



Physical exercise impacts the performance of explosives detection dogs

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Abstract: Dogs (*Canis familiaris*) are widely used as scent detectors due to their sensitive olfactory capabilities, endurance, and ability to cover large areas quickly. They are in high demand due to a global rise in terrorist threats using specialized explosive contraptions. Detection dogs are often faced with high temperatures and physical exertion, which can increase panting rate as a function of evaporative cooling, inhibiting olfactory ability. This study examined the impact of exercise on the search performance of 11 explosive detection dogs (eight labradors and three springer spaniels). They completed two trial sets: one after exercise with a ball thrower and one without exercise. They were timed while searching for three types of explosives: trinitrotoluene, composition-4, and ammonium nitrate. Data were analyzed in R using mixed effects models, revealing that exercise significantly affected search duration and success for all types of explosives. Searches averaged 29.58 seconds without exercise, while post-exercise searches took 44.91 seconds. Dogs were 1.14 times more likely to locate explosives without prior exercise. Dogs took the longest to find trinitrotoluene and were fastest with ammonium nitrate and composition-4. These findings highlight the importance of allowing detection dogs adequate rest, as even brief exercise can impact their search performance.

Key Words: *Canis familiaris*; detection dogs; exercise; explosives; olfactory system.

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Introduction

Dogs (*Canis familiaris*) are widely utilized explosive detectors due to their ability to quickly cover vast areas, their sensitivity to target odors, and their ability to generalize odors across contexts (Cablk et al., 2008; Hoffman et al., 2009). Detection dogs have been used in civilian and military settings to detect drugs (Jeziarski et al., 2014), bed bugs (Cannon et al., 2020), COVID-19 (Jendry et al., 2020), human remains (Martin et al., 2023), and most commonly explosives (Gazit & Terkel, 2003; Lazarowski & Dorman, 2014). The demand for explosive detection dogs has grown due to rising international terrorism threats and the increasing use of specialized explosive contraptions (Brady et al., 2018; Spinella et al., 2022). However, dogs must meet a demanding behavioral standard, including high endurance level and motivation, leading to many being declared unfit for deployment (Hayes et al., 2018; Lazarowski et al., 2020). This has resulted in a global shortage of detection dogs, with many countries relying on foreign procurement; for example, the USA imports between 80-90% of their detection dogs (Lazarowski et al., 2020; Leigh, 2022; U.S. Department of Defense, 2021).

Detection dogs are expected to work in challenging environments for relatively long periods (Gazit & Terkel, 2003). In hot conditions, such as the Southern USA borders or Middle Eastern war zones, dogs are at risk of overexertion and heat stress (Hoffman et al., 2009; Otto et al., 2017). In such scenarios, their body temperature can increase, provoking a rise in panting frequency and hindering their olfactory abilities (Menchetti et al., 2019), as dogs are unable to pant and sniff simultaneously (Menchetti et al., 2019; Lazarowski et al., 2020; Spinella et al., 2022). Understanding task demands and the capabilities of individual detection dogs is essential for optimizing search performance (Troisi et al., 2019).

The canine olfactory system is well understood (Dzięcioł et al., 2020; Kurian et al., 2021). During sniffing, dogs can sniff up to 420 times per minute (Frank Jr et al., 2022). This large volume of air is directed through specialized pathways and stimulates the chemoreceptors in the olfactory

epithelium of the nasal cavity (Jenkins et al., 2018; Frank Jr et al., 2022). In comparison, when solely breathing or panting, only between 12% and 13% of air reaches the olfactory region, and the rest moves through the nasopharynx to the lungs (Kokocińska-Kusiak et al., 2021; Frank Jr et al., 2022). Dogs are only able to perceive odors through the olfactory nerves and the olfactory epithelium, and so to increase the efficiency and reliability of detection dogs, it is essential for their panting to be kept at a minimum (Gazit & Terkel, 2003; Jenkins et al., 2018).

Panting frequency is influenced by climatic conditions and exercise (Gazit & Terkel, 2003; Menchetti et al., 2019). Search performance, assessed using repeated go/no go trials with decreasing odor concentrations, varies with the explosive type and climatic conditions in a laboratory setting (Fernandez et al., 2024). Here, temperature (0°C vs. 40°C) and humidity (40 – 90%) impacted the detection success and latency to indicate for composition 4 (C4), ammonium nitrate (AN), and smokeless powder, but not trinitrotoluene (TNT). Search success, measured as a correct alert on a target, was also impacted by exercise in a laboratory environment. Detection dogs were 1.49 times more likely to find their target before 30 minutes of controlled exercise on a treadmill compared to after (Angle et al., 2014). This study also revealed differences in the likelihood of success between explosive types; dogs were 4.6 and 1.18 times more likely to alert on smokeless powder and TNT, respectively, compared to AN (Angle et al., 2014).

Less is known about the impact of exercise on search duration as a measure of search performance. Search duration for C4 is significantly shorter before than after 20 minutes of exercise on a treadmill at 9 km/h, and a 12% grade (Gazit & Terkel, 2003); however, the impact of exercise on search duration for other types of explosives has not previously been assessed. Search duration is impacted by explosive type; for example, dogs were quicker to find AN than 2-ethyl-1-hexanol (Mejia et al., 2024); however, this study was conducted in an artificial indoor environment and does not assess the impact of exercise.

