

EFFECTS OF AIR TRAFFIC GEOMETRY ON PILOTS' CONFLICT DETECTION WITH COCKPIT DISPLAY OF TRAFFIC INFORMATION

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We explored the effects of conflict geometry on pilot conflict understanding, manifested in estimation accuracy of three continuous variables: miss distance, time to closest point of approach, and orientation at the closest point of approach. Results indicated (a) increased difficulty of understanding with conflicts that occurred with slower speeds, a longer time into the future, and a longer distance into the future; (b) a tendency for pilots' judgments often to be conservative, judging that conflicts were both more risky and would occur sooner than was actually the case; and (c) a "distance-over-speed" bias, such that two aircraft viewed farther apart and converging rapidly were perceived as less risky than two aircraft that were closer to each other and converging at a slower rate, even though the time until a conflict occurred was identical.

INTRODUCTION

The cockpit display of traffic information (CDTI) will play a key role in free flight, allowing pilots to detect and avoid potential conflict with other aircraft, termed hereafter "intruder." Most of the studies that investigated conflict detection in aviation have been conducted in the context of air traffic control (e.g., Endsley, Mogford, & Stein, 1997; Galster, Duley, Masalonis, & Parasuraman, 2001, Metzger & Parasuraman, 2001a, 2002b; Remington, Johnston, Ruthruff, Gold, & Romera, 2000) and only a few have focused on airborne conflict detection by pilots with the CDTI (e.g., Merwin & Wickens, 1996). Several studies have addressed only conflict resolution (as opposed to detection) using a CDTI (e.g., Alexander, Wickens, & Merwin, in press; Scallen, Smith, & Hancock, 1996; Wickens, Gempfer, & Morphew, 2000; Wickens, Helleberg, & Xu, 2002). In those investigations, when there was a failure in avoiding a conflict, it has not always been clear whether the conflict was not detected at all, was detected too late, or was detected on time but the maneuver to avoid it was unsuccessful. Furthermore, most of the studies that did investigate conflict detection evaluated only detection rate and response time using a dichotomous criterion based on whether a cylindrical protected zone was penetrated or not. It has been shown that such a binary criterion is not the best measure of conflict risk (e.g., Masalonis & Parasuraman, 2003). In a task analysis (Xu, 2003), it was demonstrated that the true risk of conflict between the ownship, whose pilot uses CDTI, and intruder aircraft can be best represented by the miss distance (MD) between the two aircraft at the closest point of approach (CPA), intruder's orientation relative to the ownship's heading at the CPA (OCPA), and intruder's time to the CPA (TCPA) (see Figure 1). We believe that the estimation accuracy of these three conflict features better reflects pilots' true understanding of conflict situations and their implications for future maneuvering than does the simple dichotomous measure.

Given the importance of conflict detection with the CDTI in free flight and its under-representation in research, the present study investigated the effects of conflict geometry on pilots' conflict awareness using a CDTI. Dependent variables were estimate errors of the above-described continuous measures of conflict risk (TCPA, MD, and OCPA). The goals of this experiment were to identify the features that would make unaided conflict detection difficult or easy and to identify the biases that would affect estimation performance.

Based on our review of the literature regarding the factors influencing time-to-contact estimation and conflict detection performance (Xu, 2003, Xu, Wickens, & Rantanen, 2004), we hypothesized that estimation would be made more difficult, manifested in increased errors, by increasing TCPA (either by increasing intruder's distance to the CPA or DCPA or reducing traffic's speed) and increasing MD. It was further predicted that for a same TCPA, pilots would estimate this time to be longer with a longer distance (DCPA) and faster speed of the intruder than with a shorter DCPA and slower speed, a phenomenon known as the distance-over-speed bias (Law et al., 1993).

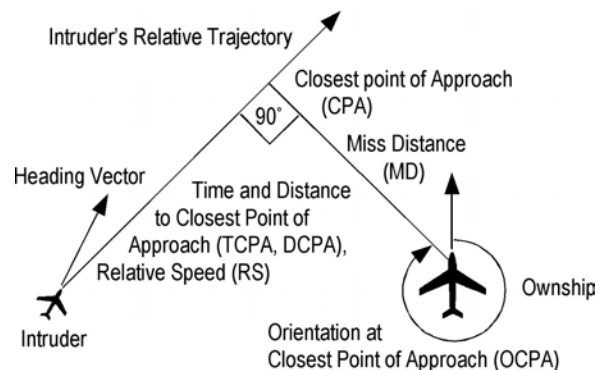


Figure 1. Conflict scenario for two aircraft flying at the same altitude at constant speeds on straight, converging courses, as shown on a CDTI. The ownship would appear to be stationary to the pilot in an egocentric frame of reference.

