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Visual Search and Conflict Mitigation Strategies Used by Expert en Route Air Traffic Controllers

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Abstract: The role of the en route air traffic control specialist (ATCS) is vital to maintaining safety and efficiency within the National Airspace System (NAS). ATCSs must vigilantly scan the airspace under their control and adjacent airspaces using an En Route Automation Modernization (ERAM) radar display. The intent of this research is to provide an understanding of the expert controller visual search and aircraft conflict mitigation strategies that could be used as scaffolding methods during ATCS training. Interviews and experiments were conducted to elicit visual scanning and conflict mitigation strategies from the retired controllers who were employed as air traffic control instructors. The interview results were characterized and classified using various heuristics. In particular, representative visual scanpaths were identified, which accord with the interview results of the visual search strategies. The highlights of our findings include: (1) participants used systematic search patterns, such as circular, spiral, linear or quadrant-based, to extract operation-relevant information; (2) participants applied an information hierarchy when aircraft information was cognitively processed (altitude -> direction -> speed); (3) altitude or direction changes were generally preferred over speed changes when imminent potential conflicts were mitigated. Potential applications exist in the implementation of the findings into the training curriculum of candidates.

Keywords: air traffic control; eye tracking; conflict mitigation; visual search; informational hierarchies

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1. Introduction

The role of air traffic control specialist (ATCS) is vital to maintaining safety and efficiency within the National Airspace System (NAS). En route ATCSs are assigned to work sectors, complex and dynamic virtual demarcations of airspace that differ along several dimensions (e.g., high or low altitude, international or regional airports, letters of agreement). En Route Automation Modernization (ERAM) radar displays represent these demarcations and present information including the location of aircraft that enter the airspace. Within the designated airspace, ATCSs' must identify and attend to these aircraft, guiding them to their destination in a timely manner, while maintaining safety protocols (e.g., vertical and horizontal separation) and coordinating with other controllers.

To achieve efficiency and effectiveness in aircraft conflict detection and aircraft conflict mitigation, the controllers constantly apply visual search strategies to extract operation-relevant information from the environment (e.g., altitudes, speeds, directions, destinations) needed to make decisions. ATCSs translate these decisions into clearances, which they relay to pilots, using correct phraseology, via radio or data communications. The inherit nature of the environment, sheer number of air traffic characteristics, plus the required interactions with other ATCSs, lead to a myriad of applicable conflict mitigation strategies. Novice controllers must learn myriad strategies, and under which circumstances each strategy should be applied. Analyses of expert controllers' visual scanpaths, paired with controller narratives of the conflict mitigation strategies used, could provide valuable input to the design of the training curriculum for future air traffic controllers. Eleven retired air traffic controllers, employed as instructors by the Federal Aviation Administration (FAA) (Washington, DC, USA) Academy participated in an eye-tracking experiment, using a high-fidelity simulation of an en route sector, with the goal of mapping their visual search strategies and conflict mitigation heuristics. The task was carried out through (1) content analysis of in-depth post-experiment interviews, and (2) finding the representative visual scanpaths (from the eye-tracking data collected from the experiment) which accords with the protocol analyses results.

1.1. Eye Tracking Technology and Visual Scanning Strategies

Advances in eye tracking technology have augmented our capacity to explore and understand how individuals interact with their environment in the presence of diverse visual stimuli [1–3]. Environmental cues that draw attention, dictate responses, and signify possible actions become more accurately and precisely specifiable. For example, the use of eye-tracking technology has enabled researchers to explore how users interact with interfaces [4], the environmental information they gather, and the workload imposed by a given task [5].

Investigation into the relationship between humans' cognitive processes and eye movements, such as eye fixations and saccades, among others, became a pivotal research area in the domain of air traffic control when more accurate eye trackers became available in the 1980s and 1990s [6,7]. More recent research in en route air traffic control involves an investigation into the differences in eye fixation durations or frequency based on expertise [8,9], and how eye tracking can be used to train novices [10–13]. Especially, in [10], experts' visual scanpaths were used to train novices, in which the novices significantly reduced false alarms (i.e., believing that aircraft conflict will occur when the conflict does not actually happen). Furthermore, the visual scanpaths were characterized to analyze (1) how conflicts are detected [14], (2) how visual groupings are formed [15], and (3) how the individual gathers information [16].

Analysis of visual scanpaths (see Figure 1) can be challenging due to the variability involved in humans' eye movements [17–19]. Nonetheless, advances have been made in this area, for example, by grouping the individual scanpaths of experts per a particular criterion, such as their geometrical shape [20]. One way that the knowledge embedded in an experts' visual search strategy can be transferred is via their visualization in the form of scanpaths, the sequential accumulation of eye fixations and saccades over time (Figure 1) [10]. Research in this area has shown that novices modify their own visual search strategies when presented with the strategies used by an expert. This type of intervention has led novices to exhibit lower rates of false alarms in a conflict detection task [21], as well as to higher degrees of task accuracy [22]. Thus, a better understanding of expert strategies in air traffic control can be beneficial in the ATCS training process.

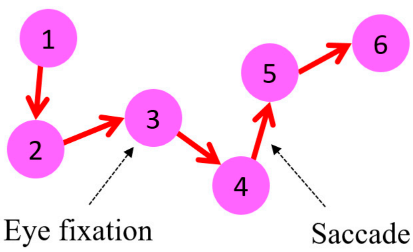


Figure 1. Representative example of a scanpath.

