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Assessing learning, behaviour, and stress level in goats while testing a virtual fencing training protocol

L. Wilms [a,*], D. Hamidi [a], C.H.U. Lüntzel [a], M. Hamidi [b], M. Komainda [a], R. Palme [c], J. Isselstein [a], S. Waiblinger [d], M. Egerbacher [e]

[a] Department of Crop Sciences, Grassland Science, Georg-August-University of Göttingen, Von-Siebold-Str. 8, 37075 Göttingen, Germany
[b] Heisterholz-Mühle 1, D-30916 Isernhagen, Germany
[c] Department of Biological Sciences and Pathobiology, Unit of Experimental Endocrinology, University of Veterinary Medicine, Veterinärplatz 1, 1210 Vienna, Austria
[d] Centre of Animal Nutrition and Welfare, Clinical Department for Farm Animals and Security of Food Systems, University of Veterinary Medicine, Veterinärplatz 1, 1210 Vienna, Austria
[e] Venn Research Association for the Promotion of Virtual Fencing in Tyrol and the Alpine region. Brixnerstraße 1, 6020 Innsbruck, Austria

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A B S T R A C T

Virtual fencing (**VF**) is a modern fencing technology using Global Positioning System-enabled collars which emit acoustic signals and, if the animal does not respond, electric pulses. Studies with cattle indicate successful learning and no distinct negative impact on the animals' behaviours and stress level. However, the number of studies testing VF with goats is relatively small. In this study, we used VF collars to test a VF training protocol recently applied to heifers to assess the development of goats' learning to avoid the electric pulse, their behaviour, and faecal cortisol metabolites (**FCM**s) as an indicator for physiological stress in a grazing experiment. Twenty adult 'Blobe' goats with offspring were divided into two groups and assigned to the VF or physical fencing treatment in a cross-over design with two periods of 12 days each. The VF treatment involved a virtual fence at one side of the paddock, to which the goats were gradually introduced over the first 2 days (additional physical fence or posts as visual support). On day eight, the grazing areas were enlarged by shifting the virtual fence and one side of the physical fencing treatment. The experiment lasted 4 h per day. During this time, the following behaviours were recorded via instantaneous scan sampling of all goats every 2 min: grazing, lying, standing, standing vigilant, walking, and running. Additionally, faecal samples were collected once, or twice daily and FCM concentrations were measured. The VF collars delivered the number of acoustic signals and electric pulses and the duration of the acoustic signals. The daily number of acoustic signals and electric pulses of each goat was used to calculate a 'success ratio'. A significant increase in the success ratio and a general decrease in the signal duration indicate the successful association of acoustic signals and electric pulses at the group level. Behavioural analyses revealed no clear influence of the VF treatment except for standing vigilant. Virtually fenced goats stood significantly more vigilant than physically fenced ones. However, free-moving kids could have had an influence. The VF treatment had no significant effect on the FCM concentrations, which decreased significantly over time. In summary, goats showed signs of learning when avoiding receiving electric pulses by responding appropriately to the acoustic signals. A higher occurrence of vigilance behaviour may suggest insecurity, but FCM concentrations did not indicate increased physiological stress. Future research needs to confirm these results and test VF with goats under practical conditions.

Implications

Virtual fencing is a modern fencing technology which has mainly been tested with cattle and sheep. In the current study, goats were virtually fenced to evaluate learning and to compare behaviour and stress level of virtually fenced goats and physically fenced goats. The results show signs of successful learning and no clear effect on physical stress or basic behaviours, but an elevated level of vigilance, which may indicate insecurity. Virtual fencing has the potential to be a suitable technology for goats, but possible negative long-term impacts on goat welfare need to be investigated in further studies.

* Corresponding author.
E-mail address: lisa.wilms@uni-goettingen.de (L. Wilms).

