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Estimation of Conflict Risk Using Cockpit Displays of Traffic Information

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Abstract

This report describes an experiment that evaluated pilots' ability to understand and detect air traffic conflicts on a cockpit display of traffic information (CDTI), without the aid of an automated conflict alerting system. This ability was manifested in estimation accuracy of three continuous variables: miss distance at closest point of approach, time to closest point of approach, and orientation at closest point of approach.

Twenty-four licensed pilots viewed a series of dynamic encounters on a 2-D CDTI. The scenarios varied widely in their difficulty, influenced by horizontal conflict geometry (conflict angle, speed, miss distance at closest approach of approach, and distance and time till closest point of approach). Pilots were asked to estimate the point and time of closest approach at varying times before that point was reached.

The results indicated that (1) decreased estimation accuracy was associated with conflicts that occurred with slower speeds, a longer time into the future, and a longer distance into the future; (2) 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 (3) 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 and converging slower, even though the time till a conflict occurred was identical. Finally, the cognitive mechanisms that underlie the biases observed in this study are discussed.

1. Introduction

1.1 Overview

The three main tasks a pilot must perform may be summed up as aviation, navigation, and communication. For navigation, a major component of the task is to prevent collision between the pilot's own aircraft (referred to hereafter as "ownship") and the terrain, and equally importantly, between the ownship and other aircraft (referred to hereafter as "intruder aircraft" or "traffic"). To prevent collision with the terrain, it is essential that the pilot be able to predict the future status of the ownship relative to the terrain. For prevention of collision with intruder aircraft, the pilot needs to be able to predict the future status of both the ownship and the intruder traffic, both of which are moving at great speed in a 3-D environment, to foresee if the spacing between the two aircraft will be below certain prescribed minima. This is a task that is termed as *conflict detection*. If the pilot determines that two aircraft will be in conflict at a point in the future (below separation minima), he/she will need to maneuver the aircraft in order to avoid such a danger, a task referred to as *conflict resolution*. More specifically, the pilot, depending on the situation at the time, can make vertical or horizontal avoidance maneuvers or a combination of the two types. Vertical maneuvers consist of climbs and descents, and horizontal maneuvers can be carried out either laterally (right or left) or longitudinally (increase or reduction in speed).

Timely conflict detection—aided by various onboard technologies—will be one of the most important tasks of pilots in the envisioned free flight environment. Applying signal detection theory (SDT), failure in this respect can result in both "misses" (the pilot calls a true conflict a safe separation) and "false alarms" (the pilot calls a safe separation a conflict). Both of these errors obviously have serious consequences. A conflict not detected or detected very late (constituting a "miss") may result in a violation of separation minima or even in a catastrophic collision. False alarms will induce unnecessary evasive maneuvers resulting in deviation from planned flight parameters and thus reduced fuel efficiency, potential conflict with traffic besides the original "conflict traffic," and reduced passenger comfort or even compromised passenger safety. Conflict detection performance is also meaningful in the context of concurrent task(s). Often the pilot needs to handle multiple conflict situations involving multiple aircraft and perform multiple concurrent tasks such as aviation and communication. If aircraft are predicted to be on conflict courses, then how soon the pilot will need to resolve the conflict, how aggressive the avoidance maneuver(s) must be, or how much time he or she can spend on concurrent tasks before eventually returning to resolve it may depend on the perceived time available till the occurrence of the conflict.

As discussed above, prediction lies at the heart of conflict detection because of the importance of detecting the potential for conflict well before it occurs. Prediction is also considered an important part of situation awareness (SA), which, according to one definition (Endsley, 1995), consists of three hierarchical phases: Level 1 SA, perception of the elements in the environment, Level 2 SA, comprehension of the current situation, and Level 3 SA, projection of future status. In the context of conflict detection, the pilot needs to predict what will happen in the future based on Levels 1 and 2 SA to achieve Level 3 SA (e.g., the ownship and the intruder aircraft on converging courses will probably collide in three minutes if no action is taken). Thus, conflict detection (whether, where, and when a conflict will occur) is critically linked with situation awareness. This task is very resource-demanding. Indeed, midair collisions and, more frequently, near midair collisions have occurred due to the inability of pilots and/or controllers to predict and/or prevent the loss of separation between aircraft (Wiener, 1980). Prediction is largely dependent on spatial working memory to "compute" the future status of aircraft (Wickens, Mavor, & McGee, 1997). Especially, when relative trajectories and positions of multiple aircraft need to be predicted, the pilot's processing capabilities will be heavily taxed, thus limiting the accuracy of prediction (Alexander, Wickens, & Merwin, in press; Wickens, Gempler, & Morphew, 2000). Understanding of the underlying perceptual and cognitive mechanisms is therefore necessary in order to identify the human limitations in conflict detection and to seek ways to overcome them through development or improvement of automation to aid human performance in conflict detection.

The ability to predict future status of aircraft is especially important for pilots operating under visual flight rules (VFR) (usually general aviation pilots), who do not receive air traffic control (ATC) service and are themselves responsible for separation from other aircraft. Under the current ATC system, pilots flying under instrument flight rules (IFR) (usually airline pilots) must fly according to the flight parameters approved or assigned by ATC, and it is ATC that is responsible for separation between aircraft and to a certain extent, between aircraft and terrain (Wickens et al., 1997). However, implementation of the free flight concept will shift the responsibility of keeping safe separation from ATC to pilots (Planzer & Jenny, 1995; RTCA, 1995a, 1995b; Johnson, Battiste, & Bochow, 1999; Wickens, Helleberg, & Xu, 2002). Due to its inherent limitations, the current ATC system has failed to accommodate the ever-growing air traffic volume, causing increased fuel consumption, prolonged flight delays, passenger complaints, and other problems. The free flight program is under development by the FAA and NASA to address these system inefficiencies. Free flight would allow pilots to increase flexibility in selecting routes to their destinations and also allow them to avoid traffic and weather without ATC approval or instructions (RTCA, 1995a, 1995b; Planzer & Jenny, 1995; Wickens, Helleberg, & Xu, 2002). New systems such as Global Position System (GPS), Automatic Dependent Surveillance-Broadcast (ADS-B), Data Link, and the Cockpit Display of Traffic Information (CDTI) provide the technologies that will make free flight possible (Wickens, 1998; Wickens et al., 2002). Of these systems, the CDTI will play the central role in the free flight system and is the focus of this report. The CDTI can provide the pilot with information regarding nearby traffic's locations, speeds, altitudes, and other types of information relative to "ownship" in a graphic form so that the pilot can take timely measures to prevent collisions with them (Kreifeldt, 1980).

The goal of the experiment described in this report was to discover the geometric properties of midair conflicts that make them difficult for pilots to understand. We first conducted a task analysis of conflict detection with a reliance on traffic information presented on the CDTI for the point and volume of space as the conflict criterion, respectively. Two types of prediction involved in the conflict detection will be outlined, one being a dichotomous and the other a continuous measure of *conflict risk*. The task analysis was followed by a comprehensive literature review of both applied and the basic research paradigms to examine the factors and features that influence performance related to conflict detection. More specifically, we began with an examination of the effects that various geometric features have on conflict detection performance in the contexts of the flight cockpit and ATC, followed by an examination of two time prediction paradigms to identify variables that make time prediction involving moving objects easy or difficult, along with the resultant judgment biases that have been found.

1.2 Task Analysis of Conflict Detection with CDTI

1.2.1. Point Conflict Criterion

Many versions of the CDTI provide a 2-D depiction of air traffic in the nearby airspace, where the ownship symbol remains "fixed" or stationary on the display and the intruder traffic symbol is moving relative to the ownship symbol (see Figure 1.1 for an illustration) and to the pilot observing the traffic situation. Figure 1.1 shows a top-down "map" view and a forward-looking view of the traffic situation in an ego-centered reference frame (ERF). For the top-down view, the depiction of the intruder traffic's direction is specific to and dependent upon the ownship's current location, heading, and speed, rendering a track-up (moving map) air traffic display.

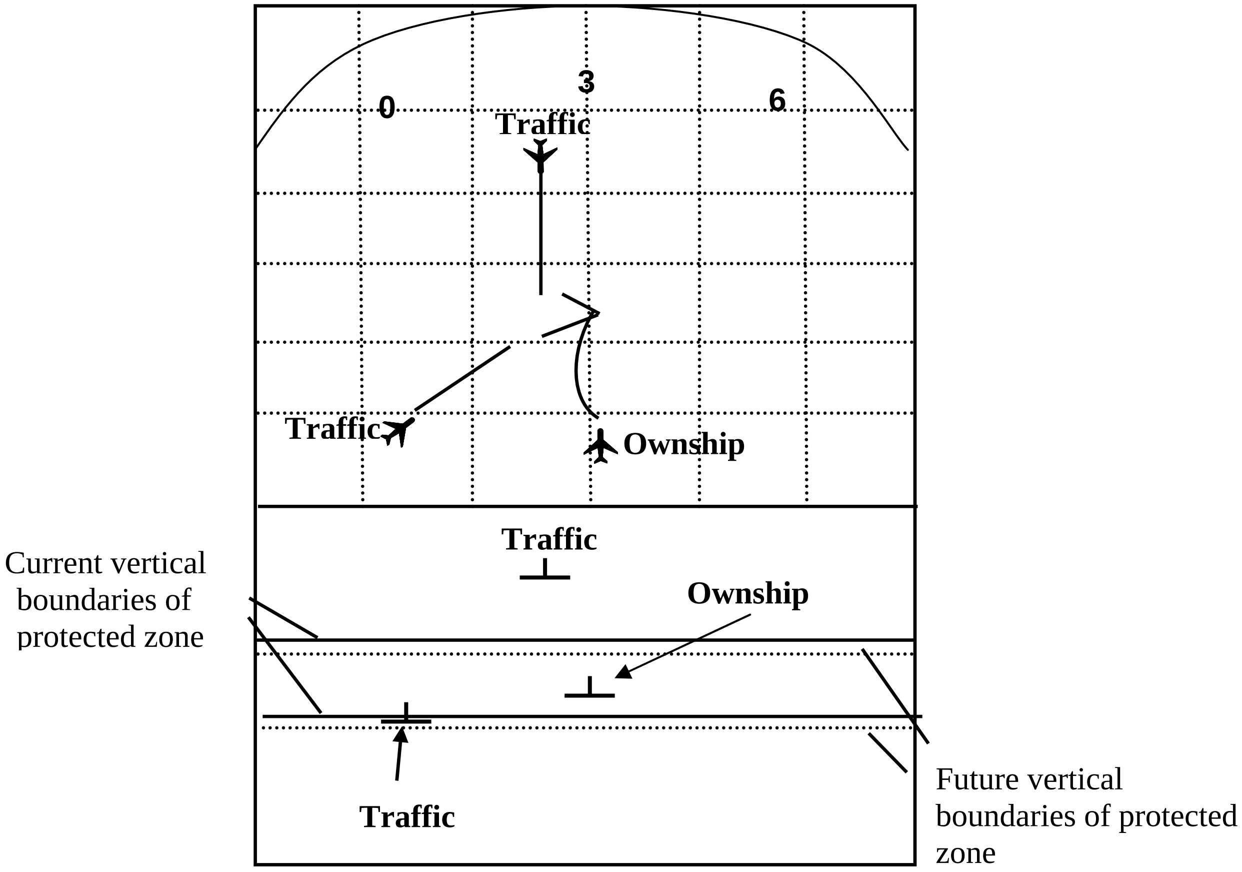

Figure 1.1. A schematic illustration of a typical coplanar CDTI showing a top-down view (top panel) and a forward-looking profile view from behind ownship (bottom panel) of the traffic situation.

Although there are occasions where predictions involving more than two aircraft need to be made, we will for the sake of simplicity limit the discussion here to situations where only two aircraft are present. Consider two aircraft flying at the same altitude on straight collision courses, at constant but not necessarily the equal velocities (see Figure 1.2 for an illustration of the traffic situation in a world-centered reference frame or WRF and in an ERF). In the ERF as shown in Panel B of Figure 1.2, if the two aircraft will collide, one must be on the extended course of the other. Thus, *whether* these two aircraft will collide in this scenario is relatively easy to judge for a pilot relying on information presented on the CDTI. However, another and more difficult prediction task is to estimate at what future time the two aircraft will be in conflict (time-to-contact or collision; TTC) or how much time will be available until the collision occurs. The TTC is specified by the actual distance between the two aircraft divided by the velocity at which the intruder traffic is approaching the ownship. It can also be specified by the distance between the two aircraft symbols on the CDTI divided by the velocity at which the intruder aircraft symbol is approaching the ownship symbol on the CDTI.

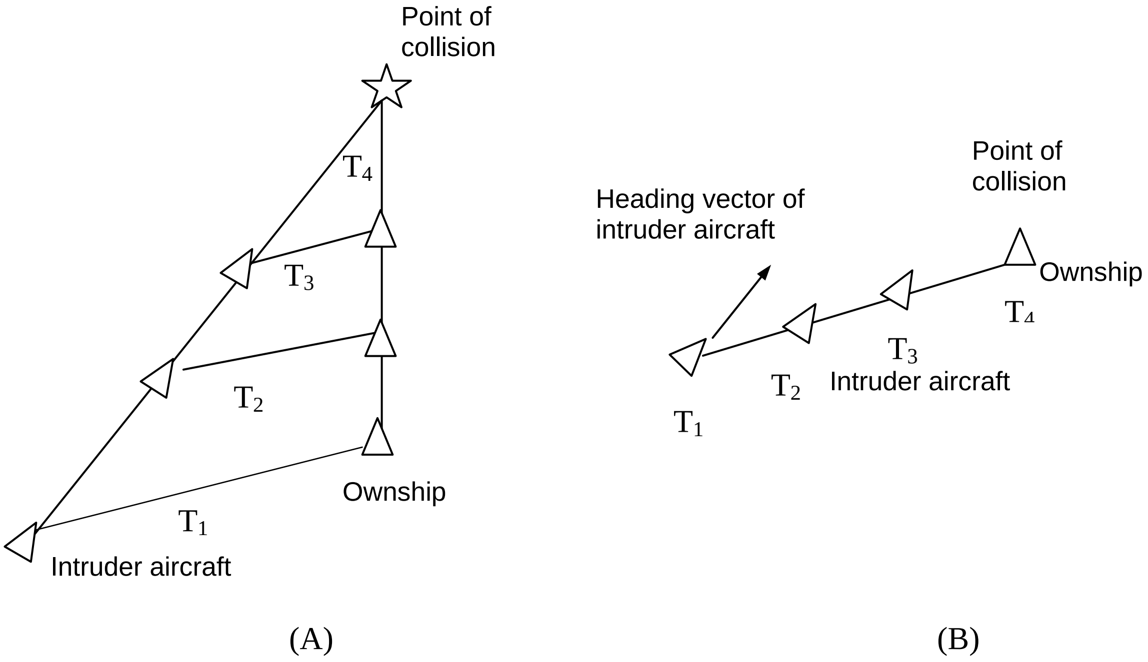

Figure 1.2. A schematic illustration of two aircraft flying at same altitude on straight collision courses, at constant velocities. Panel A shows the aircraft's positions at different times ($T_1 \ldots T_4$) and their trajectories in a world-centered reference frame (WRF) as presented on an air traffic control radar screen. Panel B shows the positions and the trajectories in an ego-centered reference frame (ERF) as presented on a CDTI; here the representation is one of relative motion in which ownship is depicted at a fixed position.

Note that for a more general case (3-D), the overlapping of two aircraft's positions on the horizontal plane is only necessary but not sufficient for the two aircraft to collide; only when two aircraft are also at the same altitude will a collision take place. Therefore, the pilot would need to perform predictions for the horizontal and the vertical planes at the same time. The prediction for the vertical plane—given vertical speeds and current altitudes of the two aircraft—involves "computation" whether the aircraft will reach the same altitude at the time of the position overlap on the horizontal plane. The TTC for the vertical plane is specified by the actual vertical distance between the two aircraft divided by their relative vertical speed. However, vertical (changing altitude) flight will not be addressed in the current research.

1.2.2. Volume of Space as Conflict Criterion

In the actual ATC operation, a cylindrical volume of space around an aircraft, often known as the *protected zone*, is used as the conflict criterion. The protected zone is not fixed in size; rather, it varies under different circumstances. According to the Federal Aviation Administration (FAA) rules (FAA, 2000), an airspace of 5 nautical miles[1] in radius and 1000 ft above and below an aircraft is considered as the protected zone into which no other aircraft is allowed to penetrate in the en-route (cross country) ATC environment (see Figure 1.3). In the terminal control areas, the volume is reduced to 3 miles and ± 1000 ft (FAA, 2000; Wickens et al., 1997). Under certain circumstances, the separation minima in the same environment can be increased or reduced; such was the case when the horizontal separation minima was increased to 7 miles when the above cited accident over the German-Swiss border occurred due to the malfunction of the ground-based ATC equipment (Flottau, 2002). It should be further noted that it has not been decided as to what type and what volume of airspace will be used under various circumstances in the free flight environment.

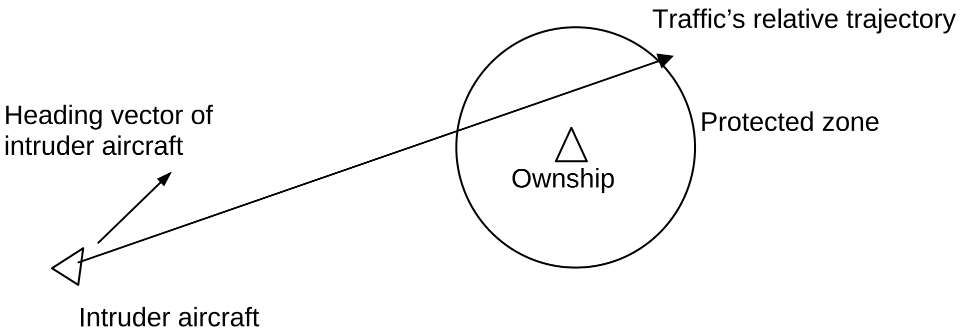

Figure 1.3. A schematic illustration of a top-down view of two aircraft flying at the same altitude on straight conflict courses at constant velocities as shown on a CDTI, using a protected zone as the conflict criteria.

With the space criterion adopted, now the pilot first needs to estimate whether the intruder aircraft will penetrate the ownship's protected zone on the horizontal plane and if so, when the penetration will happen. As noted above, the pilot also needs to estimate whether the protected zone will be penetrated on the vertical plane at the time of the horizontal penetration.

1.2.3. Three Attributes of Conflict Understanding

In the above analyses, whether or not there will be a conflict is a dichotomous judgment. For the point conflict criteria, it is either a collision or not; for the space conflict criteria, it is either penetration of the protected zone or not. However, this should not reflect the actual pilot

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[1] The distance unit in this study is always nautical mile, and hereafter it will be referred to as mile.

decision making process. Instead, it is more meaningful and important to estimate how close the aircraft actually will be to each other, yielding a continuous measure of the *conflict risk* or probability. There are two primary reasons why it is important to do this. First, if the dichotomous prediction were perfectly accurate, there would be no necessity to resort to the continuous measure of conflict risk—for instance, two non-conflict situations would be equally safe regardless whether the shortest distance between aircraft (i.e., miss distance or MD) is shorter in one situation than in the other, as long as both distances are greater than the radius of the protected zone. However, due to both the inherent changing flight environment (e.g., wind shift) and to the inaccuracy of human judgment, it is impossible to be able to predict with certainty that conflict will or will not occur (Kuchar, 2001; Thomas, Wickens, & Rantanen, 2003). Thus, the situation in which two aircraft are closer in distance will involve higher risk or probability of conflict than the one where the aircraft are farther apart, and such important information will inevitably be lost in the dichotomous decision process. Using a continuous metric of MD can avoid this problem. The second reason is that the pilot has available a range of possible conflict avoidance responses (vertical, lateral, longitudinal, or any combination of the three). Some of these maneuvers are more aggressive and disruptive but must be used when the probability of conflict is higher, while others are less so, and therefore are more preferable when the conflict probability is lower. A continuous measure of the probability of conflict therefore enables the pilot to choose the right avoidance maneuver or maneuvers that are appropriate for the traffic situation. The issue of prediction uncertainty will be further discussed in the literature review that follows this section.

We choose the *miss distance* (MD) at closest point of approach as the primary measure to achieve this purpose of quantifying conflict risk, defined as the *distance* between two aircraft at the closest point of approach (CPA), where the distance is the shortest as they fly on their respective courses (see Figure 1.4). Correspondingly, it is also important for the pilot to be able to estimate the *orientation* at closest point of approach (OCPA), which is the relative bearing of the intruder aircraft to the ownship when the CPA is reached. This parameter determines the direction in which the ownship's pilot needs to look to see the intruder traffic and the type of maneuver for conflict avoidance. For example, if the OCPA is 180°, the pilot would need to look "behind" the ownship to find the intruder and need to increase speed; if it is 90°, the pilot would need to look to the right, and would avoid making a right turn. The third parameter reflecting pilot conflict understanding is the *time* to the closest point of approach (TCPA), defined as the elapsed duration between a certain moment and the moment the CPA is reached. Normally, this time is specified *relative* to some certain event, such as when a particular alert is given or when an avoidance maneuver is or should be initiated. For example, given the nature of aircraft dynamics, a lateral maneuver should be initiated at a longer (earlier) TCPA than a vertical maneuver (Krozel & Peters, 1997).

