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Improving Visual Inspection Reliability in Aircraft Maintenance

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Visual inspection is a fundamental safety critical task in the air transport industry. This study investigates how a visual search strategy with a specific eye scanning pattern can be used to improve the observation of aircraft defects during visual inspection tasks. N=100 aircraft maintenance technicians were recruited and N=48 were allocated to a control condition. This group conducted pre-flight visual inspections on aircraft, using their normal custom and practice. The remaining N=52 experimental group participants were trained to use a specific eye scanning pattern during their pre-flight inspection called systematic visual search. Prior to inspections, the number of observable defects on each aircraft has been ascertained by the researchers. The results demonstrated that the use of systematic visual search increased the mean number of defects observed from circa 36% to circa 56%. The experimental group were then tasked with further visual inspections using systematic visual search in order to investigate the effect of practice and feedback. This resulted in mean defect observation rates increasing to a plateau of circa 70%. The results clearly demonstrate that; by using a set eye scanning pattern as directed by the systematic visual search method, visual inspection reliability can be improved.

Keywords: Visual, Inspection, Hazard, Defect, Observation, Improving, Search, Reliability,

1. Introduction

Vision is our pre-dominant sense. We humans receive most understanding of our immediate environment from what we see (Lukas, Philip and Kock, 2010). It is therefore no surprise, that when we conduct a visual search task such as an inspection with a higher degree of reliability, we observe more objects of interest. But the question that arises is what is the most reliable way of observing, or how best to use our eyes when conducting a visual search during these inspections. In short, what visual search behaviour or eye scanning pattern are humans best suited to when looking for observable defects, hazards or other objects of interest. It has been axiomatically stated that observing the entirety of the object under analysis will result in all observable hazards being seen. But this rather obvious statement is difficult to achieve in practice. The reality is that visual search is an error prone task and difficult to do well (for example see Biggs & Mitroff, 2013 or Gallwey, 2006).

Even so, visual inspection is the most widely used safety technique in the aircraft industry representing circa 80% of all inspection used (Drury & Watson 2002). As expected in this highly regulated sector, visual inspection during the maintenance repair and overhaul of aircraft is highly proceduralised and based on extensive research dating back to the 1950s (See, 2012). One example of a specific visual inspection technique in the aviation sector is the use of pre-flight inspections. These are described by Lafiosca & Fan, (2020) and typically involve a walk around the aircraft under analysis in order to observe any abnormalities as listed on a checklist or held in memory. These visual inspections are designed to ensure that any observable defects are identified and further investigated for any necessary repairs, manipulation or maintenance.

Objects of interest during visual inspections conducted in the aviation sector include mechanical damage or disrepair from impact, friction, fatigue, wear & tear, required maintenance interventions, and loose objects.

Together with periodic in-depth visual inspections, a high level of safety has been long established and maintained in the aviation sector. Nevertheless, visual inspection error is still possible and observable defects missed. For example See, (2012) reports on 111 fatalities from an aircraft crash landing in 1989 which was attributed to a visual inspection failure. But it remains that the fundamental visual search behaviour used by aircraft maintenance technicians, and in particular, the eye scanning patterns adopted during their visual inspections has not received sufficient academic attention. A recent study by Hrymak & de Vries, (2020) reported that the use of a specific eye scanning pattern during visual inspections increased the observation of hazards during workplace safety inspections. This study set out to apply the same thinking to the aircraft industry. The aim was to ascertain if the number or observable defects seen by aircraft maintenance technicians during their pre-flight inspections, could be increased and thereby result in improved reliability for this safety critical task.

2. Methodology

After ethical approval had been granted by Technological University Dublin, N=100 aircraft maintenance technicians were recruited as participants in this study. Of these participants, N= 61 were apprentice aircraft maintenance technicians in full time education. The remaining N=39 participants were full time aircraft maintenance technicians, professionally recognised by the relevant aviation safety

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regulator (see Table 1). All participants in this study had pre-flight visual inspection experience.