The current study aims to measure both search success and duration of detection dogs locating three types of explosives (TNT, C4, and AN) in an outdoor (“more life-like”; Salamon et al., 2024) environment with and without a relatively short and lower intensity period of exercise, hypothesizing that exercise will negatively impact search performance.

Methods

Study dogs

Eleven detection dogs were involved in this study (three female springer spaniels and eight male labradors). All dogs were aged between one and two years old at the time of data collection. Three of the labradors were from the same litter. This sample size is similar to two comparable studies based on six dogs (Gazit & Terkel, 2003) and eighteen dogs (Angle et al., 2014). To combat the effects of a small sample size and to retain external validity, all dogs completed all trials twice (Lazarowski et al., 2020). In addition, all subjects completed the exercise and no-exercise trials rather than using different sets of dogs for each trial (Lazarowski et al., 2020). This was done to reduce the risk of group variance between these trials (Lazarowski et al., 2020). Despite this sample being heavily weighted towards male subjects, no sex disparities have been found in the olfactory apparatus in dogs (Dale et al., 2017), and sex does not significantly impact trainability (Serpell & Hsu, 2005). None of the dogs were neutered, as a study on police dogs found that intact dogs had significantly more accurate olfactory ability than those who were neutered (Fattah and Abdel-Hamid, 2020).

The dogs were owned by Dog Detectives, Cheshire, England, a company that produces fully trained detection dogs to supply global organizations (Dog Detectives, 2022). They were all housed in kennels overnight and in dog van transit boxes throughout the day, including when the experiment occurred. As part of their daily routine, they are each walked or exercised with a ball

thrower and trained several times throughout the day. All dogs had access to water *ad libitum* and had the opportunity to rest after each trial, with only one trial being done in a day.

The dogs were selected based on their ability to detect explosive substances; they had to consistently find different types of explosives at near 100% accuracy, make no false indications on blanks (plastic bags that do not contain any substances), and have a solid sit that clearly indicates the location of the hide (the hidden material; Dog Detectives Trainer, personal communication, August 2023). These conditions must be met to be considered fully trained at Dog Detectives. Based on the above criteria, the 11 dogs involved in this study were the only ones available and suitable at Dog Detectives at the time of data collection.

Explosives

Samples of trinitrotoluene (TNT; 50g), composition 4 (C4; 40g), and ammonium nitrate (AN; 75g) were secured in plastic bags. All dogs had been previously trained to detect these explosives inside the same plastic bags. Three explosive materials were used to cover for differing odor properties, such as volatility and vapor pressures, which can impact detection thresholds (Frank Jr et al., 2022; Gallegos et al., 2023).

Quantity can alter the odor signature (Oxley and Waggoner, 2009; Aviles-Rosa et al., 2021); therefore, the amount of explosive material depended on what was provided by Dog Detectives and was kept consistent with their training quantities. Dogs trained with large amounts of an explosive may not recognize smaller amounts of the same material, and vice versa (Oxley and Waggoner, 2009; Aviles-Rosa et al., 2021).

Experimental setup

The experiment was conducted from late September to early November 2023 and was only carried out during conditions of little to no winds, as although the testing area provided some wind protection, there was still some exposure. This was controlled for because air currents carry the odor molecules from the source, so wind greatly impacts the distribution and concentration of these molecules (Mejia et al., 2024). In addition, the environmental temperature was also recorded via a location-based weather app and varied from 12°C to 17°C. Minimal temperature variation throughout the experiment is ideal because warmer temperatures increase odor dissipation so that molecules spread further from the source, advancing the difficulty for source identification, whilst colder temperatures have the opposite effect (Farr et al., 2021). Climatic variation between 0°C and 25°C does not significantly impact search performance for food in outdoor environments (Salamon et al., 2024); therefore, variation between 12°C and 17°C is unlikely to affect search performance in this study.

All dogs were tested in the same areas (bays), where they were routinely trained to account for location bias. Detection dogs may discriminate between areas in which they have previously found hides and those that have previously been empty, as the detection rate was significantly lower in the latter when hides were reintroduced (Gazit et al., 2005). The bays were concrete spaces with a roof, a back wall, a metal gate lined with thick black plastic, and 1.5 m walls on either side that separated them from the next bay (Figure 1). Inside the bays along the walls were household appliances and furnishings such as cupboards, a chest of drawers, and washing machines, and the middle part of the floor remained clear except for a small concrete step.



Figure 1. Three bays used to hide the explosive materials: trinitrotoluene (TNT; left), composition 4 (C4; middle) and ammonium nitrate (AN; right). Each bay was 5 m wide and 10 m long — photos taken by EJ.