METHOD

Participants

Twenty-four certified flight instructors and non-instructor pilots (20 male and four female), with mean age 23.3 years (range 18-49 years) were recruited from the Institute of Aviation, the University of Illinois at Urbana-Champaign.

Display and Task

The CDTI depicted ownship and intruder in a map (top-down) view (see Figure 2). The display represented ownship by a white triangle and the intruder by a solid circle in cyan. Ownship icon was positioned in the center of the display throughout the whole experiment, thus yielding an egocentric view of the traffic situation where the ownship icon appeared to be stationary to the participant. The ownship and the intruder were flying at the same altitude on straight converging courses and at constant but not necessarily same speeds. Participants individually observed the development of a conflict scenario for 15 sec, after which the scenario froze. They were then required to mentally extrapolate the development of the scenario, press a key when they estimated that the CPA was reached, thereby providing the estimate accuracy of TCPA, and move the cursor to a location that they believed was the CPA, thus providing the estimate accuracy of MD and OCPA.

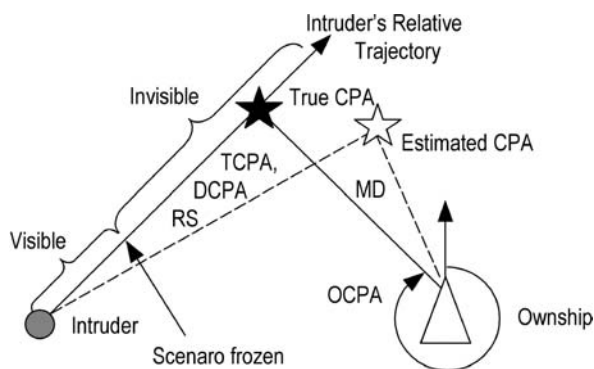


Figure 2. Schematic illustration of key components of the experimental paradigm and independent variables. The ownship icon was stationary to the participant.

Experimental Design

Independent variables. Independent variables employed were (1) intruder's distance to CPA (DCPA) at freezing point (1.33 nautical miles or nm, 2.67 nm, and 4.0 nm), (2) intruder's speed relative to ownship (RS or speed), which was defined as the speed at which the intruder was moving in the ownship-centered frame of reference and thus determined how rapidly the two aircraft would converge (160 knots, 240 knots, and 480 knots), and (3) miss distance (MD) (.67 nm, 2.67 nm, and 4.67 nm). Note that coupling the longest DCPA (4.0 nm) with the slowest speed (160 knots) resulted in a TCPA of 90 s, and as this TCPA might have been excessively long resulting

in participant distraction and impatience, it was excluded from the experiment. Within the above-described DCPA and speed levels, some pairs of trials had the same TCPA when the freezing occurred, but different DCPA because of different speed levels. This allowed for the testing of the distance-over-speed bias hypothesis.

DCPA was varied between subjects and the other variables varied within-subjects. For the 1.33-nm and 2.67-nm DCPA groups, crossing three conflict angle (CA) conditions with the three speed levels and the three MD levels yielded 27 conflict geometries. Four replicates of each of the 27 conditions resulted in 108 trials in total for each of the two DCPA groups. For the 4.0 mile DCPA group, there were a total of 72 trials (3 CAs \times 2 faster speeds \times 3 MDs \times 4 replicates). These trials were presented to the participants in a quasi-random fashion but appearing to be random to them.

Dependent variables. Dependent variables reported below were absolute and signed MD estimate errors, and absolute and signed TCPA estimate errors, derived by subtracting the true values from their corresponding estimated values (i.e., |estimated values – true values| and estimated values – true values). The absolute errors would reveal the estimation accuracy, whereas the signed errors would reveal the estimation directions (whether under- or overestimate), an indication of biases. OCPA estimate errors were also analyzed, but their results are not reported below both due to space constraint and their relatively lesser degree of importance.

Procedure

Pilots first participated in one practice session, in which they encountered some representative conflict geometries. After this, participants completed two (for the 4.0 nm DCPA group) or three blocks (for the 1.33 nm and 2.67 nm DCPA groups) of 36 trials each in a single session. Between each two blocks, the participants were allowed to take a short break to avoid fatigue effects.

RESULTS

Full details of the results can be found in Xu et al. (2004), including the effect of conflict angle (CA), and the effects on OCPA estimate error.