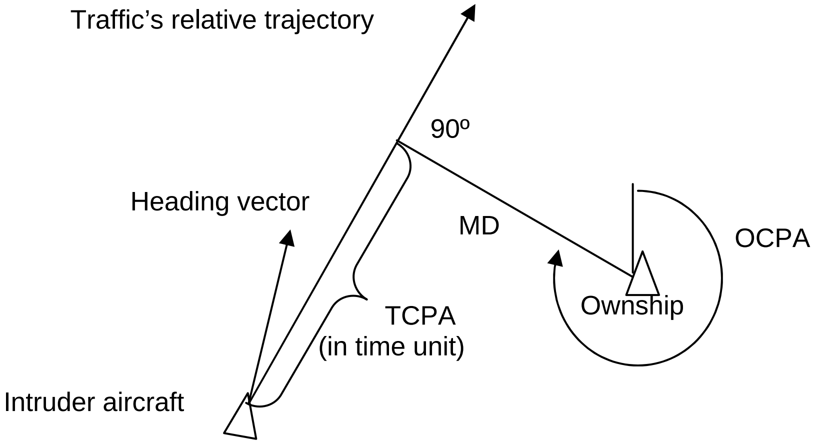

Figure 1.4. Horizontal MD, OCPA, and TCPA for two aircraft flying at the same altitude on straight converging courses at constant speeds as shown on a CDTI.

In summary, the MD is a measure of risk or probability of conflict between two aircraft; the OCPA—along with the MD—and the TCPA indicate where and when it occurs, respectively. These metrics are applicable to both the vertical and the horizontal planes. Clearly, the situation becomes risky to the extent that the MD is short, and urgent to the extent that the TCPA is early (or is short on a relative scale). As with the dichotomous judgment of conflict or no conflict, pilot errors in estimating these parameters may also have severe safety implications. For example, over-estimation of MD and/or TCPA may place the aircraft in a dangerous situation (violation of separation minima or even a collision) and under-estimation may lead to unnecessary evasive maneuvering.

For two aircraft flying at the same altitude on straight and convergent courses at constant speeds (see Figure 1.4), the MD on the horizontal plane occurs when the intruder traffic passes the ownship forming a right angle between its course and the line connecting the course and the ownship. For the vertical MD, it is the shortest vertical distance between the two aircraft and it will be 0 if the two aircraft will be at the same altitude or they will pass (descend or climb) through each other’s altitude. Combining the horizontal and vertical planes, now the conflict risk will be defined by the horizontal MD, OCPA, and the TCPA, and the vertical distance between the two aircraft at the horizontal TCPA. Or one can define this alternatively by the vertical MD, OCPA, and TCPA, and the value of the horizontal distance between the aircraft at the vertical TCPA.

1.3 Research on Conflict Detection Performance

Studies that have directly investigated the MD, OCPA, and TCPA judgment performance have not been found. In aviation, especially in ATC, there are quite a few empirical studies that addressed conflict detection (e.g., Endsley, Mogford, Allendoerfer, Snyder, & Stein 1997a; Endsley, Mogford, & Stein, 1997b; Galster, Duley, Masalonis, & Parasuraman, 2001; Merwin & Wickens, 1996; Metzger & Parasuraman, 2001a; Metzger & Parasuraman, 2001b; Remington, Johnston, Ruthruff, Gold, & Romera, 2000). However, most of these studies were concerned with air traffic controllers’ or pilots’ performance on conflict detection accuracy (i.e., the success rate of detecting conflicts as defined by the dichotomous measure) and timeliness (measured in response time), and no studies have been found to address performance on the MD, OCPA, and TCPA estimation. The dichotomous measure of detection accuracy and the response time examined in these investigations seem to be the measures of the final *product* of conflict detection, whereas the MD, OCPA, and TCPA estimation accuracy and response time would be the measures of the *process* as well as the product. While it is important to examine the product, vast amount of information is inevitably lost when the process is not examined.

Regarding the air traffic controller studies, using the world referenced traffic display (panel A in Figure 1.2), Endsley et al. (1997a) and Endsley et al. (1997b) investigated how free flight affected controller awareness of weather impact on aircraft and awareness of aircraft's next sector; both were measures of Level 3 SA (i.e., prediction). Parasuraman and colleagues (e.g., Galster et al., 2001; Metzger & Parasuraman, 2001a; Metzger & Parasuraman, 2001b) mainly investigated the effects of various factors in the free flight context on controller's conflict detection accuracy and timeliness of such detection. Remington et al. (2000) examined how various factors influenced the time needed for air traffic controllers to detect a conflict and the accuracy of conflict detection, but not on the estimation accuracy of time-to-collide per se, in the free flight like vs. traditional ATC environment. With regard to pilot studies, using the ego referenced CDTI (panel B in Figure 1.2), Merwin and Wickens (1996) asked pilots, assisted by a CDTI, to indicate whether the ownship would be in conflict with the intruder traffic, before maneuvering around the traffic to avoid the conflict. An issue, among others, addressed in that study was the effects of different display types (3-D perspective and 2-D coplanar) on conflict detection accuracy and response time. Some of those studies examined how properties of the conflict geometry influenced the ease of conflict detection and this will be described below. Nevertheless, as noted before, all simply measured dichotomous or product-oriented properties of the judgment.

1.3.1 Factors Influencing Conflict Detection Performance

Research in the domain of aviation has shown that an increase in the conflict angle between two aircraft, defined as the interior angle formed by the courses of two converging aircraft (see Figure 1.5), results in increased time needed to make trajectory prediction (Ellis, 1982; Smith, Ellis, & Lee, 1984). Using world referenced ATC display, Remington et al. (2000) found that an increase in conflict angle significantly increased the response time in detecting a conflict between two aircraft. Traffic density had the same effect—an increase in the number of aircraft among which a conflict was to be detected caused an increase in the response time. Remington et al. also found that increasing traffic density and increasing conflict angle caused more “commission errors” (when an incorrect pair was selected as being in conflict).

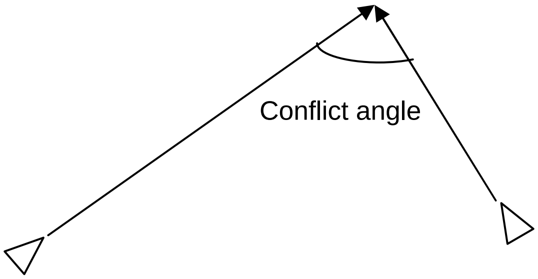

Figure 1.5. Conflict angle between two aircraft in a WRF (Remington et al., 2000).

Another factor Remington et al. (2000) considered was the time to conflict (the time before conflict occurred), which is closely linked with the parameter TCPA discussed above. They reasoned that a longer time to conflict, which, in their experiment, was directly translated to longer distance between the aircraft for a given conflict angle, makes it more difficult to project the trajectories. Indeed they found that longer time to conflict was significantly associated with longer response time to detect a conflict pair. It should be noted that time is generally correlated with distance across different geometric features, and unless the two can be separated in an orthogonal design, it is hard to determine the relative contribution of each to conflict prediction difficulty. That is, it may be harder to detect the conflict if the two aircraft are further apart on the display, even if the time to conflict is equal. We address this confound in the current research. Remington et al. (2000) also found a significant interaction between conflict angle and time to conflict, indicating that the effect of conflict angle was amplified by an increase in time to conflict. This finding could also be explained if detection difficulty was related to the distance between the aircraft on the display.

Galster et al. (2001b) examined air traffic controllers, acting mostly as passive monitors of air traffic situation in a “mature” free flight environment, in which pilots have the highest degree of freedom of route and altitude choice. They examined how well controllers could detect conflict between aircraft and self-separation initiated by aircraft. Using an ATC simulator, they found that controllers’ performance on conflict detection under high traffic density was remarkably poorer than under the moderate traffic density both in terms of detection rate and response time, thereby replicating the findings in Remington et al (2000). Galster et al. (2001b), however, did not examine the effect of conflict geometry.

In light of the controller’s possible role change from active controlling to passive monitoring with free flight, Metzger and Parasuraman (2001b) compared controller performance in conflict detection in these two conditions. They found that it took controllers longer time to detect conflicts in the passive monitoring condition than in the active controlling condition, in which the controllers were free to issue instructions to aircraft to resolve conflicts. Similarly, Endsley and Rodgers (1998) found that controller performance showed degradation in detecting conflicts when passively monitoring traffic. Neither of these studies examined the effects of conflict geometry, however.

As noted, most of the studies that investigated conflict detection performance were ATC oriented and a very limited number of such studies were focused on conflict detection by pilots with a CDTI. Merwin and Wickens (1996) was one of the few of this kind, revealing the advantage of a 2-D coplanar CDTI over a 3-D perspective one in that the former helped pilots detect more conflicts and tended to foster higher detection sensitivity and shorter detection time than the latter.

In contrast to conflict detection, there are quite a few studies in aviation that have addressed the issue of conflict *avoidance* or conflict *resolution*; that is, how a pilot or controller should change the trajectory of the aircraft to avoid a conflict or loss of separation. At least some of these have examined the influence of conflict geometry (e.g., Alexander et al., in press; Merwin & Wickens, 1996; Scallen, Smith, & Hancock, 1996, Wickens, Gempler, & Morphew; Wickens, Helleberg, & Xu, 2002). Scallen et al. (1996) examined safety measures for pilots who flew in a simulated free flight environment. They found that the overtaking (0º) conflict course induced the largest number of conflicts, but traffic density had no substantial effect on this dependent measure. In Merwin and Wickens (1996), pilots had greater difficulty avoiding conflicts with the traffic when the conflict angle was 135° than when it was 90° and 45°. Also pilots were more likely in conflict with traffic approaching from the left than from the right.

Implicitly, pilots or controllers need to detect conflicts before taking or commanding evasive maneuvers. It is not clear, however, whether the losses of separation that occurred in those conflict research studies resulted because the conflicts failed to be detected or were detected late, or rather they were difficult to avoid even if they were detected on time. For instance, the higher conflict rate for 135° of convergence angle found in Merwin and Wickens (1996) was probably due to the high closure rate of the "head-on" approach of the traffic, as the authors suggested, but not necessarily due to the difficulty of conflict detection itself for this angle. Similarly, it cannot be determined with certainty whether the larger number of conflicts with overtaking conflict course revealed by Scallen et al. (1996) were caused by the greater difficulty in detecting the conflict or rather by the greater difficulty in avoiding it in this traffic situation. Furthermore, in both of these studies, differences in approaching versus overtaking angles were confounded with the distance to conflict, if time to conflict was held constant, and were confounded with the time, if the distance was held constant.

1.4. Research on Time Prediction for Moving Objects

Turning from the applied CDTI studies to the more basic laboratory research in motion prediction, there are two major paradigms of research on time prediction involving moving objects. One is what is often referred to as relative judgment (RJ), where subjects are asked to indicate which of two or more moving objects would reach their common or respective destinations first (e.g., Bootsma, & Oudejans, 1993; DeLucia, 1991; DeLucia & Novak, 1997; Law, Pelegrino, Mitchell, Fischer, McDonald, & Hunt, 1993; Todd, 1980; Tresilian, 1995). The other is time-to-contact (TTC) estimation, where subjects are required to predict the time at which one or more moving objects would reach their destination(s) (e.g., Hancock & Manser, 1998; Kimball, 1970; Kimbal, Hofmann, & Nossaman, 1973; Peterken, Brown, & Bowman, 1991; Tresilian, 1991, 1995). The research on TTC estimation is directly relevant to the present study in that both TCPA (for the present study) and TTC estimations involve the prediction of time when one or multiple objects will arrive at their destinations. The research on RJ is somewhat relevant to the present study based on the assumption that often times the TTC estimate of each moving object with its destination point is necessary (although not when heuristics are available such that TTC is not necessary) to draw the RJ conclusion. Therefore, the literature on both of these two paradigms can be drawn upon to guide the present research project.

1.4.1 Factors Influencing RJ Performance

Researchers have investigated performance on RJ tasks in both 3-D egocentric and 2-D exocentric paradigms. Often the 3-D egocentric stimulation was simulated on a 2-D display surface and typically two or more objects were approaching the subject. The subject was to report which one would hit the observation point first had the display not been stopped when it had completed a portion of its distance to the observation point. This type of display is less relevant to the 2-D and egocentric display that underlies the CDTI. In the 3-D paradigm, the object is looming as it approaches the observer and the TTC is reciprocally related to the size of the object, whereas in the 2-D paradigm, the object is moving orthogonal to the observer and the TTC is linearly proportional to the distance traveled. Figure 1.6 illustrates the TTC on a 3-D egocentric display and a 2-D display as a function of the object size and distance, respectively. Briefly, the following results, among others, have emerged in experiments involving the 3-D egocentric display.

1. As the difference between TTC of two objects moving toward the observation point increased, the accuracy of TTC judgments also increased (Todd, 1980);

2. A large but far object appeared to the subject to arrive at the viewpoint earlier than a nearer but smaller object even when the latter would have reached the viewer earlier (DeLucia, 1991; DeLucia & Novak, 1997). That is, the size of the retinal image appeared to dominate the perceived distance in judging TTC. This phenomenon has an important 2-D parallel where we discuss the distance-over-speed bias below.

3. Judgment accuracy was above chance probability even when as many as eight objects were displayed to the observer, but response time was longer with eight objects than with two objects (DeLucia & Novak, 1997).

More relevant to the CDTI is a 2-D study by Law et al. (1993), for although the reference frame used in this study was different from that for the CDTI, TTC in both reference frames is linearly proportional to the distance change on the display. In Law et al's paradigm, two small objects were moving to a contact point or points on a 2-D exocentric transverse display plane in a variety of configurations, with nine possible combinations of path types (converging, diverging, and crossing) and path relationship (parallel, oblique, and perpendicular) (see Figure 1.7). One of the objects would have reached its contact point first, had the display not been stopped when it had completed two thirds of the entire distance. The task for the subjects was to indicate which of the two targets would reach its contact point first. The authors reported some important findings as summarized in Table 1.1.

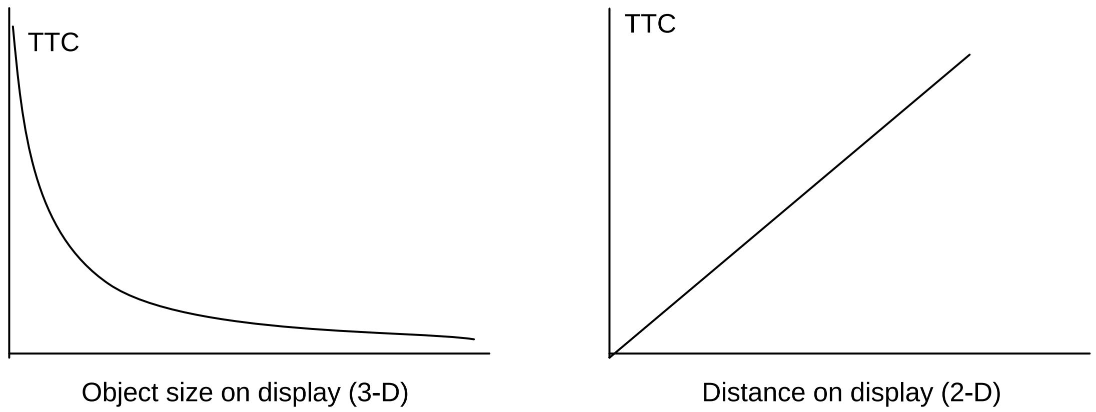

Figure 1.6. TTC on a 3-D egocentric display (DeLucia, 1991; DeLucia & Novak, 1997; Todd, 1980) and on a 2-D display (Law et al., 1993) as a function of the object size and distance.

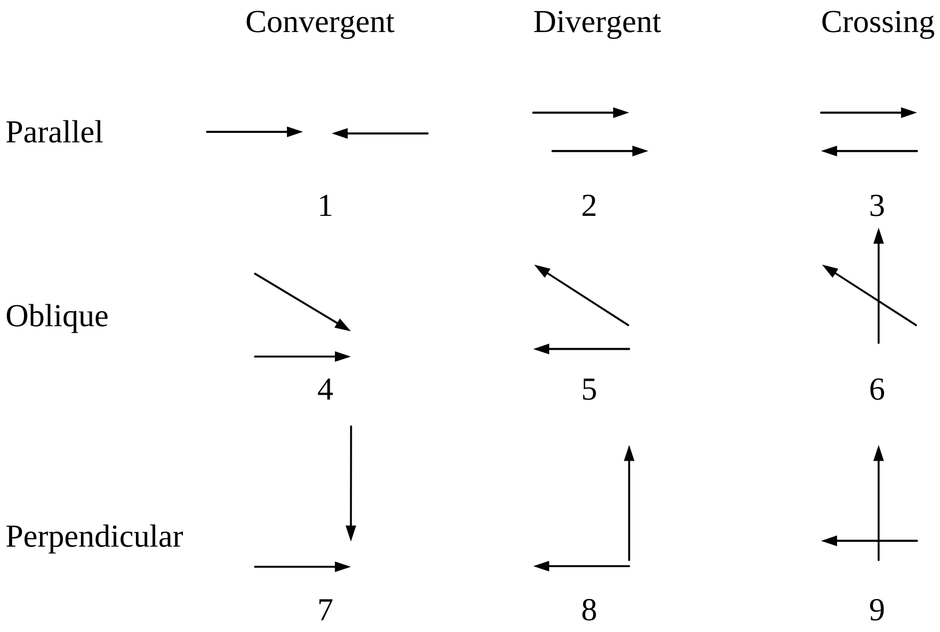

Figure 1.7. Various stimulus configurations for a RJ task in Law at el. (1993).

Law et al. (1993) interpreted their results in the following way: When the velocity ratio was 1:1, it was straightforward that the object closer to the contact point would reach the contact point first based solely on the distance information, and the task became easier as the arrival time difference increased. In the different velocity conditions, however, good performance must be based on both the distance *and* the velocity information, which was a more complex situation due to the multiple-dimensional nature of the task, leading to decrement in performance. For instance, a closer/slower object was perceived to have a shorter TTC than a faster/farther one, even when the true TTC of the latter was shorter. This is a phenomenon known as the distance-over-speed bias, meaning that in judging TTC, distance information is dominant over speed information. The distance-over-speed bias suggests, according to the authors, that the velocity information is not processed with ease or rather it is not well integrated with the distance information for the distance-divided-by-velocity strategy (for "computing" TTC).

According to the authors' interpretation, the effect of configuration was related to the amount of visual scanning required; that is, performance accuracy decreased with an increase in the distance between the two objects. An important omission is that the authors did not include 135° angle.

Table 1.1. Effects of Stimulus Configurations on RJ Accuracy in Law et al. (1993)

1. When the two objects were moving at the same velocity and one of the objects was closer to the contact point (i.e., the closer target was the first to arrive), the subjects generally made the correct choices using the rule of "the closer object was the first to arrive." When the two objects were moving at different speeds expressed as the ratio of the two velocities, subjects still tended to use the "closer arrives first" rule even when the closer object would have arrived first only in half of the trials, suggesting that they placed too much weight in their judgment in distance relative to speed.

2. The performance accuracy decreased as the relative velocity of the two increased (from 1:1 to 1.5:1 to 2:1 velocity ratio) due mainly to the distance-over-speed bias.

3. As the arrival-time differential between the two objects increased, the RJ accuracy also increased.

4. The effect of arrival time difference was attenuated in the 2:1 velocity ratio condition.

5. Configuration had a significant effect on performance, with the parallel tracks (except Configuration 3) being the easiest, oblique ones more difficult, and the perpendicular ones being the most difficult, a finding for the most part consistent with Remington et al. (2000) regarding how the convergence angle influenced response time and accuracy in controllers' conflict detection.

6. There is also a significant interaction between configuration and velocity ratio, being that the effect of relative velocity was attenuated in the more difficult configurations and the effect of configuration attenuated in the 1.5:1 and 2:1 velocity ratio conditions.

1.4.2 Factors Influencing TTC Estimation Performance

As with the RJ studies, there are numerous studies on TTC estimation performance in the 3-D egocentric paradigm, which is also of less direct relevance to the present investigation for the CDTI. Hancock and Manser (1998) reviewed the contemporary research on TTC in the context in which typically a vehicle is approaching an observer in a 3-D egocentric manner. Often the target would disappear after being viewed for some time and the observer would need to press a button to indicate the moment it would have hit him/her, had it not been removed or occluded from the view. They summarized the findings in this area as shown in Table 1.2.

Table 1.2. Effects of Factors on TTC Estimation Accuracy in 3-D TTC Estimation Tasks as Summarized by Hancock and Manser (1998)

1. Higher velocity of the approaching target results in more accurate estimation of TTC than slower velocity (McLeod & Ross, 1983; Schiff, Oldak, & Shah, 1992).
2. Longer periods of view time before the disappearance of the target is associated with better estimation of TTC (McLeod & Ross, 1983; Schiff & Oldak, 1990; Caird & Hancock, 1994)
3. Greater viewing distance before the disappearance of the target is associated with better estimation of TTC, even when the viewing time was held constant (Tresilian, 1991).
4. Males perform better than females when estimating TTC (McLeod & Ross, 1983; Schiff et al., 1992; Caird & Hancock, 1994).
5. Estimates of TTC are more accurate when the target is approaching the observer on a head-on collision course as compared to other angles of convergence (Manser & Hancock, 1996).
6. Importantly, TTC is typically under-estimated in a progressive fashion, with increase in actual TTC (Carel, 1961; Caird & Hancock, 1994; Cavallo & Laurent, 1988; McLeod & Ross, 1983; Schiff & Detwiler, 1979).

