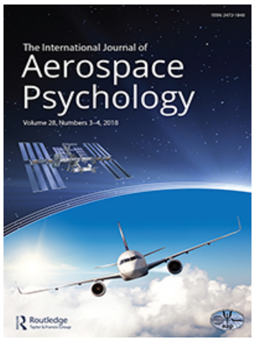

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Eye-Tracking Measures in Aviation: A Selective Literature Review

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ABSTRACT

Objective: The aim of this article is to present a comprehensive review of eye-tracking measures and discuss different application areas of the method of eye tracking in the field of aviation.

Background: Psychophysiological measures such as eye tracking in pilots are useful for detecting fatigue or high-workload conditions, for investigating motion sickness and hypoxia, or for assessing display improvements and expertise.

Method: We review the uses of eye tracking on pilots and include eye-tracking studies published in aviation journals, with both a historical and contemporary view. We include 79 papers and assign the results to the following three categories: Human performance, aircraft design, health and physiological factors affecting performance. We then summarize the different uses of eye tracking in each category and highlight metrics which turned out to be useful in each area. Our review is complementary to that of Ziv (2016).

Results: On the basis of these analyses, we propose useful application areas for the measurement of eye tracking. Eye tracking has the potential to be effective in terms of preventing errors or injuries by detecting, for example, fatigue or performance decrements. Applied in an appropriate manner in simulated or real flight it can help to ensure optimal functioning of man–machine systems.

Conclusion: Further aviation psychology and aerospace medicine research will benefit from measurement of eye movements.

Geratewohl (1987) said the eye was the most important sensory organ of the pilot as it was said to process 80% of all flight information. With the continuing development of technology, automation, and sophisticated sensing in both military and commercial aviation, human information processing changed. For instance, pilots do not process as much visual information outside the cockpit as in the early years of aviation, but have to extract information from multiple sources (from more instruments inside the cockpit) and integrate it into a coherent picture to manage the flight. Human processing of visual data remains one of the key elements of aviation safety and effectiveness (Mosier, 2010; Vidulich, Wickens, Tsang, & Flach, 2010).

From this perspective it seems obvious that visual information processing should be analyzed when trying to understand flying performance decrements or factors affecting performance such as fatigue or stress. A good method to analyze visual information processing is to examine eye movement data (e.g., Rayner, 1978). Ziv (2016) argued that optimal scanning behavior is important to achieve better aviation performance. As systematic reviews on the application of eye tracking in aviation have been rare up to now, this article attempts to close this gap and presents a comprehensive review of eye-tracking use in aviation research, specifically on the flight deck, by addressing the areas and studies not addressed by the comprehensive review of cockpit scanning literature carried out by Ziv (2016).

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Method

This study provides a comprehensive review of eye-tracking studies in the field of aviation with results applicable to pilots. The goal of this article is to complement the recent review of aviation eye-movement studies published by Ziv (2016). His review covered many important topics, and this article is intended to cover additional topics and research in this important area that were not addressed by Ziv, and thereby, collectively, with the two articles, to provide the reader with a relatively exhaustive summary of all research done in this area. In this article, we address the topics of human performance, aircraft design, and health and physiological factors affecting pilot performance, and their relation to scanning and aviation, specifically research that was not covered by Ziv (2016). The databases PsycINFO and Web of Science were searched using the terms (eye mov* OR eye track*) and (aviat* OR pilots; PsycINFO: 500 results; Web of Science: 698 results). Papers in the field of air traffic control and papers dealing with eye movements and alcohol or drugs were excluded. Additional literature could be found by using the reference lists of the identified papers and by searching with the terms (eye mov* OR eye track*) AND (uav* OR unmanned aerial vehicle OR drone* OR remotely piloted aircraft*). Eye-tracking studies that were not conducted on pilots but published in an aviation journal such as *The International Journal of Aviation Psychology* or *Aviation, Space and Environmental Medicine* were included in the review. The papers were published between 1976 and 2017. Altogether 79 papers were identified and included in the review.