Each explosive material was placed in separate bays, and the order of search trials was kept consistent across the experiment and for each dog (TNT, C4, and AN). Explosives were randomly placed in a household appliance and left for at least 20 minutes to allow the odor to disperse into the surrounding air (Mejia et al., 2024). This is important, as a detection dog's search technique begins with casting, where they move in and out of the edges of the odor plume to localize the source (Mejia et al., 2024). The dogs were trained by one of two different handlers, and both handlers used the same training techniques consisting of positive reinforcement and clicker training (De Miranda-Magalhães et al., 2023). To ensure consistency, the handler used for each experimental trial was the same person who had previously trained that dog, as an unfamiliar handler can reduce the dog's motivation to perform a task (Mariti et al., 2013). Photos and notes were taken of each hide's location to ensure they would be put in the same locations when necessary. Each dog did an exercise trial first and then a non-exercise trial no less than a week later to reduce the chance of the dogs remembering the location of the hides (Johnen et al., 2017). All trials involved searching for all three explosive materials consecutively. The locations of each explosive material were kept the same for each dog during a trial to prevent contamination of scent when moving them to a different place (Johnen et al., 2017). This process was then replicated for the second set of trials, but with different hide locations. No blanks were used during any of the trials.

Exercise

Dogs were continuously exercised with a handheld tennis ball thrower on a grass lawn for five minutes. After this time, some dogs slowed down or stopped chasing the ball according to personal observations before this experiment; therefore, five minutes was chosen to ensure that all dogs could be exercised for the same amount of time. Similar studies used a treadmill to exercise their dogs rather than a standard ball thrower (Gazit & Terkel, 2003; Angle et al., 2014). However, this group of study dogs was unfamiliar with a treadmill and exercised with a ball thrower at least twice a week. Using a familiar exercise method reduces the variance of physiological stress throughout the experiment, which could impact the results as the dogs were tested twice (Ferasin

& Marcora, 2009). For this study, exercise was used as a proxy for panting intensity, as previous work has shown that panting increases with exercise (Gazit & Terkel, 2003); for trials without exercise, dogs were considered to be lightly panting, while for trials with exercise, they were considered to be heavily panting.

Measuring pulse and body temperature

Heart rate and body temperature increase during exercise and have been used to assess the physical fitness of dogs in numerous studies (Rovira et al., 2008; Ferasin & Marcora, 2009; Menchetti et al., 2019). In the current study, the pulse was measured just before each search trial; the familiar dog handler applied slight pressure using their hand on the femoral arteries in their hind legs to find a pulse. Handlers were consistent for each dog to ensure intra-individual consistency, and both handlers involved in the study received training on measuring dog pulse rates to ensure consistency between individuals. As the dogs were not likely to stay still for one minute, the pulse was counted for 15 seconds using a stopwatch, and this was then multiplied by four to calculate beats per minute. Body temperature was taken on the bicep femoris muscle using a Sovarcate HS960D non-contact infrared thermometer. Similar methods were used by Queiroz et al. (2016), who reported a temperature increase in this same area after exercise, and Pichová et al. (2023), who noted that the change of surface temperature on the limbs was the most apparent when using infrared thermography. It is important to note that surface temperature, measured using infrared thermography, is lower than average dog body temperature (38.3°C – 39.2°C); Pichová et al. (2023) reported surface temperature for the bicep femoris region to vary between 20.5°C and 26.5°C.

Measuring search duration and search success

Search duration and accuracy are two measures of detection dog performance (Jeziński et al., 2014). For this study, both indices have been chosen because detection dogs must have high accuracy and be required to work quickly and efficiently (Jeziński et al., 2014).

Once the pulse and body temperature were taken, the handler followed their usual training practice and walked the dog inside the bay before telling them to sit just in front of the first household object on the left side of the bay so that the handler could direct them onto the first object to start their search. The dog's lead was unclipped so that they could freely roam the bay and not be influenced by the handler's movements of the lead (Lazarowski et al., 2020). To further reduce any cues given by the handler, they stood still behind the 1.5 m gate, allowing only their chest upwards to be visible to the dogs. This is because dogs are sensitive to subtle body movements such as body orientation and hand signals (Lazarowski et al., 2020). The search duration was measured from the initial "search" command to the exact moment the dog gave a sit indication. These are the standard signals to quantify search duration and were clear markers to follow, allowing for consistency across each dog (Jeziński et al., 2014). To prevent any obstruction for the dog, both the handler and the person with the stopwatch stood behind the gate, and each dog was familiar with the person timing, so they were not distracted by any new people.

Each dog was given a maximum of two minutes to find each hide, and if they did not find it, they were put back on their lead and taken to the next bay to find the next explosive material. This was then analyzed as 120 seconds for study purposes. This maximum time was chosen due to personal observations, as this is when dogs typically become disinterested in continuing the search, and previously published work found a decrease in motivation when hides became less likely to be found (Gazit et al., 2005). As false and missed indications are measures of detection accuracy, they were also noted (Jeziński et al., 2014). Dog behavior was monitored throughout the observation period, and the trial would have been stopped if any signs of stress, such as excessive yawning, body shivering, or whining, were observed (Pastore et al., 2011). No dogs were observed to exhibit these behaviors during the study.

Statistical analysis

Statistical analysis was conducted in R (Version 4.3.3; R Core Team, 2024). All explanatory variables were initially assessed to ensure none correlated above 0.4, which could result in collinearity (Freckleton, 2010; Midi et al., 2010); pulse rate and post-exercise temperature were removed as potential variables, as both correlated with exercise, a key explanatory variable for this study. The impact of exercise on temperature and pulse rate was separately assessed using a Wilcoxon signed-rank test. Response variables (search duration and success) were visually inspected and transformed to obtain more normal distributions when necessary (this was the case for search duration; Pinheiro et al., 2001). Search duration was transformed using a log 10 transformation because the data were positively skewed (Ennos & Johnson, 2017). Transformations were not possible for search success as this was a binary variable.

