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Perceptual Cues and Imagined Viewpoints Modulate Visual Search in Air Traffic Control Displays

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Planview air traffic displays depict latitude and longitude of aircraft graphically via display position but depict altitude alphanumerically via data tags. Operators must integrate both graphical and alphanumeric information to generate mental models of air traffic, perhaps limiting performance. Palmer, Clausner & Kellman (2008) showed that aircraft icons with altitude-correlated size and contrast improved detection of potential collisions. These cues may have been effective because they corresponded to the depth cues of relative size and aerial perspective, thus providing naturalistic visual metaphors for interpreting the displays. Here, we varied whether icons were correlated with depth or not and also whether observers assumed a from-above or from-below viewing perspective. In Experiment 1, the from-above perspective with depth-consistent icons yielded better performance than the from-below perspective with depth-inconsistent icons, despite these displays being physically identical. Experiment 2 replicated the finding and showed that contrast/grayscale variations evoke the perspective effect but color variations do not.

EXPERIMENT 1

Air traffic control displays use a 2D planview projection to depict the 3D positions of aircraft within a sector. In such displays, aircraft altitude is presented alphanumerically within a data tag associated with each aircraft. Consequently, the 3D position of aircraft (latitude, longitude, and altitude) is communicated to the operator through two information processing channels: graphical encoding for latitude and longitude and alphanumeric encoding for altitude. Air traffic controllers must integrate these two information sources to generate accurate mental models of the 3D air traffic situation (Roske-Hofstrand & Murphy, 1998).

Palmer, Clausner, and Kellman (2008) showed that presentation of altitude information in a graphical format can greatly improve participants' ability to detect aircraft conflicts (i.e., potential mid-air collisions). They varied the size and contrast (i.e., grayscale) of aircraft icons in a manner that was consistent with naturalistic depth cues from an overhead viewing perspective of the air traffic situation. Aircraft at higher altitudes would appear closer in this operator perspective, and thus were encoded by larger and darker icons. Aircraft at lower altitudes would appear farther from the operator and thus were encoded by smaller and lighter icons. Relative to the no-cue baseline condition, participants in the combined-cue condition (both size and contrast) showed dramatic improvements in conflict detection, equivalent to processing five more aircraft than the no-cue condition for a given level of performance.

What was the source of the benefit observed by Palmer, et al. (2008)? We propose three hypotheses. H1: Any encoding of altitude using size and contrast might improve performance, regardless of whether or not the cues are consistent with depth from the operator's perspective. Under this hypothesis, any size and contrast variations would allow guided visual search (e.g., Wolfe, 1994) and therefore more efficient detection of aircraft conflicts. H2: Another possibility is that operators benefitted from the cues because LARGER and DARKER are interpreted by conceptual metaphors to mean MORE (Clausner, 2002; Clausner & Croft, 1997). Graphical depictions of quantity that are consistent with mental metaphors of quantity should lead to better magnitude estimations (i.e., better appreciation of altitude). Specifically, displays in which high altitude aircraft are larger and darker should lead to better conflict detection, regardless of whether the operator assumes a from-above or from-below perspective.

H3: Finally, the benefit might have occurred because the size and contrast cues were consistent with depth cues from the operators' perspective, thus affording perceptual interpretations of the displays that connected to operators' ecological perceptual experiences (Norman, 1988; Gibson, 1979). Under this hypothesis, identical displays with identical size and contrast altitude assignments might yield different performance, depending on whether the operator assumes a from-above or from-below viewing perspective. If the size and contrast altitude assignments are consistent with ecological depth ordering from the operator's assumed perspective, this fact should ground operators' perceptual and cognitive interpretations of the displays and improve their processing of them (e.g., Barsalou, 1999).

We addressed these hypotheses by manipulating the mapping of size and contrast cues to altitude so that they could either be consistent or inconsistent with ecological depth from the operator's assumed viewpoint. We also manipulated whether or not operators assumed a from-above or from-below viewing perspective. If any graphical coding of altitude helps, then we expect equivalent performance in all conditions. If conceptual representations of magnitude lead to better performance, then we expect better conflict detection when higher altitude planes are larger and darker, regardless of viewing perspective. Finally, if ecologically valid displays afford better perceptual processing, then we expect conditions in which size and contrast cues are consistent with depth will yield better performance.