The experimental design attempted to replicate a randomised controlled trial paradigm as closely as possible. However, due work scheduling requirements at the aircraft maintenance facility as well as aircraft availability, random allocation of individual participants into control and experimental groups was not possible. Instead, groups of participants that were known in advance to be attending the aircraft maintenance facility for work duties, were randomly allocated to control or experimental conditions. This was a logistical experimental design requirement given that the primary duty of the participants was to conduct aircraft maintenance activities as directed by management. Whilst randomised controlled trial conditions were not fully provided for this study, an interventional quasi-experimental design with control and experimental conditions was pragmatically achieved (Breakwell, Smith & Wright (2012).

In the control condition N=48 participants were tasked with conducting a pre-flight inspection on one of three types of aircraft using their normal custom and practice. In the experimental condition, N=52 participants were directed to use a set eye scanning pattern called systematic visual search by the researchers (explained in section 2.6). In the experimental condition, participants were firstly assembled in a class room and given a forty minute PowerPoint based training session in the conduct of systematic visual search. Immediately after this training, the experimental group were directed to conduct a pre-flight inspection on the same aircraft used by their control group colleagues, but using a set eye scanning pattern as directed in the systematic visual search training session.

2.1. *The pre-flight visual inspection procedure*

Each participant conducted their pre-flight visual inspection as follows. Trial participants belonging to either the control or experimental condition were assembled in a meeting room close to where the aircraft under analysis was parked. Groups of four aircraft maintenance technicians were then brought out to the aircraft, under the direction of the researchers. Control group participants were directed to conduct their pre-flight inspection with their normal custom and practice and usual documentation on which they wrote down defects observed. On completion, the researchers collated all documents used by participants to write down the observed defects.

The four participants were assembled around the aircraft so that they kept their distance from each other as they walked around the aircraft. Four participants at a time were used due to researcher time constraints. With the constantly varying numbers of potential participants available per trial, assembling four aircraft maintenance personnel per aircraft allowed the trial to be completed in a morning, afternoon or evening session. Allowing one participant at a time to conduct their visual inspection would not have been feasible given the time that this approach would have taken. All participants were given as much time as they needed to complete their pre-flight inspections.

Once the visual inspections were completed, all participants returned to their normal scheduled aircraft maintenance duties. These trials were also carefully scheduled and completed so that control and experimental groups did not come into contact with each other, until all pre-flight inspections were completed. This was designed to preclude participants from control and experimental groups from discussing their trials between themselves.

2.2. *The effect of feedback and practice*

Training and task performance feedback to achieve or improve a particular skill is a normative recommendation found in the vast majority of disciplines. Visual inspection in the aviation sector is no different and numerous studies have reported the beneficial effects of training and feedback for aircraft maintenance technicians (for example see Drury & Watson, 2002; Gramopadhye, et al, 2002; Gramopadhye et al, 1997)

In order to ascertain the effect of training and feedback on systematic visual search users, three additional trials for experimental group participants were conducted. This longitudinal experimental design (Breakwell et al, 2012) was achieved by directing the original N=52 experimental participants to conduct an additional three trials using systematic visual search. After each of these additional trials, participants were provided with feedback on their visual search reliability. Due to Covid-19 restrictions, only N=18 experimental group participants were allowed to conduct pre-flight inspections in the fourth and final trial.

In effect, Trial 1 allowed the creation of a baseline reliability dataset for those participants who conducted their pre-flight inspections with their normal custom and practice. Trials 2, 3 and 4 were conducted to investigate the effect of practice and feedback events on participants using systematic visual search which included the experimental group in Trial 1. Due to the scheduling of participants more than four trials were run. Results from these multiple trials have been aggregated into the four presented for this study, in order to improve readability and allow a clear comparative analysis between control and experimental participants. Over 90% of participants in the trials conducted their pre-flight inspections during a six month period.

The procedures used for feedback in this longitudinal design involved experimental group participants being re-assembled in a meeting room for a 30 minute review session, an hour or so after their trial. A listing of the general areas of the aircraft where defects were being missed in the previous trial, were then detailed by the researchers using a PowerPoint presentation. This feedback approach was chosen in preference to presenting those non-observed defects in order facilitate the continued use of the systematic visual search method.

The researchers used an informal manner in in these feedback sessions with the general advice to use keep using systematic visual search for future pre-flight inspections. Individual participant scores were not released due to ethical confidentiality restrictions. In this manner, experimental group participants were given four opportunities to practice systematic visual search with feedback as to the areas they had not fully observed.