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Introduction

Grazing grasslands with livestock maintains and enhances the diversity of flora and fauna for various reasons (Rook and Tallowin, 2003; reviewed by Metera et al., 2010; Fraser et al., 2022). Grazing can also prevent areas from scrub and forest encroachment, especially in alpine or mountain pastures, where the use of machines can be difficult or unfeasible (Bailey et al., 1998; Cislaghi et al., 2019). Nevertheless, livestock farming in European mountain regions has decreased in recent decades (MacDonald et al., 2000; Streifeneder, 2010; Buchgraber et al., 2011), which leads to the loss of extensive grassland (Buchgraber et al., 2011). The reasons for this include socio-economic changes (Tasser et al., 2011) and general issues like difficult accessibility, farming conditions, and lack of profitability (Schermer and Kirchengast, 2006).

In this context, virtual fencing (**VF**) offers the potential to facilitate the grazing of livestock, as the high flexibility compared to physical fencing (**PF**) allows an improvement of the efficiency of grazing management (Umstatter, 2011; Hamidi et al., 2023). Additionally, costs for material and labour are reduced, wildlife remains unaffected, and livestock can be tracked via Global Positioning System (**GPS**; Umstatter, 2011; Hamidi et al., 2023). VF is a modern fencing technology that is commercially available in several countries worldwide and allows the farmer to set up and customise the virtual fences of the paddocks on their mobile device at any time (Eftang et al., 2022). The information gets transmitted via mobile network to the GPS-enabled collars which the animals are required to wear. When an animal approaches a VF boundary, an acoustic signal gets emitted by the collar, which is followed by an electric pulse if the animal does not turn around (Campbell et al., 2017). So far, four systems are known from practice or research (reviewed by Goliński et al., 2022), of which only the Norwegian company Nofence (® Nofence, AS, Batnfjordsøra, Norway) has developed a special collar for small ruminants like goats and sheep (Eftang et al., 2023). Accordingly, the majority of studies tested the functionality of VF and its impacts on the animals' behaviour and welfare with cattle (e.g. Campbell et al., 2019; Lee and Campbell, 2021; Hamidi et al., 2022). Utilising VF on sheep is more challenging as the neck fleece needs to be removed regularly to ensure the VF electrodes are in contact with the skin (Marini et al., 2018b; Campbell et al., 2023). Nevertheless, there are research groups who have analysed different aspects of VF with sheep, like the general application (e.g. Jouven et al., 2012; Brunberg et al., 2016 and 2017; Marini et al., 2018a and b; Marini et al., 2022; Campbell et al., 2023), effects of VF stimuli under different conditions (e.g. Kearton et al., 2019 and 2020), social influences (e.g. Marini et al., 2020; Kearton et al., 2022), and learning (e.g. Marini et al., 2019; Eftang et al., 2023). At this point, there are only three studies published in which VF was tested on goats (Fay et al., 1989; Eftang et al., 2022; Log et al., 2022). In Fay et al. (1989), electric impulse collars for dogs were tested to contain a group of goats when the proportion of collared goats decreased over time. Eftang et al. (2022) analysed the ability of naïve and experienced goats to adapt to the Nofence VF system on different Norwegian goat farms. In Log et al. (2022), VF was specifically used in a living lab approach to let goats graze fire-prone plants.

Regardless of the animal species, it is essential for the animals to understand the acoustic signal as a prediction for the following electric pulse if they do not show the desired reaction (Lee et al., 2018). Otherwise, if an animal is not able to associate the acoustic signal and electric pulse, chronic stress can occur which leads to poor welfare (Lee et al., 2018). Methods of how to measure stress in virtually fenced animals are presented by Lee and Campbell (2021) and include physiological and behavioural indicators. A recently published review (Wilms et al., 2024) compared the results of VF studies with cattle regarding animal welfare and learning behaviour, showing both proof for the successful learning of the VF technology and a lack of reliable evidence that VF negatively impacts cattle welfare. While concerns have been expressed in early studies with virtually fenced sheep (Brunberg et al., 2016 and 2017), subsequent research indicates that sheep can learn the system (Eftang et al., 2022; Campbell et al., 2023) without deviations in grazing behaviour (Marini et al., 2022).