The recently published review by Ziv (2016) covered 50 papers. The two reviews are intended to be complementary and are overlapping in only 14 papers because the authors felt those papers contributed directly to the themes of the current review. 65 papers of the present review are not mentioned in Ziv's review, whereas Ziv included 36 papers not mentioned in the present review. An overview of the applied classification is shown in Table 1. Papers also included in Ziv's review are italicized. In particular, this review contains sections on workload, the comparison of experts versus novices, fatigue, motion sickness and hypoxia, spatial disorientation, and the use of eye tracking in unmanned aerial vehicle (UAV) operators, topics that were not highlighted in Ziv's review.

Results: Content of Reviewed Articles

Human Performance

General Characteristics of Eye Movements

In the 1970s and 1980s, researchers were especially interested in visual search behavior and general characteristics of eye movements (Baloh & Honrubia, 1976; for a review on visual scan patterns see Ziv, 2016). Barnes, Benson, and Prior (1978) examined, for example, the degree to which inappropriate vestibular reflex eye movements could be suppressed by visual means. They demonstrated that the mechanisms responsible for suppression of vestibular reflex eye movements and pursuit eye movements were very similar. Enderle (1988) investigated saccadic eye-movement system (SEM) performance in Air National Guard pilots to determine whether motor and neurosensory function could be improved by training. His findings suggest that a time-optimal central nervous system control mechanism exists that cannot be improved by training. Saccadic eye movements and saccade latency in response to auditory and visual stimuli were investigated in several further studies (Engelken & Stevens, 1989; Engelken, Stevens, & Enderle, 1991). Furthermore, coordination of head, hand, and eye movements (e.g., to fixate targets) had been an earlier topic of eye-tracking research (Gauthier, Martin, & Stark, 1986; Mather & Lackner, 1980; Regan & Beverley, 1980; Vercher, Lolle, & Gauthier, 1993). Direct visually guided control of the hand can, for example, compensate for performance decrements caused by hand vibration in the cockpit (Martin, Roll, & Di Renzo, 1991).

Table 1. Overview of papers included in the review.

Paper	Human Performance					Aircraft Design		Health & Physiological Factors Affecting Performance			
	General Characteristics of Eye Movements	SA	Workload	Cognitive Processes	Experts vs. Novices	Aviation Displays	Remotely Piloted Aircraft	Fatigue/ Stress/Sleep	Motion Sickness	Hypoxia	Spatial Disorientation
Allsop & Gray, 2014								X			
Baloh & Honrubia, 1976	X										
Barnes et al., 1978	X										
Bellenkes et al., 1997					X						
Beringer & Ball, 2001						X					
Bos et al., 2002					X				X		
Causse et al., 2011				X							
Charbonneau et al., 2010						X					
Cheung & Hofer, 2003											X
Cheung et al., 2004											X
Dahlstrom et al., 2007											X
Dahlstrom & Nahlinder, 2009			X								
DeMaio et al., 1978					X						
Di Stasi et al., 2014										X	
Di Stasi et al., 2016								X			
Diaz-Piedra et al., 2016								X			
Diels et al., 2007								X			
Doane & Sohn, 2000				X							
Duley, 2001						X					
Enderle, 1988	X										
Engelken & Stevens, 1989	X										
Engelken et al., 1991	X										
Gauthier et al., 1986	X										
Hankins & Wilson, 1998			X								
Heaton et al., 2014								X			

(*Continued*)

Table 1. (Continued).