2.3. *Comparability of Treatment Groups*

As stated above, random allocation of individual participants to treatment groups could not be fully achieved due to scheduling difficulties. Instead, it was groups of attendees to the aircraft maintenance facility who were randomly allocated to control or experimental conditions. This necessary compromise did impinge on comparability to an extent (see Table 1). If random allocation of all the individual full time and apprentice participants had occurred on an expected 50:50 basis; then four less full time participants and six more apprentices would have been expected in the control condition.

Nevertheless taking the total N= 100 participants recruited, a roughly equal number were allocated to both conditions. In addition, the mean years of experience within conditions was also kept close. Furthermore, gender was not a factor in terms of comparability as there was only one female technician recruited in the total N=100 participants. In this manner the effect of systematic visual search on visual inspection reliability was as far as possible, isolated as an independent variable for subsequent statistical and qualitative analysis.

Table 1. Descriptive data for Trial 1

	Control	Experimental
N	48	52
N full timers	24	15
N apprentices	24	37
Mean years of experience of full timers	M= 19.37 SD = 7.05	M= 21.13 SD = 8.77
Mean years of experience of apprentices	M= 2.58 SD= 0.81	M= 1.05 SD = 0.32

2.4. *Ecological Validity*

An important aim of the experimental design was to ensure that real word pre-flight inspection conditions were created as far as possible. Accordingly, all participants in this study had conducted pre-flight inspections. Furthermore, the aircraft used for the pre-flight visual inspection task, were all in use for the training of aircraft maintenance technicians and located in their normal positions. In addition and some two years prior to this study, a number of these aircraft were fully operational and airworthy before being re-assigned for aircraft maintenance training use. In short, these aircraft typified normal aircraft maintenance facility use and reflected real word conditions for pre-flight inspections as far as possible.

However, there were two relatively minor differences between the procedures described in this study and real world conditions. The first was that participants conducted their visual inspections in groups of four. Secondly experimental group participants were supplied with paperwork designed to facilitate the use of the systematic visual search method. In this latter regard, the order in which their visual inspection of specific elements was to be conducted was detailed in writing, prior to commencement. This order was as follows; external front of aircraft, port, rear, starboard, engine, top and underneath. Then an internal visual search again; front of aircraft, port, rear starboard, ceiling and finally floor. In all other respects, these procedures very closely resembled normal pre-flight visual inspection conduct.

2.5. *Ascertaining observable defects on each aircraft*

A key component of the experimental design was to ascertain the actual number of observable defects on the aircraft under analysis. A master list of observable defects was therefore compiled for each aircraft in four ways. Firstly, the researchers used the systematic visual search method themselves to conduct pre-flight inspections. Secondly, the researchers introduced a number of “planted” defects onto the aircraft. For example, loose items were left in the cockpit or split pins were removed form mechanical components. Thirdly, two senior individuals from aircraft maintenance management were tasked to conduct pre-flight inspections themselves as well as assist in the planting of hazards. Finally, by reading the pre-flight inspection reports compiled by participants, the researchers were able to confirm the vast majority of defects that were present on the aircraft. By varying the number of planted defects, the researchers also able to keep the mean number of defects close to thirty five per aircraft.

One observable defect; small cracks defined as less than 26mm in any one direction, were not used in the subsequent analysis. This was due to ambiguity in location from the written descriptions. It was felt that rather than introduce a possible source of error into the dataset, this relatively infrequent type of observable defect was excluded from the statistical analysis. Examples of the observable defects on the aircraft under analysis are summarised by a non-exhaustive listing as follows;

- Pens, torches or phones left in the cabin
- Tools left in the engine compartment
- Date expired fire extinguishers left in the cabin
- Spark plugs left unsecured
- Panels left unsecured
- Areas of corrosion
- Areas of cracking
- Oil caps left off
- Magnetos left unconnected

- Gaskets in poor condition
- Engine wires or cables left cut or missing
- Battery trays left unsecured
- Cracked fuel gauges
- Leaks
- Antennas removed from tail sections
- Steering components removed
- Removed or missing rivets, screws or split pins
- Tyres left underinflated
- Cloths left over pitot heads