In this study, we investigated the behaviour and a stress parameter (faecal cortisol metabolites, **FCM**s) of virtually fenced goats while grazing on pasture and compared it with a group of physically electric−fenced goats in a cross-over design in two periods of 12 days each. The VF group went through a training protocol which was successfully tested on Fleckvieh heifers by Hamidi et al. (2022). The aim of this study was to determine if the goats were able to learn to avoid the electric pulse and whether the VF system would result in FCM concentrations indicating physiological stress, which could be caused by the VF system. Additionally, basic behaviours, including vigilance, which has not been examined in VF studies so far, were analysed.

Material and methods

The experiment took place on a commercial farm in Längenfeld, Tirol, Austria (1 179 m above sea level) in May and June 2023. The climatic conditions were measured at a weather station in Umhausen (distance to study side: 6.7 km) and the information was provided by GeoSphere Austria (Bundesanstalt für Geologie, Geophysik, Klimatologie und Meterologie, 2023). The average temperature (2 m above the ground) during the experimental time was 13.5 °C in period one and 20.1 °C in period two. The total precipitation was 52.8 mm in period one and 24.6 mm in period two.

Animals

Twenty female 'Blobe' goats (aged between 1 and 9 years, most with offspring), that were familiar to electric fences but naïve to VF, were used in this trial. Ten days prior to the start of the experiment, the goats were divided into two groups of 10 adult goats each, depending on their compatibility with each other (based on the owner's experience) and their age to get the most even distribution possible (average age ± SD in month group one: 39.6 ± 24.0, group two: 37.2 ± 33.3; number of goats with kid at foot group one: eight, group two: four). Until the end of the experiment, the goats stayed in their groups, independently of being in- or outdoors. All adult goats were used to living indoors in the wintertime and independent of humans in the mountains in the summer. They were also accustomed to the pasture close to the farm where the experiment took place. In each group, the goats were marked with the numbers 1–10 on both sides of the body. For dark grey and black goats, bleaching hair colouring was used, while bright grey goats were marked with black hair colouring. The goats were weighed and checked by a veterinarian at the start (average live weight ± SD group one: 36 ± 8.4 kg; group two: 33.1 ± 9.6 kg), between the periods (average live weight ± SD group one: 37.9 ± 9 .9 kg; group two: 35 ± 9.7 kg) and at the end (average live weight ± SD group one: 41.3 ± 9.3 kg; group two: 39.6 ± 8.7 kg) of the experiment. Before the start of the experiment, each goat was fitted with a VF collar once for habituation (one day on pasture) and became accustomed to putting on and wearing the heart frequency belt (data not analysed in this article). The goats were already familiar with commonly used nylon neck straps for goats to simplify handling.

Virtual fencing system

The VF company Nofence (® Nofence AS, Batnfjordsøra Norway) has developed a size-adapted VF collar for sheep and goats. The system uses GPS, mobile network, and the Nofence App to allow the users to set up their pastures and check on their animals' locations on a smartphone or tablet. The collar (weight: 505 g) consists of a rubber neck piece, two metal chains and a box with solar panels. When an animal approaches the virtual fence line, an acoustic signal (2–4.2 kHz; duration: 5–20 s depending on the animals' reaction and speed; rising pitch) gets emitted by the collar which is followed by an electric pulse (1.5 kV; 0.1 J; duration: 0.5 s) if the animal keeps moving forward (technical information from the Nofence user manual, 2023). Whenever an animal does not react to the first combination of acoustic signal and electric pulse, i.e. if the animal passes the VF line, the procedure can be repeated twice before the collar gets deactivated, and a notification is sent to the farmer ('escape'). A return to the virtually fenced area activates the collar again.