Paper	Human Performance					Aircraft Design		Health & Physiological Factors Affecting Performance			
	General Characteristics of Eye Movements	SA	Workload	Cognitive Processes	Experts vs. Novices	Aviation Displays	Remotely Piloted Aircraft	Fatigue/ Stress/Sleep	Motion Sickness	Hypoxia	Spatial Disorientation
Helleberg & Wickens, 2003						X					
Hoepf et al., 2015							X				
Hu & Stern, 1998									X		
Hughes & Creed, 1994						X					
Itoh et al., 1990			X			X					
Kilingaru et al., 2013		X			X						
Kim et al., 2010					X						
Kirby et al., 2014					X						
Kooi, 2011						X					
Kotulak & Morse, 1994						X					
Kotulak & Morse, 1995						X					
Kowalczuk et al., 2016										X	
LeDuc et al., 2005								X			
Lefrancois et al., 2016	X										
Li et al., 2016	X			X							
Malcolm, 1984						X					
Martin et al., 1991	X										
Mather & Lackner, 1980	X										
McIntire et al., 2013							X				
McKinley et al., 2011							X	X			
Morris, 1985								X			
Morris & Miller, 1996								X			
Muehlethaler & Knecht, 2016		X									
Muthard & Wickens, 2006						X					
Ottati et al., 1999					X						
Pialoux et al., 1976					X						

(*Continued*)

Table 1. (Continued).

Paper	Human Performance					Aircraft Design		Health & Physiological Factors Affecting Performance			
	General Characteristics of Eye Movements	SA	Workload	Cognitive Processes	Experts vs. Novices	Aviation Displays	Remotely Piloted Aircraft	Fatigue/ Stress/Sleep	Motion Sickness	Hypoxia	Spatial Disorientation
Previc et al., 2009								X			
Regan & Beverley, 1980	X										
Robinski & Stein, 2013					X						
Rowland et al., 2005								X			
Schriver et al., 2008				X	X						
Sirevaag et al., 1999	X										
Stepanek et al., 2014										X	
Stern et al., 1990									X		
Sullivan et al., 2011					X						
Szczechura et al., 1998			X								
Tichon et al., 2014								X			
Tole et al., 1982			X								
Tvaryanas, 2004							X				
Van De Merwe et al., 2012		X									
Vercher et al., 1993	X										
Vine et al., 2015								X			
Webb & Griffin, 2002									X		
Wickens & Alexander, 2009	X					X					
Wickens et al., 2003	X					X					
Wickens et al., 2007	X	X									
Wickens, 2015		X	X								
Wright & McGown, 2001								X			
Wright et al., 2005								X			
Wu et al., 2015								X			
Yang et al., 2013					X						
Yu et al., 2014	X	X	X								
Yu et al., 2016	X				X						
Ziv, 2016	X		X		X	X					

Note. General characteristics of eye movements = research on basic scanning behavior, on basic attentional models and on general characteristics of eye movements; SA = situation awareness. Papers included in Ziv's (2016) review are shown in italics.

Performance Decrements and Situational Awareness

The most common use of eye tracking in the field of aviation is still in the context of performance. Several researchers have attempted to find explanations for performance decrements by means of eye-tracking measures. For instance, Sirevaag et al. (1999) studied performance of helicopter pilots in a high-fidelity simulator along with indices of oculomotor activity during low-level flight. This study was part of a larger project with the goal of developing an oculomotor-based system capable of real-time attention monitoring especially in aviation operational situations. The study revealed that time on task, across the 50-min simulation, resulted in longer blink duration and fewer and later reactive saccades, and this was coupled with increased performance variability, even as overall performance did not decline. Overall, Sirevaag et al. (1999) found several relationships between performance and other nonvisual psychophysiological metrics.