Search duration was analyzed using a linear mixed model (LMM) using the R package 'lme4' (Bates et al., 2015). A maximal model was built, including exercise, breed, explosive type, and trial number as explanatory variables with animal ID as a random factor. Model stability was assessed by visually inspecting the qq-plots and histograms of residuals generated using the R packages 'performance' (Lüdtke et al., 2021a), 'see' (Lüdtke et al., 2021b), and 'patchwork' (Pedersen, 2024). Where the model was stable, predictor variables with the greatest P value were removed in a stepwise manner (Meteyard & Davies, 2020) to attain a final model comprising only key explanatory variables (exercise) and other explanatory variables with $P \leq 0.05$ (Li et al., 2017). The 'anova' function was used to compare the fit of the final model against the null model (a model retaining the random effect but with all fixed effects removed and an intercept of 1 specified), and the final model was accepted only if it provided a significantly better fit than the null at $P < 0.05$. Post hoc analysis was conducted using the emmeans function in the R package 'emmeans' (Lenth et al., 2024). Confidence intervals for model parameters were assessed using the function 'confint' to measure the reliability and precision of the results inferred from the model (Hazra, 2017). Non-transformed data were used for plotting purposes to aid interpretation.

Search success was analyzed using a generalized linear model (GLM). A GLM was used due to its ability to handle binary variables (Dunteman & Ho, 2006). A binomial distribution was used to fit the model to binary data (Naimi & Whitcomb, 2020; Griffith, 2024). A maximal model was built, including the same explanatory variables used for search duration (exercise, breed, explosive type, and trial number), and model stability was assessed in the same way by visually inspecting the qq-plots and histograms of residuals. Non-significant explanatory variables were again progressively removed in a stepwise manner until only the key variable (exercise) and those with $P \leq 0.05$ were left in the model.

Results

Eleven dogs (eight male labradors and three female springer spaniels) completed a total of 132 trials (44 for each explosive). Half of the trials (66) were conducted when the dogs had been exercised, and the other half (66) when the dogs had not been exercised. No trials were removed from the analysis. Dogs spent an average of 37.24 seconds searching for the hide across all trials, and dogs found the hide within the 120-second time limit in 122 trials (92.42%). Average surface temperature and pulse rate significantly increased with exercise (Table 1). Breed and trial number were not significantly associated with search duration or success. Individual mean surface temperature, pulse rate, percentage success, and search duration are shown in Table 2.

Table 1. Physiological parameters for dogs measured before explosive target detection trials conducted with and without five minutes of exercise using a ball thrower.

	Without exercise	With exercise	P value	V
Surface temperature (C°)	20.2 (2.0)	21.2 (2.8)	<0.001	1959
Pulse (per 1 minute)	106 (19)	164 (24)	< 0.001	2211

Average body temperature and pulse are presented as median (interquartile range). Sample size for each parameter was 66 measurements (one measurement per day) for each dog (n=11) without exercise and 66 measurements (one measurement per day) for each dog (n=11) with exercise. Statistical analysis: Wilcoxon signed rank test.

Table 2. Mean surface temperature, pulse rate, percentage success, and search duration with and without exercise for explosive detection dogs (mean ± SEM).

ID	Sex	Breed	Exercise	Mean temperature (°C)	Mean pulse (per 1 minute)	Percentage success	Mean duration (s)
1	F	Spaniel	Yes	23.4 ± 0.022	153 ± 7.977	83.33 ± 0.167	52.33 ± 16.985
			No	19.6 ± 0.313	105 ± 2.616	100 ± 0.000	31.00 ± 13.070
2	F	Spaniel	Yes	24.0 ± 0.224	149 ± 2.667	83.33 ± 0.167	44.83 ± 17.583
			No	21.8 ± 1.140	109 ± 3.040	100 ± 0.000	31.83 ± 6.720
3	F	Spaniel	Yes	20.2 ± 0.358	150 ± 2.000	100 ± 0.000	38.00 ± 15.124
			No	21.9 ± 1.319	111 ± 4.780	100 ± 0.000	35.33 ± 9.168
4	M	Labrador	Yes	23.4 ± 0.693	152 ± 10.930	100 ± 0.000	27.67 ± 8.381
			No	21.4 ± 0.089	115 ± 3.040	100 ± 0.000	15.50 ± 3.490
5	M	Labrador	Yes	22.3 ± 0.805	164 ± 1.033	83.33 ± 0.167	42.83 ± 16.123
			No	20.6 ± 0.179	111 ± 0.843	100 ± 0.000	45.00 ± 20.445
6	M	Labrador	Yes	22.5 ± 0.514	170 ± 1.366	100 ± 0.000	28.83 ± 7.134
			No	19.9 ± 0.022	101 ± 8.369	83.33 ± 0.167	48.00 ± 17.752
7	M	Labrador	Yes	21.8 ± 0.201	156 ± 5.060	50 ± 0.224	75.83 ± 20.472
			No	19.0 ± 0.089	85 ± 4.551	100 ± 0.000	27.33 ± 9.047
8	M	Labrador	Yes	22.7 ± 0.917	161 ± 6.422	83.33 ± 0.167	48.17 ± 15.572
			No	20.8 ± 0.045	98 ± 3.225	100 ± 0.000	21.83 ± 3.919
9	M	Labrador	Yes	23.4 ± 0.559	152 ± 3.724	66.67 ± 0.211	57.33 ± 20.832
			No	21.0 ± 0.201	95 ± 9.615	100 ± 0.000	15.83 ± 5.003
10	M	Labrador	Yes	24.1 ± 0.201	177 ± 0.843	100 ± 0.000	46.00 ± 10.109
			No	17.3 ± 1.498	103 ± 2.458	100 ± 0.000	32.33 ± 12.476
11	M	Labrador	Yes	20.2 ± 0.626	180 ± 3.425	100 ± 0.000	32.27 ± 13.057
			No	17.8 ± 1.543	103 ± 1.687	100 ± 0.000	35.33 ± 9.521