The system differentiates between a teach and an operating mode, which specifies the reaction the animal needs to show to stop the acoustic signal. In teach mode, a turn of the head is sufficient, while in operating mode, the animal is required to move away from the virtual boundary. The switch of the modes occurs after 20 acoustic signals without a following electric pulse.

Nofence shelter beacons disable the GPS receivers of the collars via Bluetooth and were therefore put up in the barn to protect the animals from receiving unwanted VF signals.

Experimental design

A 120 × 60 m fenced pasture area was split into four paddocks of 30 × 50 m each, which were enclosed by electrified sheep net fences and equipped with water troughs. One fence side of each paddock was either virtually fenced (permeable for the kids; n = 2) or physically fenced (posts and electrified wire; impermeable for the kids; n = 2). A nearby barn with access to hay and water served as accommodation whenever the goats did not graze outside. After a 10-day preparation and habituation phase where the goats could get used to their group members, paddocks and the equipment, the experiment started on 11 May 2023. The two goat groups (group one and two) were assigned to two treatments (VF or PF) in a cross-over design (group one started with VF; Fig. 1) with two periods of 12 days each (11.05.–22.05. and 25.05.–05.06.) and a 2-day break in between. Accordingly, each goat had experienced the VF system for a period of 12 days at the end of the experiment.

Depending on the treatment, the 12 days were organised in a schedule according to Hamidi et al. (2022). The VF treatment had a special training phase on the first 2 days of the experiment, where the virtual boundary was visually supported by a physical fence (posts and an electrified wire on the 1st day and posts only on the 2nd day). On day eight of the experiment, the VF line was shifted (11 m) to enlarge the grazing area (Fig. 2). The same happened on day eight of the PF treatment. The experiment was carried out for 4 h in the afternoon of each day and started after the goats were let out to pasture and ended just before the goats were herded back into the nearby barn. Since it became apparent on the 1st day of the experiment that the goats were very excited when let out on pasture, a person was placed about 5 m outside the virtual boundary to prevent the animals from crossing it while running around (on the 2nd day of training and 1st day without visual support in both periods). After 30 min, the person left the paddock without disturbing the goats.

Data collection

Nofence data

The VF collars recorded the time of each acoustic signal, electric pulse, and escape. Additionally, the durations of the acoustic signals were measured (signal duration), and the animals' GPS position was registered (every 15 min; when an animal approached the boundary, four positions per second were recorded). Technical problems occurred on the 1st day of the experiment as the batteries were not properly engaged in the collars which led to some batteries falling out and one collar not working at all (goat number one). The issue was solved within 2 h. Another problem was the data loss from one collar in the first period so that only nine animals could be included in the statistical analysis (1st day with data from only eight animals). During observations, it was noticed that the smallest goats did not reliably receive electric pulses as they did not always show a reaction when the collar registered delivering an electric pulse. This was most likely caused by the small size of some goats (weight range from 20 kg to 47.5 kg at the beginning of the experiment). Nofence does not make any specifications on the animals' weight, height, or age, but they warn of an inefficient electric pulse when a neck is too small to ensure a decent signal transmission (Nofence user manual, 2023). Nevertheless, all data were included in the analyses as no affected goat escaped.

Global positioning system data

The GPS positions of the physically fenced goats were supposed to be registered by GPS livestock tracker (infoStars®) which were integrated into an additional collar. After technical problems, the tracker was replaced with Polar sport watches (https://www.polar.com) on day six in the first period. Each watch was placed in a little bag which was fitted to an additional neck collar. On the last day of both periods, the Polar sport watches were fitted to the animals of the VF treatment since the animals of the PF treatment were equipped with the heart frequency monitor belts. Because of missing GPS accuracy and comparability with the Nofence data, the information did not get analysed any further.

Behaviour

All animals' behaviours as listed in Table 1 were observed via scan sampling and instantaneous recording (Martin and Bateson, 2007) every 2 min by one observer per group (recorded with Obslog app ©Dina and Masud Hamidi). The observers swapped the group after 2 h each day. In total, four trained observers took turns over the two periods (each observer observed each group 12 times) with a high inter-observer reliability of Kappa ranging from 0.843 to 0.992 (tested before data recording).