Performance decrements and pilot errors sometimes occur because of a lack of situation awareness (SA; Kilingaru, Tweedale, Thatcher, & Jain, 2013). SA is frequently defined as "the perception of elements in the environment within a volume of time and space [Level 1], the comprehension of their meaning [Level 2] and the projection of their status in the near future [Level 3]" (Endsley, 1988). Inasmuch as the first stage of SA depends on perception and because the majority of information in a cockpit is presented visually, one method to measure situational awareness in a cockpit is by examining eye movements. For this reason it seems plausible to assess a pilot's SA by observing eye movements (Kilingaru et al., 2013; Van De Merwe, Van Dijk, & Zon, 2012). Wickens et al. (2007) assessed Stage 1 of SA directly via the allocation of visual attention. The authors' attention-situational-awareness model using SEEV (salience, effort, expectancy, value; see Wickens, 2015) was based on the notion that eye movements can be a direct indicator of attention among pilots and that at least Stage 1 of SA can be assessed via eye tracking. Van De Merwe et al. (2012) measured SA by studying the pilots' search patterns (fixation rates on the display, dwell time on the display, and scanning entropy) in relation to information acquisition. The authors stated that this was done to assess Stage 1 as well as Stage 3 SA via eye tracking. Specifically, pilots had to deal with a fuel leak that was expected to hamper SA. Pilots with high SA as assessed by their scanning measure (e.g., high fixation rate on the electronic centralized aircraft monitoring display) found the source of the malfunction earlier, showing more structured and predictable cockpit scanning. Yu, Wang, Li, and Braithwaite (2014) suggested integrating eye-tracking devices into simulators for promoting SA training. They found pilots with better SA performance in the simulator showing lower perceived workload. Muehlethaler and Knecht (2016) developed a SA training design for General Aviation pilots using eye measurements.

Wickens and McCarley (2008) developed an attention–situation awareness (A–SA) model that predicted the level of pilot SA from the optimality of the pilot's scan path as prescribed by the SEEV model of visual scanning (see earlier). A second component of the model was related to the decay of SA of a displayed variable, during the unattended interval following the most recent visual scan of that display. They found that the A–SA model could predict differences in traffic awareness of General Aviation pilots.

Workload

Of course, pilot errors and performance decrements can result from causes beyond a loss of SA. Lefrancois, Matton, Gourinat, Peysakhovich, and Causse (2016) named *automation addiction* due to pressure and fatigue as a factor leading to errors in monitoring flight instruments. They examined 20 pilots who were instructed to land an Airbus A320 manually in a flight simulator. A quarter of the pilots were unable to stabilize the aircraft and made the decision to go around. The authors concluded that gaze patterns for these pilots were suboptimal in comparison to those of the pilots who stabilized and landed the aircraft most precisely. For example, they did not sufficiently scan primary flight instruments to fly the approach. The authors assumed that these pilots were not sufficiently trained to fly manual approaches. In a closely related experiment, Dehais, Behrend, Peysakhovich, Causse, and Wickens (2017) compared pilot groups who inappropriately flew on during an ill-advised approach and those who appropriately decided to go around. They observed differences in visual allocation of attention between the two groups, as well as differences between the pilot flying and the copilot navigating. The latter differences were quantified and reflected both in where the two types looked inside and outside the cockpit, and also in the qualitative style of eye movements.

Some researchers have attempted to use eye movements for an assessment of mental workload during different tasks or for assessing workload influence on flight performance (e.g., Dahlstrom & Nahlinder, 2009; Hankins & Wilson, 1998; Li, Yu, Braithwaite, & Greaves, 2016; Szczechura, Terelak, Kobos, & Pinkowski, 1998). In addition, the visual scanning of flight instruments was found to vary as a function of the level of difficulty of a task (Tole, Stevens, Harris, & Ephrath, 1982), in a way that indicated that the average dwell time of each fixation on the instrument panel increased as a function of the load and increased as a function of the estimated skill level of a pilot. The authors concluded that visual scanning of instruments might be an indicator for both skill and workload (besides showing a difference between experts and novices, with novices being affected by high workload much more than experts).

Cognitive Processes

In addition to measuring workload and attentional processes, eye tracking is used for representing cognitive processes involved in decision making or action planning. As an example, Doane and Sohn (2000) presented a predictive cognitive model called ADAPT that models performance in a changing flight environment and predicts pilots' visual attention. Another result in the context of decision making is that fixation times are longer for situations with high uncertainty than for situations with low uncertainty and low risk (fixating on a simplified instrument-landing-system instrument during landing; Causse, Baracat, Pastor, & Dehais, 2011).

