WELL CLEAR:
GENERAL AVIATION AND COMMERCIAL PILOTS' PERCEPTION OF UNMANNED AERIAL VEHICLES IN THE NATIONAL AIRSPACE SYSTEM

This research explored how different pilots perceived the concept of the Well Clear Boundary (WCB) and observed if that boundary changed when dealing with manned versus unmanned aircraft systems (UAS), and the effects of other variables. Pilots' WCB perceptions were collected objectively through simulator recordings and subjectively through questionnaires. Objectively, significant differences were found in WCB perception between two pilot types (general aviation [GA], and Airline Transport Pilots [ATPs]), and significant WCB differences were evident when comparing two intruder types (manned versus unmanned aircraft). Differences were dependent on other manipulated variables (intruder approach angle, ownship speed, and background traffic levels). Subjectively, there were differences in WCB perception across pilot types; GA pilots trusted UAS aircraft higher than the more experienced ATPs. Conclusions indicate pilots' WCB mental models are more easily perceived as time-based boundaries in front of ownship, and more easily perceived as distance-based boundaries to the rear of ownship.

INTRODUCTION

Background

Our National Airspace System (NAS) is undergoing major transition as it is upgraded to the NextGen environment. This upgrade is imperative to our NAS's future, which faces challenges of higher air traffic levels, more congested airports, and the need for precise timing and coordination to avoid "gridlock" scenarios (FAA, 2013). The NextGen NAS will allow more aircraft to fly closer together, ensuring skies have room for continued growth and increased safety (FAA, 2013).

The safe integration of Unmanned Aerial Systems (UASs) is part of this evolution. UASs are piloted remotely by humans in ground-control stations, and are optionally controlled autonomously. UASs are faced with the need to become integrated into civilian operations. Many UAS aircraft originally designed for use in the military are now in high demand for use in the current NAS for a multitude of civilian and less traditional military roles. There is much potential for UASs, but large challenges remain in our efforts to safely integrate them into the NAS.

Over 100 incidents or accidents involving UASs have been experienced globally, and this figure continues to rise (Drone Wars UK, 2013). Aside from these incidents, a major challenge facing UAS integration is their unavoidable interaction with the most numerous pilot type in our NAS, General Aviation (GA) pilots. GA is comprised of civil aviation operations, including everything from single engine aircraft to small corporate jets. As of March 2011, the number of GA certificated pilots in the US was 339,127, more than any other pilot type out of the total US pilot population of 627,588. Many GA pilots are student pilots who are learning to fly and have very little experience (Aircraft Owners and Pilots Association, 2011).

GA aircraft, unlike airlines, mostly do not have technology on board capable of indicating and/or guiding them around air traffic in their near vicinity. Many don't have transponders installed to indicate their position on radars either. This means that despite legal separation minima, out-the-window see-and-avoid strategies are still very much in effect for proper collision avoidance in uncontrolled airspace (i.e. Class E airspace where no air traffic control is required) for a major portion of NAS traffic. It is difficult to translate this see-and-avoid strategy to autonomous UAS. Many challenges need resolution in order to successfully transfer what has been up to this point, human generated skill, judgment, and knowledge in manned aircraft, over to UAS platforms. One difficult area of this manned to UAS conversion is the concept of "Well Clear".

The Issue at Hand - Well Clear

The term "Well Clear" or remaining "Clear" originated as a phrase used in Air Traffic Control (ATC) environment when interacting with manned aircraft over the radio communications. Typically, a controller will issue an alert to pilots over the radio that nearby traffic has the possibility of breaching legal separation, or may come close to doing so. After notifying pilots of such possible incursions, ATC will then ask them to report once they are "Clear" (i.e., "Well Clear") from the aircraft that posed a collision concern.

"There are currently no regulated time- or distance-based standards regarding what it means for two aircraft to be 'well clear'" (Lee, Park, Johnson, & Mueller, 2013, p. 1). Due to the highly dynamic flight environment of the NAS, pilots are left on their own to determine when and where they feel this "Well Clear" boundary exists in Class E airspace, and must rely on their own skills and senses in reporting once they believe a collision is no longer possible with intruding aircraft indicated by ATC.