Faecal cortisol metabolites

Individual faecal samples were taken daily at seven in the morning (**am**; except for days five and seven) and at midnight (**pm**) on days one, three, and eight in both periods. Additional samples were taken three and 7 days before the experiment started to determine a base value. For sampling, goats were tied up and faeces was collected either after a spontaneous defaecation or rectally. Occasionally, samples were missing when an animal had recently defecated unobserved. The faecal samples were frozen (−18 °C) within an hour after collection. The measurement of FCM concentrations was performed via an 11-oxoaetiocholanolone enzyme immunoassay (for details, see Möstl et al., 2002) after the extraction of the defrosted faeces with methanol (80%). Inter-assay coefficients of variation (n = 15) of a high− and low−concentration pool sample were 8.6% and 12.5%, respectively. The assay's limit of detection was 2 ng/g faeces. In goats, the measured FCMs

Fig. 1. 'Blobe' goat number two (group one) with equipment (goat collar, Nofence virtual fencing collar, heart frequency belt) on pasture.

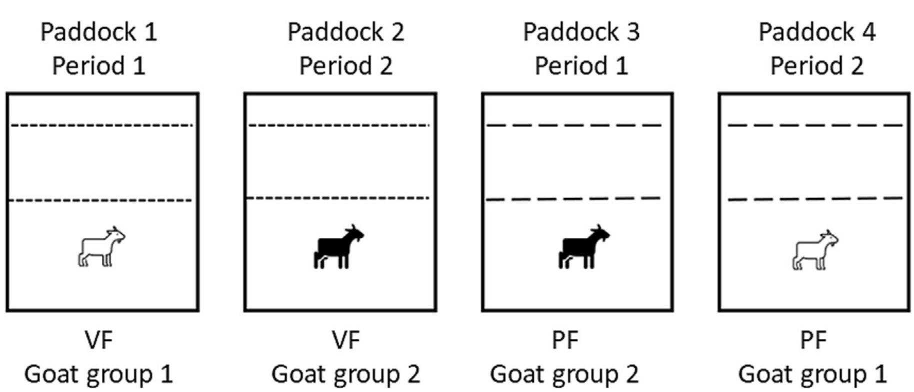

Fig. 2. The experimental paddocks with schematically drawn fence lines: paddocks 1 and 2 with a virtual fence line (dotted line) and paddocks 3 and 4 with a physical fence (dashed line; posts and wire). The second fence line represents the fence shift on day eight in all four paddocks. In period one, paddock 1 was grazed by goat group 1 (virtual fencing treatment, VF) and paddock 3 by goat group 2 (physical fencing treatment, PF). In period two, the goat groups switched the fencing system, equipment, and paddocks so that group 2 was virtually fenced in paddock 2 and group 1 had a physical fence in paddock 4.

provide information on the cortisol secretion about 13 h earlier (Kleinsasser et al., 2010).

Standing herbage on offer

Standing herbage on offer was estimated for all four paddocks by taking compressed sward height measurements (rising plate meter: diameter of 30 cm and plate weight of 200 g; Castle, 1976) at 20 locations per paddock at the beginning and the end of each experimental period (i.e. pre- and postgrazing). All sampling points were randomly allocated across the entire paddock area. At four locations per paddock and date, the standing herbage on offer of known compressed sward height was measured by

Table 1
Definitions of recorded behaviours of goats on pasture when either virtually or physically fenced.