Experts and Novices

Performance-related studies often include pilots with varied flying experience, and thus examine how scanning changes with expertise, where this can be operationally defined by the total flight hours, flying qualifications, and the proficiency level of the pilot (Wickens & Dehais, 2018). More experienced pilots seem to make better decisions in terms of speed and accuracy, allocate more attention to relevant cues when failures are present (measured by percentage dwell time on areas of interest), and show better performance in motion anticipation (Schriver, Morrow, Wickens, & Talleur, 2008). Additionally, the amount of attention to cues seems to be associated with decision accuracy (Schriver et al., 2008). Expert pilots adapt their attentional strategies by more flexibly responding to changing demands (Bellenkes, Wickens, & Kramer, 1997). In comparison with novice pilots, they better maintain a constant altitude with a helicopter and differ generally in visual instrument scan patterns or in eye movements in response to motion (Bos, Bles, & De Graaf, 2002; DeMaio, Parkinson, & Crosby, 1978; Kirby, Kennedy, & Yang, 2014; Pialoux et al., 1976; Sullivan, Day, & Kennedy, 2011). For example, experienced helicopter pilots and novice pilots differ in the frequency of scanning out of the window (Sullivan et al., 2011; Yang, Kennedy, Sullivan, & Fricker, 2013; Yu, Wang, Li, Braithwaite, & Greaves, 2016). Whether experts or novices show more or less out-the-window (OTW) gazes is not generally agreed and depends on factors such as mission demands. Independently, it can be expected that scans by experts are more targeted than scans by novices. Robinski and Stein (2013) investigated experienced and inexperienced military helicopter pilots and proposed eye tracking as a feedback tool for pilots during training as the pilots were not always aware of their actual scanning techniques. Along similar lines, studies by Kim, Palmisano, Ash, and Allison (2010) and Ottati, Hickox, and Richter (1999) also revealed that experienced pilots develop unique eye-scanning strategies for better performance. Fox, Merwin, Marsh, McConkie, and Kramer (1996) observed that expert pilots used qualitatively different scanning patterns than novices and had better mental models of their aircraft.

Several models of visual attention have been proposed. Senders (1964), for example, developed the first quantitative model of human monitoring and controlling behavior in the tradition of queuing theory and supervisory control. Carbonell, Ward, and Senders (1968) validated this theoretical model in the field, specifically during approach and landing in a flight simulator. Based on this early research of Senders (1964) and, in the cockpit, of Carbonell et al. (1968), it has been argued that optimal models of information seeking and scanning can be used to set a "gold standard" for optimal scanning, and therefore maintaining optimal SA. Wickens, Goh, Helleberg, Horrey, and Talleur (2003) developed such a model—the SEEV model—based on the idea that optimal scanning is driven by the bandwidth (or expectancy) of flight-deck information to the extent that such information is valuable; and resisting unwanted influences of effort (scanning long distances) and salience, unless these commodities are positively correlated with expectancy and value. As noted earlier, they found that pilots who better adhered to these prescriptions were superior in maintaining traffic awareness (Wickens & McCarley, 2008).

In summary, eye-movement measures have proven to be valuable for detecting certain performance decrements, assessing high-workload conditions and SA, and discriminating between more-experienced and less-experienced pilots. Depending on author and theory, at least Stage 1 of SA can be assessed via eye tracking. Pilots with high SA have shown, for instance, high fixation rates on the electronic centralized aircraft monitoring display when searching for a special malfunction together with a structured scanning behaviour (Van De Merwe et al., 2012). Structured cockpit scanning and more attention to relevant cues when failures are present (e.g., the percentage dwell time on areas of interest) can be an indicator of expertise and good performance. The average dwell time of fixations on the instrument panel can be an indicator of workload, whereas the parameter of fixation time can be useful to estimate uncertainty and risk of a situation. Different models of visual attention and scanning were proposed (e.g., modeling performance in a changing flight environment and predicting visual attention; e.g., ADAPT; Doane & Sohn, 2000) or predicting the level of pilot SA from the optimality of the pilot's scan path (A–SA; Wickens & McCarley, 2008). An important finding of the reviewed eye-tracking studies is that pilots were not always aware of their actual scanning techniques. The importance of appropriate visual scanning techniques to support flight performance, decision making, and SA suggests that eye-tracking devices integrated into flight simulators could be useful for training to promote SA and efficient and effective scanning behavior.