Search duration

Search duration was significantly longer after exercise (mean = 44.91s ± 4.53s) compared to when the dogs had not been exercised (mean = 29.58s ± 3.39s, CI = 0.09-0.32LRT, X = 11.883, t = 3.526, df = 1, P < 0.001; Figure 2a).

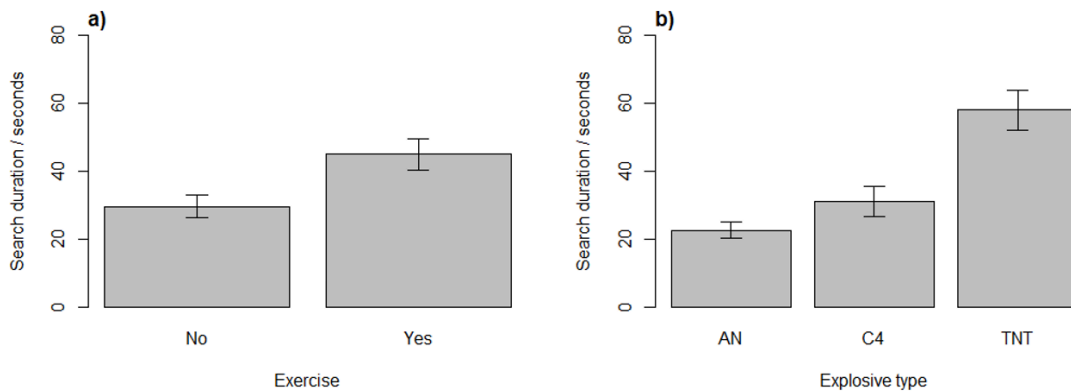


Figure 2. a) Average search duration (in seconds) of detection dogs for any explosive type when they have not been exercised and following exercise (mean \pm SEM). b) Average search duration (in seconds) of detection dogs for three explosive types: ammonium nitrate (AN), composition 4 (C4), and trinitrotoluene (TNT), regardless of whether they have been exercised or not (mean \pm SEM).

Explosive type was significantly associated with search duration (LRT, $X = 28.670$, $df = 2$, $P < 0.001$; Figure 2b). Dogs were 2.57 times faster to alert on AN than TNT (CI = 0.24-0.53, $t = 5.409$, $P < 0.001$) and 1.86 times faster to alert on C4 than TNT (CI = 0.15-0.43, $t = -4.056$, $P = 0.001$). Although the interaction between exercise and explosive type was not significant, the pattern of search duration, with AN having the shortest duration and TNT having the longest duration, was seen both with and without exercise (Figure 3).

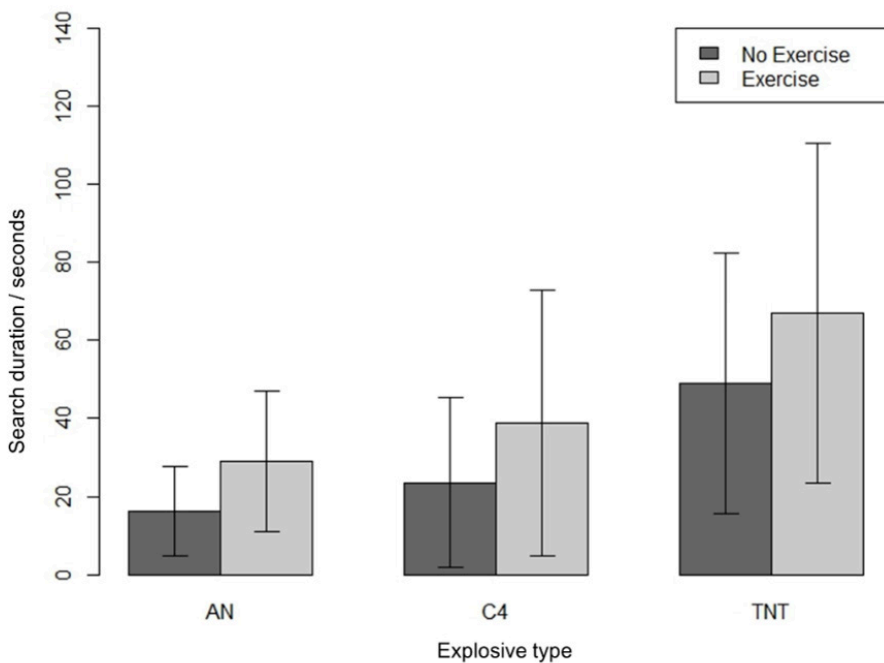


Figure 3. Average search duration (in seconds) of detection dogs when they searched for the explosives, ammonium nitrate (AN), composition 4 (C4), and trinitrotoluene (TNT) after they were either exercised or not exercised (mean \pm SEM).