Due to the lack of an objective definition for "Well Clear", also called the "Well Clear Boundary" (WCB), and because there is wide variability in human perception across pilots (Cooke, 2006), it is highly likely that pilot perception of the WCB is different across pilot types due to various skill levels. It is also possible that pilot perception of the WCB with regards to a manned aircraft is different than their perception of WCB from an unmanned vehicle due to various parameters such as size and speed differences, as well as variance in trust of automation and/or new technology. The current research aimed to uncover these differences, and also to determine what other variables may have an impact in the WCB opinion

METHOD

Participants

A total of 34 participants between the ages of 21 and 69 with a mean age of 41 were recruited. The participants consisted of 3 females and 31 males. Collectively, the pilots had a total of 173,405 flight hours, with a total of 78,325 of those hours spent in glass. This led to an average of 5,100 total flight hours, with an average of 2,373 of those hours being in glass cockpits per pilot. All participants were required to be licensed pilots.

Since examining differences between pilot types involved a direct comparison, an equal number of GA and Commercial/ATP pilots was selected, with 17 of each type of pilot. The ATP pilots averaged 48 years of age with 28 years of flying experience. They also averaged 9,627 flight hours, averaging 4,533 in glass cockpits. The GA pilots had a mean age of 34, averaging 13 years of flying experience. They averaged 573 flight hours, with a mean of 79 hours in glass cockpits.

Experimental Design

A mixed design was used. There were several within-subject variables, and pilot type served as a between-subjects variable. To assess differences in WCB perception across two different pilot experience levels, a five-factor mixed design was implemented. The between-subjects variable of pilot type was the comparison of highest interest in the current study, closely followed by the comparison of intruder type, which varied between manned and unmanned aircraft in the experimental scenarios.

To determine what affects the WCB perception for pilots, four independent variables were compared across both pilot groups. These repeated measures factors were; intruder type (2 levels), intruder aircraft approach geometry (8 levels), background distractor traffic (2 levels: high and low), and ownship speed (2 levels). Altogether, this yielded an 8x2x2x2x2 design. In order to control for any order and/or learning effects resulting from the factorial combination of the four within-subjects variables, presentation of all combinations were randomized for all participants.

Apparatus and Stimuli

Apparatus. Testing took place in the Flight Deck Display Research Lab (FDDRL) at NASA Ames Research Center in Moffett Field, California. The FDDRL-developed Cockpit Situational Display (CSD) was used as the primary display for this research. The CSD was configured to have a display similar to present day traffic collision avoidance systems (TCAS), and was displayed on a desktop computer.

Stimuli. Pilots viewed the CSD with their ownship at the center of the moving map traffic display. No out-the-window view was provided, the only display available was the CSD. There were no active air traffic controllers speaking with or directing pilots, as pilots had no control over their aircraft's pre-designated flight path while flying in this simulated Class E airspace. Yet, pilots did have control over range zoom on the display and had the ability to change zoom levels at will.

Intruder Types and Approach Geometry Levels. This independent variable involved intruder aircraft, which varied between manned or unmanned as counterbalanced throughout scenarios. There was only one intruder aircraft per scenario, and it was always on a collision course with the participant's ownship. Its purpose was to cause a WCB breach, which cued participants to press a button to pause the simulation once they felt the intruder reached the WCB surrounding ownship. Once paused, the location of the intruder ship was recorded. There were eight approach geometries for the intruder aircraft, each offset 45° from each other, and it approached from one geometry per scenario (see Figure 1).

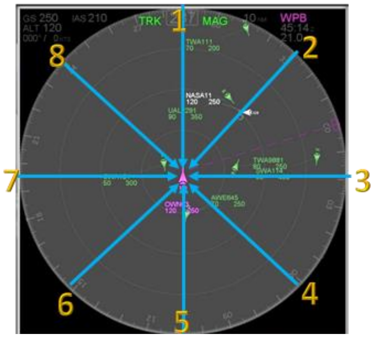

Figure 1: CSD depicting ownship at center, with 8 intruder approach geometries and background traffic

Distractor Traffic Levels. Two levels of the distractor traffic variable were present in scenarios. This air traffic served to create a real-world representation of traffic loads typically experienced in the immediate airspace surrounding ownship. This traffic was all flown on pre-designated flight paths, not controlled in real time. Their flight paths were straight and level designed not to cause any conflicts with ownship (all flown at altitudes at least 2,000 feet above or below ownship, indicated by their displayed data tags). Each trial involved either a low level of 4, or a medium level of 8 distractor planes.

Ownship Speed Levels. Two levels of the ownship speed independent variable were designed into scenarios. This tested ownship speeds representing realistic speeds that the two different pilot types would typically encounter. The high speed was 250 knots, and the low speed was 150 knots.