Behaviour	Definition
Grazing	Consuming grass and herbs while standing or walking with the head above the grass (and biting off grass). The head can be lifted in between for not more than 5 s.
Lying	Torso in contact with the ground and no weight on the extremities or only on the hind legs when standing up or lying down (lying down begins when both carpal joints touch the ground when lying down and ends when the animal stands on all four extremities again). Eating while "kneeling" on the carpal joints does not belong to lying.
Standing	Weight on all four claws or on three if one leg is lifted. No change in the animal's position.
Standing vigilant	Standing with the head raised, ears pricked and looking in one direction. No chewing movements (no chewing or ruminating).
Walking	Moving forward in a regular way without grazing.
Running	Movement is faster than walking (trot or canter).
Personal care	Scratching with own leg, licking, rubbing, nibbling, scrubbing.

cutting manually close to ground level, thereby carefully avoiding any soil contamination. The manually cut samples were frozen for transport and later dried in a force air oven at 60 °C for 48 h to calculate the standing DM.

Statistical analyses

For the statistical analyses, the software program R (R Core Team, 2022) and the following packages were used: 'glmmTMB' (Brooks et al., 2017), 'nlme' (Pinheiro et al., 2018), 'ggplot2′ (Ginestet, 2011), 'DHARMa' (Hartig, 2022), and 'emmeans' (Lenth, 2022). The two 12-day periods were divided into five phases: days one and two as phase one, days three and four as phase two, days five till seven as phase three, days eight and nine as phase four and days ten till twelve as phase five. Generalised linear mixed effect models (**GLMMs**) or linear mixed effect models were calculated (period: n = 2 levels, phase: n = 5 levels, treatment: n = 2 levels, animal-ID generally: n = 20 replicate animals in total with 10 animals per treatment × period). The residuals were checked (package 'DHARMa'), and posthoc tests (Tukey's honestly significant difference test) for significant differences were performed (package 'emmeans').

In period two, goat number one suffered an injury in her flank from a fight with another goat, which was treated by a veterinarian. Thus, her data from the last 3 days of the experiment was removed from the analysis.

Success ratio

The number of acoustic signals and electric pulses was used to calculate a success ratio (**SR**) per animal and day after Eftang et al. (2022 and 2023):

$$SR = \frac{\text{number of acoustic signals without a following electric pulse}}{\text{number of all acoustic signals}}$$

Therefore, the values for SR could range between zero and one. In 46 cases, an animal did not receive a signal in 1 day, and no SR could be calculated. To solve the problem, we decided to test three different approaches (the results of the second and third approaches can be found in the supplementary material, Supplementary Tables S1 and S2):

1. We removed the 46 cases from the calculation,
2. The 46 cases were defined as success (SR = one) as it was done in Eftang et al. (2022 and 2023),
3. The 46 cases were defined as failures (SR = zero).

Since the data were not normally distributed, beta regression was chosen and a GLMM with phase, period, and their interactions as fixed effects and animal-ID as a random factor was calculated.

Signal duration

To improve the normality of residuals, the data were log-transformed. When analysing the signal duration, it is possible to distinguish between the two types of acoustic signals, as there are the ones that are followed by an electric pulse (**acousticWithElec**) and the ones that are not followed by an electric pulse (**acousticNoElec**). Therefore, we tested two approaches. First, we calculated a GLMM with phase, period, acoustic signal type (acousticWithElec or acousticNoElec, n = 2 levels), and their interactions as fixed effects and animal-ID as a random factor to find possible significant differences between the types of acoustic signals. Second, we computed individual GLMMs with phase, period, and their interactions as fixed effects and animal-ID as a random factor for the different types of acoustic signals (all acoustic signals, acousticWithElec, acousticNoElec) to show the development over time for each type.

Behaviour

Statistical analyses were performed only for the following behaviours: grazing, lying, standing, standing vigilant, walking, as the amount of data for running and self-grooming was insufficient. We added the times of each recorded behaviour (scans) and divided it by the daily observation time, resulting in the daily proportion of total scans. Accordingly, beta regression was chosen and GLMMs with treatment, period, phase, and their interactions as fixed effects and animal-ID and the daily combination of observers (n = 4 levels) as crossed random effects were calculated.