Search success

Search success was significantly associated with exercise. After exercise, dogs were less likely to find the hide (86.36% success \pm 0.31) compared to without exercise (98.48% success \pm 0.99; $z = -2.290$, $P < 0.05$).

Explosive type was also significantly associated with search success, with a significant difference between success for TNT (81.82% \pm 0.32) compared to C4 (95.45% \pm 0.69; $P < 0.050$) and TNT compared to AN (100%; $P < 0.05$). There was no significant difference between C4 and AN.

Success rate for each explosive type varied between exercise and non-exercise trials. After no exercise, dogs were 100% successful in finding all C4 and AN hides and 95.45% (\pm 0.98) successful in finding all TNT hides. After exercise, dogs were 100% successful in finding all AN hides, 90.91% (\pm 0.67) successful in finding C4 hides, and 68.18% (\pm 0.31) successful in finding all TNT hides. However, the analysis showed no significant interaction between exercise and explosive type. No false indications occurred in any of the trials.

Discussion

Detection dogs must operate in demanding settings with intense physical conditions, which can increase panting (Gazit & Terkel, 2003). The present study aimed to investigate the effect of exercise on the performance of explosive detection dogs, using search duration and search success as performance measures. Both measures were shown to be impacted by exercise, with increased search duration and decreased search success for dogs that had just been exercised. Research into this field can further our understanding of the extent to which working conditions restrict the olfactory capabilities of detection dogs (Gazit & Terkel, 2003; Angle et al., 2014). This is critical at a time when the use of specialized explosive devices is rising along with the global threats of terrorism, calling for higher numbers of explosive detection dogs (Brady et al., 2018; Spinella et al., 2022).

Exercise impacts search duration and success

Exercise had a significant effect on search duration and success. Dogs were slower and 1.14 times less likely to find all three types of explosives (TNT, AN, and C4) after exercise compared to when they had not been exercised. This finding is significant as it builds on previous research that showed exercise increased search duration and decreased search success (Gazit & Terkel, 2003; Angle et al., 2014); however, we used a much gentler form of exercise that more closely matches a normal activity bout for a detection dog, for example, at Brisbane Airport, dogs will search for between five and ten minutes per flight with a break between each flight (Bronish, 2020). Angle et al. (2014) used 30 minutes of controlled exercise on a treadmill, and Gazit and Terkel (2003) used 20 minutes of exercise on a treadmill at 9 km/h and a 12% grade. Here, we used five minutes of continuous exercise with a handheld tennis ball thrower, allowing the dogs to regulate the speed and consistency of their running. This suggests that even relatively short periods of exercise, like those they would experience as part of their role, can impact detection dog search performance.

Panting is a dog's primary method of cooling down; however, this results in a decreased sniffing rate as airflow is instead directed through the mouth, and dogs cannot simultaneously sniff and pant (Reed et al., 2011; De Miranda-Magalhães et al., 2023). This diminishes their olfactory capabilities by up to 40% (De Miranda-Magalhães et al., 2023). In addition, dogs who proceed through strenuous working conditions are at high risk of collapse, heat stress, or stroke, as they keep their mouths closed to sniff and so cannot properly maintain thermoregulation in order to cope with their environment (Otto et al., 2017; De Miranda-Magalhães et al., 2023).

The results of this study suggest that dogs persist in working following exertion from exercise

and must work longer to detect hidden explosives. Therefore, it is in the interest of the dog's welfare to provide them with appropriate breaks and monitor their panting levels or other physiological signs of overexertion (De Miranda-Magalhães et al., 2023). Management of dog activity levels before deployment may assist in their ability to cope with such demanding work conditions (Jenkins et al., 2018). Frequent exercise can acclimatize them to the strenuous activity involved in search work (Jenkins et al., 2018). This benefits their welfare and can also help their performance, as dogs conditioned to extensive exercise perform better at olfactory tasks when challenged with exercise than those who are not (Jenkins et al., 2018). Another method of acclimatization involves temperature, where dogs can be repetitively exposed to slight elevations in temperature to enable them to acclimatize to hot settings, as well as triggering cellular changes to obtain a heightened thermal tolerance (De Miranda-Magalhães et al., 2023). A study by Kane et al. (2024) suggested that an acclimatization plan improves the detection ability of dogs when exposed to adverse environmental conditions. High endurance should be considered a behavioral trait necessary for search work (Hayes et al., 2018; Lazarowski et al., 2020).