Measures

Objective Metrics. Through the repetitive process of administering intruder aircraft from different approach angles surrounding ownship throughout 64 trials, we created spatial representations of the averaged WCB points directly surrounding ownship for each pilot group. Two metrics were used, we calculated a distance metric for the measured WCB point from ownship called distance from ownship (dOWN) in feet, and a time metric of the WCB points by measuring time to closest point of approach (tCPA) in seconds between each point and ownship. The main WCB maps of interest were for the two different pilot types, and for the two different intruder types.

Subjective Metrics. Subjective metrics were designed to complement the objective metrics, along with providing further insight into the concept of the WCB. After all experimental trials were complete, a post-experiment questionnaire was administered. It had 15 open-ended, and 5 rating scale questions. A final question asked the pilots to draw two pictures of what they thought the WCB looked like for both manned and unmanned aircraft surrounding ownship. Participants also indicated the appropriate range on blank range rings to accurately depict their perception. The drawings were then sorted by common shapes/features and tallied up to summarize findings. This subjective feedback was compared to the objective data described above.

RESULTS

Objective Results

WCB Maps. The results of the WCB measurements are presented below in the form of maps, with separate maps for the dOWN distance metric as well as the tCPA time metric. These maps have not been subjected to any form of statistical analysis other than averaging results per intruder approach angle to aggregate mean values. Multiple maps were created for each independent variable (IV) by collapsing data across every IV to show the effect each one had on the overall WCB map shape. Only the WCB by intruder direction, pilot type, and intruder type are shown here.

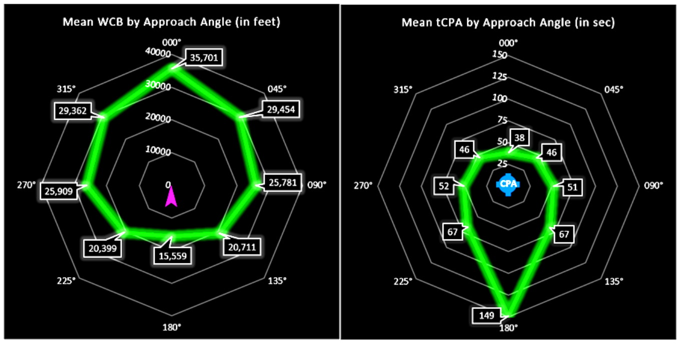

Figure 2: WCB by direction in feet (left) and seconds (right)

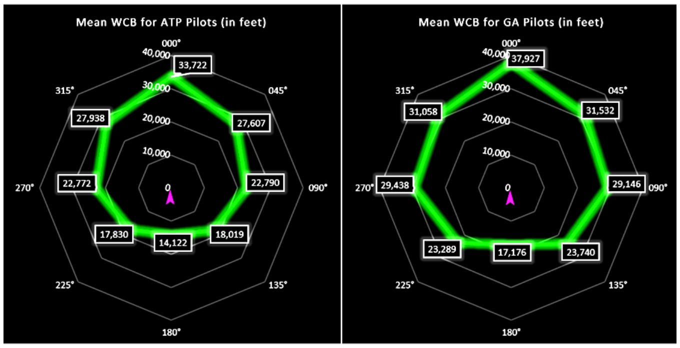

Figure 3: WCB by Pilot Type (ATP on left, GA on right) in feet

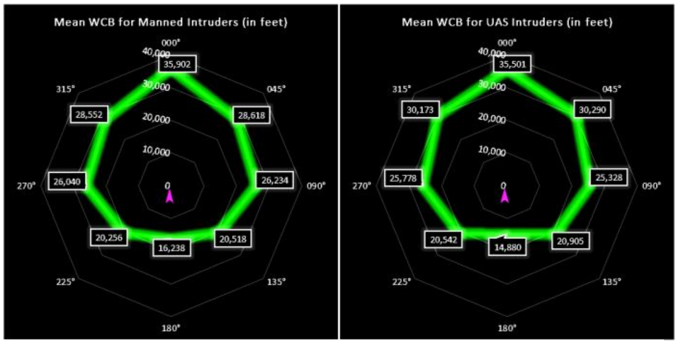

Figure 4: WCB by Intruder Type (Manned on left, UAS on right) in feet

Statistical Objective Results. Two five-way mixed analyses of variance (ANOVAs) were used to analyze these quantitative WCB measures. The first five-way ANOVA was performed on the dOWN measure, which was the distance from ownship in feet indicating the WCB. This consisted of an 8x2x2x2x2 ANOVA for significant differences among approach angles, intruder types, ownship speeds, traffic levels, and pilot types (pilot type was treated as a between-groups variable).