1.2. Impact of Increased Air Traffic Demand on the ATCSs Task

Visual search is one of the ATCSs' key tasks. They must be able to create, maintain and update their understanding of the environment as it evolves over time. Developing an understanding of the environment is often referred to as creating a "mental picture" within the ATCS community [23], a representation of current traffic and environmental conditions.

The mental picture paradigm is related to Neisser's cyclic theory of perception, which is defined as the cyclical update of an individual's understanding of the environment, which influences the individual's future actions when the individual constantly interacts with the environment [24,25]. Neisser's theory could imply that experts can have an integrated experiential model that reduces the perceived complexity of the environment, leading them to develop certain strategies, such as visual scanning and conflict mitigation strategies.

Continuously maintaining a "mental picture" is a difficult task due to the dynamic nature and complexity of the environment, which can negatively impact performance by taxing the mental resources of the controller [26–30]. In addition, the information associated with each individual aircraft (e.g., altitude, speed, and direction) needs to be continuously monitored to identify potential conflicts and anticipate future events [31–33].

One partial source of future environmental complexity is the increased aggregated demand within the air traffic sector [34], which may exacerbate the workload placed on the ATCSs [35]. The incorporation of new technologies and procedures into the training curriculum for future ATCSs will be important in mitigating the adversarial effects that this rise in aggregated demand may have on operations. For example, deficient visual search strategies can lead to significant sources of error in aviation [36,37], such as poor judgement in both decision-making and communication [38]. Thus, the incorporation of an experts' visual search and the conflict mitigation strategies they lead to into the training curriculum of candidate ATCSs could help alleviate the negative impact that increased aggregated demand may have on future controllers.

1.3. Scope of Research

The aim of the research presented in this paper is to investigate how the controllers visually search for potential aircraft conflicts and how to mitigate those conflicts using realistic scenarios that are very similar to those used in the air traffic training academy. In more detail, interviews are held with the controllers to classify their visual search and conflict mitigation strategies, then, based on the answers regarding their visual search strategies (such as circular or linear), collected eye tracking data are used to find representative visual scanpaths that match with their verbal answers.

2. Materials and Methods

The eye movements of the participants were recorded when they participated in all of the scenarios. Interviews with the participants were held after all the scenarios were administered, so the interview results are not associated with any specific scenario. The goal of the interview was to better understand the heuristics, and the environmental cues that might affect the participants' decision making processes. During the interview, we replayed a few recordings (after they went through all the scenarios) as needed if the participants felt the need to see them to better explain their search and/or mitigation strategies. Details are as follows.

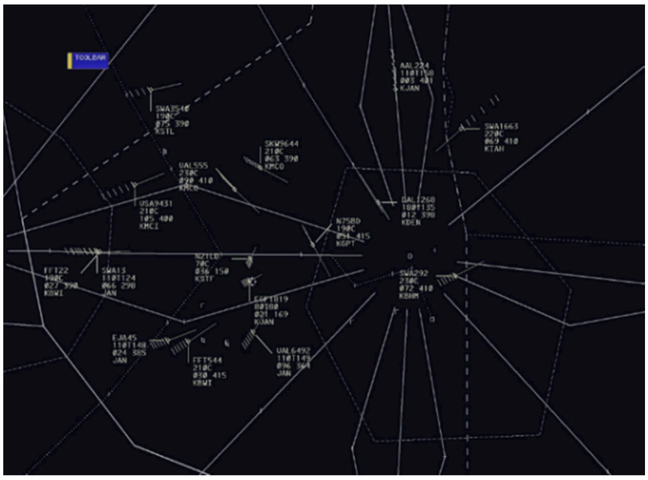
2.1. Apparatus

The FAA provided use of a Kongsberg I-Sim simulator for this study. I-Sim simulators present a high-fidelity simulation of an actual radar display used in air traffic control. A 24-by-24-inch monitor was used to present the simulated radar sector. The eye movements were recorded using a Tobii TX300 eye tracker. The sampling rate of Tobii TX300 was 300 Hz. The visual angle error of the eye tracker was 0.4°, meaning that the eye fixation coordinates collected by the eye tracker can be different up to approximately 1 cm from the actual eye fixation location (or coordinates) when the participant is 1 m away from the display. The eye fixation threshold was set to 60 ms, meaning that an eye fixation occurred if a participant observed a location for more than 60 ms. A simulated radio communication channel was used for communication between the participant ATCS and the pseudo pilot, with a frequency of 300 Hz.

