# Dynamic Aspects of Spatial Information in Air Traffic Controller Displays

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## Abstract

Despite the ubiquitous use of motion in animated displays, its impact may be minimal unless the motion can highlight task-relevant features. An examination of static vs. dynamic route presentations revealed that a continuous motion of routes in animated displays inhibited encoding of task-relevant landmarks – i.e. landmarks at turns – because the continuous motion focused participants' attention more equally across critical and less important landmarks along the route. These findings are relevant in research on air traffic controller displays. Current displays represent airplanes as "dots" that move at the radar update rate, typically every twelve seconds. With an upcoming GPS-based technology, some planes will be capable of providing aircraft position information at much faster update rates. The faster update rates have two potential implications for the display design. First, it is an open question whether a display with fast update rates, which resembles a dynamic motion display, will be better than a display with slower update rates that presents traffic information as a sequence of static images. Second, a mixture of aircraft with different update rates will be likely in the airspace until all aircrafts migrate to GPS-based technology, which may disrupt controllers' cognitive model of the airspace. This paper discusses these issues and some of the solutions considered by designers, users, and researchers in this field.

## Introduction

Animations have become an integral part of graphical displays as computers have become more powerful and animations more sophisticated. The property of motion in animated graphics has shown some promise as an effective mechanism for visually organizing complex information by grabbing user's attention and perceptually grouping otherwise dissimilar objects (Bartram & Ware, 2002). Several approaches aim to classify dynamic processes and relate their characteristics to properties of graphic displays (e.g., DiBiase et al., 1992). Despite an intuitive feeling that animations should help us to process information as they focus our attention, provide additional information, and motivate interactions, they have failed to show any significant advantage in experimental settings (e.g. Hegarty, 1992; Palmiter & Elkerton, 1993; Tversky, Morrison, & Betrancourt, 2002). This finding is especially surprising when the animated content has a natural dynamic component, such as weather (Bogacz & Trafton, 2002; Jones & Scaife, 2000).

A potential cognitive constraint that limits the efficacy of animations may be that people conceive events as being composed of discrete steps (Zacks et al., 2001), and the discretizations occur at task-relevant points when viewing animations (Lee, Klippel, & Tappe, 2003). Therefore, a sequence of static graphics that focuses on the correct set of task-relevant events may be more effective than animated graphics where the user has to discretize the information herself. Lee and his colleagues (Lee, Klippel et al., 2003) examined this hypothesis, a summary of which is described in the next section.



## Dynamic vs. Static Presentation of Routes

When people recall route information, they decompose the route into a set of discrete route parts often bounded by decision points, for instance, intersections, and/or landmarks (Couclelis, 1996; Denis, 1997; Jackson, 1998). Decision points with a direction change (i.e. turns) are better remembered than the non-turning points (decision points with no direction change). In an experiment designed to demonstrate how motion affects task performance, a route in a fictitious town was presented statically or dynamically. The static condition presented the complete route between a start and a destination point as a solid line, and the dynamic condition conveyed the route by a moving dot (Fig. 1). The participants viewed the map for 3 minutes and then asked to draw the route and all of the landmarks that they could remember.

The prediction was that dynamically presented route information focuses users' attention on the motion itself, resulting in more equal allocation of attention and equally good memory to the landmarks at turning (DP+) and non-turning (DP-) points on the route. In contrast, we predicted that a static route would allow users to allocate their attention according to the task goals, resulting in a better memory for the landmarks at the turns.

Lee, P. U., & Klippel, A. (to appear). Dynamic aspects of spatial information in air traffic controller displays. In AAAI 2005 Spring Symposium Series, Reasoning with Mental and External Diagrams: Computational Modeling and Spatial Assistance. Stanford.

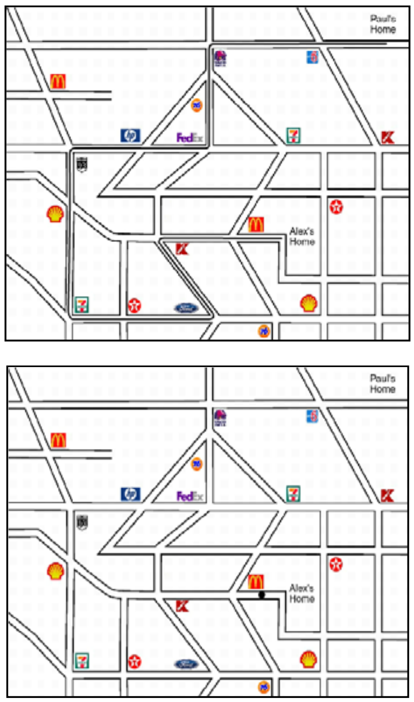


Fig. 1. Top: static route shown as a solid line; bottom: dynamic route conveyed by a moving dot tracing the route over time

The results (Fig. 2) confirmed our hypothesis that the presentation mode would affect the type of landmarks recalled. $F(1,37) = 4.1$, $p < 0.05$. The difference in the recall rate between DP+ (turns) and DP- (non-turns) landmarks were greater for the static condition (80.0% for DP+; 24.6% for DP-) than for the dynamic condition (65.2% for DP+; 29.4% for DP-).