Results found two significant interactions and three main effects. A significant three-way interaction was evident among intruder type, ownship speed, and pilot type, $F(1, 32) = 4.56$, $p = .041$. This indicates that the effect of intruder type depends on ownship speed and that differs across pilot type. A significant two-way interaction was also observed with ownship speed and intruder approach angle, $F(5,175) = 6.85$, $p = .004$. Main effects were also found for intruder approach angle, $F(1, 55) = 27.68$, $p < 0.001$, ownship speed, $F(1, 32) = 9.76$, $p = 0.004$, and traffic level, $F(1, 32) = 5$, $p = 0.045$. Besides these interactions, no other effects for the metric of dOWN in feet were found to be significant.

The second five-way ANOVA was performed on the tCPA measurement results. These were the times until ownship was projected to intersect flight paths (time to closest point of approach) with ownship from each of the eight intruder approach angles. An 8x2x2x2x2 ANOVA was used to analyze these data.

Three interactions and two main effects were statistically significant. There was a significant four-way interaction among intruder type, traffic level, ownship speed, and intruder approach angle, $F(6,200) = 6.28$, $p = 0.008$. This shows that the effect of intruder type depends on traffic level and ownship speed, and this relationship differs across intruder approach angles. A significant three-way interaction was found among intruder type, traffic level, and ownship speed, $F(1, 32) = 4.16$, $p = 0.049$. This means that the effect of intruder type depends on traffic level, which differs across ownship speeds. A significant two-way interaction was observed between ownship speed and intruder approach angle, $F(5,170) = 6.85$, $p < 0.001$, indicating that the effect of ownship speed depends on intruder approach angle. Main effects were also found for intruder approach angle, $F(2, 83) = 370.02$, $p < 0.001$, and for ownship speed, $F(1, 32) = 8.57$, $p = 0.006$. Aside from these interactions, all other effects for the metric of tCPA in feet were not significant.

Subjective Results

Post-simulation subjective questionnaires categorized by the following question topics: WCB perception, CDTI/CSD technology preferences, manned vs. unmanned intruder types, UAS specific questions, and other pilot type opinions.

WCB perception. Responses for how participants primarily perceived the WCB indicated that they consider it to be a factor of distance, time, or both. Yet, more than double the percentage of GA pilots thought of the WCB as a measurement of distance. Almost double the percentage of ATPs primarily thought of the WCB in terms of time, or combination of time and distance than GA pilots did. When asked what affected the WCB opinion the most, all pilot types mostly agreed closure rate was the biggest factor over intruder angle or aircraft maneuverability. All pilots believed the WCB to be different from other similar terms mainly because it varies personally while other definitions have set parameters. Over half of overall pilot responses showed they were comfortable with the current definition of Well Clear. When asked what the vertical component of WCB should be most pilots thought it should be 1000 feet vertical separation. ATPs were split in their want between 1000 feet and greater than 1000 feet while most GA pilots agreed upon 1000 feet. Both pilot types strongly agreed that ownship speed affected WCB dimensions. Pilots moderately agreed that background traffic density affected the WCB.

Manned Vs Unmanned Intruders. When asked if UASs should abide by the same WCB as manned aircraft, responses were almost 50/50 split. Nearly half the pilots answered yes, while barely below half said no. GA pilots answered yes more than ATPs. When asked about arousal differences, most of both pilot types answered no, while almost a third experienced more stress with UAS intruders. Both pilot types felt that the most threatening intruder angle was from head-on approaches. Yet, for ATPs this was closely followed by right/left directions, and trailed by overtake (rear) directions. When asked about perceived safety levels both pilot types felt much safer with manned intruders over UAS. Yet, GA pilots showed an even split in opinion. When asked to rate perceived trust levels between intruder types, both pilot types trusted manned and UAS evenly. GA pilots showed higher trust ratings. When dissected by pilot type the responses showed slightly higher ratings for manned trust than UAS intruders overall.

UAS Specific Questions. When asked if UAS could autonomously abide the current WCB definition, over half of all pilots and pilot types said no with a higher yes answer percentage for GA pilots over ATPs. When asked if their WCB would change if two or more UASs were involved, half of all pilots said no. When broken down by pilot type most GA pilots said no, while over half of ATPs said yes. When asked how they felt about UAS integration, most pilots answered safe if proven. A lower percentage felt that it was unsafe, with more ATPs than GA pilots offering the response of unsafe.