The literature of the 2-D exocentric paradigm, which bears the closest relevance to the present investigation(s), further consists of two sub-categories. One is mostly concerned with TTC estimates involving a single object moving at a constant speed along a straight line, and another is concerned with two or more objects moving in straight lines hitting a common point or a line. A typical experiment paradigm for the former, illustrated in Figure 1.8, is that an object is moving from A to B along a straight line at a constant speed for some predetermined interval and then is occluded, and the subject is asked to indicate when the object is estimated to pass a third point, C. The independent variables typically manipulated in this paradigm include the distance or time for which the object is seen (the viewing interval: A-B) and for which it is not seen (the occluded interval: B-C), the velocity at which the object moves, and the strategies available to the subject for predicting the object future position (e.g., eye movement allowed or not allowed) (Peterken et al., 1991). There are also different dependent variables measured and analyzed in this research paradigm. Some analyzed prediction time error or prediction distance error, some looked at the error as a proportion of total time for the object to move from point of appearance to the prediction point, some examined the variability of responses under different conditions, and some computed the "subjective velocity" from subjects' responses and compared it with the actual speed of the object (see Peterken et al., 1991 for a summary). The major findings in this area are summarized in Table 1.3.

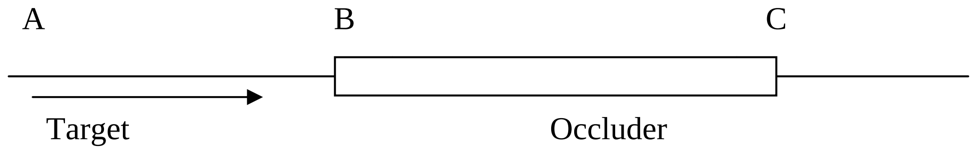

Figure 1.8. Experimental paradigm for prediction of outcome of movement of a single object moving on a 2-D display.

Table 1.3. Effects of Factors on TTC Estimation Accuracy for a Single Object Moving on a 2-D Display

1. Over-estimation of TTC and therefore under-estimation of object speed (Slater-Hammel, 1955). (Note the somewhat conflicting result with 6) in Table 1.2 in the 3-D TTC estimation literature.)

2. Over-estimation of TTC for fast-moving object but under-estimation for slower object (Bonnet & Kolehmainen, 1970; Ellingstad, 1967). This finding suggests a phenomenon of regression toward the mean (Cohen & Cohen, 1983).

3. Slower velocity led to greater TTC estimation errors (Peterken et al., 1991).

4. Longer occlusion time (Peterken et al., 1991) or distance (Slater-Hammel, 1955) resulted in longer TTC estimate.

5. Occlusion distance or time had a greater effect on TTC estimation than viewing distance or time (Peterken et al., 1991).

The reason for the different results with regard to the TTC—more under-estimation as TTC increases as reviewed by Hancock and Manser (1998) and over-estimation found in Slater-Hammel (1955)— might lie in the different experimental setting used in the two paradigms. Regarding the under-estimation of TTC in the 3-D paradigm, some researchers (e.g., Schiff & Oldak, 1990) suggested that people tend to under estimate the TTC for biological/evolutionary reasons to be wrong on the conservative side to protect themselves from dangerous situations such as the one in which a looming object is seen approaching them. In the research involving the estimation of TTC in the 2-D paradigm, the object was moving on the transverse plane parallel to the retina field, rather than moving towards the observer, and therefore without requiring the “biological” need to underestimate the time for protection.

Peterken et al. (1991) summarized the results of existing research by stating that "The general consensus...is that the prediction distance has a greater effect on performance than the distance over which the target is viewed, and that the velocity significantly affects the performance, with slower velocities leading to greater errors in position prediction" (p. 6). They pointed out that the above findings can be interpreted differently, "Both greater distances and slower velocities correspond to longer temporal intervals in the cited experiments, and it is possible that it is a longer viewing or prediction time which causes a reduction in the accuracy of prediction" (p. 6). To overcome the problem of confounding of distance with velocity, Peterken et al manipulated time and distance in a systematic and independent way and found that the important variable was the prediction time (B-C shown in Figure 1.8). More specifically, longer time between B and C resulted in under-estimation of the distance the target traveled. Thus, they showed that the time interval rather than distance during which the object is not visible is important, whereas previous research suggested the latter is more important, in affecting prediction performance.

With respect to the TTC estimation involving multiple objects, Kimball (1970) and Kimbal et al. (1973) appear to be the only studies in which absolute arrival times or TTC were estimated involving two objects approaching a common destination. Kimball (1970) examined how the manipulation of target velocity and convergence angle influenced the accuracy of arrival time estimation of two moving objects. The two targets, simulated by two rows of lights flashing in a serial order, were perceived to be moving at equal velocities. Subjects were instructed to observe the objects until they disappeared at a point halfway to the extrapolated intersection point and then pressed a switch to indicate when they thought the objects would intersect. Using essentially the same experimental setting and task as in Kimball (1970), Kimball et al. (1973) examined how differential velocity (between the two objects), plane conditions (vertical and horizontal), and experience (air traffic controller and control group) influenced the estimation accuracy of intersection time of two targets moving on converging paths. One major difference between this study and that of Kimball (1970) was that the latter used two inferred moving targets approaching a common point at equal velocities on a given trial (but varied velocities across trials), whereas for the former the two targets were moving at different velocities. Therefore, the subject needed to press two switches, one for the intersection time estimations of the horizontal target and the other for the vertical target vector. The major findings from the two experiments are summarized in Table 1.4.

1.5. Summary

In the previous task analysis of conflict detection relying on the information shown on the CDTI, it was revealed that the task involves several critical components: a) whether the ownship will be in conflict with the intruder aircraft, and if so, b) when and where the conflict will occur. However, it is also shown that this dichotomous judgment of whether there will be a conflict does not reflect the actual judgmental *process* and is not an optimal way of judging the probability of conflict. Instead, we have shown that the metrics of the MD, OCPA, and TCPA represent continuous and superior measures of conflict risk, the location of the risk, and the time at which it will occur, respectively. And, estimation accuracy of these measures would collectively represent the pilot's understanding of the conflict situation. In the literature review following the task analysis, first studies that addressed conflict detection were examined to reveal the effects that various factors have on conflict judgment performance. Although numerous studies in the domain of aviation have been concerned with conflict detection performance, researchers have been mainly interested in the performance measures of conflict detection accuracy and response time based on the dichotomous criterion of conflict and the research in this respect has been heavily ATC oriented. As we have argued, it is more meaningful to examine factors that potentially influence performance expressed in MD, OCPA, and TCPA estimate accuracy and response time. Then results from two research areas—RJ and TTC estimation—were examined to guide the selection of parameters for the current investigation. Importantly, a number of geometric features have been identified with which performance in conflict detection, RJ, and TTC estimates were poor or showed certain types of biases. However, these features were not examined in an unconfounded manner in the CDTI conflict detection studies. Some of those parameters were used for the present study and were hypothesized to also affect the MD, OCPA, and TCPA estimates that will be investigated. Table 1.5 summarizes the effects that some variables have on various performance measures with respect to conflict detection and time prediction involving objects moving on 2-D display surfaces.

Table 1.4. Effects of Factors on TTC Estimation Accuracy for Two Objects Moving on a 2-D Display (Kimball, 1970; Kimball et al., 1973)

1. TTC estimates were underestimated at slower velocities and overestimated for faster velocities, thereby replicating finding 2) in Table 1.3.
2. TTC estimates were more accurate at faster velocities than at slower velocities.
3. TTC estimates were more accurate at 30° than at 90° of convergence angle.
4. ATC experience did not improve performance.
5. TTC estimates were better when the two objects were at the same speed than when the speeds were different.

Evidently, past research has done a reasonably good job in answering the question of what factors and how they influence conflict detection, RJ, and TTC estimation for one or two moving objects that are displayed on a 2-D surface with a world referenced top-down view as in the case of ATC display and in some RJ and TTC studies, or on a 2-D surface with a ego-centric motion referenced top-down view as in studies involving the use of CDTI stimulations. Of interest to us is whether these effects will also be found in the present study, where the dependent measures will be the accuracy and timeliness of MD, OCPA, and TCPA estimations and where the influences of time, distance, and speed can be unconfounded as they have not been the case with previous CDTI studies. In particular, we intend to investigate whether the "*distance dominance over speed*" effect (closer/slower object perceived to arrive first) similar to that observed in Law et al. (1993), as well as in Bonnet and Kolehmainen, 1970), Ellingstad (1967), and Kimball (1970), will also be found in the present study.

Table 1.5. Effects of Some Variables on Conflict Detection and Time Prediction Performance on 2-D Displays

	Variable	Effect on Performance
A	Increase in arrival-time difference between two objects	Increase in RJ accuracy (Law et al., 1993)
B	Increase in time-to-contact or conflict (TTC)	Increase in RT for conflict detection (Remington et al., 2000)
C	Dominance (closer/slower vs. faster/further arrives first)	Subjects chose a closer/slower object as arriving earlier even when it arrives later than a faster/farther object for a RJ task, suggesting distance dominance over speed (Law et al., 1993)
D	Increase in conflict angle or convergence angle	Increase in RT for trajectory prediction (Ellis, 1982; Smith et al., 1984), conflict detection and "commission error" (Remington et al., 2000); Reduction in RJ accuracy (Law et al., 1993); Reduction in TTC estimation accuracy (Kimball, 1970)
E	Increase in relative velocity (velocity ratio) between two objects	Reduction in RJ accuracy (when the closer/slower object arrives at the destination later than the farther/faster object) (Law et al., 1993); Reduction in TTC estimate accuracy for two objects (Kimball et al., 1973)
F	Arrival time difference × relative velocity interaction	Effect of arrival time difference on RJ accuracy was attenuated in a high relative velocity condition (Law et al., 1993)
G	Convergence angle × relative velocity interaction	Relative velocity effect on RJ accuracy was attenuated in the more difficult (larger angle) conditions and effect of angle was attenuated in the higher relative velocity conditions (Law et al., 1993)
H	Convergence angle × time-to-conflict interaction	Effect of convergence angle on conflict detection RT was amplified with long conflict time (Remington et al., 2000)
I	Increase in absolute velocity	Increase in TTC estimate accuracy for single object (Peterken et al., 1991); Increase in TTC estimate accuracy for two objects (Kimball, 1970; Kimball et al., 1973); Under-estimation of velocity and thus over-estimation of TTC for a faster-moving object, but over-estimation of speed and thus under-estimation of TTC for slower object (Bonnet & Kolehmainen, 1970; Ellingstad, 1967; Kimball, 1970)
J	Increase in prediction distance	Increase in estimated TTC for single object (Slater-Hammel, 1955)
K	Increase in prediction time	Increase in estimated TTC for single object (Peterken et al., 1991)
L	Dominant influence (distance vs. time)	Time dominance over distance influencing TTC estimate (Peterken et al., 1991)

Another question that needs further exploration is the relative contributions of the distance to conflict and the time to conflict or TTC (they will be distance to the point of closest point of approach or DCPA and the TCPA, respectively, for the present research) in influencing performance. There is a controversy in the literature over this issue. For instance, Remington et al. (2000) imply that distance to conflict is the more decisive factor than time to conflict in influencing conflict detection performance, whereas Peterken et al. (1991) argue that the actual TTC is more important in influencing TTC estimation. As pointed out earlier, it is difficult to separate the individual effects of these two factors unless they are manipulated in a manner in which time and distance are not always confounded, which will indeed be part of our experimental design.

2. Method

Given the vital role that the CDTI will play in the free flight environment and the under-representation of research on conflict detection with the CDTI, there is clearly a need for further research to be conducted on this important component of the free flight system. The goals of this experiment were threefold. The first goal was to identify the geometric factors that influence the difficulty of unaided conflict detection with skilled pilots, as assessed by MD, OCPA, and TCPA estimate accuracy, and to assess the degree of convergence of those findings with those in the more basic literature. The second goal of the experiment was to identify biases that pilots may show in estimating the three conflict parameters. The third goal was to provide baseline data for an unaided conflict detection, which can be compared to the data for pilots using an imperfect, alert system in further experiments.

2.1. Subjects

Eight flight instructors and 16 certified pilots (20 male and four female; age ranging between 18-49 years, with a mean of 23.3 years) were recruited from the Institute of Aviation, the University of Illinois at Urbana-Champaign. An equal number of pilots (i.e., eight) were assigned to each of the three groups of distance to the closest point of approach (DCPA) in such a way that the flying proficiency was approximately the same across the three groups. The subject was paid $8/hr for his/her participation.

2.2. Simulation and Display

The part task simulation was run on a Dell PC and viewed on a 21-in. color display. The display screen resolution was 1280 × 1024 pixels and was run at a frequency of 75 Hz. The CDTI used for this experiment was a modified version of the coplanar display developed by Merwin and Wickens (1996; Wickens et al., 2000). However, it only depicted ownship and traffic in a map (top-down) view (see Figure 2.1). The display contained aircraft symbology consisting of the ownship icon, represented by a white triangle, and the intruder's aircraft icon, represented by a solid circle in cyan. The ownship icon was positioned in the center of the display throughout the whole experiment; thus, the pilot commanded a top-down egocentric view of the ownship and the traffic. In addition, two concentric range rings, centered on the ownship's icon and representing five nautical miles and 10 miles from the ownship, respectively, were also presented on the CDTI. In this experiment, there was no prediction automation to assist task performance; that is, the task was performed manually.

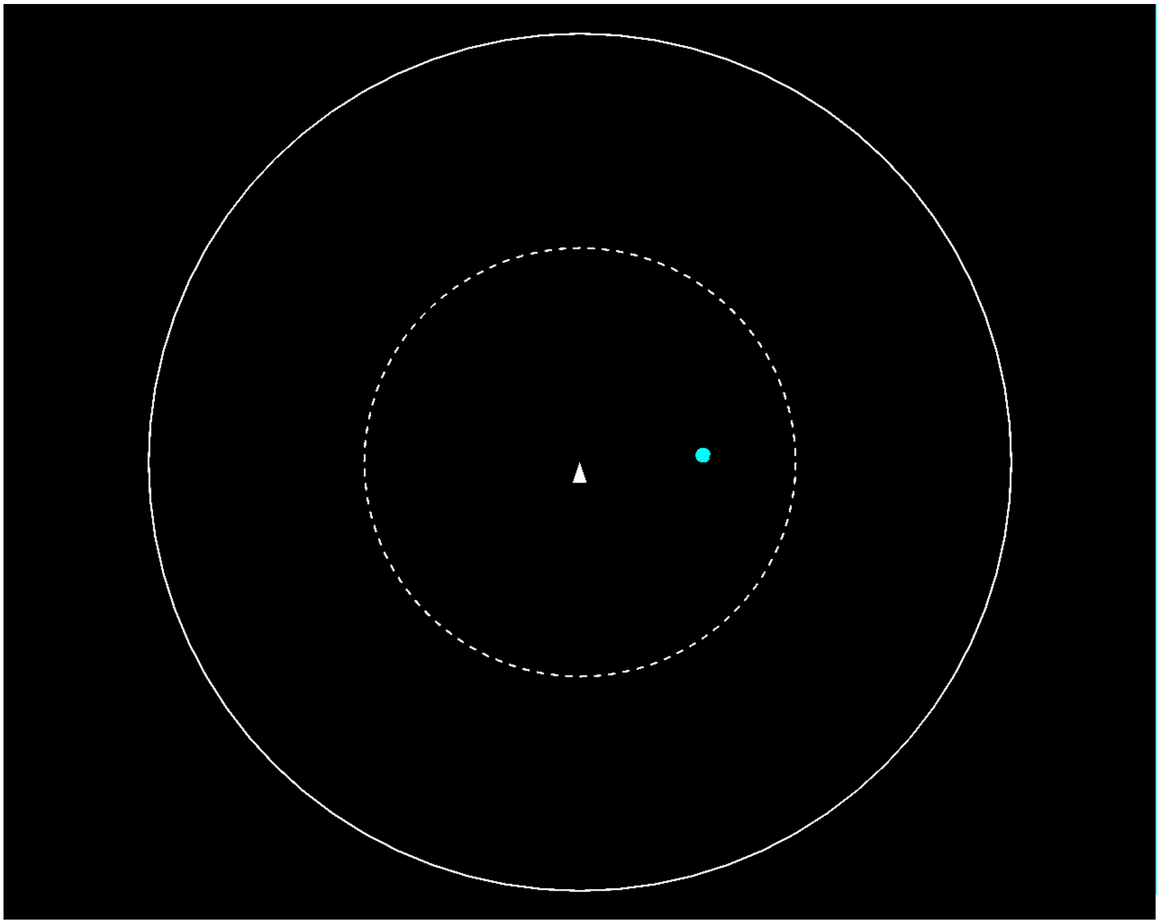

Figure 2.1. The 2-D CDTI used in Experiment 1, showing a top-down map view of the traffic situation.

2.3. Experimental Task

Each pilot observed the development of conflicts in two or three blocks, depending on which experiment group a subject was assigned to, in one experimental session for a total time of approximately 120 min. Each block contained 36 trials and in each trial, the ownship was flying to a designated navigation waypoint located directly ahead (above on the display) of the ownship. The ownship and the intruder traffic were flying at the same altitude on straight converging courses (meaning that the distance between the two aircraft was initially decreasing until the miss distance, or MD, was reached), and each aircraft was flying at a constant speed. Figure 2.2 shows the characteristics and event timeline of a trial.

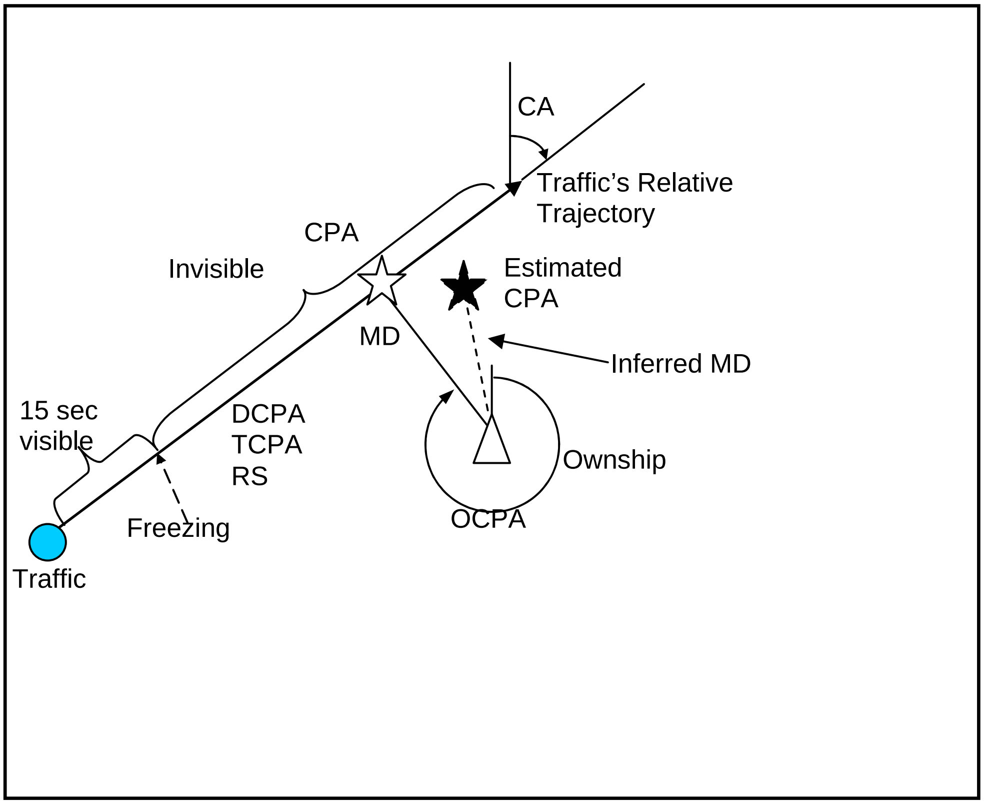

Figure 2.2. Schematic illustration of key components of the experimental paradigm. In the particular example here, the intruder traffic approaches at a 45°conflict angle (CA) from the left with a 315° OCPA. The black and white stars represent, respectively, the pilot's estimate and the true value of the conflict properties that the pilot was asked to extrapolate after the freezing point. Subject estimates of MD and OCPA were inferred from the location of the estimated CPA, and the differences between these two values and their true counterparts were used as measures of performance. The intruder's DCPA at the freezing was held constant for a given subject, but varied between subject groups, and the time to the closest point of approach (TCPA) at the freezing within a DCPA group varied inversely with the intruder's relative speed (RS).