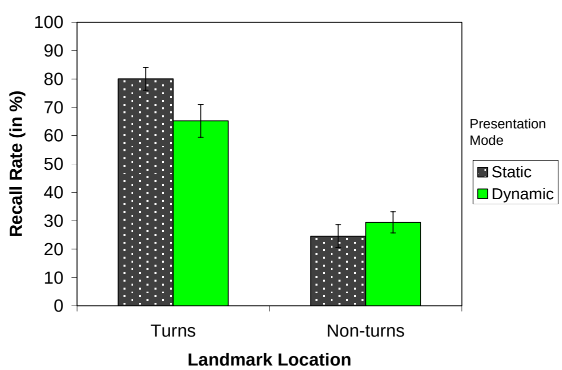


Fig. 2. Effects of presentation modes on the landmark recalls

As predicted, the dynamic route presentation reduced the recall rate of landmarks at the turns and increased the recall of landmarks along the route, suggesting that it guided the participants' attention. However, the dynamic presentation did not completely override the task goals since they still recalled the DP+ landmarks more often than the DP- landmarks.

Additionally, the dynamic condition revealed the route in piecemeal, taking away the “big picture” of the overall route and forcing the participants to attend to the moving dot to gather the route information. Despite the lack of the “big picture” in the dynamic condition, the overall landmark recall rate did not vary significantly across conditions (52.3% for static and 47.3% for dynamic), suggesting that the dynamic condition was not significantly handicapped compared to the static condition. $F(1,37) = 1.53$, $p > 0.2$. In addition, the accuracy of the generated route seemed slightly better for the dynamic (85%) than for the static condition (74%) although the results were not significant. $\chi_1 = 0.77$, $p > 0.38$.

In a follow up study, we modified the procedures to further examine the effect of motion on the recall of route relevant landmarks (see Lee, Klippel et al. 2003 for detailed descriptions of the results). In particular, we made a change in the procedures such that participants verbalized the routes during the viewing sessions. We also allowed the participants to view the routes multiple times to eliminate the inherent disadvantage of the dynamic presentation in revealing the route in piecemeal. Unfortunately, the multiple presentations seemed to have lessened the recall effects due to presentation modes. The difference in the recall rate between DP+ and DP- landmarks were greater for the static condition (57.2% for DP+; 46.1% for DP-) than for the dynamic condition (52.0% for DP+; 50.9% for DP-) but the interaction was not significant. Similarly, the accuracy of the generated route seemed to be better for the static condition (78%) than for the dynamic condition (68%) but the results were not significant. $\chi_1 = 0.41$, $p > 0.52$.

However, the verbalization data of DP- landmarks supported the hypothesis that the static condition would allow more efficient allocation of attention to the pertinent landmarks than the dynamic condition. As expected, DP- landmarks were verbalized at a lower rate in the static condition (30.6%) than in the dynamic (56.5%). $\chi_1 = 14.8$, $p < 0.0002$. Low verbalization rate of DP- landmarks in the static condition was expected since normal route directions tend to omit these landmarks. Higher verbalization rate of DP- landmarks in the dynamic condition suggested that the verbalization of the route traced by the moving dot prompted the participants to mention more of the DP- landmarks (see Table 1).

Table 1. Verbalization and recall of verbalized DP- landmarks (non-turns)

| | Verbalized DP- Landmarks | Recall of Verbalized DP- Landmarks |
|---|---|---|
| Static | **30.6** | **84.8** |
| Dynamic | **56.5** | **63.9** |

Although the verbalization rate for the DP- landmarks was the lowest for the static condition, the verbalized DP-landmarks were recalled better in the static condition (84.8%) than the dynamic condition (63.9%), (see Table 1). $\chi_1 = 4.6$, $p < 0.04$. The participants in the static condition seemed to verbalize only a certain subset of DP- landmarks that seemed to have route-relevant functions, such as keeping the navigator on a long straight path, which may explain a stronger correlation between verbalized and recalled DP- landmarks in the static condition. For DP+ landmarks, most landmarks were verbalized but only half of the verbalized landmarks were recalled (54% for static; 53% for dynamic). $\chi_1 = 0.017$, $p > 0.89$. It seems that while verbalized DP- landmarks indicate participants' selective attention to those landmarks and better subsequent recall, verbalized DP+ landmarks indicate their inherent importance in route directions and is not a predictor for subsequent recall.