Dogs can alter their search technique based on the ambient environment (Jinn et al., 2020). During cool and humid conditions, dogs search significantly closer to the scent trail, possibly due to lower odor dissipation (Jinn et al., 2020). During hot, dry, or windy conditions, dogs often search further from the scent trail as odor dissipation increases. These changes in environmental ambiance also impact the speed, as dogs move quickest when close to the trail (Jinn et al., 2020). When dogs search in conditions with a reduced scent dispersal, it is important that their olfactory abilities are not further impeded by a high panting rate (Reed et al., 2011; Kane et al., 2024).

Explosive type impacts search duration and success

The type of explosive was significantly associated with search duration and success regardless of whether or not the dog had been exercised. TNT had the longest average duration, and AN had the shortest average duration. When searching for TNT, dogs were also the least successful, while when searching for C4 and AN, they were the most successful. The difference between explosives may be due to the varying detection thresholds of each explosive because of their unique odor properties; for example, a higher volatility, vapor pressure, and diffusivity can increase the detection threshold (Frank Jr et al., 2022; Gallegos et al., 2023; Mejia et al., 2024). When comparing these explosives, Fernandez et al. (2024) found that dogs were most sensitive to C4 odorants and least sensitive to TNT odorants.

The first behavior exhibited during scent detection is casting, where dogs move in a zig-zag pattern to locate the edges of the scent plume (Mejia et al., 2024). From here, they can follow the concentration gradient to find the source, although this gradient is not linear as dispersal is susceptible to turbulence (Mejia et al., 2024). If the explosive material has a low dispersal rate, the odor molecules will remain close to the source, and the dog will find it harder to detect the scent cues initially (Farr et al., 2021). Contrarily, if the explosive material has a high dispersal rate, the dog will find it harder to localize the target odor source as odor molecules move away from the source (Farr et al., 2021). In addition, the mass of each explosive material varied (TN: 50g; C4: 40g; AN: 75g), as the amounts used in this study were subject to the usual training amounts used at Dog Detectives. This could have impacted the detection rate as the quantity can alter the odor signature (Oxley and Waggoner, 2009; Aviles-Rosa et al., 2021).

Recommendations for future research

Within the sample, there was a bias towards Labrador retrievers, with only three out of eleven subjects being springer spaniels. Ideally, this would be a larger sample in future studies. All dogs available at the time of the experiment were observed in this study, and Dog Detectives commu-

nicated that there was a high demand for male Labrador detection dogs. Nevertheless, the breeds used in this study are two of the most commonly employed breeds in detection tasks due to their obedience, trainability, and intelligence, as well as being known for their high level of olfactory abilities (Robin et al., 2009; Polgár et al., 2016). Therefore, these types of dogs provide a relevant insight into detection dog efficacy (Robin et al., 2009; Polgár et al., 2016).

It can be argued that the detection performance of different breeds varies due to morphological variation, which usually coincides with behavioral differences (Cobb et al., 2015). Breed is also significantly associated with stamina (Robbins et al., 2017). However, the results in this study indicate that breed did not significantly influence either measure of detection performance. This could be because all dogs at Dog Detectives are assessed during their training course and require high levels of motivation to complete the search tasks and obedience toward their handler (Dog Detectives Trainer, personal communication, August 2023). Rising evidence suggests that behavioral characteristics, such as trainability and motivation, impact detection performance more than morphological traits (Lazarowski et al., 2020). For example, breeds with an elongated nose are traditionally selected for detection work. Still, despite having a flat nose, pugs were more successful than German shepherds at an odor discrimination task, even when the target odor had been diluted (Hall et al., 2015). However, the behavior of dogs is greatly influenced by the purposes for which they were bred (Cobb et al., 2015), and so it is important to note that German shepherds were not bred for detection purposes and instead are commonly used as a multi-purpose dog in the security sector (Lazarowski et al., 2020). Contrasting results were reported in a study by Polgár et al. (2016), where dogs with an elongated nose outperformed dogs with a short nose, although they did not use German Shepherds in their study. The discrepancy between these results could have been derived from the experimental designs, as Hall et al. (2015) trained their subjects prior to the experiment, whereas Polgár et al. (2016) did not. This highlights how performance in a search task is not solely based on olfactory capabilities but also on trainability and motivation (Polgár et al., 2016).

Conversely, the current study uses both springer spaniels and Labradors, which were traditionally bred for roles related to olfaction, such as sport hunting and retrieving game (Serpell & Hsu, 2005). This was reflected in a test for trainability by Serpell and Hsu (2005), who used the Canine Behavioural Assessment and Research Questionnaire (C-BARQ) to compare Labradors and springer spaniels bred for show purposes to those bred for working purposes. Working dogs scored significantly higher for both breeds than show dogs (Serpell and Hsu, 2005). This result emphasizes that selective breeding for conformation traits may have deleterious effects on key behaviors relating to working performance, with the opposite effect demonstrated in successful working dog breeding programs (Bray et al., 2021).

Body temperature and pulse rate were used as indicators of physical fitness, and exercise was used as a proxy for panting in this study, as exercise is known to increase pant frequency (Gazit & Terkel, 2003). Future studies could use specialized equipment similar to Gazit and Terkel's (2003) study, as not only did they measure these indices, but their study measured the sniffing and breathing rate by using a small microphone and transmitter. This allowed them to distinguish an inverse ratio between panting increase and sniffing decrease (Gazit & Terkel, 2003). These tools were not accessible for the current experiment, and so body temperature and pulse rate provided a cheaper and more attainable alternative that still coincides with panting rate (Ferasin & Marcora, 2009; Menchetti et al., 2019; Pichová et al., 2023).