At 15 sec after the start of a trial, the scenario was frozen retaining the depiction of the aircraft symbols as well as their headings, and the pilot was asked to mentally extrapolate the movement forward and estimate the TCPA by pressing a key on the computer when he or she estimated that CPA was reached, had the scenario not been frozen. Immediately after the key pressing, the value of the TCPA estimate was indicated visually on the screen in numeric form and remained there until the end of a trial. Furthermore, to assess the pilot's accuracy in estimating the MD and OCPA, the pilot was then (after estimating the TCPA) required to move the cursor to his or her best estimate of the location of the closest point of approach (CPA) and click the left mouse button, thus yielding the measures of the estimated MD and OCPA. A red cross appeared at the estimated location of the CPA immediately after the cursor was moved there and the left mouse button was clicked. The estimated MD and OCPA were recorded and stored in the computer to provide the necessary information for evaluation of conflict judgment accuracy. In this experiment, because the two aircraft were at the same altitude (i.e., vertical violation was present all the time), only predictions of horizontal MD, OCPA, and TCPA were required of the pilot.

2.4. Experimental Design

This was a mixed design. Intruder traffic's distance to CPA at the freezing was varied between subjects, whereas CA, intruder traffic's RS, and MD were varied within subjects. Each of these independent variables is described below.

The DCPA at the time of freezing had three levels: 1.33 miles, 2.67 miles, and 4.0 miles. The elapsed time from the start time of a trial to the freezing time (i.e., the viewing time of the intruder traffic) was held constant for 15 sec across the three levels of DCPA. Thus, on average, conflict trials varied in duration across the three DCPA groups. CA, the angular difference between the traffic's relative trajectory and the ownship's heading, had three levels (45°, 90°, and 135°). All these three angles were replicated from the left and the right. Additionally, the traffic was approaching the ownship with three alternative true OCPAs (0°, 45°, and 315°) either on the "front" aspect or on the "behind" aspect. OCPA was the relative bearing of the traffic to the ownship when the traffic reached CPA. Figure 2.3 illustrates the various levels of CA with the two approach sides and the alternative OCPAs with the two aspects, along with the relationships between the CAs and OCPAs.

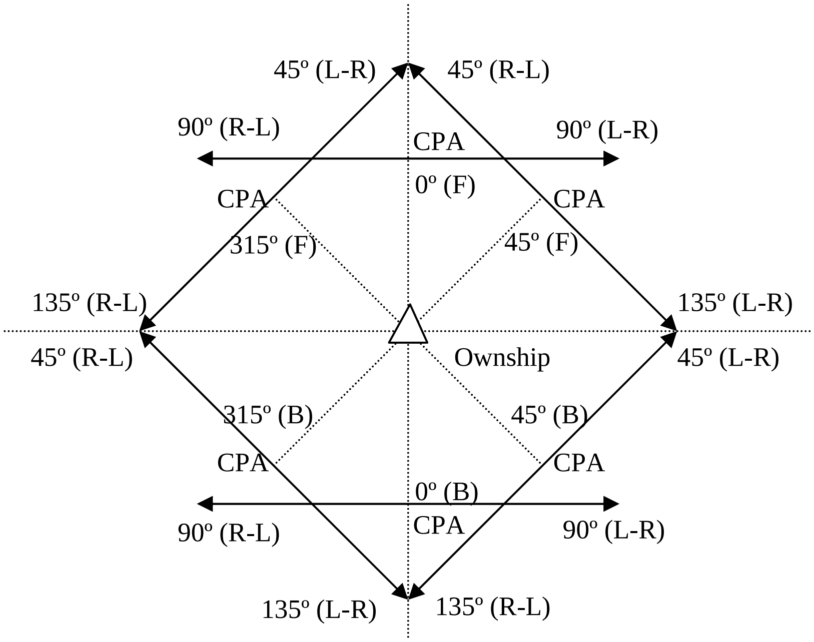

Figure 2.3. Intruder traffic's alternative CAs and alternative OCPAs. "R-L" indicates the CAs at which the traffic was approaching the ownship from the right to the left and "L-R" from the left to the right; "F" indicates the OCPAs at which the traffic was passing in front of the ownship and "B" behind the ownship.

The relative speed (RS) was the speed in nautical miles (knots) at which the traffic was moving in the ownship-centered frame of reference and thus determined how rapidly the two aircraft would converge. RS had three levels (480 knots, 240 knots, and 160 knots). These speeds resulted in three TCPA values of 10 sec, 20 sec, and 30 sec, respectively, for DCPA of 1.33 miles. These same three speeds corresponded to TCPA of 20 sec, 40 sec, and 60 sec, respectively, for DCPA of 2.67 miles, and TCPA of 30 sec, 60 sec, and 90 sec, respectively, for DCPA of 4.0 miles. An illustration of different combinations of RS and TCPA for each level of DCPA is shown in Figure 2.4. It is to be noted that in the 4.0 mile DCPA group, pilots only encountered trials with two levels of RS (240 knots and 480 knots). There were no trials associated with 160 knots, because of the concern that the TCPA of 90 sec resultant from the combination of DCPA and RS in this group would be excessively long, possibly causing distraction and impatience to the pilot.

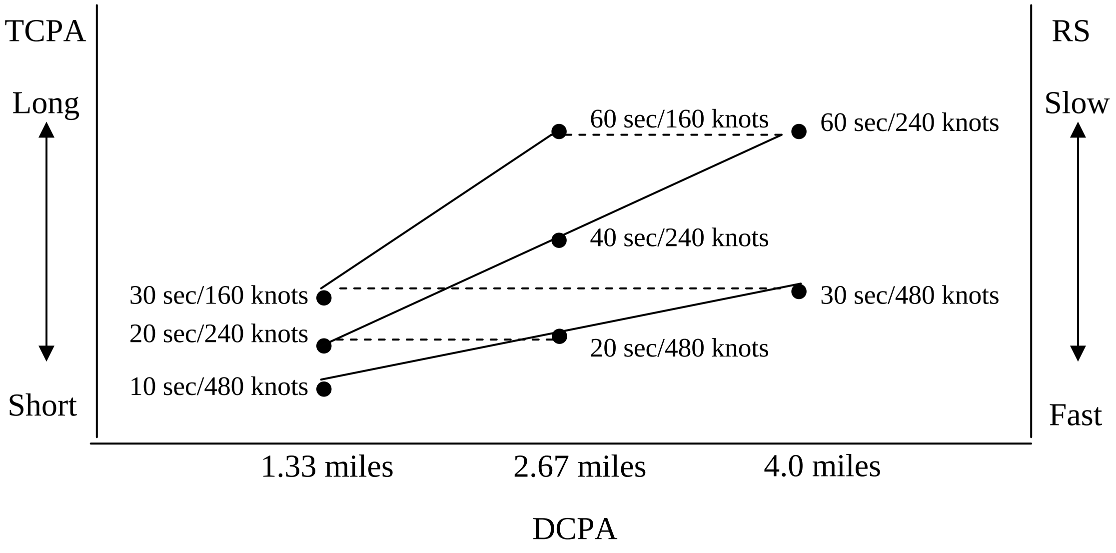

Figure 2.4. Trials resulting from different combinations of DCPA, TCPA, and RS, including pairs of trials that had same TCPA but different DCPAs, represented by the dashed lines, because of different RSs; and trials of same DCPA with different TCPAs and RSs. The trials connected by the solid lines were those having the same RS but with different DCPAs and TCPAs.

A final independent variable was another conflict property not specified by the geometry above, namely the miss distance (MD). The three levels of MD were large (M = 4.67 miles), medium (M = 2.67 miles), and small (M = .67 mile), each sampled at an increment of 12.5% from the following ranges: 3.73 miles—5.60 miles, 2.13 miles—3.20 miles, and .53 mile—.80 mile, respectively. This variability was imposed to create more naturalistic and less predictable conditions. The full range of variability, from .80 mile to 5.60 mile MD can be thought of as a continuum of “signal strength.”

For the 1.33 mile and 2.67 mile DCPA groups, crossing the three CA conditions with the *three* RS levels and the six MD levels yielded 54 conflict geometries. Thus, with two replicates of each of the 54 conditions, there were 108 trials in total for each of these two DCPA groups. However, as noted above, for the 4.0 mile DCPA group, we crossed the three CA conditions with only *two* RS conditions, using the two faster speeds. Thus, for the 4.0 mile group, there were 36 conflict geometries, and with two replicates of each condition, there were a total of 72 trials for this DCPA group. These 108 trials (or 72 for the 4.0 mile group) were presented to the pilot in a quasi-random fashion such that the order would appear to be random to him/her, but across pilots, the levels of the independent variables were not confounded with presentation sequence.

It is also to be noted that TCPA was specified by the DCPA at the time of freezing divided by the relative speed (RS); therefore, an independent manipulation of TCPA was not necessary. TCPA defined the amount of look-ahead time that the subject would have available before the MD was reached. In a probabilistic world, it would determine the amount of uncertainty in the actual conflict downstream, as discussed in the previous chapter. In our simulation, TCPA was partially correlated with the DCPA existing at the time the conflict judgment was requested (i.e., at the freezing time) as can be seen in Figure 2.4 and the two variables were perfectly correlated within trials of a constant RS. However, as also seen in Figure 2.4, we also created specific pairs of trials that had the same TCPA when the freezing occurred but different DCPA because of different RSs, as well as pairs that had the same DCPA but different values of TCPA. This would allow for the testing of the distance-over-speed bias hypothesis as outlined in the previous chapter. Ideally, these trials should emerge from the combinations of the DCPA levels and the RS levels that were already generated, without the need to create extra trials (Rantanen & Xu, 2001). We were indeed able to achieve this. For instance, as seen in Figure 2.4, we were able to have the identical TCPA with two different combinations of RSs and DCPAs—one with shorter DCPA/slower speed, and another with longer DCPA/faster speed—*within* the existing DCPA levels and RS levels. In a similar way, we had trials with the same DCPA resulting from different TCPA values and RSs.

2.5. Dependent Measures

Estimate errors of MD, TCPA, and OCPA were calculated and analyzed as the main dependent variables. Specifically, five dependent measures were generated based on the raw data. For the TCPA estimate and the MD estimate, the error was defined by the difference between the estimated value and the true value, both in signed and absolute terms, thus resulting in four dependent measures (i.e., absolute TCPA and MD estimate errors and signed TCPA and MD estimate errors). For the OCPA estimate, only absolute estimate error (i.e., absolute OCPA estimate error) was employed, defined by the difference between the estimated value and the true value.

2.6. Procedure

Pilots first participated in one practice session. In this session, they first read instructions and were explained the task and display symbology used in the experiment. Pilots then completed nine practice trials in which they had a chance to perform the task encountering some representative convergence geometries. In addition to the visually displayed estimated TCPA (by a number in sec) and CPA location (by a red cross), extra feedback information was provided in the following way. After the pilot made his/her MD and OCPA estimates, the dynamics of the simulation was restored, playing out the movement of the intruder across the display from the point of freezing to the true CPA. When the CPA was reached, the scenario stopped, retaining all the display symbology, and the pilot could compare this with his or her own estimates. Along with the playing-out of the intruder movement, the actual TCPA (from the freezing time) was also played out visually in numeric form to allow the pilot to compare the estimated TCPA and the true value. A new trial began at the pilot's discretion.

Following the practice session, pilots participated in one experimental session to complete two (for the 4.0 mile DCPA group) or three blocks (for the 1.33 mile and 2.67 mile DCPA groups) of 36 trials each. The subject's estimated TCPA and estimated CPA location were displayed on the screen, as in the case of the practice session, but the playing-out feedback was not available during the experiment session. Between each two blocks, pilots were allowed to take a short break to avoid fatigue effects. In order to enhance the motivation for good performance, pilots were told that they could receive a bonus of $15, $10, and $5, for the most, second most, and third most accurate performance, respectively, within each DCPA group. Performance was assessed by the weighted measure of the three estimate errors using the following formula: [.4 * (absolute TCPA estimate error) + .4 * (absolute MD estimate error) + .2 * (absolute OCPA estimate error)]. The rationale for assigning different weights to the three types of estimate errors was that the estimate accuracy of TCPA and MD were more critical than that of OCPA to the safety in a conflict detection and avoidance situation. Importantly, the same formula was used to identify easy and hard trials in Experiment 1, with lower scores of the weighted measure being associated with better performance (and thus easy trials) and higher scores with poorer performance (and thus hard trials). On this basis, an independent variable of task difficulty (easy vs. hard) was employed for Experiment 2 (to be described in Chapter 3). That is, a subset of trials (both "easy" and "hard" determined using the above formula) sampled from Experiment 1 were used in Experiment 2 with the addition of automation (to be described in Chapter 3), and the corresponding trials in Experiment 1 were used as the control conditions for Experiment 2.

2.7. Hypotheses

The following results were expected based upon the review of the literature and, where possible, these hypotheses are linked to the lettered rows in Table 1.5 in Chapter 1.

Hypothesis 1A: The side from which the intruder traffic was approaching the ownship (from the right to the left vs. from the left to the right) would have no effect on the estimation of MD, OCPA, and TCPA.

Hypothesis 1B: The CA at which the intruder traffic was approaching the ownship would have no effect on the estimation of MD, OCPA, and TCPA, given that distance and time to CPA were controlled.

Hypothesis 2: The aspect from which the intruder traffic was approaching the ownship (in front of vs. behind the ownship) would have no effect on the estimations of MD, OCPA, and TCPA.

Hypothesis 3A: The estimations of MD, OCPA, and TCPA would be made more difficult by decreasing intruder traffic's RS, increasing DCPA, or increasing TCPA (i.e., estimations would be more difficult at slower speed, over longer space, or over longer time) (rows B, J, and K).

Hypothesis 3B: Estimations of MD, OCPA, and TCPA would be made more difficult by increasing MD when TCPA was held constant (according to Weber's law, error of distance judgment increases with magnitude of distance).

Hypothesis 4: For two conditions with a same true TCPA, the TCPA estimate would be longer in the condition with a longer DCPA and faster RS than that with a shorter DCPA and slower RS (i.e., distance-over-speed bias; row C).

Hypothesis 5: For conditions with a same DCPA, there would be relative overestimation of TCPA for shorter TCPAs (at faster RSs) than for longer TCPAs (at slower RSs) (based on the regression toward the mean found in the literature; row I).

3. Results

All statistical analyses were performed using SPSS version 11.5 for Windows. All error bars depicted on the figures represent 95% confidence intervals. The interested reader may look ahead to Table 3.2 to overview the overall pattern of significant effects.

3.1. Effects of Traffic's Approach Side and Conflict Angle (CA)

It was predicted, according to Hypothesis 1, that the approach side (Hypothesis 1A) and CA (Hypothesis 1B) would have no influence on the estimate errors. As described in the Method, the traffic could approach the ownship at three alternative CAs (45°, 90°, and 135°) either from the right to the left, or from the left to the right (see Figure 2.3). The data on the three aspects of conflict understanding (absolute TCPA estimate error, absolute MD estimate error, and absolute OCPA estimate error) were first subjected to three separate within-subjects 2 (right-to-left and left-to-right) × 3 (45°, 90°, and 135°) ANOVAs to examine the effect of approach side (see Figures 3.1, 3.2, and 3.3). The results showed that there was no significant effect of approach side on absolute TCPA estimate error, $\underline{F}(1, 23) = .42$, $\underline{p} = .53$ (observed power = .095); on absolute MD estimate error, $\underline{F}(1, 23) = .78$, $\underline{p} = .39$ (observed power = .14); or on absolute OCPA estimate error, $\underline{F}(1, 23) = .043$, $\underline{p} = .84$ (observed power = .055). It is therefore concluded that the approach side of the traffic posed no difference in these three measures of conflict detection performance in this experiment.

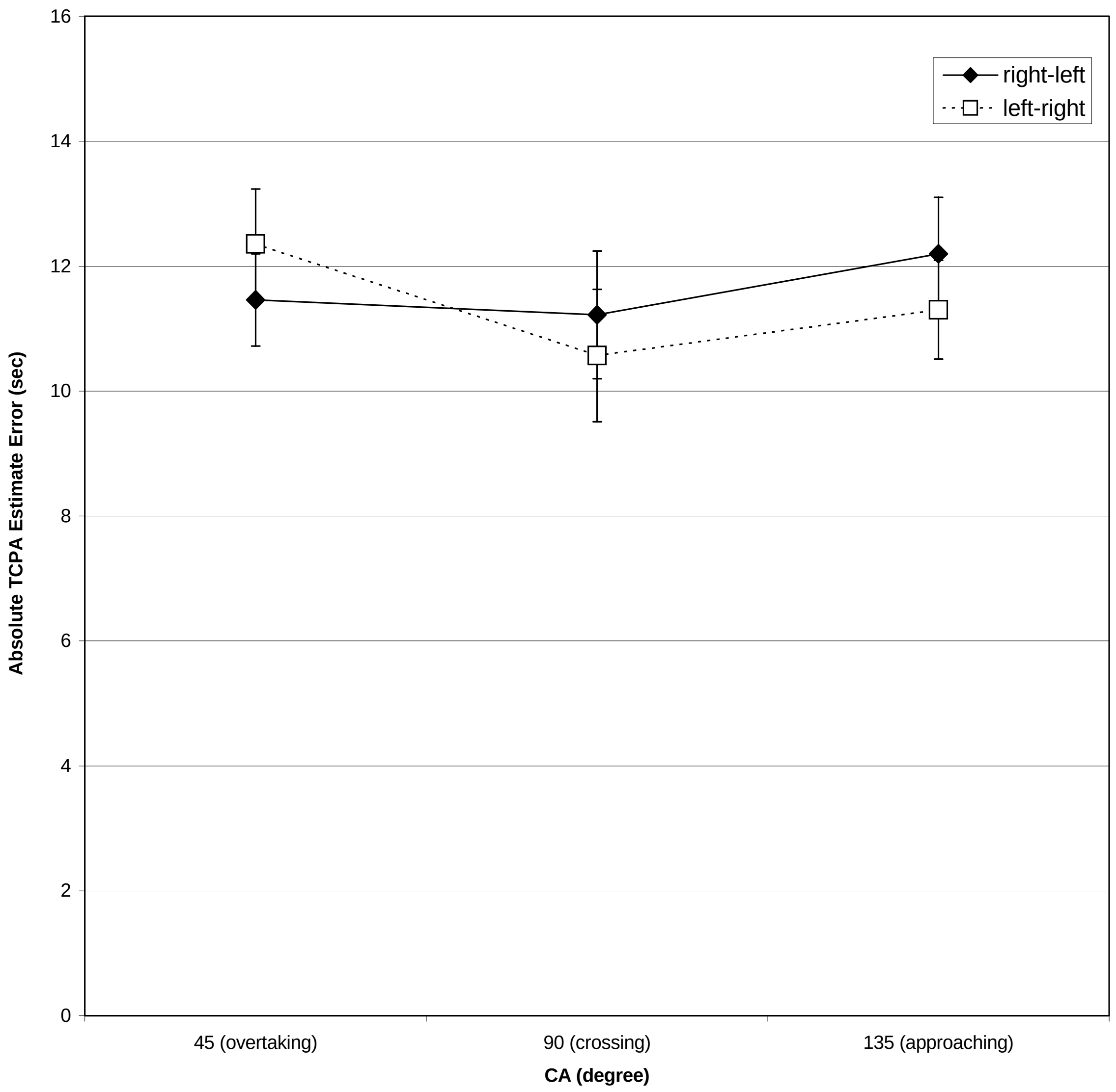

Figure 3.1. Absolute TCPA estimate errors (|estimated TCPA – true TCPA|) for two approach sides and three CAs.

The results of the same three ANOVAs revealed that conflict angle (CA) did not significantly influence absolute TCPA estimate error, F(2, 46) = 1.62, p = .21 (observed power = .33), but significantly influenced absolute MD estimate error, F(2, 46) = 17.40, p < .0001 (observed power = 1.0) (Figure 3.2), and absolute OCPA estimate error, F(2, 46) = 13.79, p < .0001 (observed power = .99) (Figure 3.3). The interaction between CA and approach side was significant for absolute TCPA estimate error, F(2, 46) = 3.42, p = .041 (observed power = .61) (Figure 3.1), but not significant for absolute MD estimate error, F(2, 46) = 1.87, p = .17 (observed power = .37), or for absolute OCPA estimate error, F(2, 46) = .74, p = .48 (observed power = .17).