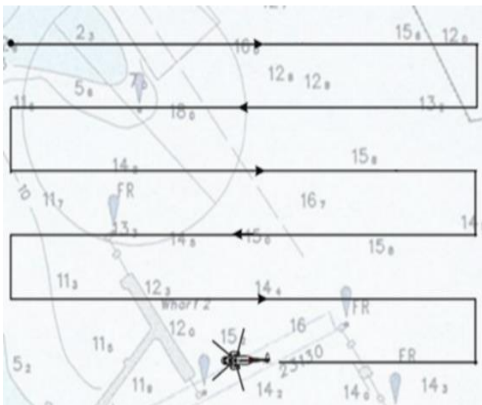
2.6. *The systematic visual search method*

The training and instruction for systematic visual search consisted of a 40 minute PowerPoint session where the method was explained in detail to experimental group participants. This visual search behavioural algorithm consists of two distinct stages. Firstly, the aircraft under analysis is broken down into individual elements or areas, for example external port side, external starboard side etc. Secondly, each element is then selected for specific observational analysis and is not returned to again. The order specified was designed to follow an approximate anti-clockwise walk-around the aircraft.

Once the aircraft element has been selected, the next stage is to apply the eye scanning pattern to the element and observe accordingly. During this stage, observation begins by directing the gaze and fixating at the top left hand corner of the element. The line of vision then scans to the right until the end of the element is reached whereby observation continues in a left right pattern, underneath the area already observed.

When attention is drawn to any objects of interest, the participant can investigate further or write the defect down. This “reverse snakes and ladders” pattern then continues until the element has been completely observed. This visual search behaviour is then applied to the next element selected until the entire aircraft has been observed. Figure 1 depicts this “reverse snakes and ladders” eye scanning pattern using a graphical flight path analogy.

Fig. 1. The reverse snakes & ladders eye scanning pattern



2.7. *The aircraft used in the study*

The participants conducted pre-flight inspections on one of three aircraft as exemplified in Figures 2-4.

Fig. 2. Cessna 172

Fig. 3. Fouga Magister

Fig. 4. Allouette III

2.8. *The qualitative research conducted*

In addition to the quantitative data generated as described in this methodology section above, the researchers felt it was important to gather qualitative data from the participants. This was achieved by directing participants to write down their experiences of their visual search methods used after each trial. This provided an additional important data set on participant visual search behaviour.

3. Results

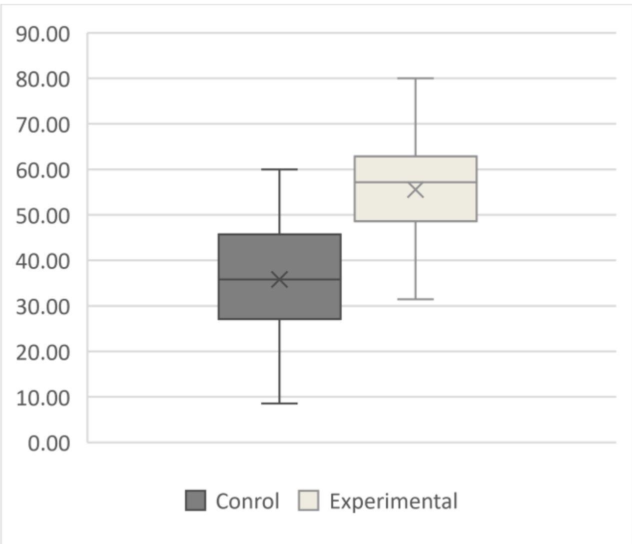
It was demonstrated in Trial 1, that by using systematic visual search, the mean percentage of defects observed increased from; 35.70% achieved by the N=48 control group participants, 55.55% by experimental group participants. This increase was highly significant and represented a large effect size ($p = \leq .001$; Cohen’s $d = 1.68$).

A further noteworthy finding was that systematic visual search users took a mean 22 minutes and 17 seconds longer to complete their inspections which was also highly significant with a large effect size ($p = \leq .001$; Cohen's $d = 5.98$). This indicated greater cognitive effort and visual search diligence during their inspection task. These results are shown in Table 2 and with a graphical comparison between conditions in Figure 5. Furthermore, Chi Square testing demonstrated that the aircraft used did not have a statistically significant effect on defect observation rates.