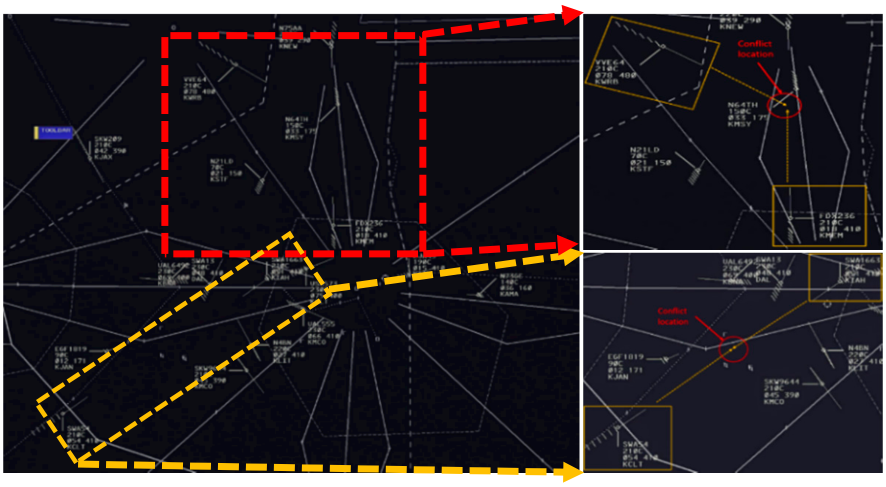
2.2. Participants and Scenarios

Twelve realistic scenarios of a high-fidelity en-route air traffic control simulation were presented to eleven male retired ATCS, recruited with the assistance of the FAA Civil Aerospace Medical Institute (CAMI) in Oklahoma City, OK, USA. The retired controllers' age ranged approximately between 50 and 60.

The developed scenarios were similar to those used at the FAA Academy for training. Examples of the scenarios are provided in Figures 2 and 3. The scenarios were designed to present the participants with a nominal en-route control environment. None of the scenarios contained hazardous weather elements (e.g., wind or rain) or additional off-nominal situations (e.g., dynamic restricted airspace). A pseudo-pilot coordinated the aircraft movements, with the control clearances issued by participants, as well as making scripted pilot requests at various intervals. The scenarios were ordered randomly for each participant to reduce the impact of possible confounding effects (e.g., fatigue). Each scenario lasted from approximately 15 to 20 min. Therefore, the total experiment time per participant for all 12 scenarios was approximately 4 h. Each participant took a short break of approximately 5 min or less after going through each scenario.

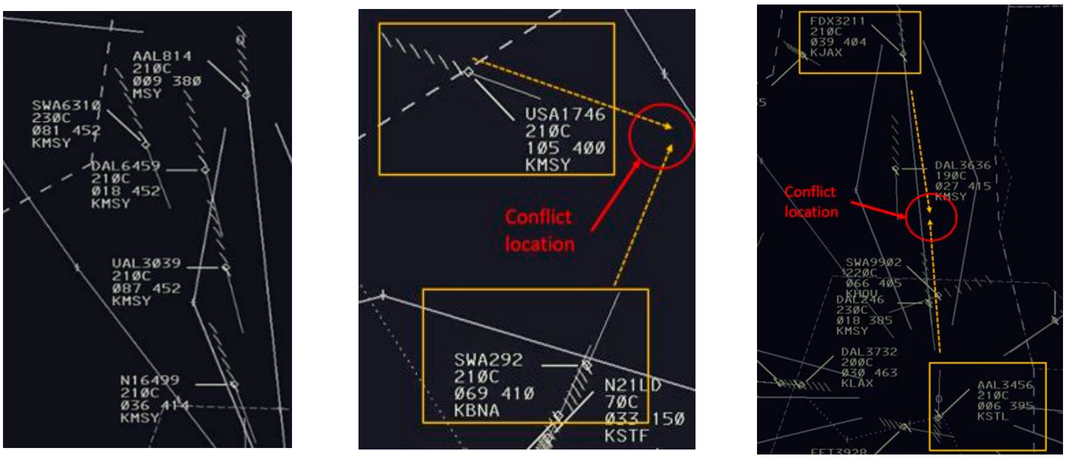


(**a**)



(**b**)

Figure 2. Example scenarios: (**a**) Layout of aircraft during an experiment using one of the scenarios; (**b**) Example of aircraft conflicts highlighted in red and yellow (left side shows the aircraft layout at a certain point in time, and the right side shows the future conflict locations.



(**a**) (**b**) (**c**)

Figure 3. More detailed examples of aircraft conflicts presented to participants: Aircraft that will have a conflict in the near future are highlighted with yellow boxes and the conflict locations in the near future (approximately a few minutes for these examples) are highlighted with red circles. The subfigures (**a**–**c**), correspond to examples of an overtaking, converging, and head-on conflicts.

The questionnaire was designed in a structured manner to elicit tacit knowledge from the participants (Table 1). In addition, the structure enabled us to quantify and compare responses across participants. The questionnaire was divided into four main stages; the first one, Overall scanning strategy, was created to better comprehend participant visual search strategies. The second and third stages, "Searching for conflicts" and "How conflicts are detected", were designed to identify the environmental cues that ATCS observe, in what order observations are made, their reasoning, and how their decisions shape their strategies. Lastly, "Control strategies" focused on how ATCS mitigate conflicts.

Table 1. Interview questionnaire.

Stage	Question
Overall scanning strategy	What shape best describes your strategy overall? Why do you prefer your search method? What is your visual search strategy? How do you prioritize aircraft conflicts?
Searching for conflicts	What is the order in which you read information? What kind of situations cause priorities to change?
How conflicts are detected	If aircraft are converging, what information do you observe and in which order? If aircraft are overtaking, what information do you observe and in which order?
Control strategies	In general, how do you control a conflict? Why do you prefer your chosen control strategy?

2.3. Procedure

The participants were instructed to control the simulated en-route traffic and resolve any potential conflict situations. During the experiment, the ATCSs were not allowed to use the vector key (which allows them to see the trajectory of the aircraft for 8 min in the future). The ATCS provided a verbal response once they believed all the potential conflicts had been resolved, after which the scenario was stopped.