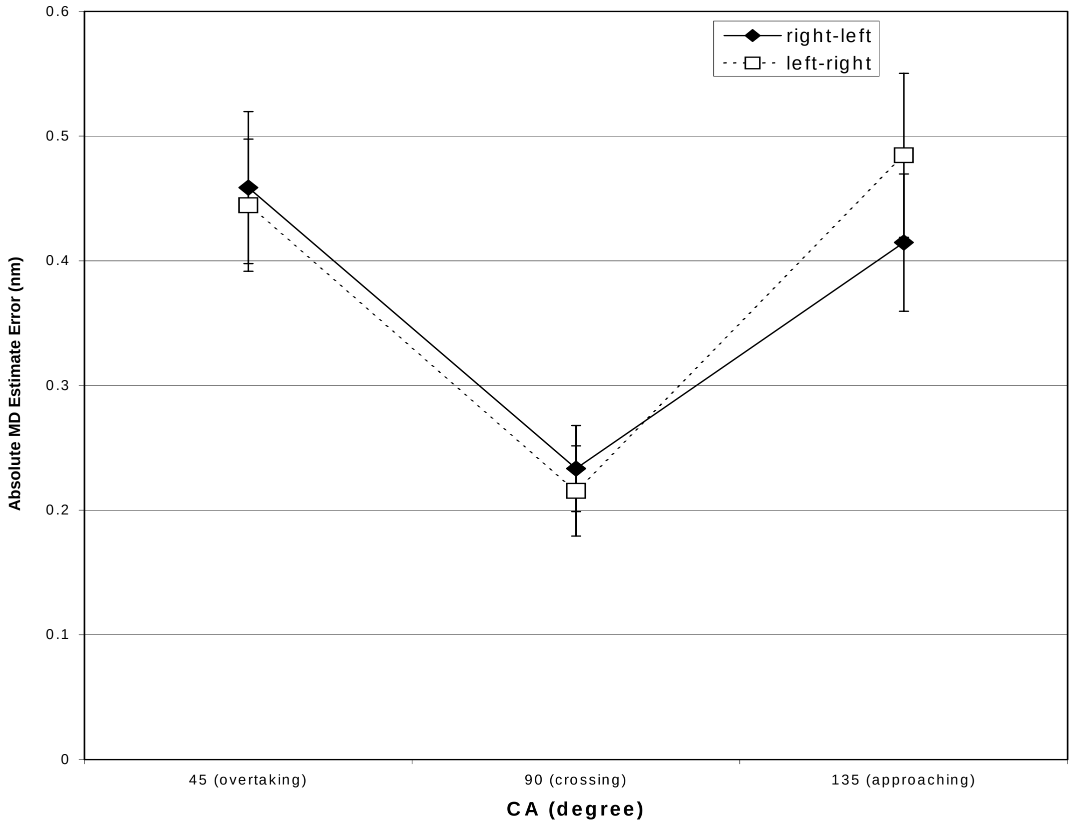

Figure 3.2. Absolute MD estimate errors (|estimated MD – true MD|) for two approach sides and three CAs.

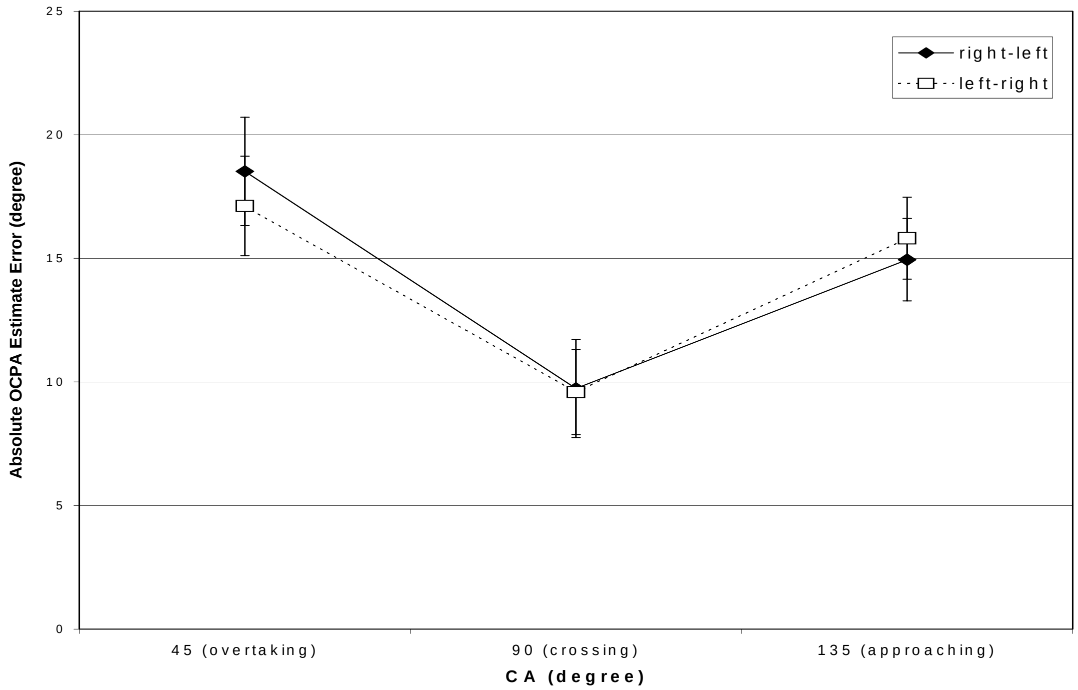

Figure 3.3. Absolute OCPA estimate errors (|estimated OCPA – true OCPA|) for two approach sides and three CAs.

Results of pair-wise comparisons revealed an identical pattern for both MD and OCPA showing better performance with the 90° (crossing) angle than either the 45º (overtaking) ($\underline{p}$ < .01) or the 135º (approaching) ($\underline{p}$ < .01), which were equivalent to each other ($\underline{p}$ > .10). The trend for TCPA estimate error was similar, although in this case the measure did not differ among the three angles ($\underline{p}$s > .10).

Because of its important relevance for safety, the analysis on TCPA estimate error was also carried out on the signed measure, in addition to the absolute measure as reported above (Figure 3.1). The results of this analysis revealed that neither approach side, $\underline{F}$(1, 23) = .51, $\underline{p}$ = .48 (observed power = .11), nor CA, $\underline{F}$(2, 46) = 1.80, $\underline{p}$ = .18 (observed power = .36), had significant impact on the TCPA measure of performance.

Similar to TCPA estimate error, the analysis on MD estimate error was also carried out on the signed measure, in addition to the absolute measure as reported above (Figure 3.2). This analysis revealed that neither approach side, $\underline{F}$(1, 23) = .27, $\underline{p}$ = .61 (observed power = .079), nor CA, $\underline{F}$(2, 46) = 1.69, $\underline{p}$ = .20 (observed power = .34), had significant impact on this measure of performance.

Thus, the increased TCPA and MD errors shown by the two oblique angles (45° and 135°) in Figures 3.1 and 3.2, respectively, were the result of increased variability of the measures, rather than a systematic directional bias away from the correct values.

Therefore, Hypothesis 1A was substantiated in that the traffic’s approach side made no difference in estimation performance. It should be noted that the relatively low power of such tests makes it hard to conclude the null hypothesis of no difference with great confidence. Hypothesis 1B was disconfirmed in that the CA for the best performance was 90°.

3.2.Effects of Traffic’s Approach Aspect

The next set of analyses was concerned with the effect of the aspect on which the traffic passed the ownship. Hypothesis 2 predicts that approach aspect would make no difference in terms of estimate errors. As noted, the traffic was approaching the ownship at three alternative true OCPAs (0°, 45°, and 315°) either on the “front” aspect or on the “behind” aspect, when the closest point of approach (CPA) was reached. The data were analyzed with a 2 (front vs. behind) × 3 (0°, 45°, and 315°) within-subjects ANOVA for each of the three absolute error measures. Since the effect of OCPA here was perfectly redundant with the effect of conflict angle (see Figures 2.2 and 2.3), the OCPA effect will not be reported here.

Results showed that for absolute TCPA estimate error, there was no significant effect of aspect, $\underline{F}$(1, 23) = .20, $\underline{p}$ = .66 (observed power = .071). For absolute MD estimate error, there was no significant effect of aspect, $\underline{F}$(1, 23) = .78, $\underline{p}$ = .39 (observed power = .14) (Figure 3.4). Finally, for absolute OCPA estimate error, the effect of aspect was significant, $\underline{F}$(1, 23) = 14.90, $\underline{p}$ = .001 (observed power = .96), with the error being constantly greater for the “behind” than the “front” traffic across the three OCPAs (Figure 3.5).

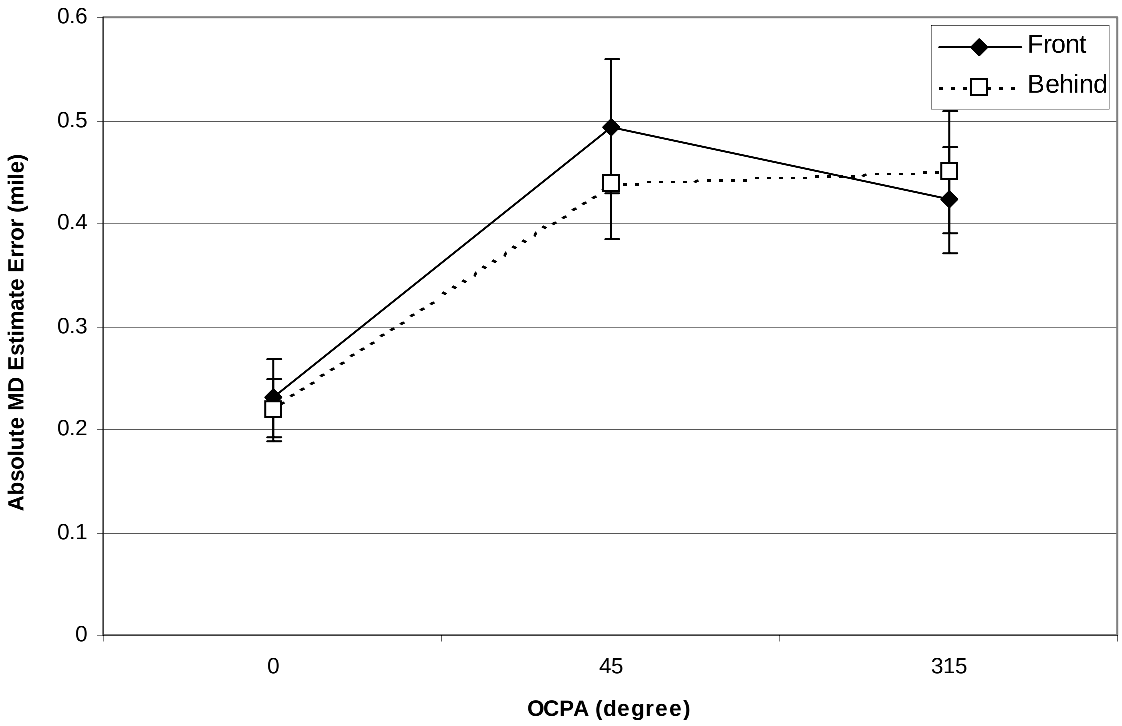

Figure 3.4. Absolute MD estimate errors (|estimated MD – true MD|) for two approach aspects and three OCPAs.

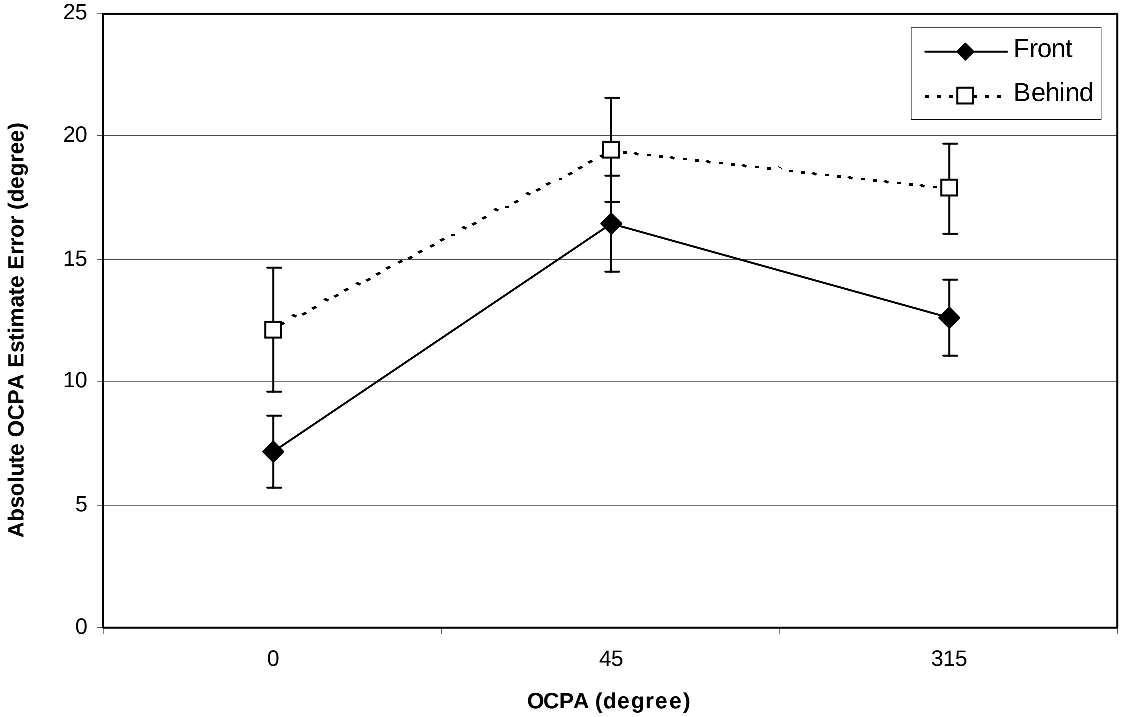

Figure 3.5. Absolute OCPA estimate errors (|estimated OCPA – true OCPA|) for two approach aspects and three OCPAs.

As with the analysis for approach side and CA, the analysis on both TCPA and MD estimate errors were also performed on the signed measures. Neither analysis revealed any significant effects, suggesting no systematic bias of the measures due to the changes in approach aspect and OCPA. Again, low power prevents a strong conclusion in confirming the null hypothesis of no difference.

Therefore, Hypothesis 2 was partially supported since the data revealed that the traffic’s approach aspect for the most part did not influence estimation performance.

3.3. Effects of Distance to Closest Point of Approach (DCPA), Relative Speed (RS), and Time to Closest Point of Approach (TCPA)

According to Hypothesis 3A, it was predicted that the three aspects of conflict understanding (estimations of TCPA, MD, and OCPA) would be made more difficult by increasing both distance and time to CPA, since both of these would have the effect of making the CPA farther into the future, in terms of distance and/or time. It was also predicted that estimations would be made more difficult by decreasing intruder traffic’s relative speed (RS). For each of the five dependent measures (absolute and signed TCPA estimate errors, absolute and signed MD estimate errors, and absolute OCPA estimate error), the data were first analyzed to examine the effects of DCPA and RS, and then the effect of TCPA. Furthermore, because of the incomplete factorial design (eight rather than nine conditions since the longest distance/slowest speed condition was dropped), the hypotheses regarding the effects of distance and speed were evaluated with two partly overlapping ANOVAs, (A) on all the three speeds at the two shortest distances and (B) on all the three distances at the two fastest speeds, where distance was a between-subjects factor and speed a within-subjects factor. These will be referred to as ANOVA (A) and (B), respectively, and as we will see, the two generally offered the same picture.

3.3.1. Effects on absolute TCPA estimate error.

Figure 3.6 presents the data on absolute TCPA estimate error as a joint function of distance to CPA and RS. The results of ANOVA (A) revealed that the main effect of DCPA was significant, $\underline{F}(1, 14) = 8.10$, $\underline{p} = .013$, indicating that the time estimate error was greater for 2.67 miles than for 1.33 miles. The main effect of RS was also significant, $\underline{F}(2, 28) = 40.00$, $\underline{p} < .0001$, indicating a monotonic increase in time estimate error as a result of slower RS. The significant interaction between DCPA and RS, $\underline{F}(2, 28) = 5.88$, $\underline{p} = .007$, suggests that the amount of increase in time estimate error as a result of DCPA increase was greatest at the slowest speed (160 knots) versus 240 knots or 480 knots.

ANOVA (B) also revealed that the main effect of DCPA was significant, $\underline{F}(2, 21) = 6.88$, $\underline{p} = .005$, with longer DCPA again leading to greater time estimate error. There was also a main effect of RS, $\underline{F}(1, 21) = 13.99$, $\underline{p} = .001$, again revealing that error was greater at slower relative speed. There was no significant interaction between the two factors, $\underline{F}(2, 21) = .86$, $\underline{p} = .44$.

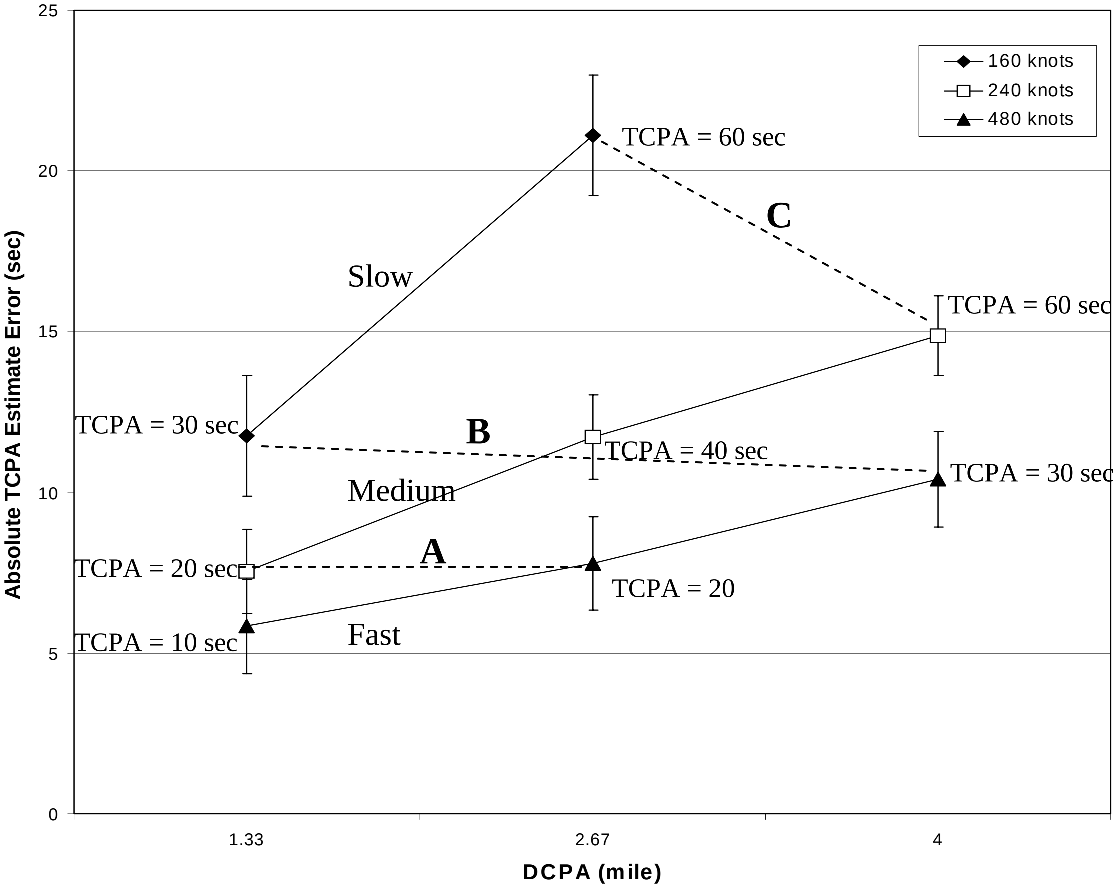

Figure 3.6. Absolute TCPA estimate errors (|estimated TCPA – true TCPA|) for three DCPA and three RS levels. The dashed lines connect pairs of points with identical times (TCPA), which differed with respect to the ratio of distance/speed: short/slow on the left side and long/fast on the right side.

Next, three separate ANOVAs were performed to examine the effect of true TCPA on absolute TCPA estimate error (the data for this analysis is also shown in Figure 3.6). Note that because of the interrelations between DCPA, RS, and the true TCPA, each data point in Figure 3.6 also represents a true TCPA value, as well as a DCPA and an RS. For example, the data point at the left bottom in the figure represents trials where DCPA was 1.33 miles and RS was 480 knots, but it also represents a TCPA of 10 sec. The TCPA values are labeled in the figure, with points having a common TCPA connected by a dashed line. A separate ANOVA was performed at each of the distances thereby demonstrating the effect of slower speed and/or longer time. The results of a one-way within-subjects ANOVA (10 sec, 20 sec, and 30 sec) for only the 1.33 mile DCPA revealed that absolute TCPA estimate error increased monotonically as the true value of TCPA increased, $\underline{F}(2, 14) = 11.40$, $\underline{p} = .001$. The results of a within-subjects ANOVA (20 sec, 40 sec, and 60 sec) for the 2.67 mile DCPA also indicated a monotonic increase in absolute TCPA estimate error as a function of the true TCPA value, $\underline{F}(2, 14) = 28.72$, $\underline{p} < .0001$. Similarly, for the 4.0 mile DCPA, as the true TCPA increased from 30 sec to 60 sec, so did absolute TCPA estimate error, F(1, 7) = 11.40, p = .078, a marginally significant result.

Also shown in Figure 3.6 is that when time to CPA is equated across conditions as indicated by the three dashed lines A, B, and C, there seems to be a penalty for shorter distances and slower speeds relative to longer distances and faster speeds particularly for line C (i.e., absolute time estimate errors were greater for the conditions of shorter DCPAs/slower speeds than those of longer DCPAs/faster speeds). To confirm this, a single ANOVA was performed 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). The ANOVA revealed that long distance (and fast speed) led to smaller absolute MD error than short distance (and slow speed) for the same true time, F(1, 42) = 3.96, p = .053, and longer time led to greater absolute MD estimate error, F(2, 42) = 24.41, p < .0001, with a marginally significant interaction, F(2, 42) = 2.53, p = .092.

3.3.2 Effects on signed TCPA estimate error.

Figure 3.7 presents the data on *signed* time estimate error as a joint function of DCPA and RS. As with the analyses for absolute time estimate error shown in Figure 3.6, the data were analyzed with two separate ANOVAs, (A) and (B). It was revealed by ANOVA (A) (3 speeds × 2 distances) that the effect of DCPA did not reach significance, F(1, 14) = 2.32, p = .15, but there was a highly significant effect of RS, F(2, 28) = 128.15, p < .0001, indicating that time to CPA was progressively underestimated as the speed was reduced. The significant DCPA and RS interaction, F(2, 28) = 15.69, p < .0001, suggests that the underestimation of time at slower speeds was amplified at the longer distance (2.67 miles relative to 1.33 miles).