In sum, the verbalization and recall data of DP- landmarks suggest that the static condition was most efficient for the route memory task since participants verbalized (and presumably attended to) mostly DP- landmarks that they recalled later. A mismatch between the attributes of motion in the dynamic route map and the route direction task, which requires selective attention to the turns, resulted in an inferior memory of the relevant route information in the dynamic presentation mode.

## Air Traffic Controller Displays

The above findings demonstrate that motion can be a distracting factor when it highlights task-irrelevant features. This attention absorbing characteristic is relevant to guide the upcoming air traffic controller display design. An air traffic controller's job entails keeping a safe separation distance between aircraft and managing air traffic flows by "directing" the planes exactly where to go. He can issue a directive, called a *clearance*, such as "United 301, turn left heading 030, vector for traffic." to instruct the pilot to turn his plane to his left on a heading of 30 degrees on an extrinsic (absolute) reference frame. The controller may add the reason for the clearance, as was done in this situation in which the heading change was due to another plane in its path.

To perform their tasks, controllers look at graphical spatial displays that present aircraft locations spatially as target symbols (e.g. diamonds, alphanumeric characters) on a 2-D display along latitude and longitude, as well as other aircraft state information such as its altitude, ground speed, and aircraft type, presented in alphanumeric texts annotating the symbols. They also present other information graphically, such as a leader line in front of the plane to indicate its current heading and history markers trailing the aircraft target indicating its locations during the past few minutes. These displays have mostly replaced radar screens, although radar screens are still used today in more remote airspace (for an overview of air traffic control, see Nolan, 1999).

Fig. 3 is an example of a controller display for terminal radar approach control (TRACON), typically in low altitude airspace (e.g. below 11,000 feet). These displays allow controllers to keep track of aircraft locations, speeds, and headings, to visually inspect the spatial relationships between planes from an extrinsic perspective.

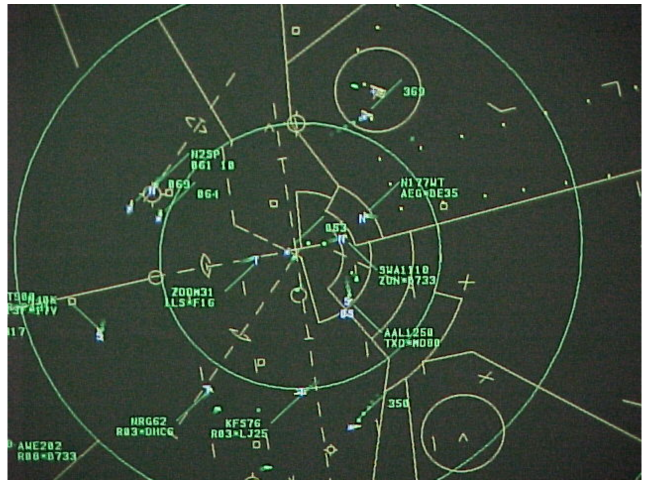

Fig. 3. An air traffic controller display in TRACON airspace

### Dynamic vs. Static Visualization

For a given *sector* – i.e. a partition of an airspace that is exclusively controlled by one or two controllers – aircraft position information is gathered from nearby radar sources and updated all at once on the controller display. Due to relatively slow acquisition rate by the current radar systems, updates of aircraft locations resemble a sequence of static "snapshots" in current controller displays (e.g. approximately every twelve seconds in some airspace). However, a surveillance technology called Automatic Dependent Surveillance-Broadcast (ADS-B) is being considered and implemented in the near future (FAA, 2000). It is based on Global Positioning System (GPS) data instead of radar-computed positions to receive aircraft information, such as position, altitude, and velocity, from ADS-B equipped aircraft at higher update rate (e.g. every second instead of every 12 seconds). The faster update rates create a more dynamic display with relatively continuous aircraft motion.

This motion has a potential to embed certain temporal components of actions, such as speed, which may be more difficult to infer from a sequence of static graphics. Therefore, continuous motion of the aircraft has a potential to highlight a task-relevant feature, i.e. aircraft speed, which can aid the controllers to visually extrapolate current aircraft heading to determine whether the aircraft will be in conflict with other aircraft in the same airspace.