2.4. Data Analysis

The eye-tracking data collected for each participant were overlaid onto the respective scenarios in order to analyze, recognize and characterize the visual search strategies. Four analysts, who are the authors, evaluated the self-reported visual search and conflict detection strategies. For each participant, the transcribed reports were interrogated for quotations dealing with visual scanning methods, aircraft selection methods, and mitigation methods. All four analysts came to an agreement with the finalized classifications, provided in this paper.

The interviews were recorded, then transcribed. After this, we followed the procedure of the content analysis [39,40] by (1) identifying the key words or key phrases used by the controllers, (2) creating classifications based-on those key word or key phrases, and then (3) tallying frequencies and providing the actual quotes. Note that the participant could freely answer the interview questions provided in Table 1, but the researchers (i.e., authors of this paper) interacted with the participant to obtain more concrete answers. For example, when asking questions related to the visual scanning strategy, the researchers would guide the participant to elicit a specific geometric shape, and the participant provided a specific term, such as circular search or spiral search. If the participant answered that s/he did not follow a specific search strategy, then the answer was classified as a random search.

3. Results

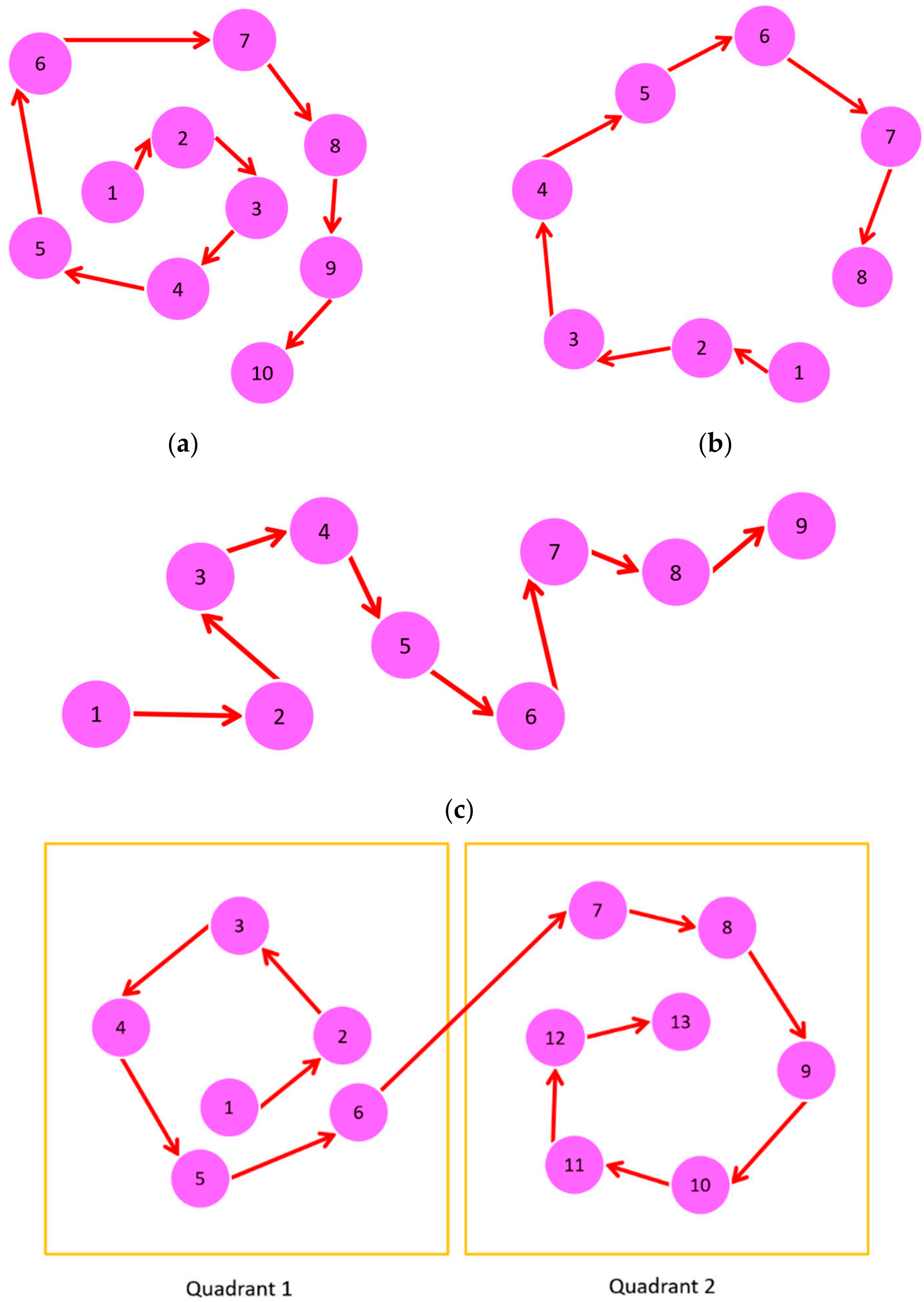
3.1. Visual Search Strategies of Former ATCS

Self-analysis results indicate that visual search strategies tend to have a recognizable geometrical shape (Table 2). The table shows that a sizeable number of participants (54%) prefer a visual search strategy which resembles a circular or spiral geometrical pattern. Other visual search strategies could be identified as: (1) linear (9%), (2) quadrants (9%) (i.e., where the screen is divided into two or more sections); (3) mixed (9%) (i.e., a combination of multiple geometrical patterns); (4) random (18%) (i.e., where no particular geometric shape can be derived). Note that Table 2 and other tables presented in this paper were developed based on the controllers' verbal inputs. Representative examples of the visual search strategies for the geometrical shapes can be seen in Figures 4 and 5.