CDTI/CSD technology preferences. Although most GA pilots did not have any experience with a CDTI, most ATPs did. For ATPs, when asked if their current display was adequate for WCB perception, more than half said yes with just over 40% said no. Pilots were also asked if they envisioned themselves primarily utilizing a CDTI or out-the-window view to maintain WCB, and most answered they would use a CDTI. All pilots strongly agreed that the CSD was better for WCB perception compared to their current CDTI or other detection method.

Opinion of how other pilot type perceives the WCB. All except one of the ATPs agreed that pilots with less experience then they have would have a different opinion of the WCB. GA pilots were split in their responses when asked if pilots with more experience than themselves would have a different WCB opinion, with most of them saying “yes”, and an equal split response between “no” and “maybe” answers.

WCB drawings. Overall, half of both pilot types depicted WCB maps with greater distance in front and less in the rear. This percentage was slightly higher with GA pilots than ATPs. Circular WCB maps closely followed for both pilot types, with the same percentage for greater in front less in rear for ATPs. Circular maps consisted of about 1/3 of the drawings for GA pilots. WCB maps classified as “other” made up a very small percentage.

DISCUSSION/CONCLUSION

Now that objective metrics for the concept of Well Clear exist, we are able to observe that the perception of the WCB differs between General Aviation pilots and Commercial ATPs (the effect of intruder type depends on ownship speed, and that differs across pilot type when measured by dOWN). Also, the WCB differs when pilots interact with manned versus unmanned aircraft (the effect of intruder type depends on traffic level and ownship speed, and that effect differs across intruder approach angles when measured by tCPA). This research additionally revealed that the effect of intruder type depends on traffic level which differs across ownship speeds when measured in tCPA. It was also found that the effect of ownship speed depended on intruder approach angle when measured in dOWN. There were several main effects evident. dOWN measurements displayed main effects with ownship speed, intruder angle, and background traffic level, while tCPA main effects were observed with ownship speed and intruder angle.

Subjective findings uncovered an important trend, that even though GA pilots indicated a larger average WCB, they tended to rate UAS aircraft with higher trust and safety ratings than ATPs did. GA pilots also appeared to have more diverse responses than ATPs did, where ATPs had more similar and uniform language in their answers. These subjective findings indicate fundamental differences in pilot experience levels, showing how their perceptions may differ based on hours and type of flight environment flown. Subjectively, it is also important to note how broad the opinion of not only the WCB, but interaction with manned versus unmanned intruders was across all pilots and between pilot types. Many different mental models and opinions were observed, which may demonstrate the need for more structured and less subjective definitions of aviation concepts, especially when it comes to aircraft spacing procedures.

The most important conclusion to draw from this research is that pilots appear to perceive the WCB in terms of what is most easily mentally computable based on the angle of approaching intruders. As can be most easily seen in the full research paper Figures, metrics of dOWN and tCPA mirror each other over the horizontal axis with dOWN having larger distance variation between angles in front of ownship, while tCPA had larger variation in angle values to the rear of ownship. So, it is reasonable to assume that since uniformity (i.e. least value variation) of the WCB is seen to the rear for distance based measurements and to the front for time based metrics, that pilots perceive the WCB like the model below in Figure 5:

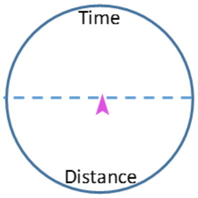

Figure 5: WCB most easily perceived as time based (front) and distance based (rear) surrounding ownship.

Since the rear of ownship experiences a low closure rate with low distance and high time to collision values, distance may be easier and quicker to mentally calculate for pilots. Conversely, to the front of ownship where a high closure rate with large distances and low times are evident, time may be easier and quicker to mentally calculate for both pilot types. This finding is supported objectively and subjectively in the data and is instrumental in the future integration of UAS into the NAS. It would mean that in defining the WCB for manned aircraft, pilots are more comfortable knowing time separation in front and distance separation to the rear. Therefore pilots may better perform separation procedures knowing specific types of intruder information depending on relative angle surrounding their aircraft, as opposed to a static WCB metric encircling them. With this data, ATC could improve their aircraft spacing tactics by advising pilots using angle and metric combinations that they can most efficiently comprehend.

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