Table 2. Trial 1 Results

	Control	Experimental
	48	52
Mean % defects observed	M= 35.82 SD = 11.64	M= 55.55 SD = 10.95
Mean time taken for inspection (mins & secs)	M= 26:27 SD = 6.50	M= 49.24 SD = 10.36

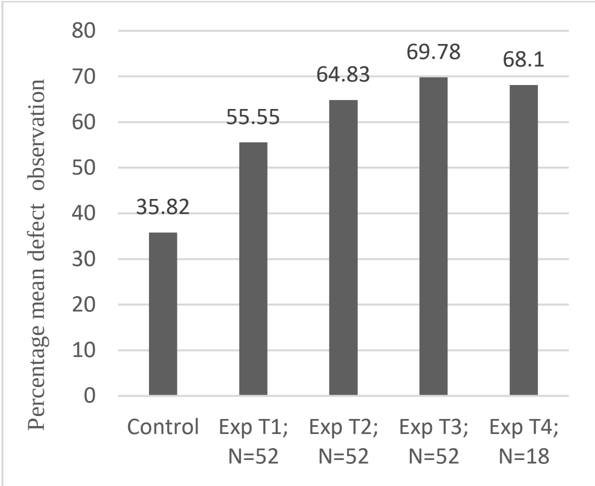
Fig.5. Box Plot Results from Trial 1



3.1. *The effect of practice and feedback*

As evidenced from Figure 6, the result of practicing and receiving feedback demonstrated a number of main findings. Firstly, the increase in visual search reliability found with Trial 1, (T1) experimental group participants (Exp) was replicated in Trials 2, 3 and 4 (T2, T3 & T4). This points to systematic visual search acting as a behavioural visual algorithm that is not a difficult skill to learn. Secondly, with the benefit of practice and feedback, systematic visual search appears to effect a continuous change in visual search behaviour reliability. Thirdly, a plateau for pre-flight inspection tasks using systematic visual search is apparent. This plateau appears to be at the circa 70% level (T3; M=69.78, SD=8.04) Trial 4 showed a slight drop in visual search reliability, but this may have been due to sample error as there were only N=18 participants in this particular trial due to Covid restrictions.

Fig. 6. Defect Observation Rates for Trials 1-4

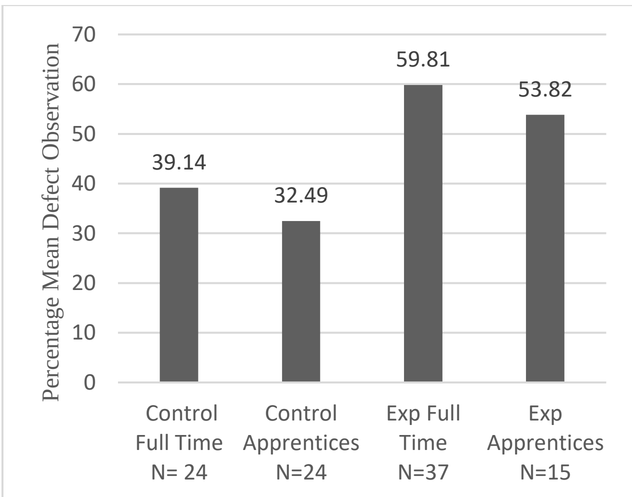


In addition, the modest amount or resources required to achieve a near doubling of visual search reliability should be considered a beneficial characteristic. To nearly double mean defect observation rates from baseline to plateau needed under five hours of total training time per participant. The total time periods needed were circa; 40 minutes for method instruction, 120 minutes for method practice and 120 minutes for feedback,