Table 2. Shape of visual search strategy and starting location.

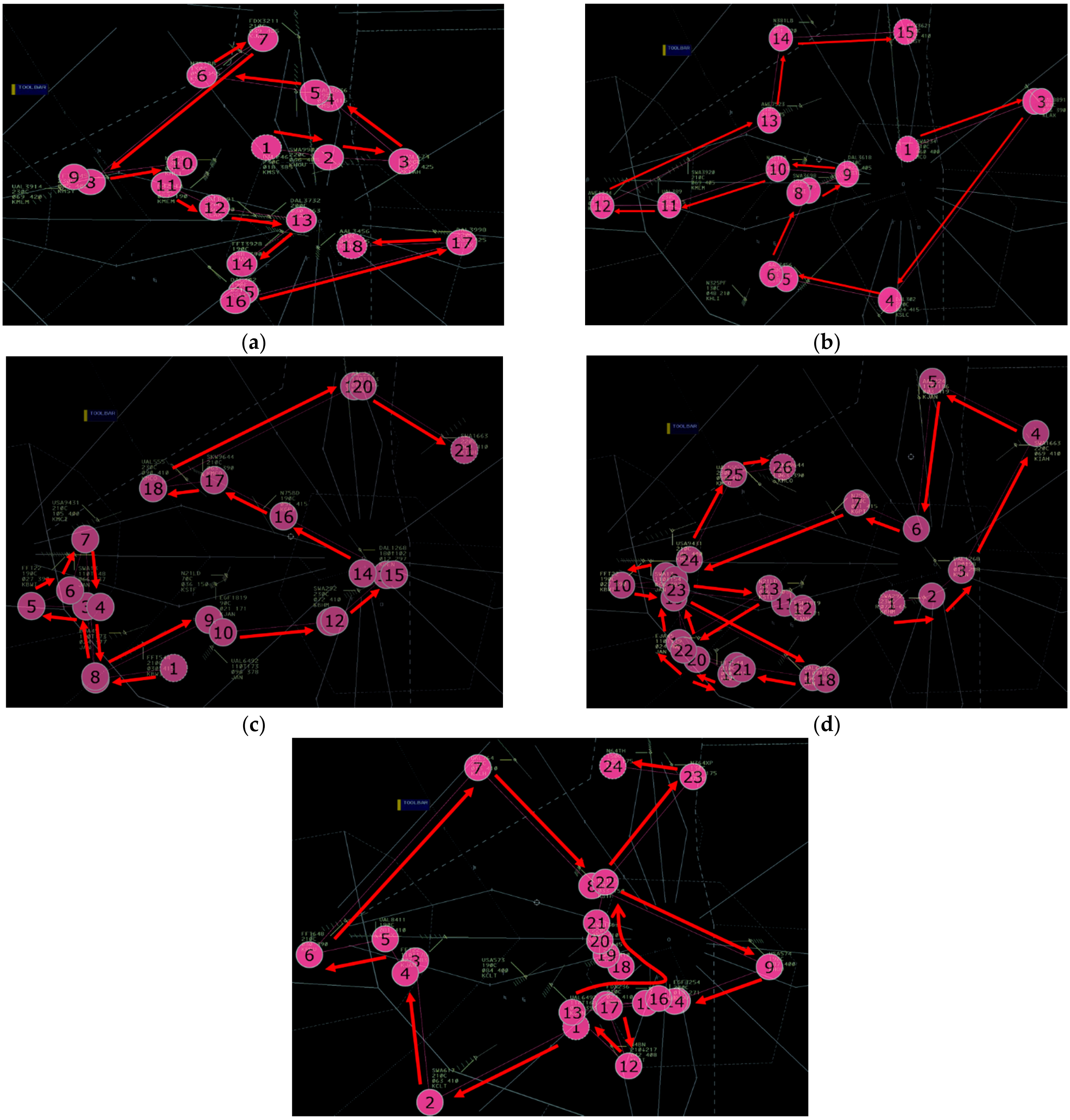
Geometrical Pattern	Freq.	Starting Location	Freq.	Participant
Spiral	4	High density-based	3	P2, P10, P11
		Sector center	1	P9
Circular	2	High density-based	1	P1
		Preference based on training and experience	1	P3
Linear (e.g., zigzag-like movement)	1	Low density-based	1	P5
Quadrants	1	Areas of conflict	1	P4
Mixed (e.g., circular and linear combined)	1	High-density based	1	P6
Random	2	Incoming sector traffic	1	P8
		High density-based	1	P7

Furthermore, most participants selected their preferred starting location (i.e., where the first fixations of the visual search strategies occur) in high-density areas (54%). Note that "high-density areas" refers to areas that have a higher number of aircraft compared to other areas. Other reported areas were: (1) sector center (9%); (2) low-density areas (9%); (3) possible areas of conflict (9%); (4) incoming traffic onto the sector (9%); (5) no specific location (9%).



(**d**)

Figure 4. Representative examples of various kinds of scanpath in a visual search task. (**a**) Spiral; (**b**) Circular; (**c**) Linear; (**d**) Quadrants.



