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Supplementary material

Use of night vision goggles for aerial forest fire detection

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Controlled conditions

Flights and observers

For each flight, detection and classification of fires was performed by a single observer. Over the course of 3 nights of detection testing, 12 observation sorties were flown (five, five, and two sorties on the evening–morning of each of 23–24, 24–25 and 25–26 April). Six observers participated in two detection sorties across different nights with different target fire configuration and locations for a total of 12 sorties. An additional three sorties were flown on 22–23 April to determine suitable ground speed and altitudes for effective detection over the terrain. All observers were trained in fire detection techniques but had no previous experience in fire spotting. Training consisted of the standard fire detection observer training course run by the OMNR, simulations of fire detection scenarios, and instruction on the set-up and use of NVGs.

The flight crew consisted of five or six people: two pilots, an audio/video technician, an experimenter, and the observer (on some flights an additional experimenter tested a tablet based fire logging system but this did not interfere with the main experiment). The *pilots* were the only members of the flight crew aware of the test grid location. However, they were not aware of fire locations and profiles and did not provide any information to the observer. Only the *observers* were responsible for detecting fires and recording them. No other crew member was allowed to assist the observer during a detection flight. The *experimenter* kept a paper log as a backup and marked detection, discrimination and confirmation waypoints and the time of detection. An *audio/video technician* continually recorded audio and video during flights.

Observers filled out a brief questionnaire to indicate the number of hours they had slept and their current level of fatigue. Sorties typically began at 2130 hours each night and continued until ~0200 hours.

After each flight the observer was required to fill out a debriefing questionnaire covering the ability to cover the search area, search strategy, visual performance, spatial orientation, NVG side effects, situational awareness and other factors (see below for details and results pertaining to the debriefing questionnaire).

Apparatus

All flights took place in an EC130 helicopter. A handheld Garmin GPS 96C was used to mark the aircraft location in real time. This unit reported aircraft position every 15 s. The specified accuracy of the Wide Area Augmentation System was less than three meters 95% of the time. In addition, automated flight following data from the aircraft was also obtained. This system reported the aircraft's position every 60 s over a radio link.

Generation III ANVIS 4949 binocular night vision goggles were used. A Canon FS200 recorded video. Audio from the cockpit was fed directly into the camera. The observer entered data on a tablet computer (Toshiba Portege M750, Toshiba Corp., Tokyo, Japan). A custom IR absorbing filter (Korry Nightshield NSX, Esterline Technologies Corporation, Bellevue, WA) was placed over the tablet display to prevent interference with the NVGs.

Plot profiles

The test grid consisted of 109 surveyed locations for precisely located test fires. Based on universal transverse mercator (UTM) coordinate system, the grid was 100 ha with each plot point spaced on 100 by 100-m grid intervals. Canopy density and type of tree coverage varied with each plot and included dense coniferous, dense or semi-dense mixed, and dense or semi-dense deciduous stands. Although it was still springtime, the canopy for the deciduous stands was beginning to fill in, likely due to the mild weather. Elevation of the plots varied between 215 m and 295 m above mean sea level (ASL).

Target fires

On each of the four nights, one to six small test fires were lit at locations within the grid. A total of six simulated fires were lit on 22–23 April (i.e. starting on the night of 22 April and continuing into the morning of 23 April), four fires on each of 23–24 and 24–25 April, and one fire on 25–26 April. Fuels for the test fires were placed in aluminium 30 × 40-cm, fire-proof containers. In many instances, multiple sources were combined in a single plot to simulate a larger fire. Fuel sources were charcoal briquettes (Royal Oak brand, 6.3 × 6.3 × 3.8-cm briquettes; ~60 briquettes lit with starter fluid), artificial fireplace logs (Ecolog Citronella Logs, 30 × 10 × 10 cm, 0.9 kg) and alcohol gel torches (385-mL can).

Fires were monitored visually and through temperature readings made with thermocouples and a data logger. Log fires tended to rise rapidly in temperature shortly after being lit, then gradually decline in temperature throughout the evening; they tended to smoulder much longer than other fires, lasting into the late morning. Charcoal briquette fires typically burned hottest after lighting, presumably due to the open flame and effects of the starter, before entering a phase of approximately exponential decay in temperature. The temperature of torch fires typically increased rapidly then burned uniformly (with spiking and oscillatory fluctuations likely due to wind gusts and variations) before decreasing rapidly. As a result, the torch fires were a well-controlled target until they began to extinguish. The rapid extinction essentially makes these sources both present and stable (on the scale of minutes although flickering on a shorter time scale), or essentially 'out'. However, they were very small and gave off little light, making them the most difficult target to spot.