Effects of Distance to Closest Point of Approach (DCPA) and Relative Speed (RS)

For absolute MD estimate error, error increased as DCPA increased (Figure 3), $F(2, 21) = 18.37, p < .0001$. There was also a main effect of speed, $F(2, 28) = 15.22, p < .0001$; error did not differ significantly between 160 knots and 240 knots ($p > .10$), but error was greater at 240 knots than at 480 knots ($p < .0001$).

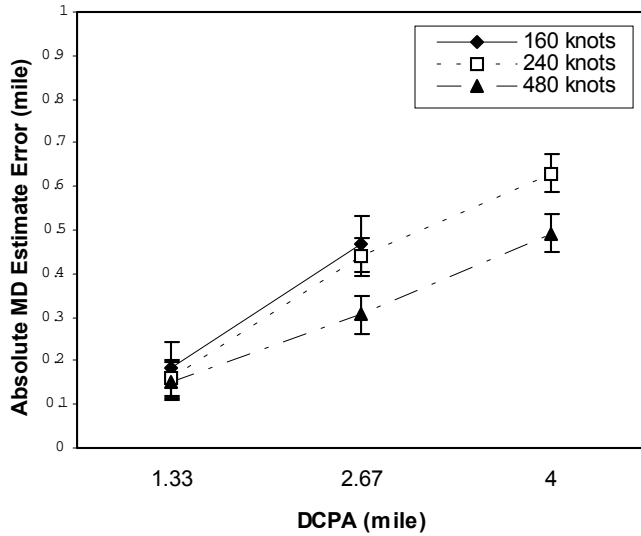


Figure 3. Absolute MD estimate errors for three DCPA and three speed levels.

For signed MD estimate error (Figure 4), there was a greater underestimate of MD at the longest DCPA relative to the two shorter DCPA levels, $F(2, 21) = 4.67, p < .05$.

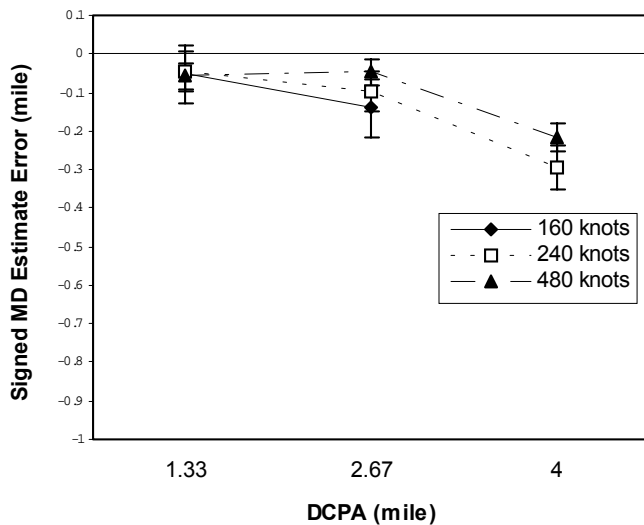


Figure 4. Signed MD estimate errors for three DCPA and three speed levels. A negative value indicates that the conflict was estimated to be more risky than it would actually be.

For absolute time (i.e., TCPA) estimate error (Figure 5), there was a monotonic increase in error as DCPA increased, $F(2, 21) = 5.75, p < .05$, and as speed decreased, $F(2, 28) = 40, p < .0001$. The interaction between DCPA and speed, $F(2, 28) = 5.88, p < .01$, suggests a greater effect of DCPA at 160 knots than at 240 knots or 480 knots.

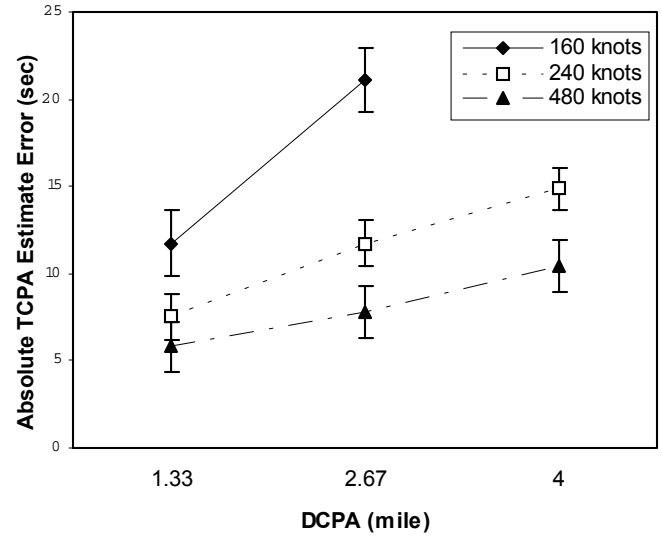


Figure 5. Absolute TCPA estimate errors for three DCPA and three speed levels.