The results of ANOVA (B) (2 speeds × 3 distances) also revealed a highly significant main effect of RS, F(1, 21) = 88.73, p < .0001, again indicating a progressively underestimate of TCPA at slower speeds. There was no significant main effect of DCPA, F(1, 21) = .77, p = .47, but the highly significant interaction between the two factors, F(2, 21) = 15.23, p < .0001, again suggests an amplification of the RS effect as the distance increased from 1.33 miles through 2.67 miles to 4.0 miles. Thus, the conclusions for the two ANOVAs were identical.

Next, three separate ANOVAs were performed to examine the effect of true time to CPA on signed time estimate error (as with the discussion of absolute time estimate error, here again these effects are portrayed in the same figure, Figure 3.7). The results of each one-way within-subjects ANOVA revealed that there was a monotonically greater underestimation of TCPA as the true value of TCPA increased [1.33 miles: F(2, 14) = 37.43, p < .0001; 2.67 miles: F(2, 14) = 92.23, p < .0001; and 4.0 miles: F(1, 7) = 42.65, p < .0001]. Thus, it appears that the pattern of the absolute time estimate error shown in Figure 3.6 can be well accounted for by increasing underestimate bias, rather than, simply, increasing variability of time estimation.

Also shown in Figure 3.7 is that when TCPA is equated across conditions as indicated by the three dashed lines A, B, and C, there seems to be a greater underestimate of TCPA for shorter distances and slower speeds than for longer distances and faster speeds. To confirm this, a single ANOVA was performed 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). The ANOVA revealed that short distance (and slow speed) led to shorter estimated TCPA than long distance (and fast speed) for the same true time, F(1, 42) = 24.61, p < .0001, and longer time led to greater underestimate of TCPA, F(2, 42) = 34.55, p < .0001, with significant interaction F(2, 42) = 3.37, p = .044.

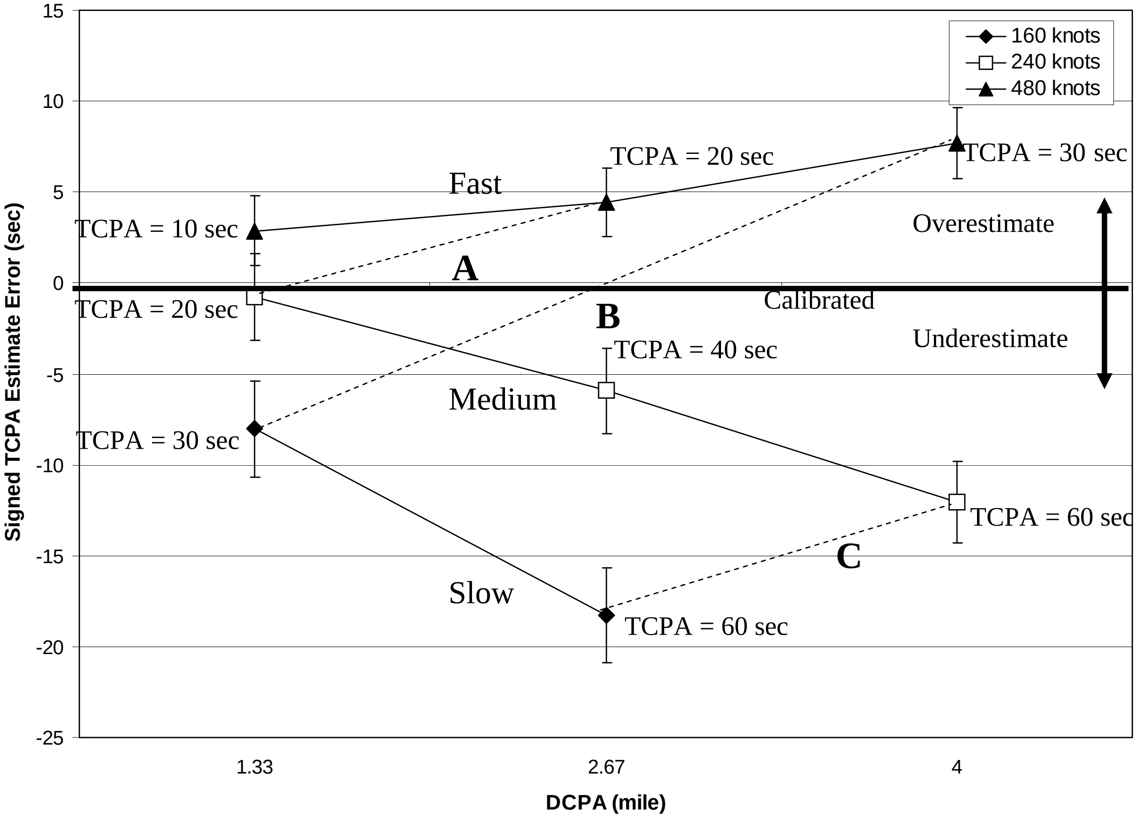

Figure 3.7. Signed TCPA estimate errors (estimated TCPA – true TCPA) for three DCPA and three RS levels. The dashed lines connect pairs of points with identical times (TCPA).

3.3.3 Effects on absolute MD estimate error.

Figure 3.8 presents the data on absolute MD estimate error as a function of DCPA and RS. The results of ANOVA (A) indicated that the MD estimate error was greater at the longer distance to CPA, F(1, 14) = 11.87, p = .004. The main effect of speed was also significant, F(2, 28) = 15.22, p < .0001, with estimate error increasing at slower relative speeds. Pairwise comparisons indicated that the MD estimate error at 240 knots was significantly greater than at 480 knots (p < .0001), but error did not differ between the two slowest speeds (p = .68). There was also a significant interaction between distance to CPA and speed, F(2, 28) = 8.80, p = .001. It is evident in Figure 3.8 and confirmed by statistical tests that this interaction occurred mainly because of the absence of significant difference in performance among the three speeds for the shortest DCPA (1.33 miles).

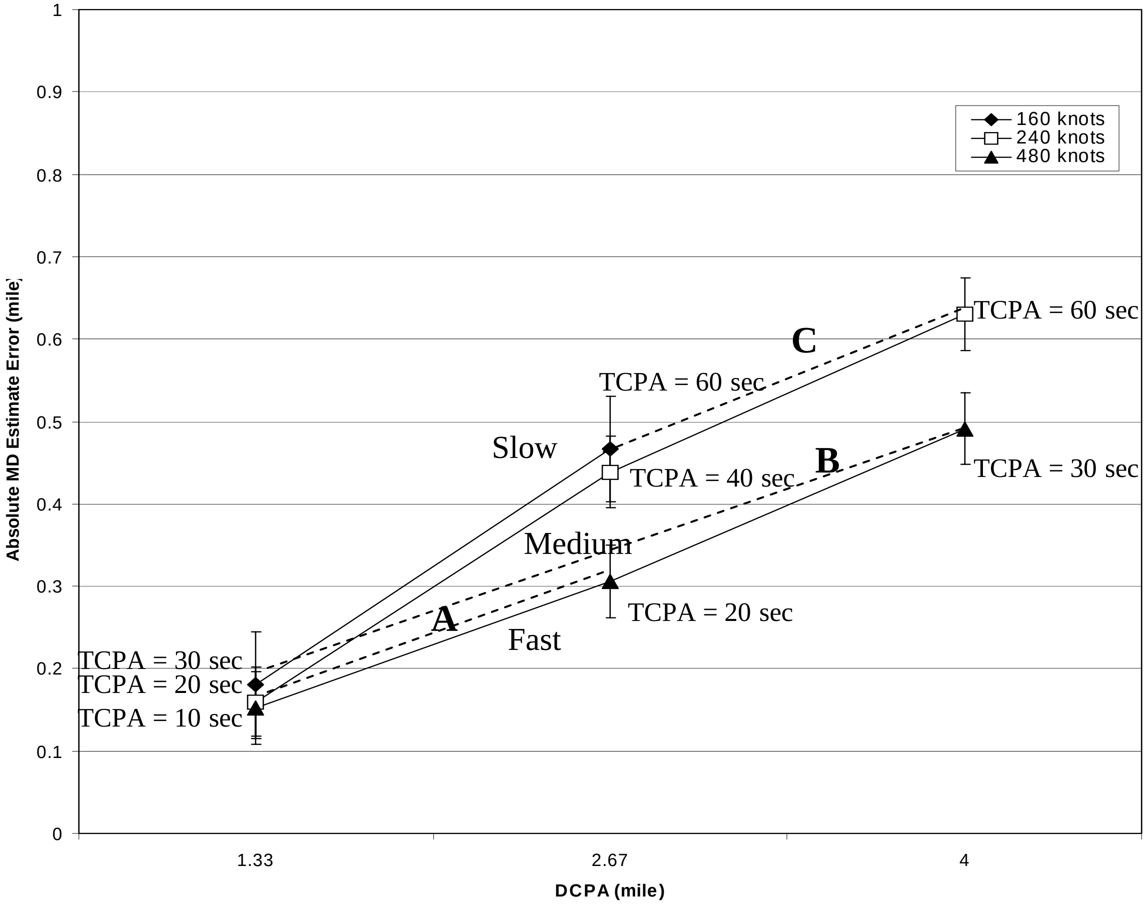

Figure 3.8. Absolute MD estimate errors (|estimated MD – true MD|) for three DCPA and three RS levels. The dashed lines connect pairs of points with identical times (TCPA).

The results of ANOVA (B) revealed, as with ANOVA (A), that MD error was greater at the longer distances to CPA [F(2, 21) = 23.60, p < .001], and at the slower speed [F(1, 21) = 38.09, p < .001], as well as a significant interaction between the two factors, F(2, 21) = 8.29, p = .002, replicating the pattern shown in the previous analysis. The interaction between DCPA and RS can again be best explained by the non-significant effect of relative speed only at the shortest distance (1.33 miles).

Next, three separate ANOVAs were performed to examine the effect of true TCPA on absolute MD estimate error (highlighted by the labels on the three dashed lines in Figure 3.9). Absolute MD estimate increased monotonically as the true value of TCPA increased. The three one-way ANOVAs revealed that MD estimate error increased with longer TCPA at the medium (2.67 miles) and longer (4.0 miles) distances, but not at the shortest distance (1.33 miles) [F(2, 14) = 14.37, p < .0001; F(1, 7) = 13.84, p = .007; and F(2, 14) = 1.92, p = .18, respectively].

Also shown in Figure 3.8 is that when time to CPA is equated across conditions as indicated by the three dashed lines, A, B, and C, there was a penalty for longer distances and faster speeds relative to shorter distances and slower speeds (i.e., absolute MD estimate errors were greater at longer DCPAs/faster speeds than at shorter DCPAs/slower speeds). To confirm this, a single ANOVA was performed 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). The ANOVA revealed that long distance (and fast speed) led to greater absolute MD error than short distance (and slow speed) for the same true time, F(1, 42) = 24.69, p < .0001, and longer time led to greater absolute MD estimate error, F(2, 42) = 19.87, p < .0001, with no interaction F(2, 42) = 1.54, p = .23.

3.3.4 Effects on signed MD estimate error.

Figure 3.9 presents the data for signed MD estimate error as a function of DCPA and RS. Generally, pilots underestimated the miss distance, judging that the point of closest approach was closer to the ownship that it actually turned to be. We can interpret the bias as erring on the side of safety. The results of ANOVA (A) showed neither significant effect of distance to CPA, F(1, 14) = .38, p = .55, nor significant effect of relative speed, F(2, 28) = 1.18, p = .32, or an interaction of these two factors, F(2, 28) = 1.42, p = .26.

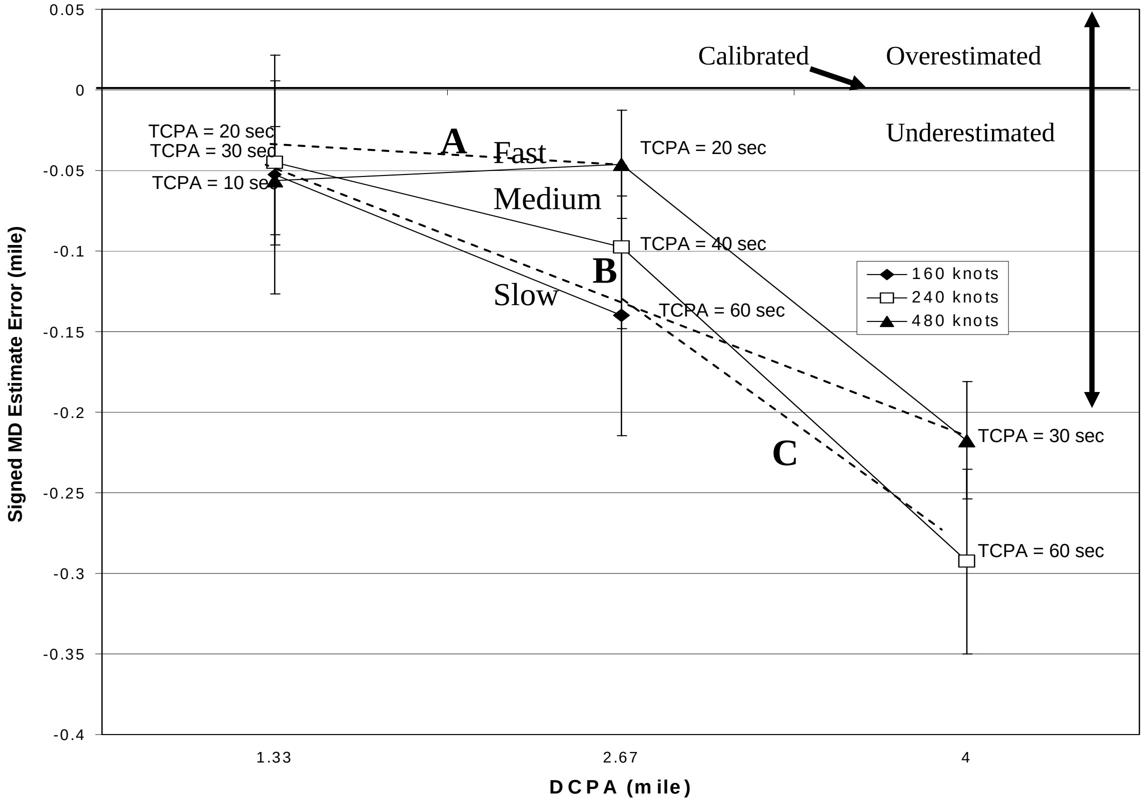

Figure 3.9. Signed MD estimate errors (estimated MD – true MD) for three DCPA and three RS levels. The dashed lines connect pairs of points with identical times (TCPA).

However, the results of ANOVA (B) revealed a significant main effect of distance to CPA, F(2, 21) = 6.85, p = .005, a non-significant main effect of RS, F(1, 21) = 2.38, p = .14, and a non-significant interaction of the two factors, F(2, 21) = 1.07, p = .36. The main effect of DCPA clearly came from the greater magnitude of underestimate as distance to CPA increased.

Next, three separate ANOVAs were performed to examine the effect of true TCPA on signed MD estimate error (also see Figure 3.9). None of the ANOVAs showed significant results, F(2, 14) = .26, p = .77 for the 1.33 mile DCPA, F(2, 14) = 1.38, p = .28 for the 2.67 mile DCPA, and F(1, 7) = 1.95, p = .21 for the 4.0 mile DCPA.

Also shown in Figure 3.9 is that when TCPA is equated across conditions as indicated by the three dashed lines, A, B, and C, miss distance was more underestimated for longer DCPAs and faster speeds relative to shorter DCPAs and slower speeds. To confirm this, a single ANOVA was performed 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). The ANOVA revealed that long distance (and fast speed) led to greater underestimate of MD than short distance (and slow speed) for the same true time, F(1, 42) = 5.17, p = .028, and longer time led to greater underestimate of MD, F(2, 42) = 4.45, p = .018, with no interaction F(2, 42) = 1.27, p = .29.

3.3.5 Effects on absolute OCPA estimate error

Figure 3.10 presents the data on absolute OCPA estimate error as a function of distance to CPA and relative speed. As with absolute TCPA and MD estimate errors, two separate ANOVAs were performed with respect to the effects of distance to CPA and speed on absolute estimate error. The results of ANOVA (A) revealed a significant effect of distance to CPA, F(1, 14) = 5.84, p = .03, a significant effect of speed, F(2, 28) = 7.74, p = .002, and a marginally significant interaction between the two factors, F(2, 28) = 3.24, p = .054. The main effect of DCPA demonstrates that OCPA error increased at longer distances, showing the exact same form and direction of effects as observed for absolute MD error (Figure 3.10). The main effect of RS shows that OCPA error increased as speed decreased. The marginally significant interaction was due to the non-significant difference among the three speeds only at 1.33 miles.

The results of ANOVA (B) again indicate a significant effect of DCPA, F(2, 21) = 4.41, p = .025, a significant effect of RS, F(1, 21) = 13.23, p = .002, and a marginally significant interaction between the two factors, F(2, 21) = 2.74, p = .087. The two main effects indicate that OCPA estimation performance was better at shorter distances and at faster speeds. The marginally interaction was again due to the non-significant difference in error between 240 knots and 480 knots at 1.33 miles, as well as, again, the reduced effect of distance at the fastest speed. It should be noted again that the pattern of results is identical to that observed for absolute miss distance error (see Figure 3.8).

Next, three separate one way ANOVAs were performed to examine the effect of true TCPA on absolute OCPA estimate error (also see Figure 3.10). Absolute OCPA estimate error seemed to increase monotonically as the true value of TCPA increased. This trend was significant for the two longer distances (4.0 and 2.67 miles), F(1, 7) = 6.27, p = .041, and F(2, 14) = 6.58, p = .010, respectively, but not for the shortest (1.33 miles) distance, F(2, 14) = 1.65, p = .23.

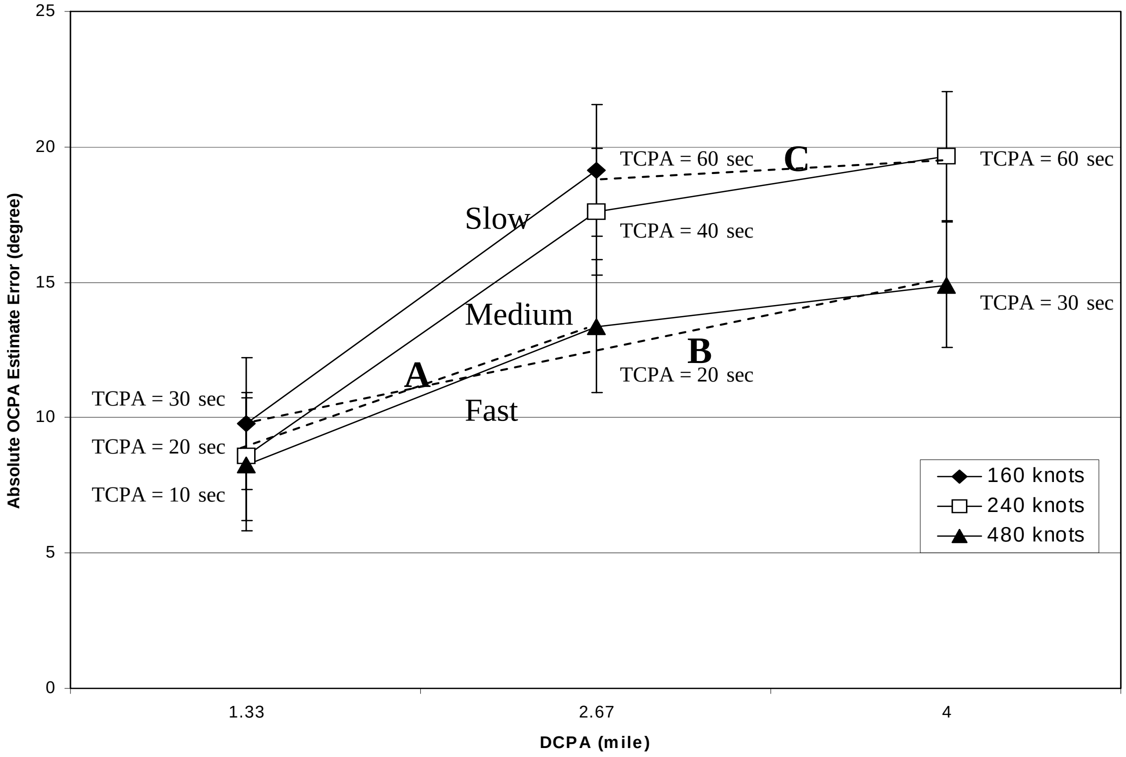

Figure 3.10. Absolute OCPA estimate errors (|estimated OCPA – true OCPA|) for three DCPA and three RS levels. The dashed lines connect pairs of points with identical times (TCPA).

Similar to absolute MD estimate error, when TCPA is equated across conditions as indicated by the three dashed lines, A, B, and C (see Figure 3.10), there seems to be a penalty for longer distances and faster speeds relative to shorter distances and slower speeds for this measure. To confirm this, a single ANOVA was performed 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). The ANOVA revealed that long distance (and fast speed) led to greater absolute MD error than short distance (and slow speed) for the same true time, F(1, 42) = 3.26, p = .078 (a marginal significance), and longer time led to greater absolute MD estimate error, F(2, 42) = 7.36, p = .002, with no interaction F(2, 42) = .59, p = .56.