Aircraft Design

Aviation Displays

A wide variety of eye-tracking studies address the topic of aviation displays. These include examining eye movements in peripheral vision displays (Malcolm, 1984), cathode-ray-tube (CRT) displays (Itoh, Hayashi, Tsukui, & Saito, 1990), color-coded avionic displays (Hughes & Creed, 1994), aviator helmet-mounted displays (e.g., for night vision; Charbonneau, Leger, & Claverie, 2010; Kotulak & Morse, 1994, 1995), cockpit displays of traffic and weather information (CDTI; Duley, 2001; Muthard & Wickens, 2006), synthetic vision displays (Thomas & Wickens, 2004; Wickens & Alexander, 2009; Wickens & McCarley, 2008), highway-in-the-sky head-up displays (Beringer & Ball, 2001), or dual-layer displays (two depth layers, physically separated; Kooi, 2011). In such studies, measuring eye movements can help one to understand performance (e.g., in terms of task management) and contributes both to understanding pilots' scanning behaviors, and generating guidance for better display design.

Details on attentional mechanisms regarding different displays are offered in the recently published literature review by Ziv (2016). The results of the review showed that various onboard technologies such as synthetic-vision displays could divert pilots' attention from outside the cockpit to the instrument panel. Hazards outside of the cockpit could be missed. Nethertheless visual presentation of information (in comparison to auditory or redundant representation) seems to be most beneficial as it is least interruptive of other tasks such as traffic montitoring (e.g., Helleberg & Wickens, 2003; Wickens et al., 2003).

Unmanned Aerial Vehicle

Only four published papers have addressed eye movements on a UAV flight display. Tvaryanas (2004) wanted to find out how pilots extracted information from an RQ1-Predator display, which he referred to as not being constructed according to basic human factors principles. On the display, airspeed, altitude, angle of attack, and vertical speed are given in text boxes moving linearly up and down the screen. Tvaryanas found dwell frequencies for the primary flight instruments to be different from those reported for more traditional aircraft (with a pilot onboard and traditional arrangement of instrumentation). The moving text boxes called for visual fixations that were typical of quantitative instruments (long dwells), which the author described as a cognitively inefficient way to present information.

Hoepf, Middendorf, Epling, and Galster (2015) reported that eye-movement data provide cues that the UAV pilot is facing increased workload. Blink duration, blink rate, and pupil diameter evidenced sensitivity to changes of workload. High-workload conditions reflected in low blink rate, shorter blink duration, and larger pupil diameter than values obrtained in low-workload conditions. The authors suggested implementing automated systems to monitor changes in physiological data (e.g., eye movements and heart rate variability), with the potential to detect impending performance decrements resulting from elevated workloads.

McKinley, McIntire, Schmidt, Repperger, and Caldwell (2011) used the metric of total eye closure duration to examine the presence of fatigue. They detected no fatigue effects in simulated UAV tasks following sleep deprivation, whereas they did find fatigue effects for other more traditional flight simulator tasks, namely a target aquisition task and a psychomotor vigilance test. The authors explained this result with an "optimal arousal" for the UAV task that was more difficult and complex in relation to the other tasks. The optimal arousal then resulted in better performance for this one task despite the sleep deprivation (see discussion of fatigue for this study as well).

The results of a study by McIntire, McKinley, McIntire, Goodyear, and Nelson (2013) indicated that eye tracking can be used to detect changes in vigilance for UAV pilots. Poor attention to a vigilance task (Cyber Defense Task) could be seen in an increase in blink rate, longer blink durations, and a longer eye closure time. It is interesting that work has not apparently been done or published that systematically compares scanning strategies between UAVs and manned aircraft, flying comparable manuevers with similar flight dynamics.