Methods

Participants. Eighty-five undergraduate and graduate psychology students from Wichita State University participated in the experiment in exchange for course credit. All participants gave informed consent, reported normal or corrected-to-normal vision and were naïve to the purposes of the experiment. Five participants' data were excluded from the analysis due to evidence they failed to search displays as instructed. A participant was excluded if RTs on 10% or more trials were two standard deviations faster than all other participants' mean fastest RTs.

Materials. Stimuli were presented and responses collected using two 2x2 GHz Apple Mac Pro computers, each driving a 17-inch (diagonal) Dell M991 monitor at a resolution of 1400 X 1050 pixels. The experiment was programmed using MATLAB (v7.5) and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997).

A five-step pedestal was constructed for instructing participants about altitude icon assignments (Figure 1A). Images depicting the aircraft icons were placed on the steps of the pedestal. In the from-above condition, the pedestal was placed at participants' feet and they looked down while receiving instructions about the icons (Figure 1B). In the from-below condition, the pedestal was hung from the ceiling above the participants' heads and they looked up while receiving instructions (Figure 1C).

Two hundred and forty experimental displays and ten practice displays were designed for this experiment. Each display consisted of 12 aircraft icons depicting a possible air traffic scenario. Each aircraft icon was displayed in one of eight orientations (0°, 45°, 90°, 135°, 180°, 225°, 270°, or 315° clockwise from vertical) and occupied one of five altitude bands (15,000, 20,000, 25,000, 30,000, or 35,000 feet above sea level). Data tags associated with each aircraft provided unambiguous altitude information in hundreds of feet. Two aircraft per display were on a trajectory to intersect paths, and in half of the experimental displays, these aircraft were in the same altitude band creating a "conflict present" scenario (Figure 2 features an example). In the remaining half of the experimental displays, the aircraft forming a path intersection were in different altitude bands, constituting "conflict absent" scenarios. For each air traffic scenario, half of the participants were shown a conflict present version of the display and half were shown a conflict absent display. The two scenarios differed only with respect to whether a path intersection between aircraft was at same or different altitudes. Displays were presented to participants in random order, one per trial. The altitudes of each aircraft icon were randomized within their specific altitude band for each trial as well.

Each path intersection between two aircraft formed one of four angles: 45°, 90°, 135°, or 180°. Additionally, the two aircraft forming a path intersection were one of three distances from the point at which the aircraft crossed paths: 4.2°, 5.9°, or 7.7° of visual angle.

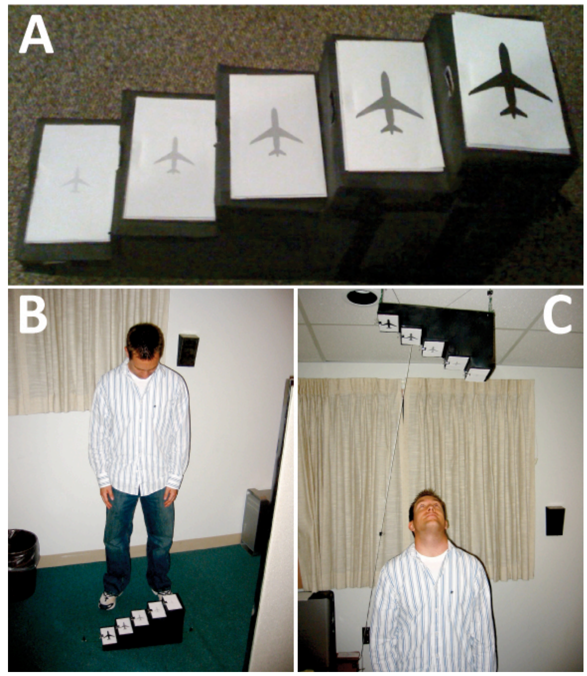

Figure 1. Perspective manipulations in these experiments. A) The five-step pedestal used in both conditions. B) The from-above condition. C) The from-below condition.

Design. There were three independent variables in this experiment with two levels each, forming eight possible conditions (Figure 3). The participant's perspective was assigned to be from-above (Figure 1B) or from-below (Figure 1C). The sizes and contrast of the icons were assigned to be either consistent or inconsistent with the depth cues of relative size and aerial perspective, respectively.