(**a**) (**b**) (**c**) (**d**) (**e**)

Figure 5. Representative examples of visual search strategies. (**a**) Spiral; (**b**) Circular; (**c**) Linear; (**d**) Quadrant, delineated by dashed yellow squares; (**e**) Mixed.

The reasoning reported by each participant for these strategies contained mixed reports, and thus, no explicit general trend can be derived from their categorization (Table 3) or quotations (Table 4). The motives behind the participants' visual search strategies consist of the following factors: (1) allows a continuous rather than disjointed (i.e., constantly moving between far-away areas) visual search strategy (18%); (2) emphasizes time-sensitive (18%) or high-density (9%) areas; (3) enables faster visual scanning (9%) or recognition of an incorrect altitude for direction of flight (9%); (4) based solely on prior training and experience (36%).

Table 3. Reason behind preferred visual search strategy.

Reason	Freq.	Participant
Continuous scan rather than disjointed	2	P1, P11
Focus on time-sensitive areas	2	P9, P5
Faster scan	1	P2
Focus on high-density areas	1	P10
Aid in recognizing wrong altitudes for direction of flight	1	P7
Preference based on training and expertise	4	P3, P4, P8, P6

Table 4. ATCSs quotations on reason behind their preferred visual search strategies.

<table>
<tr><th>Reason</th><th>Quotations from ATCSs</th></tr>
<tr><td rowspan="2">Continuous scan rather than disjointed</td><td>(P1: circular) I guess it has more continuity rather than jumping all over? You have more of a flow to what you are looking at.</td></tr>
<tr><td>(P11: spiral) Well, I think if you stay with a sweep around the sector you will not miss or are at least less likely to miss anybody.</td></tr>
<tr><td rowspan="2">Focus on time-sensitive areas</td><td>(P9: spiral) If the group is in the left of the sector it is more time critical to make control judgements</td></tr>
<tr><td>(P5: linear) The whole thing is a big puzzle with smaller puzzles. If you eliminate the smaller conflicts first, it gives you more time to look at what else is going on.</td></tr>
<tr><td>Faster scan</td><td>(P2: spiral) The main reason is because that is the fastest way to get to everybody</td></tr>
<tr><td>Focus on high-density areas</td><td>(P10: spiral) I usually try to focus on the most complex area.</td></tr>
<tr><td>Aid in recognizing wrong altitudes for direction of flight</td><td>(P7: random) If they are at the wrong altitude for the direction of their flight, I need to fix that</td></tr>
<tr><td rowspan="4">Preference based on training and experience</td><td>(P3: circular) It is just me and there is no particular reason. It is just how I do it.</td></tr>
<tr><td>(P4: quadrants) I just found that it works better for me that way.</td></tr>
<tr><td>(P6: mixed) I guess I was trained that way and I think it is a more thorough way to do it.</td></tr>
<tr><td>(P8: random) That really comes with experience. To tell somebody that there is a certain order is something that I am not sure would be very helpful.</td></tr>
</table>

Participants reported a strong (91%) hierarchy in which information is processed: (1) altitude; (2) direction; (3) speed. Only a single participant described an alternative order, which, nonetheless, still placed altitude as the highest priority (Table 5).

Table 5. Order of information processed.

Order of Information			Freq.	Participant
Altitude	Direction	Speed	10	P1, P6, P7, P10, P11, P8, P5, P9, P4, P3
Altitude	Speed	Direction	1	P2

To expand on this, participants were also surveyed regarding whether their established hierarchy is affected by environmental factors (e.g., adverse weather conditions), as shown in Table 6. Here, the majority of participants (64%) report that their information hierarchy is not affected by environmental factors, but rather that their potential control action affects this (45%). On the other hand, among those who reported that their information hierarchy is affected by environmental factors, one explicitly mentioned that it is affected by the urgency of a potential conflict.

Table 6. Effects of scenario characteristics in the order of information processed.

Effect of Scenario	Freq.	Reason	Freq.	Participant
Environmental characteristic does not affect order of information	7	Control action affects order of information.	5	P2, P6, P7, P8, P9
		Used to predict aircraft behavior.	1	P4
		Preference based on training and experience.	1	P3
Environmental characteristic affects order of information	4	Sector characteristics	3	P5, P10, P11
		Conflict urgency	1	P1

3.2. Conflict Detection and Mitigation

Among the various types of conflict, participants strongly report that aircraft in a converging conflict have priority over any others (82%), but after that, there is a lack of consensus. Some participants place the most important subsequent conflict as: (1) head-on (36%); (2) overtaking (18%); (3) diverging (9%); (4) parallel (9%). A single participant reported that their conflict hierarchy places head-on first, followed by converging, and parallel, respectively. Only two participants did not explicitly state a conflict hierarchy (Table 7). The participants' reasons for their established order showed clear tendencies towards the maintenance of safety protocols (91%). In addition to environmental factors, it may be possible that the established information hierarchy is affected by the type of conflict. In the case of overtaking aircraft (Table 8), the priority of speed is higher than direction, while altitude remains the most important variable (64%).

Table 7. Priority order of aircraft conflict types and their associated reason.