For signed time estimate error (Figure 6), there was no main effect of DCPA, $F(2, 21) = 1.83, p > .10$, but there was progressively greater underestimate of time (CPA estimated sooner than it would actually occur) as speed decreased, $F(2, 28) = 128.15, p < .0001$, and the interaction between DCPA and speed, $F(2, 28) = 15.69, p < .0001$, suggests amplified effect of speed at longer DCPA levels. That is, time overestimate increased with DCPA at the fastest speed and underestimate increased with DCPA at the slower speeds.

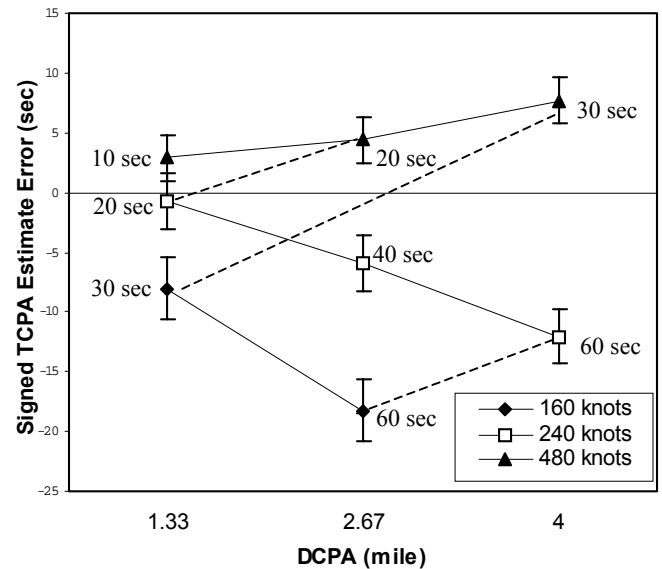


Figure 6. Signed TCPA estimate errors for three DCPA and three speed levels. A negative value indicates that the conflict was estimated to occur sooner than it actually would. The dashed lines connect pairs of points with identical times (TCPA).

Distance-over-Speed Bias

The three dashed lines in Figure 6 (for signed TCPA estimate errors) connect pairs of conditions each having a same true TCPA (20, 30, and 60 s, respectively), which differed with respect to the ratio of distance/speed: short/slow on the left and long/fast on the right. Within each pair of connected points, the estimated TCPA was always shorter (i.e., the TCPA was estimated to be sooner) for that point with the shorter distance and slower speed. An ANOVA on the data points connected by the three dashed lines, with two levels of distance (short vs. long) and three levels of time (20, 30, and 60 sec), confirmed this trend, $F(1, 42) = 24.61, p < .0001$, and also revealed that the longer time led to greater underestimate of TCPA, $F(2, 42) = 34.55, p < .0001$, with significant interaction $F(2, 42) = 3.37, p < .05$.

Effect of Miss Distance (MD)

The significant effect of MD on absolute MD estimate error, $F(2, 42) = 17.66, p < .0001$, suggests greater error as true MD increased. The significant interaction between DCPA and MD, $F(4, 42) = 5.60, p < .005$, suggests amplified effect of MD across longer DCPA levels. MD also significantly influenced signed MD estimate error (see Figure 7), $F(2, 42) = 14.49, p < .0001$; the two longer MD levels were underestimated relative to the shorter MD ($p < .01$), but there was no difference between the two longer levels ($p > .10$).

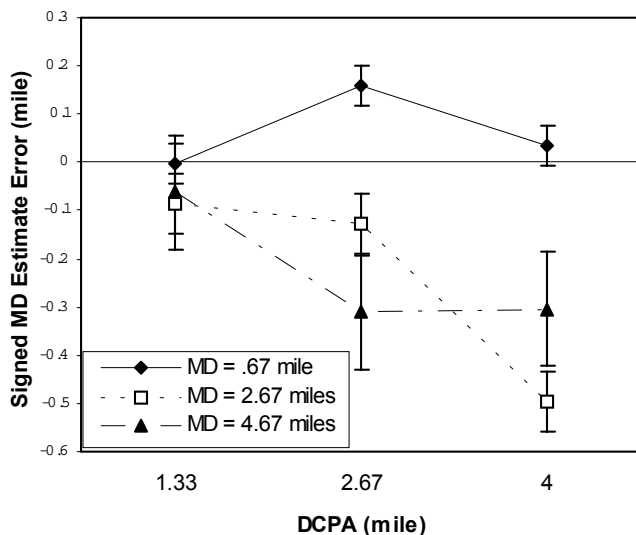


Figure 7. Signed MD estimate errors for three DCPA and three MD levels.