Procedure. Participants' task for each trial was to identify whether the display contained an aircraft conflict by pressing one button for "conflict" and a different button for "no conflict". The experiment began with an instruction phase in which participants learned about the conflict detection task and were introduced to the viewing perspective, size and contrast altitude-encoding variables. During the instruction phase, participants viewed a series of ten air traffic scenarios to determine if there was a conflict between any two aircraft in the display. A conflict was defined as two airplanes having intersecting paths and being within 300 vertical feet of each other.

After performing the first practice trial, participants were instructed on the use of the altitude data tags. Next, participants were instructed about the size and contrast cues associated with aircraft altitudes for whichever perspective, size and contrast cue conditions they were assigned to. Participants were then asked to stand and look at the stair step pedestal. In the from-above condition, the pedestal was located on the floor at the participants' feet (Figure 1B) and in the from-below condition, the pedestal was attached to the ceiling above the participants' heads (Figure 1C). The experimenter explained that each stair represented a different altitude band, and that the size and contrast of the aircraft icons were an indication of the aircraft's altitude. Afterward the participant was again seated looking straight ahead (fronto-parallel) and instructed to imagine each scenario from the perspective in which they were just trained, while performing eight more practice trials. For both the practice and experimental trials, text feedback indicated a correct (green text) or incorrect (red text) response.

In the experimental phase, participants searched through 240 air traffic scenarios and received a break after every 60 trials. The entire experiment lasted approximately 75 minutes.

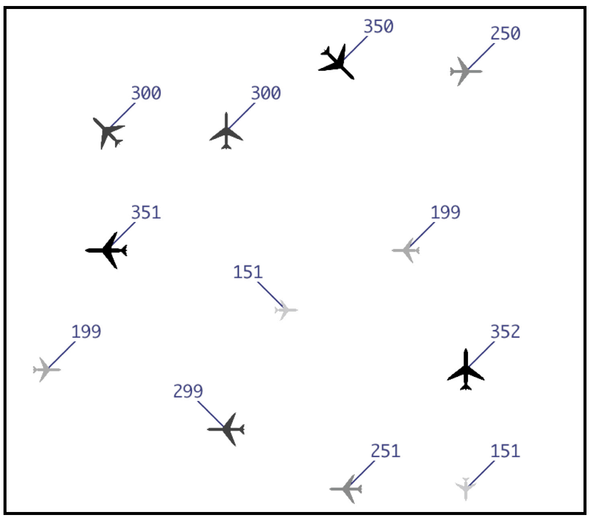

Figure 2. A sample air traffic scenario featuring a 135° conflict between aircraft at roughly 35,000 feet (upper right). In this display, higher altitudes are larger and darker than lower altitudes, which is consistent with the from-above cue consistent condition and with the from-below cue inconsistent conditions.

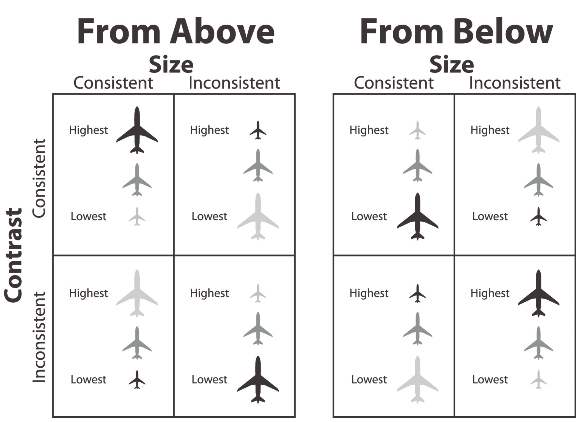

Figure 3. The eight stimulus conditions tested in Experiment 1. The axis labels refer to whether the cue is consistent or inconsistent with depth from the viewer's perspective. Notice that From-Above cues of consistent size and contrast (upper left box) are the same as From-Below cues of inconsistent size and contrast (lower right box). Only three altitudes are depicted here, though five altitudes were used in the experiment.

Results

Consistent with Palmer, et al. (2008), we predicted that the within-subjects manipulations of angle of intersection and distance to intersection would be significant factors. We also hypothesized that visual cues consistent with natural depth ordering would lead to better conflict detection than those that were not. Finally, we also expected that assumed perspective would have an effect on performance. Figure 4 graphs conflict detection performance as a function of cue consistency for size and contrast, as well as from-above vs. from-below viewing perspective.