Order of Conflict Observed			Freq.	Reason	Freq.	Participant
Converging	Head-on	Overtaking	4	Immediate safety issue	3	P1, P2, P3
				Loss of separation	1	P4
	Overtaking	Parallel/ Diverging	2	Time sensitive	2	P7, P9
	Diverging	Overtaking/ Parallel	1	Symbol recognition	1	P5
	Parallel	Overtaking/ Diverging/ Head-on	1	Immediate safety issue	1	P6
Head-on	Converging	Parallel	1	Immediate safety issue	1	P10
Order based on training and experience			2	Immediate safety issue	1	P8
				Time sensitive	1	P11

Table 8. Order of information observed for overtaking aircraft.

Order of Information Observed			Freq.	Participant
Altitude	Speed	*	5	P3, P5, P8, P10, P11
		Direction	1	P4
		Destination	1	P8
	Direction	Speed	1	P9
		*	1	P7
Speed	Altitude	Turns	1	P2
Speed	*	*	1	P6

* Information was not explicitly stated by participant (s).

For the case of converging aircraft (Table 9), the established hierarchical information remains as originally defined for most participants (54%): (1) altitude; (2) direction; (3) speed. Although the majority of participants maintain that altitude is the most important variable (91%), there is no consensus on what the subsequent order is. Only one participant did not provide an explicit information hierarchy.

Table 9. Order of information observed for converging aircraft.

Order of Information Observed			Freq.	Participant
Altitude	Direction	Speed	6	P4, P6, P7, P8, P10, P11
	Position		1	P5
	Speed		1	P1
	Destination	*	1	P9
	*		1	P2
Preference based on training and experience			1	P3

* Information was not explicitly stated by participant (s).

A key element in conflict mitigation is the selection of a variable from the hierarchy of information used for de-conflict. The participants were surveyed on their preferred conflict mitigation strategies (Table 10), with two principal conflict mitigation strategies reported: (1) altitude, vector, and speed changes (36%); (2) vector and altitude changes (36%). One participant described an alternative hierarchy, which consisted of changing altitude, followed by vectoring.

Table 10. Preferred conflict mitigation strategies.

Order of Conflict Mitigation Strategies			Freq.	Participant
Altitude change	Vector change	Speed change	4	P3. P5. P8, P10
		*	1	P1
Vector change	Altitude change	*	4	P4, P6, P7, P9
Based on sector characteristics			2	P2, P11

* Information was not explicitly stated by participant (s).

Additionally, two participants did not explicitly state a hierarchy of conflict mitigation strategies, but rather cited that the sector characteristics dictate the strategy they would apply. Participants were also surveyed on the reasoning behind their established conflict mitigation hierarchy (Table 11), with three major areas: (1) conflict characteristics (27%); (2) customer service (27%); (3) sector characteristics (27%). Only one participant provided an alternative motive, defined by the practicality of changing altitudes. The quotations explaining the reasoning behind their conflict mitigation hierarchy can be found in Table 12.

Table 11. Reason for preferred conflict mitigation strategies.

Reason	Freq.	Participant
Conflict characteristics	3	P3, P6, P11
Customer service (e.g., provide a short-cut)	3	P4, P5, P7
Sector characteristics	3	P1, P2, P9
Practicality of altitude change	1	P10
Preference based on training and experience	1	P8

Table 12. ATCSs quotations on reason for their preferred conflict mitigation strategies.

Reason	Quotations from ATCSs
Conflicts characteristics	(P3) It is hard to give a specific example because you are reacting in many instances
	(P6) Normally the speed comes into play as you are looking for the traffic and you decide: "am I going to turn the slower aircraft behind the faster aircraft"
	(P11) I cannot really say that. Sometimes routes are so much easier, you can just tweak a route or turn them behind him.
Customer service (e.g., provide a short-cut)	(P4) If I could give an aircraft a more direct route, he is happy. I am not changing his altitude, so everyone is happy in that situation.
	(P5) Airplanes like to stay on course and anytime you turn them, it takes longer and costs more money as burn more gas.
	(P7) If it's shorter for the aircraft, that's more efficient, as it saves them time and fuel, which equates to efficiency. It is more efficient for me.
Sector characteristics	(P1) Altitude or vectoring would be best. Where I have worked, these guys are coming cross country. If you start slowing down, they are going to get irritated
	(P2) If you are working on a low altitude near an airport, using speeds and having them slow down, it works really well but not so much in different airports
	(P9) Sometimes you have to do just choose one due to the scenario. There may be a scenario where you have to vector because there are no altitudes
Practicality of altitude change	(P10) I think altitude is the easiest because the pilot just has to go up or down. In vectors, the pilots may start wondering, why are they on this vector?
Preference based on training and experience	(P8) To me, it is just the easiest way to work airplanes.

4. Discussion

The objective of the present study was to identify the heuristics that experienced ATCS application, subject to the information gathered and processed from the environment, as they carry out the safe and expeditious control of air traffic, in order to incorporate what we learn into the training curriculum. The interviews held with the participants, and the subsequent two-fold analysis, composed of self-report and eye tracking methodologies, highlight several types of applied heuristics, and the environmental cues that lead to them.

First, the visual search strategies tend to be composed of continuous movements that resemble a spiral or circular geometrical pattern. This enables ATCS to cover the entirety of the sector in a systematic manner, possibly reducing the rate of duplicate information (e.g., reading the same data tag twice) that needs to be gathered and processed from the environment. The starting location of these eye movements gravitates towards areas which were self-defined as high-density, emphasizing safety, as aircraft are in close proximity to each other, and the difficulty of maintaining separation is heightened. It is important to distinguish that, although participants did not explicitly report a consensus on the reasoning behind their preferred visual search strategies, the aggregate of their responses suggests that the overall application is directed towards the maintenance of high degrees of safety in the system.