3.3.6 Relative importance of DCPA, RS, and TCPA.

Because of the interrelations among the three independent variables of DCPA, RS, and TCPA (e.g., TCPA was determined by DCPA divided by RS), the effect of one variable could well be confounded with the effects of the other two. It is therefore important to understand the unique contribution or relative importance of each variable in influencing the estimation performance, and multiple regression analyses were performed to achieve this goal. Table 3.1 shows the zero-order correlation coefficients and partial correlation coefficients between DCPA, RS, and TCPA and the five dependent variables. The zero-order correlation coefficients in the table are consistent with the main effects of DCPA, RS, and TCPA or the lack thereof reported in the above sections. A partial correlation coefficient can be interpreted as the correlation between an independent variable and a dependent variable when the linear effects of the other independent variables have been removed from both that independent variable and the dependent variable. Thus, comparing the partial correlation coefficients of the three independent variables here (DCPA, RS, and TCPA) can yield their relative importance in influencing the estimation performance.

What is evident is Table 3.1 is that for absolute TCPA estimate error, the true TCPA was a more important independent variable than DCPA and RS, since the partial correlation coefficient between the true TCPA and absolute TCPA estimate error is both larger in absolute magnitude and more significant that those for DCPA and RS. For signed TCPA estimate error, again the true TCPA was the most important factor, which was followed by DCPA in importance, with RS being the least important, based on the magnitudes of their partial correlation coefficients and their significance levels. The relatively more important role of DCPA than that of RS here is in fact consistent with the result described earlier in section 2.2.3.1 (i.e., the same TCPA was estimated to be shorter for short distance/slow speed than for long distance/fast speed), suggesting the dominant role of the distance information over the speed information. For absolute MD estimate error, only the partial correlation efficient between DCPA and absolute MD estimate error is significant, suggesting the dominance of DCPA over TCPA and RS when MD was estimated. For signed MD estimate error and absolute OCPA estimate error, none of the partial correlation coefficients is significant.

In summary (also see Table 3.2), across all these dependent measures (i.e., TCPA, MD, and OCPA estimate errors), the results of the analyses indicated a main effect of distance to CPA and time to CPA, with a monotonic increase in estimate errors (both in absolute and signed measures) as distance became greater and time became longer, either significantly or in a trend. Errors (also both in absolute and signed measures) increased monotonically with a decrease in relative speed, either significantly or in a trend. The interactions between the DCPA and RS generally suggest that the distance effect costs were greater at slower speeds and the speed effect costs were greater at further distances. It was also found that the true TCPA was the major factor (relative to DCPA and RS) in influencing TCPA estimation accuracy, and the true DCPA was more important than TCPA and RS in influencing MD estimation accuracy.

Therefore, the hypothesis concerning the effects of DCPA, RS and TCPA (Hypothesis 3A) was supported for the most part.

Table 3.1. Zero-order and Partial Correlation Coefficients between DCPA, RS, and TCPA and Dependent Variables

	Zero-order	Significance (p value)	Partial	Significance (p value)
Absolute TCPA estimate error				
DCPA	.30	.007	-.20	.11
RS	-.49	< .0001	.13	.32
TCPA	.70	< .0001	.43	< .0001
Signed TCPA estimate error				
DCPA	-.035	.39	.42	.001
RS	.71	< .0001	-.092	.48
TCPA	-.67	< .0001	-.53	< .0001
Absolute MD estimate error				
DCPA	.74	< .0001	.30	.017
RS	-.093	.23	.04	.76
TCPA	.65	< .0001	.20	.13
Signed MD estimate error				
DCPA	-.44	< .0001	-.17	.20
RS	.027	.42	.009	.95
TCPA	-.35	.002	-.041	.75
Absolute OCPA estimate error				
DCPA	.46	< .0001	.047	.72
RS	-.16	.10	.078	.55
TCPA	.51	< .0001	.21	.11

3.4. Effect of Miss Distance (MD)

According to Hypothesis 3B, estimate errors of TCPA, MD, and OCPA would increase in magnitude as a result of increased true value of MD. Figure 3.11 presents the data on absolute TCPA estimate error as a function of DCPA and MD. The results of a 3 (DCPA) × 3 (MD) mixed ANOVA revealed a significant main effect of DCPA, $F(2, 21) = 5.75$, $p = .01$ (discussed previously in the context of Figure 3.6), but neither a significant main effect of MD, $F(2, 42) = 2.08$, $p = .14$, nor a significant interaction between the two factors, $F(4, 42) = .32$, $p = .86$.

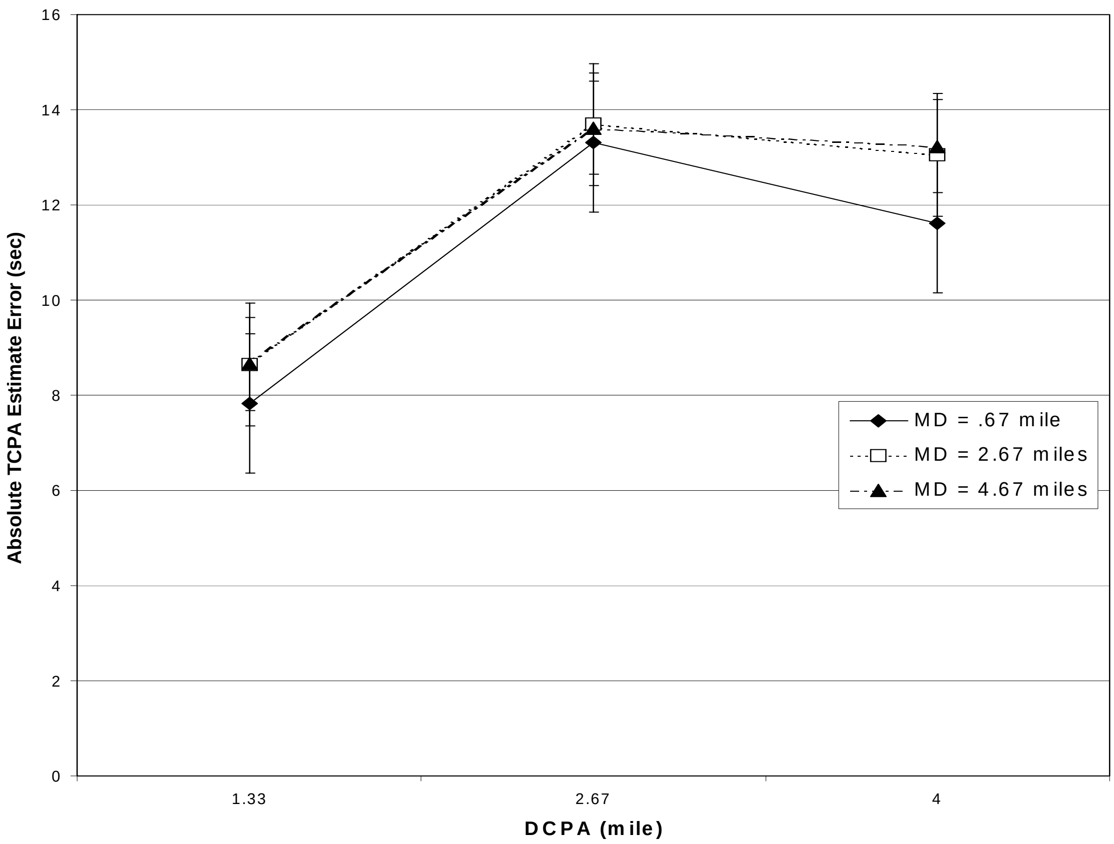

Figure 3.11. Absolute TCPA estimate errors (|estimated TCPA – true TCPA|) for three DCPA and three MD levels.

Figure 3.12 presents the data on *signed* TCPA estimate error as a function of DCPA and MD. The results of a 3 (DCPA) × 3 (MD) mixed ANOVA revealed a non-significant main effect of DCPA, F(2, 21) = 1.83, p = .19, but a significant main effect of MD, F(2, 42) = 3.38, p = .044, and a non-significant interaction between the two factors, F(4, 42) = .16, p = .96. The main effect of MD indicates that as MD became shorter (i.e., a riskier conflict situation), there was a greater underestimate of TCPA (i.e., the conflict was estimated to occur earlier).

Figure 3.13 presents the data on absolute MD estimate error as a function of DCPA and true MD. The results of a 3 (DCPA) × 3 (MD) mixed ANOVA revealed a significant main effect of DCPA, F(2, 21) = 18.46, p < .0001, which has been discussed before in the context of Figure 3.8, a significant main effect of MD, F(2, 42) = 17.66, p < .0001, and a significant interaction between the two factors, F(4, 42) = 5.60, p = .001. That is, MD estimate error generally increased as the true value of MD itself did and this effect was amplified at longer levels of DCPA.

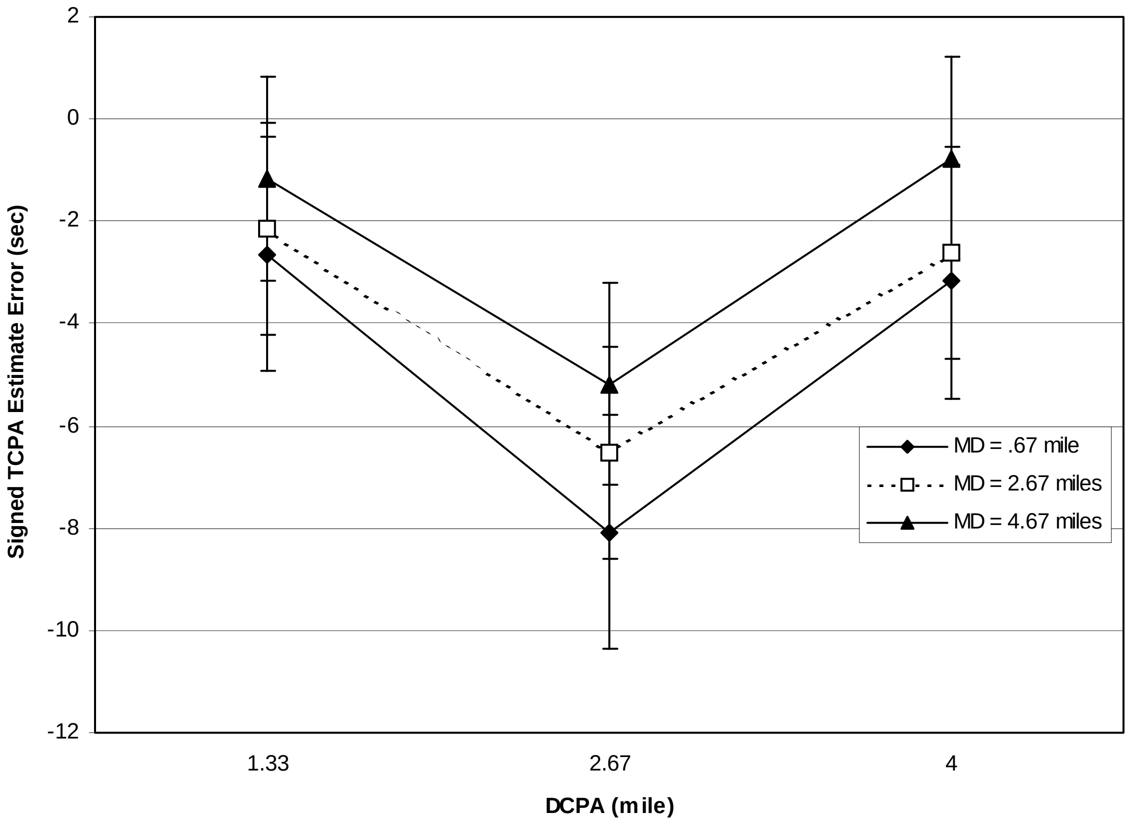

Figure 3.12. Signed TCPA estimate errors (estimated TCPA – true TCPA) for three DCPA and three MD levels.

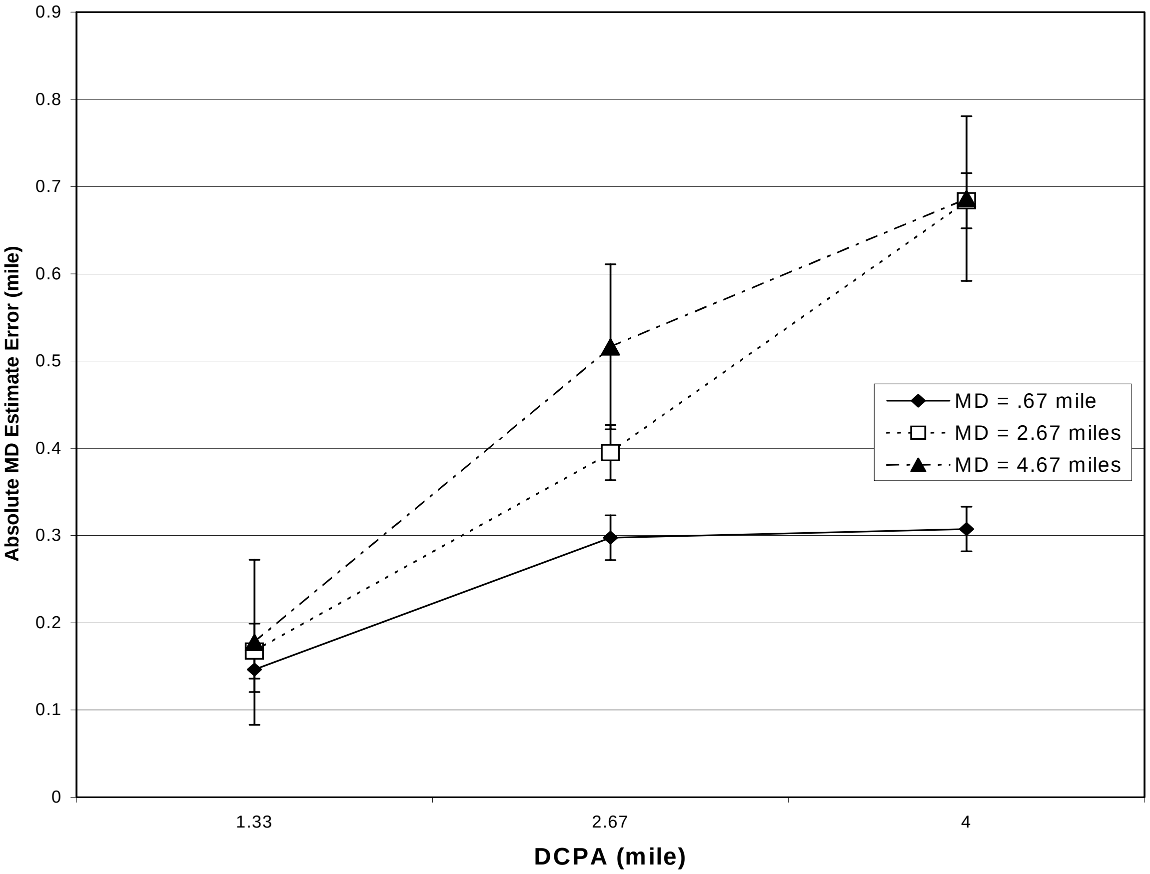

Figure 3.13. Absolute MD estimate errors (|estimated MD – true MD|) for three DCPA and three MD levels.

Figure 3.14 presents the data on **signed** MD estimate error as a function of DCPA and true MD. The results of a 3 (DCPA) × 3 (MD) mixed ANOVA revealed a significant main effect of DCPA, F(2, 21) = 4.71, p = .020 (seen before in the context of Figure 3.10), a significant main effect of MD, F(2, 42) = 14.49, p < .0001, and a significant interaction between the two factors, F(4, 42) = 3.60, p = .013. We can describe the pattern by noting that at short distance to CPA, miss distance was accurately estimated. At longer distances to CPA, the shorter miss distance tended to be overestimated, but the longer miss distances were greatly underestimated.

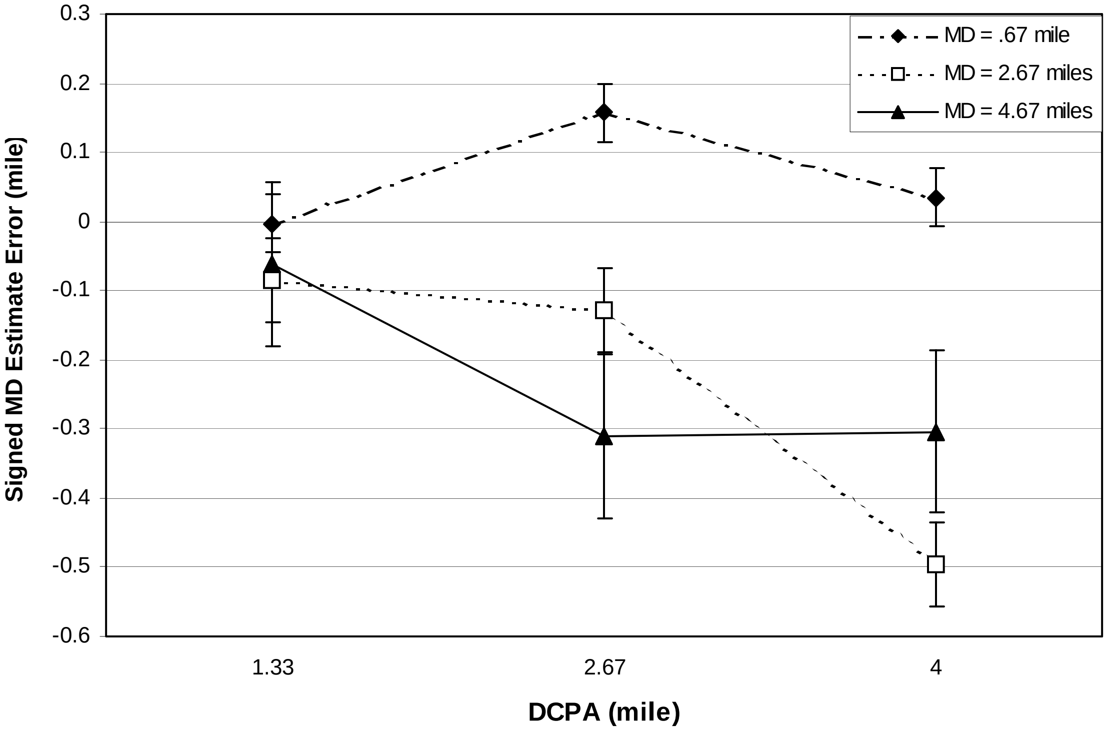

Figure 3.14. Signed MD estimate errors (estimated MD – true MD) for three DCPA and three MD levels.

Figure 3.15 presents the absolute orientation (OCPA) estimate error as a function of DCPA and MD. The results of a 3 (DCPA) × 3 (MD) mixed ANOVA revealed a significant main effect of DCPA, F(2, 21) = 4.54, p = .023 (seen before in the context of Figure 3.10), and a significant main effect of MD, F(2, 42) = 29.38, p < .0001, showing the largest error at the shortest miss distance. There was a marginally significant interaction between the two factors, F(4, 42) = 2.29, p = .076, indicating that the orientation error in judging conflicts with shorter MDs (higher risks) was amplified at longer DCPA levels.

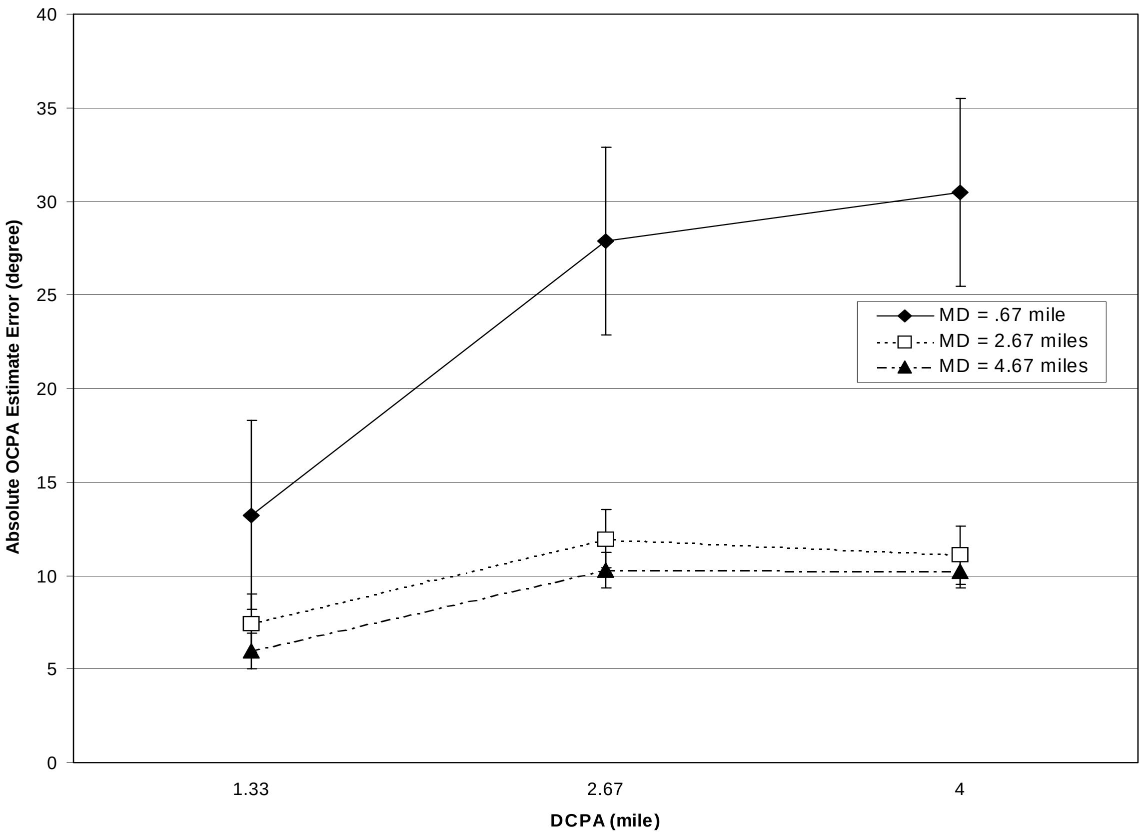

Figure 3.15. Absolute OCPA estimate errors (|estimated OCPA – true OCPA|) for three DCPA and three MD levels.