A 4 x 2 x 3 x 4 (Cue Type x Perspective x Distance to Intersection x Angle of Intersection) repeated measures ANOVA was performed to analyze these trends. Cue type and perspective were each treated as between subject variables. In terms of accuracy, the analysis resulted in significant main effects of distance, $F(2,71) = 40.19$, $p < .01$, $\eta_p^2 = 0.53$, and angle of intersection, $F(3,70) = 37.08$, $p < .01$, $\eta_p^2 = 0.61$. There was also a significant interaction between angle and size, $F(3,70) = 2.752$, $p < .05$, $\eta_p^2 = 0.11$, but there were no other significant main effects or interactions in the accuracy data.

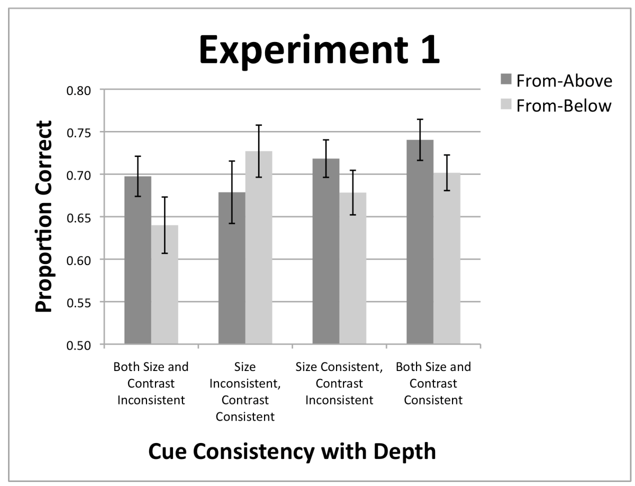

Figure 4. Results of Experiment 1. Proportion of aircraft conflicts detected as a function of cue consistency and assumed viewing perspective. Error bars represent standard error of the mean.

To more closely evaluate our hypotheses about cue consistency, assumed perspective, and magnitude, we performed a series of planned comparisons. Participants in depth consistent cue conditions from their assumed perspective were marginally more accurate at detecting conflicts than those in depth inconsistent cue conditions, $t(38) = 1.996$, $p = .053$, $d = 0.63$, n.s. Participants in the from-above perspective condition showed a numerically higher level of accuracy than participants in the from-below perspective condition, but the comparison did not reach significance, $p > .05$. Finally, performance in conditions in which higher altitude aircraft were larger and darker, regardless of viewing perspective, was not significantly better than conditions in which higher altitudes were coded as smaller and lighter, $p > .05$.

A final, important test of our hypotheses was to examine equivalent displays that differed only in assumed perspective. For instance, the air traffic scenario depicted in Figure 2 seen by participants in the from-above condition with size and contrast cues both consistent with depth is identical to the scenario seen in the from-below condition with size and contrast cues both inconsistent with depth. Comparison of those two conditions yielded a significant difference in performance,

$t(18) = 2.429$, $p < .05$, $d = 1.09$ (Figure 5). The opposite comparison of from-below, size and contrast consistent vs. from-above, size and contrast inconsistent was not statistically significant, $p > .05$.

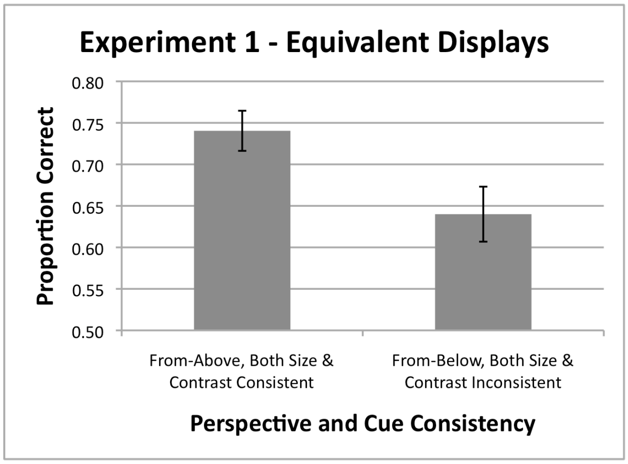

Figure 5. Performance on equivalent displays differs depending on assumed viewing perspective and cue consistency. Error bars represent standard error of the mean