MD did not influence absolute time estimate error, $F(2, 42) = 2.08, p > .10$, but its significant effect on signed time estimate error, $F(2, 42) = 3.38, p < .05$, indicates that as true MD decreased (i.e., greater conflict risk), there was a greater underestimate of time.

DISCUSSION

The general pattern of effects that were observed can be partitioned into those that generally make conflict risk judgments more difficult (less accurate), and those that reflect two systematic forms of **estimation biases** manifested by the pilots.

The results concerning the effects of DCPA, relative speed, and MD on the absolute estimate errors are mostly consistent with our predictions: Increasing DCPA and MD, and reducing speed made conflict detection more difficult, manifested by increased absolute errors. Importantly, regarding signed MD estimate error, there was a greater underestimate of MD at the longest DCPA than at the two shorter DCPA levels (Figure 4), as well as at the two longer MD levels compared to the shorter MD (Figure 7). The pilots also had a tendency to underestimate TCPA, in particular at slower speeds and over longer true TCPAs (Figure 6). These suggest the first pattern of bias—as the uncertainty regarding the true values of MD and TCPA increased, MD and TCPA were either underestimated or the amount of underestimate increased. We may describe this as a “safety bias” given that, with increased uncertainty, it is a safe strategy to overestimate conflict risk (i.e., to underestimate MD) and underestimate the time before the conflict occurs (i.e., TCPA). Furthermore, as the conflict situation became more risky (decreased MD), the time to the conflict (i.e., TCPA) was progressively underestimated. The pilots might have perceived the conflict situation to be more urgent as MD decreased, even when the time to the conflict was the same, and this bias could have invoked earlier avoidance maneuvers with the decreasing MD, had conflict resolution been required. The conservativeness found in this experiment is consistent with the time-to-contact (between vehicles) underestimate in driving (Hancock & Manser, 1998) and distance underestimate in air traffic control (Boudes & Cellier, 2000). These findings collectively suggest an inherent bias of the operator to err on the side of caution, where safety is an issue. This strategy may be good to a certain extent, but when overdone, it may potentially invoke unnecessary avoidance maneuvers resulting in wasted fuel, passenger discomfort, or even conflict with other traffic in the nearby airspace.

The second class of bias manifested in the distance-over-speed bias hypothesis was supported in that pilots were influenced more heavily by the distance information than by the speed information in estimating TCPA (see Figure 6). This phenomenon can be explained by Kahneman’s (2003) theory on the two systems (system 1 and system 2) in human perception. According to Kahneman, system 1 is intuition, which is fast and effortless; and system 2 is reasoning, which is analytical and optimal, but slow and effortful. There is evidence that humans have a tendency to substitute system 1 for system 2, especially when the information required for system 2 is not totally accessible. Time estimation in our experiment was a system 2 process involving both distance perception (a system 1 process) and speed perception (see Figure 8). When the intruder icon was not visible, the speed information was less accessible than the distance information. Therefore, it is conceivable that the pilots just substituted

distance perception for the more complex integration of distance *and* speed information. This bias may be potentially risky and may also have important safety implication in that time to conflict may be estimated too long (longer than it actually is) when intruder is far away but flying at fast speed.

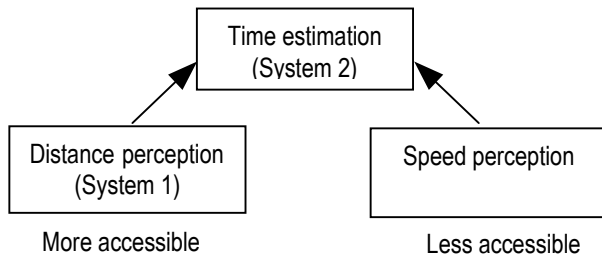


Figure 8. Illustration of time estimation as a process of integrating both distance and speed information.

In conclusion, the results reported above would provide valuable information in helping designers of CDTI improve the design to overcome human shortcomings. For example, since it is very difficult to estimate TCPA accurately unaided, an automated TCPA alerting system might take the cognitive burden off the pilot. Automated MD prediction would also increase pilots' MD estimation accuracy. Automation may also reduce the extent of bias shown in this experiment (i.e., MD and TCPA underestimates and distance-over-speed bias). Finally, information regarding the various biases might be incorporated into training programs such that pilots can be aware of the types of error to which they are susceptible.

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