3.2. *The effect of experience on defect observation*

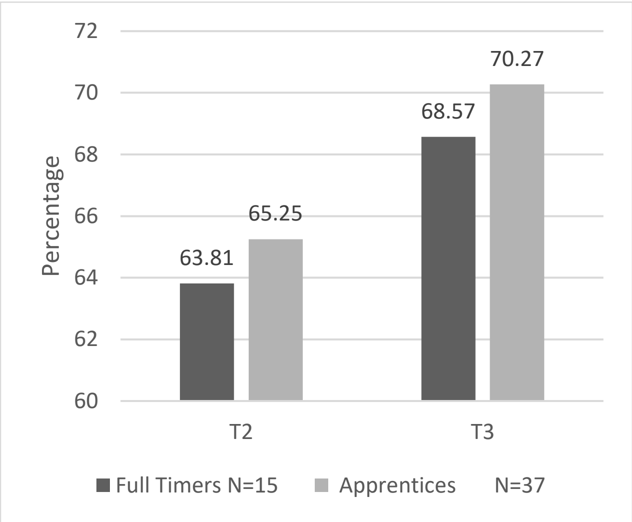
When the results were broken down to reflect full time and apprentice aircraft maintenance technicians as separate cohorts, further noteworthy findings emerged. As expected in Trial 1, both control and experimental group results demonstrated that the full time aircraft maintenance technicians had higher defect observation rates than their apprentice colleagues. Intuitively, this result should be explained by the far greater level of experience with full timers. In this regard, the full time participants in this study had on average over twenty years of work experience in contrast to their apprentice colleagues, with an average of one and half years (see figure 7).

Fig.7. Defect Observation Trial 1, Full Timers & Apprentices



However, the results from Trials 2 and 3, where a comparison could be made between full timers and apprentices in the experimental condition, demonstrated that apprentices reversed this situation. Apprentices marginally outperformed their more experienced full time colleagues in Trials 2 and 3 (see Figure 8). This finding further evidences the advantages of using a set eye scanning pattern in very quickly improving defect observation rates for apprentices to levels which are comparable with their far more experienced full time colleagues.

Fig.8. Mean Observation in T2 & T3 Experimental Condition



3.3. *Correlational analysis of experience*

As seen in Table 1, full time participants had over twenty years experience of pre-flight inspections. Table 3 presents Pearson's Product Moment Correlation (*r*) between experience (measured in years) and defect observation rates for full timers in both conditions. The results from Table 3 Trial 1, were unexpected and counter intuitive. In short, the more experienced the participants, the less defects they observed. Two, negative correlations were returned, one with a non significant medium effect, and one with a significant strong effect.

Table 3. Correlations Between Experience & Work Status

Trial	Control Full Timers N=24	Experimental Full Timers N=15
T1	r = -.31 p = ≥.05	r = -.65 p = ≤.01
T2	N/A	r = .18 p = ≥.05
T3	N/A	r = -.17 p = ≥.05

This seemingly contradictory finding can be explained by sample error, but a more compelling explanation may lie in the effect of confirmation bias. The role of bias when making decisions or judgements under conditions of uncertainty is widely reported in the psychology based literature (see for example Montibeller and von Winterfeldt, 2015). Kappes et al, (2020) summarily describes confirmation bias as; a tendency to see what you expect due to the influence of past judgements.

Therefore, the counter intuitive results in Table 3, could be explained by confirmation bias as follows. The visual searches conducted by the full timers in Trial 1, were being influenced by their past experience of where they were more likely to find defects on aircraft. This behaviour was reported by Trial 1 participants (see section 3.4). Clearly there could be other, as yet un-explained reasons for this counter intuitive finding but it remains that confirmation bias may be an important factor. If this type of bias does turn out to have played a role (and more research will be needed evidence this), then a further finding from this study is that systematic visual search appears to counter such bias. This can be seen in Table 2 Trials 2 & 3, where correlations of experience with defect observation lessened and returned small effect sizes.

3.4. *Qualitative results*

Qualitative research can greatly assist in providing a rich understanding for an experience under analysis (Petty, Thomson & Stew, 2012). This study therefore benefited from seeking participant perceptions of their trials. Accordingly and after each trial, all participants were given an opportunity to describe in writing their thoughts and opinions on their pre-flight inspections. In summary the main theme to emerge from over 90% of control group participants, was their visual search behaviour of paying particular attention to those parts of the aircraft where they expected to find defects.

In sharp contrast, the main theme that emerged from over 90% of experimental group participants was; how beneficial the use of adopting a set eye scanning pattern was in terms of thoroughness and how they intended to continue using the method. In addition, it was reported that systematic visual search represented a clear visual search behaviour to follow. A further theme was how the paperwork that stated the order in which to inspect the aircraft, was also useful. There was also a theme reported of greater mental fatigue after using systematic visual search. This fatigue has been reported in the literature, with visual search tasks being described as a cognitively demanding (see for example Biggs & Mitroff, 2013).