Discussion

We identified and tested three possible explanations for the benefits of size and contrast encoding of altitude observed by Palmer, et al. (2008). H1: The first possibility was that *any* graphical encoding of altitude via the visual cues of size and contrast would result in improved search performance, regardless of whether the cues were consistent with depth cues and regardless of participants' assumed perspective. The results (Figure 5) rule out this explanation because participants performed better when assuming a from-above viewing perspective with size and contrast encoding that is consistent with naturalistic depth ordering.

H2: The assumption that graphical encoding of altitude that matched mental representations of magnitude by having the properties of LARGER and DARKER correspond to MORE altitude was not supported. We found that this benefit only occurred when participants assumed a from-above viewing perspective.

H3: We found support for the notion that ecological depth ordering from the assumed perspective of the participant afforded better processing of the displays. According to this hypothesis, equivalent displays should yield different performance depending on cue consistency and imagined perspective. When participants assumed a from-above perspective and higher altitudes were encoded as larger and darker, they performed better at detecting conflicts than participants assuming a from-below perspective. This finding is particularly surprising because the only difference between these two conditions was the imagined viewing perspective. While our results rule out H1 only and H2 only, they do not exclude *both* depth and metaphor being engaged and modulated by imagined perspective. Therefore, we conclude that operators' imagined viewpoints of information displays determine how graphical properties are interpreted, with some viewpoints yielding better processing than others.

EXPERIMENT 2

In this experiment, we attempted to replicate the findings of Experiment 1 using only differences in contrast (i.e., grayscale) and not size. Furthermore, we were interested in directly comparing the effectiveness of equiluminant color vs. grayscale encoding of altitude in an air traffic control task. We hypothesized that encoding of altitude using grayscale would be subject to the perspective effect observed in Experiment 1, but encoding of altitude using equiluminant colors would not. The reason is that differences in grayscale can be interpreted as corresponding to the distance cue of aerial perspective whereas differences in equiluminant colors do not correspond to any depth cue. If the grayscale condition shows the perspective effect observed in Experiment 1 but the color condition does not, then this lends support to the theory that the effect is due to operators' use of egocentric depth cues when interpreting these displays.

Methods

Participants. Sixty-four undergraduate and graduate psychology students from Wichita State University participated in the experiment in exchange for course credit. The same inclusion criteria and informed consent as Experiment 1 were applied. Four participants were removed due to failure to follow experimental protocol using the same objective criteria as described in Experiment 1.

Materials. The same computers and programming languages that were used in Experiment 1 were also used here. In the color-cue condition, five colors were chosen (red, orange, green, blue, and purple) and adjusted to be equiluminant using a Photo Research Spectrascan PR650 photometer. The levels of grayscale used in this experiment were physically identical to the levels of contrast used in Experiment 1.

Design. The same design that was used in Experiment 1 was also used here, with the following exceptions. All aircraft icons in this experiment were the same size. Grayscale/contrast coding of altitude was arranged so that higher altitudes were always darker than lower altitudes, as in the from-above contrast consistent condition. Color coding of altitude, from highest to lowest altitude was always: red, orange, green, blue, purple. Half of the operators assumed a from-above perspective and half assumed a from-below perspective. Notice that for the grayscale condition, this is equivalent to the comparison of from-above, contrast consistent vs. from-below, contrast inconsistent (as in Figure 5).

Procedure. The same procedure that was used in Experiment 1 was also used here.

Results

It was hypothesized that grayscale encoding of aircraft altitude would show an effect of viewing perspective whereas color coding of altitude would not. The data from Experiment 2 are depicted in Figure 6 and indicate that our hypothesis was supported. Conflict detection in the color condition was more accurate than the grayscale/contrast condition, but did not show an effect of assumed viewing perspective.