Ground crews monitored the fires throughout the night; in some instances refuelling was required.

Detection procedure

Each night, a detection route was planned that brought the aircraft near the test grid. In flight, the observer scanned their visible area for potential fires. The observers were the only members of the flight crew responsible for detecting fires. Observers were always seated in the front right seat of the aircraft. This means they were unable to see the areas behind and to the rear-left of their position.

Once the observer spotted a target of interest they notified the pilots and experimenter. The experimenter provided the observer with a waypoint and time, which marked the aircraft's location for target detection. The pilots then deviated from the flight path towards the target. Upon closer inspection the observer either confirmed or rejected the target as a fire. Once again, a waypoint and time was recorded to mark the aircraft location for target discrimination. If the target was confirmed as a fire, its characteristics, such as intensity, size and fuel source were recorded. A final waypoint and time was recorded as the aircraft passed or hovered over the fire to mark the approximate fire location. Once all the required data were recorded the aircraft returned to the original planned flight path. If a target was identified as a bright light but not a fire, the observer attempted to categorise the target

Conditions

During data collection there was a first quarter moon, which provided ample ambient light for NVG use. All observers reported NVG visibility as good and atmospheric conditions were favourable. Unless otherwise stated, calm winds and clear skies prevailed with a visibility of 14 km (9 miles) and wind speeds between 0 and 19 km h^{-1} (0 and 10 knots), gusting to 39 km h^{-1} (21 knots) on one night.

Aerial detection patrols

Materials and methods were generally similar to the controlled experiment with the modifications for operational flights as described below.

Detection patrols

The OMNR continually monitored real-time weather information, forest fuel indices, historical trends and other indices. The flight trials were conducted when the weather and fuel indices were conducive to lightning strike fires. Each night the Aircraft Management Officer planned two detection routes that brought the aircraft over an area that had recently been subject to a large number of lightning strikes. Detection patrols typically flew at an altitude between 914 m (3000 feet) and 1219 m (4000 feet) AGL and at a speed between 111 km h^{-1} (60 knots) and 167 km h^{-1} (90 knots).

Flights typically began at 2230 hours each night and continued until ~0400 hours the following morning. Across groups of flights the moon phase varied from full to no moon. Total flight time was ~27 h and 56 min. A summary of the conditions for the flights is provided in Table S2.

Materials

Materials and apparatus were as previously described for the controlled experiment with the following exceptions: (1) detection activities involved real fires so the controlled sources and dataloggers were not required, (2) most flights took place in an EC130 helicopter; however during one sortie it was necessary to fly in an AS350 and (3) IR still images were taken using a FLIR ThermaCAM P25.

All crew wore Generation III, ANVIS 4949 binocular NVGs.

Flight crew roles

Flight crew complement and roles were similar to the controlled experiment described above; however, all crew members were responsible for detecting fires. The pilots had NVG certification and extensive detection experience. Occasionally it was necessary to fly without an audio–video technician and during three flights there was one pilot instead of two.

In flight, the scanning, detection, discrimination and classification of fires followed the same procedure as the controlled fire trials; however, all crew members now contributed to these tasks and conferred on the decisions. As in the earlier study, GPS waypoint and time were used to mark the aircraft location for target detection, target discrimination as a fire or not and approximate fire location.

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Determining ground truth

Unlike the controlled experiment where target fires were known, observers on these flights were looking for real fires in an uncontrolled environment. We were principally interested in (a) hits or the number of fires present along the route that were actually detected, (b) misses or actual fires along the route that were not found and (c) false alarms or reports of fires that did not correspond to actual fires. The difficulty in assessing these numbers is in knowing the 'ground truth'. To estimate hits and false alarms, all fires reported were followed up either by matching to the database of current fires or by visual verification on the ground. Misses were estimated from analysis of fire reports and status for the day of the flight and subsequent days as logged in the OMNR's database. This is likely to overestimate miss rates as fires take time to develop and conversely are sometimes essentially extinguished before being officially declared out. Miss rates were calculated given assumed visibility relative to the flight path with separate estimates of the rates for the reported visibility on the relevant night, a range of ±10 km and a range of ±20 km. The true number of fires in a given range was determined by measuring the distance of active (at the time of the flight) fires from the flight path and tallying fires within the specified visibility range. The hit and miss rates were calculated by dividing the number of forest fires spotted or missed by the total number of forest fires within the range of visibility.