3.5. *Drawbacks to the use of systematic visual search*

The use of a set eye scanning pattern for visual search does take longer to conduct. The time taken for pre-flight inspections increased from approximately 27 minutes for the control group to approximately 49 minutes for the experimental group (see Table 2). But this extra time used does result in an increase in observed defects and is therefore considered beneficial. This also suggests the actual amount of time required for this visual search task is longer than currently seen in normative custom and practice for pre-flight inspection practice as described in this study.

Furthermore, the long term sustainability of systematic visual search has yet to be confirmed by the researchers. Just how long experimental group participants keep on using this method is subject to further research. Additional trials are currently planned for six monthly and yearly intervals. This is to evidence whether the set eye scanning pattern used in this study, remains a sustainable learnt visual search behaviour with consistently greater visual search reliability.

4. Discussion

The experimental design used in this study had the benefit of a relatively large sample size and produced baseline data from a control group that conducted their pre-flight inspections using their normal custom and practice. An experimental group was also created for comparison that that used a set eye scanning pattern. The study also ensured an ecologically valid setting was achieved as far as possible and that real world conditions for pre-flight visual inspections were created. The experimental design therefore allowed the visual search tasks created, to be measured with a high degree of empirical evidence.

This study therefore provides strong evidence to support the main finding; that visual search reliability can be improved by the use of a quickly learnt eye scanning pattern that promotes a more meticulous and exhaustive observation of aircraft during pre-flight inspections. In addition, visual search reliability can be nearly doubled with practice and feedback. The qualitative results also demonstrated how well received the systematic visual search method was with the reported intention of continuing its use.

The wider cognitive visual psycho-physics literature offers an explanation as to how this improvement in defect observation may have occurred. Summaries of the relevant research published (for example Eckstein, 2013) suggests that using set eye scanning patterns decreases random observation which can reduce available cognitive resources. This leaves greater cognitive resources available when direct eye contact with defects, deploys the brain's attentional mechanism to perceive and recognise objects of interest.

But even with use of a set eye scanning pattern that was practiced and feedback received, it was found that circa 30% of observable defects went un-recorded by experimental group participants. So the question now becomes how to address this remaining 30% of un-observed or un-recorded defects. A first step would be to ascertain the causes for not observing these remaining defects. This is difficult to achieve and requires further research due to the many and varies causes of visual search error (for example summaries see; Biggs & Mitroff, 2013; Cain et al, 2013; Drury & Watson 2002; Eckstein, 2011, Gallwey, 2006; Hrymak & de Vries, 2020; Rao et al 2006; See, 2012; Wolfe, 2020; Wolfe, Horowitz and Kenner, 2005).

However, from a risk management perspective, it would be interesting to speculate if the range of defect observation rates found in this study (circa 36-70%) can generalise to the wider Environmental Health and Safety community. The main argument for generalising is that the participants in this study were simply using their eyes to find in-situ defects. Observing work place hazards should in theory at least, be no different for all related safety professionals who conduct visual inspections in hazard rich environments. The main argument against generalising is that the air transport industry is clearly a very different working environment to others, with its own unique safety culture, working practices and regulatory framework. But it is interesting to note that other field based studies that have investigated safety related visual search reliability, have reported broadly similar observational ranges in hazard rich workplace environments. For example construction safety studies such as Albert, Hallowell & Kleiner, (2014) and Albert et al, (2017), reported baseline level of hazard recognition from circa 32% which was increased to 80% using a variety of training based methods. Hrymak & de Vries, 2020, reported that for commercial kitchen visual inspections, observation of hazards improved from circa 33% to circa 50% with training in the use of a set eye scanning pattern.

5. Conclusions and Implications

This study has revealed that current human visual search performance when tasked with observing defects during pre-flight inspections of aircraft has limitations in terms of reliability. This can be improved with practice and feedback when using a set eye scanning pattern as exemplified by the systematic visual search method. But even with practice and feedback using the systematic visual search method, circa 30% of observable defects still went un-recorded. So the question now being addressed by the researchers is; how can this circa 30% be left with a consistently irreducible range for visual search reliability.

Finally, visual inspections occur on a daily basis in countless safety critical situations as well as in industrial quality control environments. Therefore, additional research into the reliability of these additional visual search tasks would also be in the interest of safety and quality.

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