A 2 x 2 x 3 x 4 (Cue Type x Perspective x Distance to Intersection x Angle of Intersection) repeated measures ANOVA was performed to evaluate the data trends. In this analysis, cue type and perspective were, again, treated as between subject variables. With regard to accuracy, the analysis resulted in significant main effects of distance, $F(2,55) = 43.35$, $p < .01$, $\eta_p^2 = 0.61$, and angle of intersection, $F(3,54) = 30.13$, $p < .01$, $\eta_p^2 = 0.63$. There were also significant interactions between distance and perspective, $F(2,55) = 3.40$, $p < .05$, $\eta_p^2 = 0.11$, angle and cue type, $F(3,54) = 6.10$, $p < .01$, $\eta_p^2 = 0.25$, and distance and angle, $F(6,51) = 3.26$, $p < .01$, $\eta_p^2 = 0.28$.

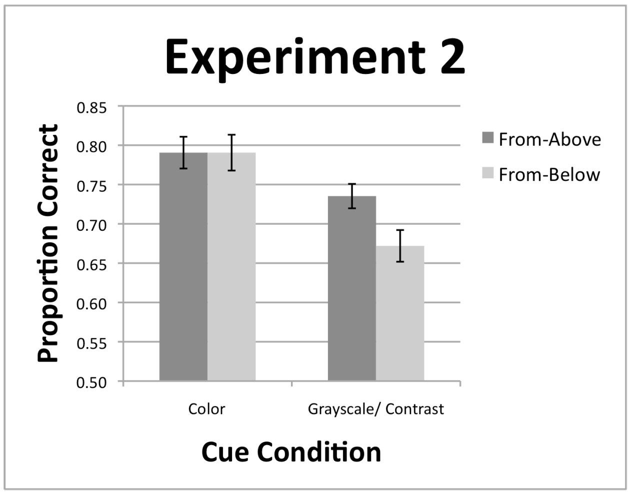

Figure 6. Results of Experiment 2. Proportion of conflicts detected as a function of cue condition and viewing perspective. Assumed perspective has an effect on grayscale/contrast encoding but not color encoding.

In addition, the analysis of between subjects effects resulted in a significant effect of cue type, $F(1,56) = 19.21$, $p < .01$, $\eta_p^2 = 0.26$. This outcome indicates that color-coding was more effective in increasing conflict detection accuracy. In this analysis, overall cue type was not affected by viewing perspective.

We also hypothesized that the imagined perspective of the participant would have a much greater effect on contrast-coded altitude than color-coded altitude. A planned comparison between the from-above and from-below perspective contrast-coded conditions indicated that participants in the from-above perspective condition were more accurate than participants in the from-below perspective condition, $t(28) = 2.067$, $p < .05$, $d = 0.75$. This effect of perspective did not appear in the color-coded altitude conditions, $p > .05$, n.s., signifying that perspective had a larger effect on contrast-coded altitude than on color-coded altitude.

Discussion

There were several important outcomes from Experiment 2. First, we replicated the finding from Experiment 1 that physically identical displays can yield better or worse performance, depending on assumed viewing perspective. This indicates that the contrast/grayscale values of the icons themselves were enough to invoke the imagined perspective effect, without requiring the co-variation of size.

Second, color encoding of aircraft yielded better overall performance than grayscale encoding. One might conclude that altitude might be better represented by color than grayscale, but note that many colors in air traffic displays are reserved for warnings and weather information, thus limiting the colors available for altitude encoding. We also suspect that the use of color for altitude in more realistic displays might create more clutter than clarity. Additionally, aircraft in the current experiments did not change altitude and we suspect that altitude change might be better represented by the continuous scale of contrast than the categorical scale of color. We are conducting experiments to examine these possibilities.

Finally, we found that not all types of graphical altitude encoding schemes produce the perspective effect. Color-coding of altitude, while yielding better conflict detection performance overall, was not modulated by imagined perspective. This implies that certain visual cues such as contrast/grayscale (and size, from Experiment 1) afford first-person, ecological, grounded cognitive processes that other cues do not (Barsalou, 1999; Gibson, 1979; Norman, 1988).

Why might some graphical cues be modulated by imagined perspective while others are not? Our contention is that graphical cues that correspond to naturalistic depth cues engage the operator in ways that graphical cues not corresponding to naturalistic depth do not. Graphical encoding of altitude information consistent with ecological depth ordering from the operator's perspective (that is, *both* magnitude metaphors *and* depth modulated by imagined perspective) yielded more accurate interpretation of displays which improved conflict detection performance in these air traffic control scenarios.

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