It is important to note that the crew were not informed of the existence or location of existing fires and thus detected fires were truly (new) hits for the detection patrol. Similarly, if known active fires within range of the aircraft were not detected, they were recorded as a miss.

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Table S1. Type of distraction for correct rejections and percentage of events that were fires during the 2010 trials over the test grid

	Type of distraction			Classification of events		
	Structure	Vehicle	Unknown	Fire	Other	Fire percentage
23–24 April	7	5	0	10	14	42%
24–25 April	10	2	1	14	14	50%
25–26 April	4	0	1	2	5	29%
Total	21	7	2	26	33	44%
Percentage	70%	23%	7%			

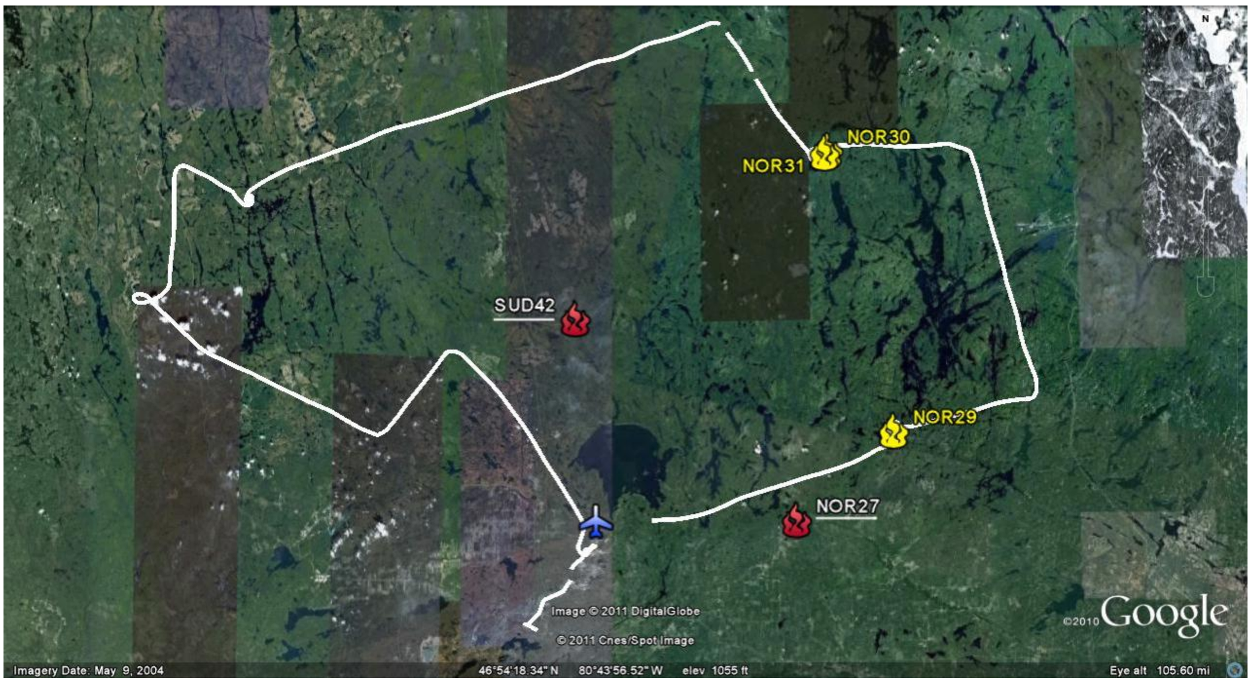

Fig. S1. Google Earth image of flight path and active fires on the evening of 27–28 May 2010. Note this shows actual flight paths rather than planned routes. For each patrol a detection flight path was planned through lightning corridors. Deviations from the planned route are due to targets being identified and subsequently investigated. Found forest fires (hits) are yellow and missed forest fires are red (with underlined labels). NOR30 was located just over 500 m from NOR31. Gaps in track resulted from GPS signal loss.

