, as well as traffic on the ground. Numerous pilots commented that having such a display would have prevented past landing accidents and other airport accidents, including Tenerife. Some pilots said that in the simulation they forgot they could access the traffic display in the air. Other crews tied scanning runway traffic to their procedures at 500', which was when traffic appeared on the display. For example, one first officer said, "Runway appears free and clear of traffic. Five hundred feet. Final flaps 30." Some pilots recommended an audio alert for a runway traffic conflict in case crews didn't look at their display. Many pilots felt that the EMM fit into their airlines' low-visibility procedures for landing, where the first officer's job is to monitor the instruments from 200 feet in the air to where the aircraft stops.

After Turn-Off. In the operational world, pilots described the time right after turn-off as high work load and high-stress. If a crew doesn't know where they are going, the captain taxies slowly until the first officer reaches ground control. The captain tries not to stop because, in the words of one captain, "If I stop this thing, it takes 30 seconds to get it rolling again." The captain then tries to hear the first few units of the clearance from ground control so that he can continue taxiing. The first officer, meanwhile, is occupied with hearing the rest of the clearance and reading it back, and also has the job of calling company to make sure their gate hasn't changed. The captains said that while their first officer was thus occupied, they were taxiing solo, without aid. Some first officers described themselves as so busy with duties that they are heads down all the way to the gate.

The pilots said that there are some busy airports where they can't reach ground control before they have to make a route decision and hence have to stop. The stop rate was estimated to be as high as 50% in some airports and was thought to contribute to airport congestion in all types of weather. Therefore the pilots appreciated having the route in front of them on the EMM (and EMM+HUD) before turn-off. In the simulation, they were told that the route that appeared on the EMM was the cleared route and that they could treat it as such before getting verbal clearance from ground. However, in some cases the pilots said they hesitated doing this, waiting for the clearance to be delivered verbally, which they were used to as being "legal." To facilitate the captain's taxiing past the turn-off in the EMM condition when verbal communication is still required, it was suggested that the first officer call out the first few route turns to the captain before going to ground, stating, for example, "Cleared route shows right on Mike 5, then left on Delta, going to ground." This would have helped to prevent the 6 errors in the EMM conditions just past turn-off.[2]

Many pilots suggested that the role of the first officer be expanded to include monitoring and communicating airport traffic as displayed on the EMM. Many first officers preferred the expanded range of the EMM to do this.

Taxiing with the HUD. One of the features most liked about the HUD was the hold-short stop signs. There were some concerns about the HUD, however. The most serious was that several captains said that they forgot that the HUD did not display traffic. "It is so much easier to taxi following the HUD, you forget you've got other information down there that is not presented up here, and traffic is one of them. . . [To see the EMM] you just have to look down, you have to pull away from the HUD." In the simulation, this captain was startled by an aircraft in front of him that had been depicted on the map but, of course, not on the HUD. In addition, three captains felt that focusing on the HUD limited their tendency to use side windows, further reducing their ability to see airport traffic. Several crews stated that when the captain is using a HUD, the first officer should systematically monitor and report traffic as it appears on the EMM and outside. If both captain and first officer had HUDs, there was a concern that no one would be monitoring traffic. Some pilots suggested an audio alert in case the first officer was not monitoring traffic.

Seven crews had concerns about crew roles and procedures when the captain was using the HUD. These concerns centered around the fact that the captain and first officer were not seeing the same thing and the first officer therefore could not monitor the captain effectively. Many pilots felt that the captain should communicate what he saw through the HUD to the first officer on a regular basis. This might require a conscious effort, since several captains made comments such as, "Whenever I had the HUD, I wasn't talking. . . I found that I wasn't doing the job that I normally like to do which is verbalize. . ." Turning to the first officer, in addition to calling out regular traffic updates, many captains liked to hear long-range route information, especially upcoming U-turns. Some captains wanted taxiways and turns called out also. It was suggested that captains make a special effort to encourage first officers to speak up when they didn't agree with or understand what the captain was doing. The biggest problem, as one captain put it, is when the captain gets "really fixed" on the HUD and the copilot thinks the captain knows exactly what he's doing.

Training. The pilots suggested a video for both the EMM and EMM+HUD, but in addition, simulator or actual taxiing experience with an instructor for the HUD so that the captain could learn how to coordinate the HUD with the out-the-window view. Four captains stated that it wasn't until the end of the 7 HUD trials that they began to learn how to do this.

SUMMARY

In addition to increasing taxi-speed and reducing errors, the new technologies reduced ATC interactions and appeared to increase traffic awareness. More communication was shown to be associated with non-error trials before the error location. However, in the error trials which took place on the first third of the taxiways, there might not have been time for the captains and first officers to communicate. Visual input appeared to be especially helpful at this juncture: the EMM reduced errors and the EMM+HUD eliminated them. In the debriefings, the pilots suggested strategies on how to use the technologies safely.

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[2] Pilots appreciated airports where tower provides the first few turns before turning them over to ground, especially if directional indicators (e.g. left or right) are also given. Pilots described airports which, in an effort to speed things up at this juncture, have a system of customized lights that lead from turn-off to the gate.