Faecal cortisol metabolites

The data were log-transformed to improve the normality of residuals. Four different calculations were performed to address the following issues:

1. A general model gives an overview of the influences of different factors during the experiment. Therefore, a GLMM with treatment, period, phase, time (sampling time: am or pm, n = 2 levels), and the interactions of treatment × period, treatment × phase, treatment × time as fixed effects and animal-ID as a random factor was calculated.
2. As it was not possible to test every interaction in the general model mentioned above, separate models for each sampling time (am and pm) during the experiment were selected. Therefore, two GLMMs with treatment, phase, period, and their interactions as fixed effects and animal-ID as a random factor were calculated.
3. To see if time in general had an influence, the data from the samples taken before the experiment had started were summarised with the data from the am samples of the 11 May and used to create a baseline (period zero). A GLMM with

treatment, period (n = 3 levels), and their interactions as fixed effects and animal-ID as a random factor was calculated. Also, a second calculation including only the data from the am sampling was performed.

4. To test whether the two groups showed a fundamental difference in their FCM levels, the baseline data (period zero) were used to calculate a GLMM with group (n = 2 levels) as a fixed effect and animal-ID as a random factor.

Standing herbage on offer

A linear regression model was developed between the compressed sward height and the standing herbage on offer (y = 4.91 x + 46.85, R^2 = 0.58). This relationship was used to predict the standing herbage on offer at all other compressed sward height measurement points to obtain a representative value of herbage on offer. Hence, 20 points per paddock were used for calculation per date. For the standing herbage on offer in g DM/m^{2,} a linear mixed effect model with treatment, period, sample time (pre- or postgrazing, n = 2 levels), and their interactions as fixed effects and sample number per paddock (20 per paddock) as a random factor was calculated.

Results

All 10 collars emitted acoustic signals and electric pulses during the experiment. In total, 563 (period one) and 411 (period two) acoustic signals and 73 (period one) and 54 (period two) electric pulses were recorded by the Nofence collars. Fig. 3 shows the range of the number of acoustic signals (Fig. 3A) and electric pulses (Fig. 3B) per animal and day for both periods. On average (mean ± SD), a goat received 5.3 ± 6.0 (period one) or 3.4 ± 3.5 (period two) acoustic signals and 0.7 ± 0.9 (period one) or 0.4 ± 0.7 (period two) electric pulses per day.

During the two periods, two obvious breakouts occurred in period one on days nine (all 10 goats; Fig. 4A) and ten (only goat number 10; Fig. 4B) without a goat being registered as escaped. On day nine, all ten goats left the virtually fenced area and stayed there for a few minutes while receiving acoustic signals. Only goat number seven received an electric pulse and returned immediately to the virtually fenced area. The other goats followed slowly, taking breaks to graze in between. The next day, only goat number six followed the kids across the border, whilst the other adult goats stopped in front of the virtual boundary. Goat number six received