A suggestion for further research in this field is to identify patterns between panting dissipation and search duration. Once the dog has been exercised, they could participate in multiple consecutive search trials of the same explosive material, and their panting rate could be measured before each search. A gradual decrease in search duration would be expected as panting dissipates over time from the point of exercise, and Gazit and Terkel (2003) found an inverse ratio between panting and search duration. The current study also revealed an increased search duration and reduced search accuracy directly after short periods of exercise. These results were not evident in

the study by Angle et al. (2014), who instead stated that there was no pattern of increased search success as trials advanced. Nevertheless, their study focused on search success rather than search duration, and panting rate may have a larger impact on search duration than accuracy (Rooney & Clark, 2021). Further research is necessary in both measures of performance to support these findings. Studies should compare shorter and longer exercise periods on panting dissipation and search performance to determine appropriate work-rest schedules for explosive detection dogs.

The current study did not assess the impacts of dehydration, which could be a key variable affecting detection dogs' performance. Exercise and dry weather conditions may lead to dehydration or a dry nose, hindering a dog's scent detection abilities (Reed et al., 2011; Goucher et al., 2019). Working dogs can be so motivated to fulfill the task that they have been commanded to do that they become unresponsive to physiological indicators of thirst brought on by exercise (Goucher et al., 2019). Dehydration was reported in search and rescue canines that were deployed after the terrorist attacks at the World Trade Center, the Haiti earthquake, and the Washington landslide (Jenkins et al., 2018). It is known that dehydration of the nasal mucosal membrane can inhibit the detection of odors due to a decrease in enzyme activity and a decrease in the fluidity of the membrane (Callewaert et al., 2023). In addition, when dogs cannot dissipate their body heat at the same rate as the heat being generated, they resort to evaporative cooling, whereby water is lost through panting (Otto et al., 2017). This contributes to dehydration and, when severe, can result in heat stroke (Otto et al., 2017).

Conclusion

This study indicates that exercise significantly influences detection performance, as dogs were slower and less likely to detect hidden explosives after exercise than without prior exercise. The results also demonstrate a difference between the search duration and search success of all three types of explosives, with TNT being the slowest to be found with the lowest detection rate. Conversely, AN had the quickest detection time and a 100% detection rate for both exercise and no-exercise trials. The outcome of this study highlights the importance of providing detection dogs with necessary breaks between search tasks and monitoring any physiological indicators of overexertion in the interests of their welfare and performance. We demonstrated that short durations of relatively gentle exercise impact detection dog performance, which could critically impact a real-life detection scenario. We recommend that future research and management investigate methods to mitigate the effects of overexertion, including appropriate rest times to return to peak performance.

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Declaration of interests

Authors declare no Conflict of Interests for this article.

Author contribution

EJ conceived and designed the study, acquired and interpreted the data, and conducted the data analysis. EJ wrote the first draft of the article, and EJ and EH were involved in revisions. EH supervised the project.

Ethical statement

Ethical approval was granted by the University of Chester in September 2023 and by Dog Detectives in August 2023. All subject dogs would have been involved in the search training activities regardless of their involvement in this study.

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L'esercizio fisico influisce sulle prestazioni dei cani da ricerca di esplosivi

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Sintesi

I cani (*Canis familiaris*) sono ampiamente utilizzati come rilevatori di odori grazie alle loro capacità olfattive sensibili, alla resistenza e alla capacità di coprire rapidamente ampie aree. Sono molto richiesti a causa dell'aumento globale delle minacce terroristiche che utilizzano congegni esplosivi specializzati. I cani da ricerca devono spesso affrontare temperature elevate e sforzi fisici, che possono aumentare la frequenza respiratoria in funzione del raffreddamento evaporativo, inibendo la capacità olfattiva. Questo studio ha esaminato l'impatto dell'esercizio sulle prestazioni di ricerca di 11 cani da ricerca di esplosivi (otto labrador e tre springer spaniel). Hanno completato due serie di prove: una dopo l'esercizio con un lanciatore di palline e una senza esercizio. Sono stati cronometrati durante la ricerca di tre tipi di esplosivi: trinitrotoluene, composizione-4 e nitrato di ammonio. I dati sono stati analizzati in R utilizzando modelli a effetti misti, rivelando che l'esercizio fisico ha influenzato significativamente la durata e il successo della ricerca per tutti i tipi di esplosivo. Le ricerche sono durate in media 29,58 secondi senza esercizio fisico, mentre le ricerche post-esercizio hanno richiesto 44,91 secondi. I cani avevano 1,14 volte più probabilità di localizzare esplosivi senza esercizio fisico precedente. I cani hanno impiegato più tempo a trovare il trinitrotoluene ed erano più veloci con nitrato di ammonio e composizione-4. Questi risultati evidenziano l'importanza di consentire ai cani da rilevamento un riposo adeguato, poiché anche un breve esercizio fisico può influire sulle loro prestazioni di ricerca.