In summary (also see Table 3.2), the true MD had no effect on absolute time estimate error, but time to CPA was progressively underestimated—the conflict was judged to occur sooner than it would—as the true MD value decreased (i.e., as the conflict became more dangerous). Also, as the true MD value increased, there was an increase in absolute MD estimate error mostly resulting from underestimate of the longer MDs at the longer distance to CPA. This is not quite consistent with Weber's law in that it predicts an increase in variability (i.e., absolute MD estimate error), but not an increase in bias (i.e., signed MD estimate error), with an increase in the true MD value. Finally, MD had an effect on OCPA estimation in a rather interesting way—performance suffered as the true MD decreased, and did so more at longer MDs.

Thus, the hypothesis regarding the effect of true MD on performance (Hypothesis 3B) was partially substantiated.

3.5 Summary of Effects of Independent Variables on Dependent Variables

Table 3.2 summarizes the effects of all the independent variables (rows) on the five dependent measures (columns).

Table 3.2. Summary of Effects of Independent Variables on Dependent Variables

	Effect on:				
Effect of:	Absolute TCPA estimate error	Signed TCPA estimate error	Absolute MD estimate error	Signed MD estimate error	Absolute OCPA estimate error
Approach side	No effect	No effect	No effect	No effect	No effect
CA	No effect	No effect	90° was best	No effect	90° was best
Approach aspect	No effect	No effect	No effect	No effect	“Front” was better
DCPA	Farther was worse (particularly at slower RSs and over longer TCPAs)	No effect	Farther was worse (at slower RSs and over longer TCPAs in particular)	Farther led to underestimate	Farther was worse (at slower RSs and over longer TCPAs in particular)
RS	Slower was worse (particularly at farther DCPAs and over longer TCPAs)	Slower led to greater underestimate (particularly at farther DCPAs and over longer TCPAs)	Slower was worse (at farther DCPAs and over longer TCPAs in particular)	No effect	Slower was worse (particularly at farther DCPAs and over longer TCPAs)
TCPA	Longer was worse (particularly at slower RSs/shorter DCPAs)	Longer led to underestimate (particularly at slower RSs/shorter DCPAs)	Longer was worse (at farther DCPAs/faster RSs in particular)	Longer led to greater underestimate	Longer was worse (particularly at farther DCPAs/faster RSs)
MD	No effect	Smaller led to greater underestimate	Greater was worse (at longer DCPAs in particular)	Greater led to underestimate (particularly at longer DCPAs)	Smaller was worse (particularly at longer DCPAs)

3.6 Distance-over-Speed Bias

The distance-over-speed bias hypothesis (Hypothesis 4) states that for two conditions with a same true TCPA (connected by the dashed lines in Figure 3.7), the estimate of time to CPA would be longer in the condition with a longer DCPA and faster RS than that with a shorter DCPA and slower RS. It is to be noted that the testing for this hypothesis has been conducted before in the context of Figure 3.7. In other words, the results of this bias testing are imbedded in those for the effects of distance to closest point of approach (DCPA), traffic’s relative speed (RS), and time to closest point of approach (TCPA) on signed TCPA estimate error in section 2.2.3.2. As reported in section 2.2.3.2, statistical testing showed that for the same true time, longer distance (and faster speed) indeed led to longer estimated TCPA than shorter distance (and slower speed).

Figure 3.16 provides another way of presenting the data and shows the estimated TCPA (rather than signed TCPA estimate error as in Figure 3.7) for the pair of conditions that had a same true TCPA resulting from different combinations of DCPA and RS (i.e., short DCPA/slow RS and long DCPA/fast RS). A 3 (20 sec, 30 sec, and 60 sec) × 2 (short DCPA/slow RS vs. long DCPA/fast RS) between-subjects ANOVA revealed that for the same true TCPA, long DCPA/fast RS always resulted in longer estimated TCPA than short DCPA/slow RS, $\underline{F}(1, 42) = 24.62$, $\underline{p} < .0001$.

Thus, Hypothesis 4 was fully supported by the data.

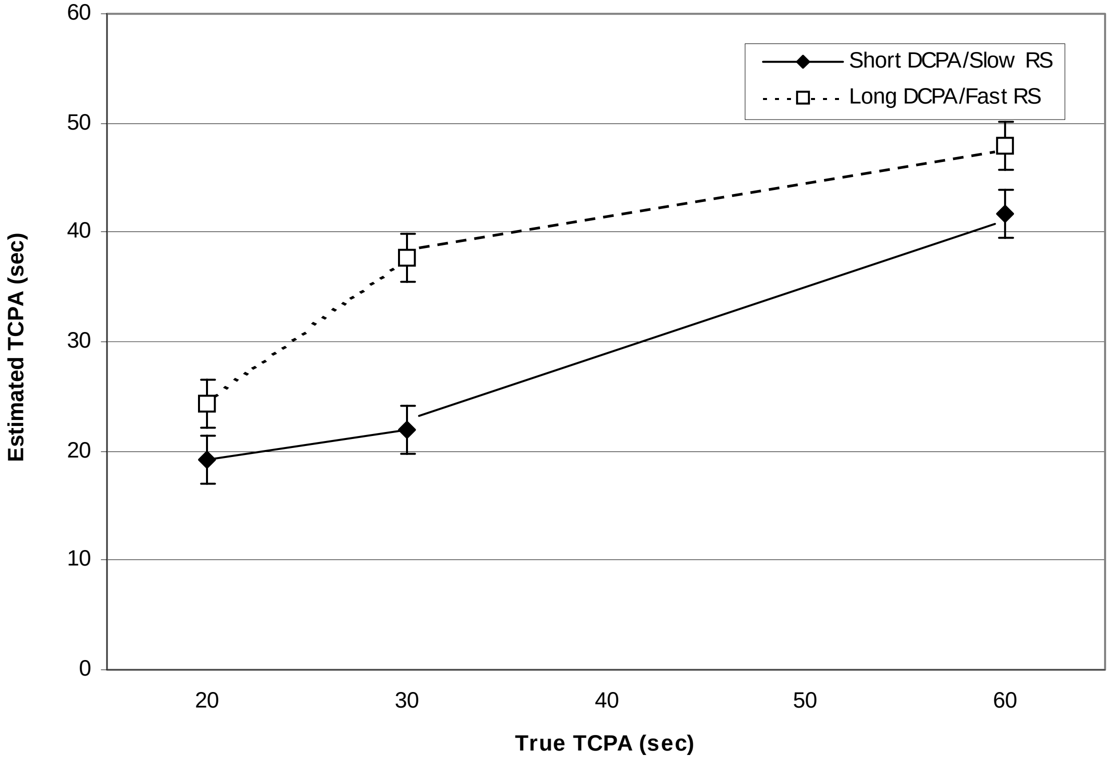

Figure 3.16. Estimated TCPA of same true TCPA for short DCPA/slow RS and long DCPA/fast RS.

3.7 Relation between True TCPA and Estimated TCPA

According to Hypothesis 5, for a same DCPA, there would be relative overestimation of TCPA for shorter TCPAs (at faster RSs) than for longer TCPAs (at slower RSs). As in the case of testing Hypothesis 4, the testing for this hypothesis has been conducted before in the context of Figure 3.7 and reported in section 2.2.3.2. As seen in Figure 3.7, within each distance level, shorter times (at faster speeds) were relatively over estimated as compared to longer times (at slower speeds). This pattern was confirmed by the series of three ANOVAs (one on each distance) performed on the data contained in Figure 3.7.

Thus, Hypothesis 5 was also fully supported by the data in that longer times were relatively underestimated than were shorter times.

Finally, we examined separately the performance of flight instructors and student pilots and found no significant difference between these two categories of pilots except that the student pilots tended to underestimate TCPA (mean signed TCPA estimated error = -4.85 sec) and the instructors tended to overestimate TCPA (mean signed TCPA estimated error = 6.63 sec), $\underline{t}(6) = -3.41$, $\underline{p} = .014$, only for the 1.33 mile DCPA group.

4. Discussion

The goal of the experiment was to explore the conflict geometry effects in order to answer two general questions regarding pilots using a CDTI for conflict detection. First, what makes conflict understanding difficult? “Understanding” here is assessed by the vector of three measures: Miss distance or MD (a risk estimate), the time to the closest point of approach (TCPA), and orientation at the point of closest approach (OCPA). “Difficulty’ was operationally defined by an increase in the absolute error between these three parameters and the subjects’ estimation of their values. We note however that an increase in absolute error can result either from an increase in variability or from a systematic bias, or constant error away from the true value. So, particularly for the two measures of MD and TCPA, our second question asks what are the systematic **biases** to over- or underestimate a quantity, as such biases would be assessed by a measure of **signed error**. In the following, we first briefly describe the less interesting aspects of conflict angle effects, before turning toward those of greater complexity (and interest) related to time, speed, and distance.

4.1 Conflict Angle, Approach Side, and Approach Aspect

As Table 3.2 reveals, there appeared to be minimal effects of conflict angle on the three critical measures of conflict understanding. In particular it is noteworthy that the distinction between approaching (45º) and overtaking (135º) conflicts that had been found to moderate some aspects of conflict performance in other studies (e.g., Merwin & Wickens, 1996), had no effect here. The only prominent finding with regard to conflict angle was the greater ease of understanding 90º crossing conflicts, as compared to the more oblique 45º and 135º angles (see Figures 3.2 and 3.3). We can account for this “orthogonal easy” finding by the fact that traffic with 90º angle was moving perpendicular to the two vertical sides and parallel to the two horizontal sides of the computer screen. This orthogonal/parallel feature of the traffic’s relative trajectory might have benefited the extrapolation of the future positions of the traffic and thus benefited the estimation of the location of the closest point of approach (CPA) (i.e., the MD and OCPA estimations).

The failure to confirm that approaching and overtaking conflicts were different in the current study suggests that such effects, when observed in other studies (e.g., Scallen et al., 1996; Merwin & Wickens, 1996), may have been confounded with distance and relative speed effects. For example, assuming a constant ground speed of the traffic, at a constant time to closest point of approach (TCPA), an approaching conflict (large conflict angle) will be at a greater distance than an overtaking one (small conflict angle), and at a constant distance, the overtaking conflict will travel at a slower relative speed, and TCPA will be longer. When we controlled for these factors in the current experiment, the effects of angle disappeared. On the other hand, the factors of distance, time, and speed themselves had pronounced influence on conflict understanding, the issue we address below.

We did not find an effect of the approach side (i.e., traffic passing from the right to the left or vice versa), either. Merwin and Wickens (1996) found that traffic approaching the ownship from the left resulted in larger number of conflicts than those from the right and they explained that it was possibly due to pilots' tendency to turn to the right for conflict avoidance, a behavior likely influenced by the FAA regulations. The current results indeed confirmed their implication that the approach side per se is not a critical factor influencing conflict detection.

The effect of the approach aspect (passing in front of or behind the ownship) was not found in the present study, either, except for the OCPA estimate error (Figure 3.5). Merwin and Wickens (1996) found that traffic passing in front of the ownship induced more conflicts than did those coming from behind. Again, Merwin and Wickens suggests that it may be attributable to the choice of avoidance maneuvering in connection with the approach aspect of the traffic rather than the approach aspect per se that is the source of difference in conflict avoidance performance. However, the reason for the greater OCPA estimate accuracy for the "front" traffic relative to the "behind" traffic is not clear.

Finally, it needs to be noted that the power of the testing of the hypotheses regarding the null effects of approach side and aspect was generally low. When the results associated with these hypotheses were non-significant with low power, they were not necessarily conclusive.

4.2. Speed, Distance, and Time

The effects of the relative speed of the two aircraft, and the traffic's distance and time from the point of closest approach can be subdivided into two categories: How these variables degraded conflict understanding (increasing absolute error of MD, TCPA and OCPA estimation), and how they might have biased these estimates as examined by signed errors.

Regarding the first of these effects on conflict understanding difficulty, the results were conclusive and consistent (see Table 3.2). Decreasing relative speed, increasing time to CPA, and increasing distance to CPA at the time that estimations were made, all degraded the accuracy of those estimations. Furthermore, the results presented in Figures 3.6, 3.8, and 3.10 collectively suggested that each of these variables contributed independently to the degradation in performance. That is, when any one was held constant, both of the other two generally exhibited effects. The data also suggest interactions such that the degrading effect of one variable was amplified at the more degrading ("harder") level of another one. The results concerning the effects of speed, time, and distance are consistent with our hypotheses and with the literature both in aviation (e.g., Remington et al., 2000), in driving (e.g., Hancock & Manser, 1998), as well as in basic research (e.g., Kimball, 1970; Kimball et al., 1973; Peterken et al., 1991; Slater-Hammel, 1955).

Importantly, while all three variables had some effect, the data suggest that they contributed differently to the two important measures of conflict understanding (TCPA and MD estimation accuracy). The effect of the true TCPA was more pronounced than that of distance and speed on TCPA estimation as shown by the multiple regression analysis (Table 3.1). This is consistent with Peterken et al. (1991), where it was shown that it was the time rather than the distance during which a moving was not visible that was the more important factor in influencing the time-to-contact estimation accuracy. In contrast to the greater contribution of true TCPA to TCPA estimation performance, DCPA was a more important factor than TCPA and RS that contributed to the MD estimation accuracy. This was possibly because MD estimation accuracy, unlike TCPA estimation accuracy, was only determined by DCPA (i.e., accuracy decreased as DCPA increased), without the need to involve time and speed perception, other factors being equal.

Regarding the second set of effects, those on biases, these can in turn be broken into two different categories, those effects in which pilots were found to bias their responses on the side of safety, by *underestimating* both miss distance and the time till a conflict was reached, and those in which other perceptual biases were manifest. Concerning the safety or "risk avoidance" biases, we found that responses offered at greater distances to CPA tended to estimate miss distance as smaller than it actually was (underestimating MD), and that this bias could account for the overall increase in MD absolute error reported above. One possible reason for this bias is that with increasing distance to CPA went the increasing uncertainty about the true value of MD, and consequently it would make sense to be more cautious by underestimating MD. We also found that conflicts projected to produce smaller actual miss distances led pilots to estimate that they would occur sooner (i.e., shorter perceived TCPA) than they actually would, as if the greater danger that such a conflict imposed produced a reduced estimate of the time remaining (greater perceived "urgency"). Finally, greater miss distances led pilots to underestimate what the true miss distance would be, more so than with smaller miss distances. As in the case of greater underestimate of MD with increasing distance to CPA, the increasing uncertainty about the true value of the greater MD might have made it a safe strategy to be more cautious by underestimating this distance. All of these can be considered to be "adaptive" responses and are 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, and the estimates of miss distance and time to CPA were plagued by uncertainty.

Some perceptual biases were also manifest. In particular, conflicts that evolved at slower speeds and/or longer time led pilots to underestimate the waiting time until they would occur (i.e., underestimating TCPA) (see Figure 3.7). This may be thought of as a sort of "impatience" in dealing with events that play out slowly. It is a bias that might even have signaled a subject who wanted to complete the experiment sooner, although subjects were paid on an hourly rate, so there was no financial incentive to complete sooner (in fact the incentive worked in the opposite direction). However, another possible explanation of underestimating TCPA under these long-time circumstances is that subjects were also showing the bias of conservatism describe above (i.e., "erring on the side of caution")—longer times were associated with greater uncertainty regarding the future status of the traffic, and it would be only safe to further underestimate the critical parameter TCPA as uncertainty was growing. It is also possible that these two mechanisms (i.e., “impatience” and “erring on the side of caution”) were both responsible for the TCPA underestimate. Finally, this underestimate of time at slower speeds is also consistent with the regression toward the mean found in the time-to-contact literature (Bonnet & Kolehmainen, 1970; Ellingstad, 1967); that is, given a same distance, time is underestimated at slower speed and overestimated at faster speed.

A final way to interpret the bias to underestimate the TCPA for slow speed conflicts is to note that, at slower speeds but constant TCPA, the intruder would be closer to ownship than at faster speeds (see Figure 3.7). This closeness in space would have led to an underestimate of time, if distance, rather than speed, was used to estimate time, by the heuristic: Shorter distance → shorter time. This of course is a way of expressing the “distance-over-speed” bias which had been observed by Law et al (1993), and which we were able to confirm specifically by the structuring of trials, as shown in Figures 3.7 and 3.16. These two figures show that given a constant time to CPA, this time was estimated shorter when the distance was short and the speed was slow than when the distance was long and speed was fast. These effects were relatively large in magnitude, a difference in time estimates of over 15 sec in some cases.

Law et al. (1993) explained that time estimation requires the integration of both distance and speed information, and the distance-over-speed bias is possibly due to the higher salience of the distance information than that of the speed information, which in turn is due to the greater complexity of the speed information as compared to that of the distance information. We feel that this phenomenon can also be explained by Kahneman’s theory on the two systems (system 1 and system 2) in human perception (Kahneman, 2003). According to Kahneman, system 1 is intuition, which is fast and effortless; and system two is reasoning, which is analytical and optimal, but slow and effortful. Human beings have a tendency to substitute system 1 for system 2, especially when the information required for system 2 is not totally accessible than that for system 1. Time estimation in our experiment involved both distance perception (a system 1 process) and speed perception. The integration of these two types of information was effortful, involving a system 2 process (see Figure 4.1). When the traffic icon stopped moving after the freezing point, the speed information was less accessible than the distance information. Therefore, it is conceivable that pilots just substituted distance perception for the more complex integration of distance **and** speed information. It would be interesting to replicate the paradigm with either velocity continuing after the freezing point (speed more accessible) or with the traffic icon vanishing at the freezing point (distance less accessible). We predict that both of these should reduce the distance-over-speed bias.

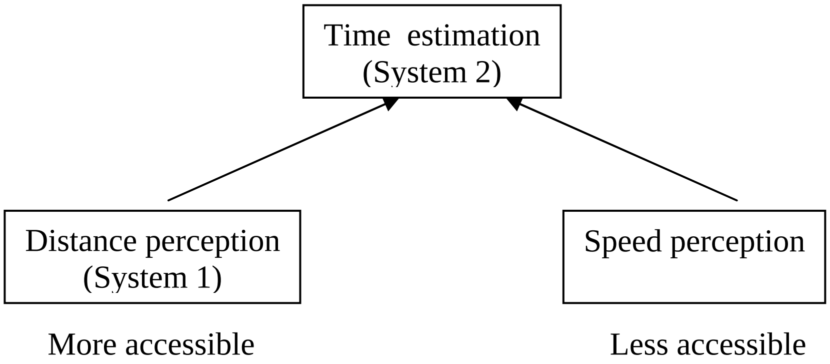

Figure 4.1. Illustration of time estimation as a process of integrating both distance and speed information in Experiment 1.

4.3 Problem Difficulty Revisited: the Role of Automation

The fact that variables of time, speed, and distance all had pronounced effects on the most important index of conflict risk perception, the estimation of miss distance, suggested that we had assessed a wide range of problem difficulties. According to the literature that we reviewed in a separate technical report (Xu, Wickens, & Rantanen, 2004), it is likely that the support offered by an automated alerting logic should be most beneficial for the difficult problems, but offer few benefits for the easy ones. Correspondingly, it is possible that the impact of automation failures would also be greatest for the most difficult problems. In order to examine the effect of problem difficulty, the many conflicts presented in the current experiment were subdivided into “easy” and “hard” categories, by a procedure described in Xu et al. (2004), and then both were re-presented, to a new group of pilots, with an imperfect alerting automation (also see Xu et al., 2004 for results).

5. Summary and Conclusion

This research project was an effort to bridge the gap between the literature and research necessity on conflict detection with the CDTI, as well as the gap between the basic (time-to-conflict) and applied (conflict detection) research and we found that some of the important findings in the basic research could scale up to an applied setting where safety is a vital issue. We systematically investigated the effects of air traffic geometry on conflict detection using estimation errors of continuous measures of conflict risk as dependent variables. Among other findings, we have identified several important biases manifested when pilots were manually detecting conflicts including the overall tendency to underestimate miss distance and time to conflict, and the distance-over-speed bias, both of which have important safety implications for the future free flight environment. We also discussed the cognitive mechanisms underlying those biases. Finally, the conflict geometry in this experiment allowed another study to investigate the effect of conflict problem difficulty on performance when automation on conflict detection with CDTI was introduced.

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