Table S2. Summary of flight conditions for the 2010 aerial detection patrols

Period (night–morning)	Visibility	Moon	Weather	Sorties	Fires found
27–28 May 28–29 May 29–30 May 30–31 May	24 km	Full	Broken clouds at 2438 m (8000 feet) to unlimited. Air temperature 14–20°C. Dew point 10–12°C. Wind speed 6–19 km h^{-1} (3–10 knots)	7	14
13–14 July 14–15 July	24 km	None, waxing crescent rising after the flights	No cloud. Air temperature 18–25°C. Dew point 11–14°C. Wind speed 6–11 km h^{-1} (3–6 knots).	4	3
7–8 August 8–9 August	24 km 16 km	Waning crescent that rose at 0200 hours and thus absent for two of the three sorties	Broken clouds at 6706 m (22 000 feet) Air temperature 16–19°C. Dew point 10–17°C. Wind speed 6–15 km h^{-1} (3–8 knots)	3	1

Table S3. Signal detection rates for the 2010 aerial detection patrols

Events are pooled across all nights at ±10-km and ±20-km visibility; CR, correct rejection; campfires not included. Miss counts at 20 km are inclusive of misses at 10 km

	Hits	CR	Hit (%)	Miss (%)	Number of misses
10-km visibility	20	35	62.5	37.5	12
20-km visibility	20	35	51	49	19

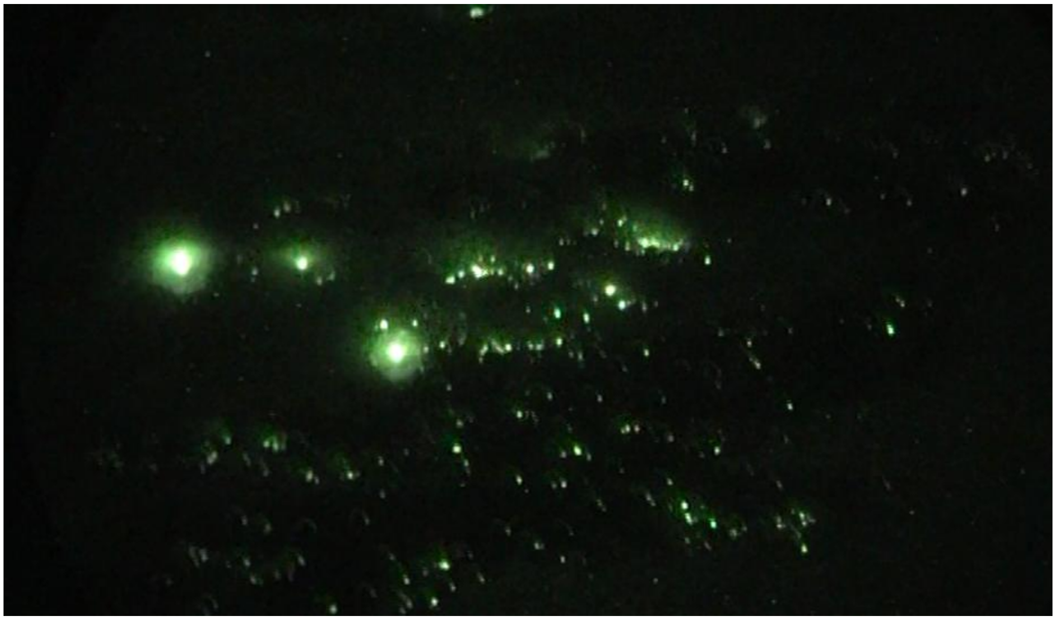

Fig. S2. NVG image of TIM13 on 28 May 2010.

Fig. S3. NVG image of vehicle travelling along a road. Note the beam of light.

Debriefing

After each flight the observer was required to fill out a debriefing questionnaire (see Fig. S4) that consisted of 32 questions covering ability to cover the search area, search strategy, visual performance, spatial orientation, NVG side effects, situational awareness and other factors.

Debrief findings following trials with controlled fires

In the debrief questionnaire, all observers rated their own ability to cover the search area as 'good'. In addition, they also reported using consistent scanning techniques; the most common technique used was horizontal scanning. Visual performance, spatial orientation and situational awareness were reported as being 'average' or 'good'. One observer reported feeling disorientated when looking up after writing on the tablet to enter the waypoints. It should be noted that several observers were novices to helicopter flying.

Observers were required to rate their confidence in detecting fires on a scale from 1 (not confident) to 5 (very confident). Most observers reported a confidence level of 4, one reported 3 and another 5. In addition, observers reported that both their skills and their confidence in detecting fires increased across sorties. Observers also reported alertness levels both before and after flights on a scale from 1 (not alert) to 5 (very alert). Pre- and post-flight alertness levels were exactly the same for all but one observer, who rated their alertness as 5 pre-flight and 4 post-flight. The most common symptoms experienced during flight were eye strain, headaches and sore necks. Most observers stated that they did not feel over-loaded during the flight. However, one observer reported that recording fire characteristics for four targets situated so close together was difficult. This type of scenario is unlikely to occur in a real operational context because forest fires would not be restricted to such a small geographical area. The most difficult task reported was sifting through the distractions to detect fires.