As can be seen in this section, displays for unmanned aircraft are not always designed according to basic human factors principles to present information such that it is easily recognized and interpreted. With synthetic-vision displays, for instance, pilots' attention could be diverted too much from outside the cockpit to inside the cockpit. The moving text boxes of the RQ1-Predator (airspeed, altitude, angle of attack, vertical speed) might result in longer dwells compared to a more traditional instrument panel arrangement. The visual behavior measurements of dwells, blink duration, blink rate, pupil diameter, and eye closure time have proven to be useful in UAV studies (e.g., showing changes in workload).

Health and Physiological Factors Affecting Performance

Fatigue, Sleep, and Stress

Fatigue places pilots at elevated risk for impaired performance, errors, and accidents. Therefore, a research goal is to detect fatigue or fatigue-related performance decrements early to prevent errors and injury as well as to ensure optimal piloting. The measurement of eye movements has proven to be a valuable method to achieve this goal (e.g., Heaton, Maule, Maruta, Krystow, & Ghajar, 2014; McKinley et al., 2011; Morris, 1985).

Researchers have investigated fatigue by depriving individuals of sleep and then trying to find metrics to detect fatigue. Previc et al. (2009) reported a peak in flying errors after about 24 to 28 hr of wakefulness together with peaks in subjective fatigue. Instrument scanning was largely unaffected by sleep deprivation. Heaton et al. (2014) observed that attention in terms of reaction time and gaze position (visual tracking) is impaired after acute sleep deprivation (26 hr). The authors provided an approach for detecting fatigue and assessing readiness in flight personnel (including ground-support crews).

Rowland et al. (2005) and LeDuc, Greig, and Dumond (2005) found that *saccadic velocity* was sensitive to (declined with) total sleep deprivation. Di Stasi et al. (2016) obtained similar results by finding the metric saccadic velocity decreased after long simulated flights in comparison to short simulated flights. The authors suggested saccadic velocity as a biomarker for aviator fatigue as did Diaz-Piedra et al. (2016) for warfighter fatigue. McKinley et al. (2011) evaluated two kinds of eye metrics—namely *total eye closure duration* and *approximate entropy*—to detect fatigue in tasks relevant to military aviation after sleep deprivation (14–28 hr). McKinley et al. found the metric of appropriate entropy (ApEn) correlates with performance decrements and suggested using this metric as a detector of fatigue in both manned and unmanned military aviation tasks. Their results regarding eye-closure duration were ambigious, as these generally increased with the level of sleep deprivation but not consistently over all sessions (as described earlier). Morris and Miller (1996) found that the eye metrics *long closure rate* (LCR) and *blink amplitude* (BL) were the best predictors of a fatigue-induced increase in errors in straight-and-level flying tasks.

Scanning measures can also be coupled with other measures to measure pilot fatigue passively. Wright and McGown (2001) suggested using measurements of eye movements, wrist activity or head movements as the basis of an alarm system to prevent involuntary sleep. Efforts to realize this kind of alarm system were made by Wright, Powell, McGown, Broadbent, and Loft (2005) in a study in which 21 Air New Zealand pilots wore a wrist alertness device. During a flight between Auckland and Perth the presence of sleepiness and sleep was determined using EEG and eye movements. The alertness device could awaken pilots effectively during flight and was rated acceptable to use by the aircrew. Wu, Wanyan, and Zhuang (2015) provided a mathematical model connecting pilots' visual attention allocation and flight fatigue.

In addition to sleep and fatigue, stress is another factor that can degrade flight performance. Only a few eye-tracking studies have addressed this topic (Tichon, Mavin, Wallis, Visser, & Riek, 2014; Vine et al., 2015). Nevertheless, results are interesting, as eye movements seem to react very consistently to stressors such as an engine failure on take-off or can show negative emotions such as anxiety. For example, under anxiety, attentional control is negatively affected as reflected by an increase in the percentage of dwell time toward the outside world (Allsop & Gray, 2014). More details on studies concerning anxiety and stress are reviewed by Ziv (2016).