A series of human-in-the-loop simulation studies was conducted at NASA Ames Research Center in order to examine future air traffic control concepts. Participants controlled simulated traffic with different update rates (e.g. Lee, P. U., Mercer, J. S., Martin, L., et al., 2003; Prevot, T., Crane, B., Palmer, E. A., & Smith, N., 2000). Based on controller feedback, the faster update rates seemed to have positive effects, but mainly due to more precise and reliable information available at a faster rate due to better surveillance technology. Whether the dynamic display played a significant role in their performance could not be determined from their feedback, and future research is necessary to isolate the effects of dynamic visualization in air traffic control.

One area in which motion may help to identify potential conflicts may be in TRACON airspace where the aircraft routes contain tight turns, complex routes, and varying speeds. Fig. 4 illustrates a schematic picture of aircraft flow into Dallas-Forth Worth (DFW) from the northwest and the southwest directions. Because the planes in this airspace are descending to land at DFW airport, they frequently change their altitudes and speeds, making it more difficult to project the current position and speeds to assess future conflicts. The southwest flow from FEVER, in particular, has a number of tight turns, which can be either shortcut or be extended to avoid conflicts and deliver the planes to the airport efficiently. In these cases it can be difficult to project how changes will play out in the future and to maintain an accurate mental image of the shape of the route.

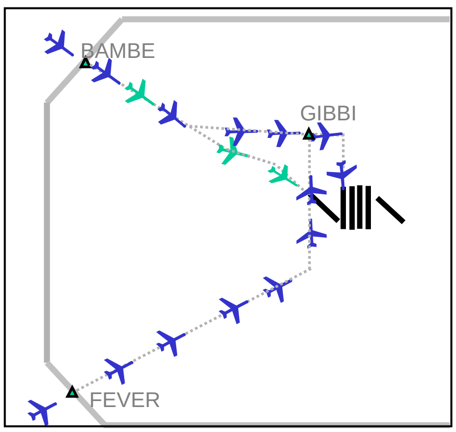


Fig. 4. A schematic of an aircraft flow into Dallas Forth-Worth TRACON airspace

In these types of traffic situations, faster updates seem to have multiple advantages. The heading and speed changes are captured more dynamically, which provide controllers with better aircraft information in an environment where these changes occur frequently. Along with better aircraft information, the controllers seemed to simulate the traffic situation mentally better by extrapolating the current heading and speed than with slower update rates, which especially seemed to help controllers who were experts in TRACON operations but were unfamiliar with this particular airspace. In actual operations, controllers spend many months/years becoming familiar with a particular airspace prior to being allowed to work that airspace.

Although faster update rates seem to highlight task-relevant features in motion, they may still result in worse performance due to a mismatch with controllers' heuristics. For example, in a level flight, in which aircraft generally do not change speeds or altitudes, controllers may have developed a set of heuristics based on current, more static displays. In a traffic situation shown in Fig. 5, a controller can actively monitor well-established traffic merge points and look for planes that are equal distance away from a merge point, flying at similar ground speeds (470 nm for AAL142; 473 nm for FDX112). Controllers are adept at using various distance markers and merge points on their displays to quickly recognize these types of potential conflicts. Ironically, it is possible that continuous motion can interfere with some of these static display based heuristics, resulting in worse performance.


Fig. 5. An example of an aircraft conflict – the large red circles highlight aircraft targets and the small red circles illustrate the predicted point of conflict at the merge point

## Effects of Mixed Update Rates

Although fast updates of aircraft state information via ADS-B technology may enhance controllers' situation awareness and ability to control traffic, there will be a significant period of time in which aircraft equipped with ADS-B technology will update its information at a faster rate than aircraft that are unequipped. A preliminary set of findings suggest that mixing aircraft equipage results in higher workload and worse situational awareness of the traffic compared to the current operations where all aircraft are monitored by the slow radar rate (e.g. Major, Johannsson, Davison, Hvannberg & Hansman, 2004).

Mixed equipage situations seem to interfere heavily with cognitive processes at multiple levels. Displaying spatial information, such as aircraft locations, at different update rates seems to interfere with controller heuristics that rely on static "snapshots" of traffic situations because some of the planes change their locations before the controller had enough time to form spatial mental models of the traffic situation.

Different display update rates for mixed equipage airspace were explored at NASA Ames Research Center, which led to the conclusion that mixed update rates of aircraft position information would be unacceptable to the controllers. Instead, it was updated at the slower radar rate for all aircraft, and different equipage markers were added to indicate that the position information was more accurate for the ADS-B equipped aircraft than the unequipped aircraft. This implementation was acceptable to our controller participants who did not show any difficulties in using it.