Both canopy density and altitude were reported as factors affecting task difficulty. A dense canopy made fires more difficult to detect and discriminate. As previously stated, a higher altitude made detection easier, but discrimination more difficult. Most reported that neither topography nor speed affected their performance. However, one observer stated that the hills were more likely to obscure targets at low altitudes. Terrain relief was modest in the vicinity of the trials.

No one reported any problems with internal aircraft lighting. The only reported problem with external lighting was from one observer who stated that the reflection of the moon on the water was distracting. Observers estimated scanning distance to be between 10 and 20 km; weather reports indicated that visibility was 9 miles or 14 km. Both fuel sources and fire intensity rank were visible to all observers; at lower altitude it was easier to determine fire characteristics.

Debrief findings following aerial detection patrols

On the debriefing questionnaire, all observers rated their own ability to cover the search area as 'good', except for one observer who reported focussing more on areas close to the aircraft and forward. They estimated that they covered ~80–90% of their search area. In addition, most observers reported using consistent scanning techniques: everyone reported using a mixture of horizontal and vertical scanning. Visual performance was generally reported as 'good', but goggle scintillation was noted as present during the July and August flights (on moonless nights). Ability to orient did not seem to be a significant problem and only one observer reported having some difficulty in orienting themselves spatially. Additionally, one observer stated that they had difficulty maintaining situational awareness and often lost track of fires when they were out of sight.

All observers stated that their skills and confidence at detecting fires increased both during and across flights. The exception to this was during the August flights on which both observers stated that they were less confident. This may have been because they found no fires. However, follow-up data show that there were no fires to find along their routes. Alertness levels pre- and post-flight were rated on a scale of 1 (not alert) to 5 (fully alert). Before the flight all observers reported an alertness level of 4 and all but one observer stated that they felt well rested. After the flight, most observers reported a slightly lower alertness level of 3, whereas one observer remained the same. The most common symptoms experienced were eye strain, headaches and sore necks.

Observers reported that a dense canopy made fires more difficult to detect and discriminate. Consistent with observer reports from the controlled experiments, higher altitudes allowed for more effective detection but lower altitudes were required for discriminating fires. In all cases fuel stands and open flame were reported as visible from the air.

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Name: Date:
Sortie number: Time:

1. How would you assess your ability to adequately cover the search area with the night vision goggles (NVGs)?

2. While flying with NVGs did you note any change in your search strategies (e.g. head and visual scanning, eye and head movement, visual workload, visual performance, ability to see or interpret the task information or external visual information) during any phase of night flight? If yes, please explain (e.g. description, duration, reason).

3. Did you scan using horizontal or vertical head movements? ☐ Horizontal ☐ Vertical ☐ Both
   a. Did you keep your scanning technique consistent? ☐ Yes ☐ No

4. How would you describe your visual performance?

5. How would you describe your spatial orientation?

6. How would you describe your situational awareness?

7. Discuss your ability to orient yourself and maintain a sense of situational awareness relating to areas you could not see with the NVGs.

8. How confident are you in your fire detection abilities? (not confident) 1 - 2 - 3 - 4 - 5 (very confident)

9. Did you find that your skills at detecting fires increased during the sortie? ☐ Yes ☐ No
   a. Did you find that your confidence at detecting fires increased during the sortie? ☐ Yes ☐ No

10. Did you find that your skills at detecting fires increased across sorties? ☐ Yes ☐ No
    a. Did you find that your confidence at detecting fires increased across sorties? ☐ Yes ☐ No

11. Discuss the effect of internal aircraft lighting on your ability to find and recognise fires.

12. Discuss the effect of external lighting on your ability to find and recognise fires.

13. Discuss your ability to discern fires from other heat/light sources.

14. Discuss your ability to discern fires from other clutter affected by type of forest (e.g. open canopy *v*. dense)?

15. Did the topography affect your ability to detect fires? ☐ Yes ☐ No
    If yes, please explain.

16. Did the altitude affect your ability to detect fires? ☐ Yes ☐ No
    If yes, please explain.

Fig. S4. Debriefing questionnaire.