Second, through their visual search strategies, the environmental and aircraft information needed to build and maintain situational awareness is gathered. Participants concur that the former is collected through a dynamic information hierarchy, prioritizing the altitude of an aircraft over its direction and speed. This is likely driven by the three-dimensional nature of the environment. For example, if most potential conflicts consist of horizontal geometries (e.g., sectors without airports, where changes in altitude for landing or taking-off procedures are not needed) at different altitudes, the likelihood of possible conflicts among them is significantly reduced. This leads to potentially fewer altitudes needing to be encoded by ATCSs, as aircraft remain at pre-determined altitudes unless instructed otherwise. An exception is when an airport exists within a sector, in which airports necessitate a change in altitude during arrival or departure. In addition, the participants recognize that their information hierarchy must be dynamic to account for the various possible types of conflict that may be present, and the multiple ways they can be resolved. It is notable that, especially around an airport, the pilots and controllers are not stuck thinking in two dimensions, but can consider four dimensions (i.e., 3D plus time).

The results corroborate the industry-established notion of altitude being prioritized. In addition, if we use the scenarios as training tools, the fact that these scenarios present examples of the prioritization of altitude being effective means that the scenarios will be that much more useful as training examples.

Third, the participants apply a hierarchy of conflicts in their conflict detection task. In this ordinal categorization, aircraft pairs whose geometrical shape indicates convergence are given priority over all other configurations. Although there is no unanimous designation of the importance of subsequent conflicts, there is an agreement that the foundation of this hierarchy is based on the maintenance of safety protocols. This is because recognizing a converging conflict may require more time, due to the information that needs to be compared. In the case of an overtaking conflict, all involved aircraft are flying at the same altitude, heading in nearly, if not identical, directions. This generates a shift in the weights assigned to the dynamic information hierarchy, as speed becomes the second priority variable, over direction, for most participants.

Finally, the role that altitude plays in conflict mitigation strategies is quite significant. This is consistent with the hierarchies reported by controllers in other studies [41]. Second to altitude, the direction of flight is the next highest in the hierarchy. Here, ATCS are capable of enhancing the experience of their customers by providing direct routes with greater efficiency, taking advantage of favorable weather conditions, or maintaining altitude and reducing fuel costs. Although altitude provides an immediate solution to an aircraft in conflict, it requires aircraft to cross several transitory altitudes, potentially placing them in another conflict. This divide highlights one of the multiple trade-offs that ATCS must choose between to successfully and efficiently manage air traffic in a safe manner.

The retired ATCS applied a conflict mitigation hierarchy which is continually instantiated with information gathered from the simulated environment through the application of consistent visual search strategies. These strategies represent logical candidates to present to novice ATCSs during training. Presenting expert search strategies to novices would enable the novices to try to incorporate the strategies into their own behavior and potentially improve the efficiency with which they gather operationally relevant information from the environment.

Limitations and Future Research

The purpose of this research was to investigate the visual search behaviors using realistic scenarios; therefore, many possible factors, such as the speed of convergence, altitude changes, time to conflict, or number of aircraft on display at a certain timeframe, were not controlled. In addition, the interview results were created based on verbal input after all the scenarios were administered, and were not associated with a specific scenario in mind. Finally, other various eye movement metrics, such as eye fixation numbers/durations, pupil sizes, saccadic transitions (e.g., Markov Chain), scanpath duration, scanpath frequencies, and visual entropy were not analyzed.

Therefore, future research involves analysis visual search and conflict mitigation strategies using various factors, as well as the eye movement metrics mentioned above. In addition, we were able to identify the visual scanpaths within each scenario which could be mapped with the experts' verbal explanation of their visual search strategies, but we did not choose to include the sixty figures in this paper. We are currently in the process of developing a robust algorithm to better classify and represent those outputs.

5. Conclusions

Self-reported responses, along with associated visual scanpaths obtained from eleven retired ATCSs, were analyzed using a high-fidelity simulator to better understand the ATCSs' cognitive and decision-making processes during visual search and aircraft conflict mitigation. Results from the self-reported responses indicate that the participants prefer to apply a systematic and continuous visual search strategy, utilizing a circle or spiral movement, and starting in high-density areas. Furthermore, we were able to identify the visual scanpaths that accord with their self-reported responses. In addition, the self-reported responses suggest that information is gathered from the environment through a dynamic information hierarchical heuristic (i.e., altitude -> direction > speed), which might be affected by aircraft conflict characteristics. Similarly, the preferred conflict mitigation strategies, explained by the retired ATCSs, were either modifying the altitude and direction, followed by the speed, when imminent conflicts were detected.

Author Contributions: Conceptualization of the research topic and the methodology were developed by Z.K., the PI. Software and hardware were provided by J.M.C. Experiment scenarios were designed by J.M.C., Z.K. and FAA contractors. Data were collected by S.M. Data analysis approaches were devised by Z.K. and R.P.F. Data analysis was performed by S.M. and R.P.F. Original draft was prepared by R.P.F. Final draft was prepared by R.P.F., Z.K. and J.M.C. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Institutional Review Board of the University of Oklahoma (protocol code: 7930; date of approval: 31 March 2017).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. Written informed consent has been obtained from the participants to publish this paper.

Data Availability Statement: Data can be available by contacting the corresponding author, Ziho Kang.

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