Motion Sickness

Eye movements are generally related to motion sickness (MS). Visually induced MS is, for example, lowered during fixation (Webb & Griffin, 2002). Furthermore, it has been proposed that nystagmus might be responsible for MS. *Nystagmus* can be defined as a series of involuntary eye movements generated by the stimulation of the vestibular system (Newman, 2004). The results indicate that more rapid eye movement (higher frequency of nystagmus) is linked to the development of symptoms of MS (Hu & Stern, 1998). Bos et al. (2002) compared aircrew members highly susceptible to MS to aircrew members less susceptible to MS. Those highly susceptible to MS showed a slower decay of nystagmus following cessation of motion than less susceptible subjects.

Visual fixation (to suppress eye movements) under certain conditions can reduce nystagmus (Stern, Hu, Anderson, Leibowitz, & Koch, 1990) and MS (Webb & Griffin, 2002). However, the effectiveness of such fixation depends on the part of the display that the pilot is fixating. Thus Diels, Ukai, and Howarth (2007) investigated MS with radial displays and found that MS was worse when subjects were asked to focus at targets beyond the focus of expansion compared to being asked to fixate at the focus of expansion (or being free to move one' s eyes).

Hypoxia

Studies addressing the topic of flight hypoxia in combination with eye tracking are scarce. Early recognition of the onset of hypoxia symptoms is essential for pilots, as the time for efficient rescue can be very short when technical systems delivering oxygen in an aircraft fail (Kowoll, Welsch, Joscht, & Gunga, 2006). Di Stasi et al. (2014) found the eye metric intersaccadic drift velocity increased in pilots experiencing hypoxia. Stepanek et al. (2014) reported increased blink rates and increased total saccadic times under hypoxic conditions. However, Kowalczuk et al. (2016) found that short-term hypoxia is not reflected in saccadic movements.

Spatial Disorientation

Eye tracking has been recorded during spatial disorientation (e.g., Cheung, Hofer, Heskin, & Smith, 2004; Dahlstrom, Nahlinder, Wilson, & Svensson, 2007). The goal of recording psychophysiological data during disorientation was to provide a model of pilot state and as a consequence be able to understand performance and cognitive demands during flight. One result of such studies is that pitch illusion—a false sensation of pitch resulting from acceleration—affects visual scanning behavior (Cheung et al., 2004). Another interesting result is that pupil diameter significantly decreases during acceleration (Cheung & Hofer, 2003).

To summarize this section, it can be said that fatigue, stress, and hypoxia all notably affect eye movements. Several metrics can be seen as clear indicators of fatigue: visual tracking, saccadic velocity, and approximate entropy. Total eye-closure duration is responsive to fatigue in tasks with manned aircraft but not in tasks with unmanned aircraft. Long closure rate and blink amplitude predict fatigue-induced increases in errors in straight-and-level flight tasks. Anxiety is reflected in an increase in the percentage of dwell time on the outside world. MS can be reduced by visual fixation on special points on a display. Under hypoxic conditions blink rates, total saccadic times, and intersaccadic drift velocity increase. The metric of pupil diameter is mentioned in the context of spatial disorientation: Under acceleration pupil diameter decreases.

Discussion, Conclusions, and Future Directions

The present review of 79 studies has highlighted and partially integrated the extensive research that has been conducted to understand how the pilot's invaluable resource, the eyes, and by extension visual attention, contribute to the understanding of cognitive behavior as well as the pilot's underlying psychological and physiological state.

We wish to emphasize that our review should be considered complementary to that of Ziv (2016), overlapping in coverage of a few studies so that the reader can gain a relatively complete picture of the areas highlighted here without having to access that review; but more important, gain a near complete understanding of the extant research on eye movement in pilot behavior and physiology by referencing both reviews.

We believe that both reviews taken together provide a foundation from which many important research questions can be asked and answered by future experiments, particularly with the increasingly agile techniques that newer, lighter, and less intrusive recording techniques can avail, when coupled with more powerful analysis tools.

In particular, we advocate research to attain a better understanding of the capabilities of oculomotor measures, coupled with other behavioral and physiological measures, to make online, real-time inferences of the pilot's degree of engagement in the flight task. In a complementary fashion, a great deal more might be understood regarding the pilot's possible complacency in monitoring automation.

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