Interestingly, when altitude and speed – in alphanumeric texts – were presented at different update rates, these differences did not pose any difficulty for the controllers, suggesting that mixed update rates affect mainly the visuo-spatial domain; this could be attributed to limitations in visuo-spatial sketchpad in working memory. Similar conclusions were made in recent CHI (computer-human interaction) evaluations for an implementation of ADS-B in terminal airspace (FAA, 2000), in which controller displays synchronized the update rates of ADS-B equipped aircraft positions with those of radar-based aircraft positions.

Aside from the display update rates, mixed equipage presents controllers with different information, resulting in greater workload to correctly recognize and handle the different equipage class. An extreme example of the mixed equipage problem is in Oceanic control. Surveillance and communication become sparse whenever an aircraft traverses over the oceans. Most Oceanic control is out of radar coverage and therefore the position information is communicated by the pilot to the controller approximately every hour. Due to the limits of the current surveillance system, the planes are organized along parallel "tracks" that effectively reduces 4-D trajectory problems into a time-based sequencing task (see Fig. 6).

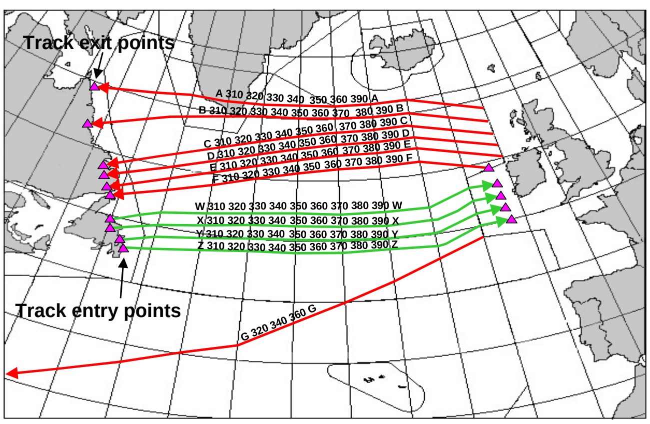


Fig. 6. Tracks across North Atlantic in Oceanic traffic (from Major et al. 2004)

The temporal information is available to the controller via *flight strips*. Flight strips are printed texts, which among other things contain estimated time to known waypoints, where complicated interactions can occur. Controllers can organize these strips according to their time of arrival and ensure safe separation distance between them by providing safe temporal spacing (e.g. keeping planes x minutes apart) via speed changes. As long as the planes arrive at particular waypoints at different times, the track structure guarantees safe distance.

Along with the flight strips, controllers also have sector maps as well as a spatial situational display (Fig. 7). The spatial situation display depicts the continuous projected path of aircraft based on the initial and updated flight plan. Although spatial displays were preferred by controllers in laboratory settings, they do not use it in current operations due to unreliable updates of this display. With the introduction of better surveillance via ADS-B and projected increase in traffic complexity in Oceanic control, controllers need to integrate the use of the spatial display with current time-based procedures using flight strips. The integration of controller heuristics based on temporal vs. spatial projection seems particularly difficult since current mental models of Oceanic controllers seem to be inconsistent with the spatial display (Major et al., 2004). As the complexity of air traffic control increases due to mixed equipage, controllers will likely treat all planes like the lowest equipage class to reduce the complexity of their spatial mental models. Further research is needed to effectively present spatial information that can allow the controllers to integrate temporal and spatial projections of different update rates and precisions into a coherent mental representation of space.

Fig. 7. U.S. Oceanic workstation with flight strips (center), sector maps (top) and spatial situational display (right) (from Major et al. 2004)

## Conclusion

Motion is an effective tool to grab users' attention which has a great potential to improve task performance if it is employed properly in graphical displays. This is especially true in many of the spatial displays, which often have dynamic components that can be represented easily via motion. Despite this potential, its efficacy fails to materialize in many displays, in which task-irrelevant features are often highlighted (Lee, Klippel, & Tappe, 2003).

Air traffic controller displays already simulate aircraft motion by updating aircraft positions over time. Due to current technology limitations, the display resembles a sequence of static images and controllers seemed to have developed heuristics that rely upon these static snapshots of traffic situations. In the near future, ADS-B technology will significantly increase the update rates, which may require a different set of heuristics to control traffic based on a more dynamic display of motion. A significant challenge exists, especially in mixed equipage situations, as planes gradually migrate from current to future technology with improved precision and update rates of aircraft information. Future research is needed to explore presentation methods that are compatible with controllers' heuristics, their corresponding mental representation of space, and their task goals.

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