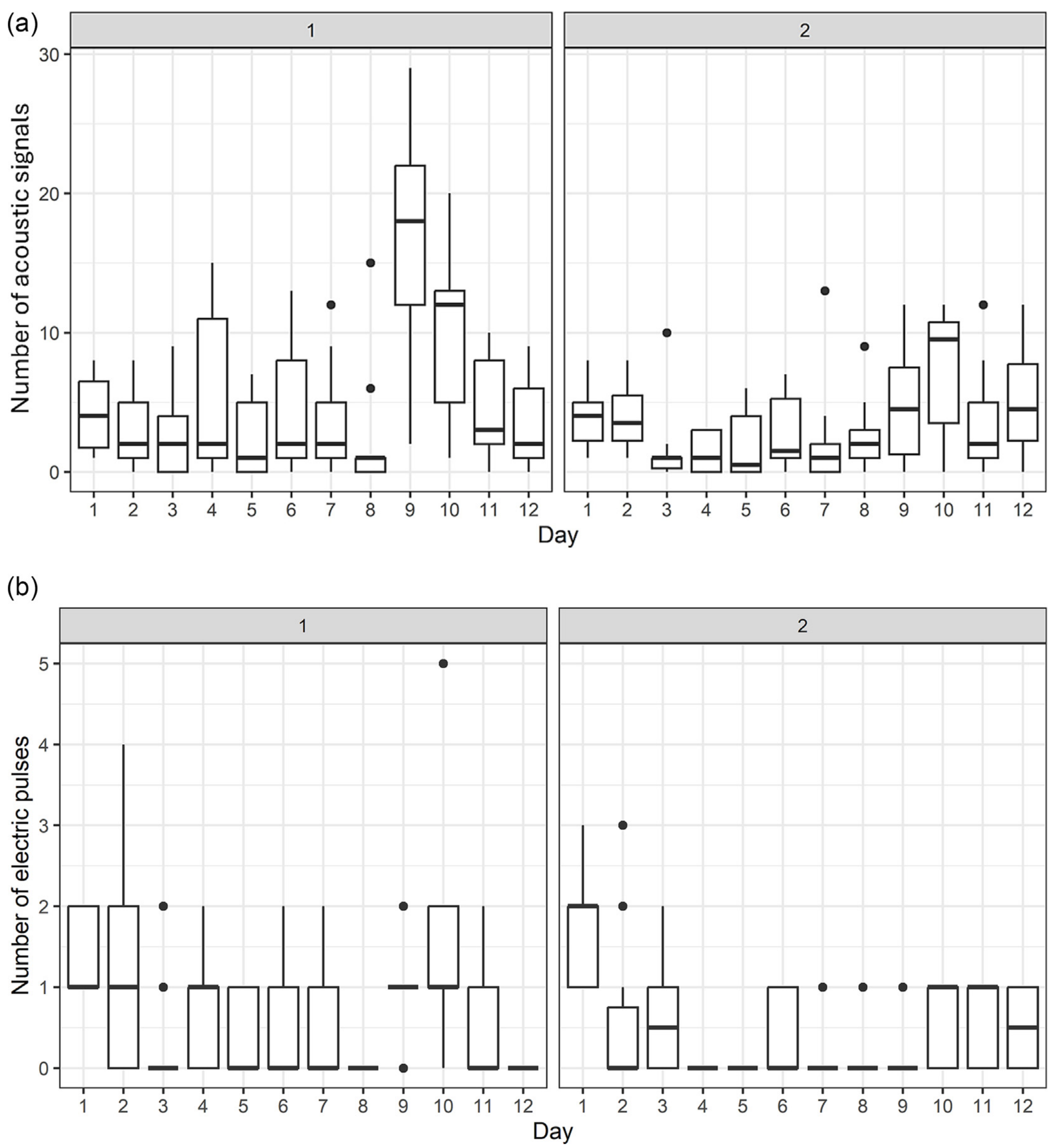

Fig. 3. Box plots of the number of acoustic signals (a) and electric pulses (b) per day of goats in a virtual fencing experiment over two periods of 12 days each.

Fig. 4. GPS positions from virtually fenced goats from day nine (A) and day 10 (B) of the first period. Green dots are positional data which were regularly recorded by the Nofence collars (every 15 min). Additionally, GPS positions were documented whenever an animal received an acoustic signal (blue dots) or electric pulse (red dots). GPS = Global positioning system.

an electric pulse and ran back into the virtually fenced area. Another breakout occurred on the 2nd day of period one, where goat number one was registered as escaped after the collar had emitted three acoustic signals followed by electric pulses. Since the goat did not show a reaction, it was assumed that the goat was too small to actually perceive the electric pulse. Disregarding this case, the effectiveness of the virtual fence was 90.8% in period one and 100% in period two.

Table 2
Output of generalised linear mixed effect models for the analysed parameters of interest to compare virtually (VF) and physically (PF) fenced goats[1].

Target variable	Fixed and interaction effects	*P*-values	Marginal R^2/ Conditional R^2
Success ratio	Phase [2]	1.81 *	
	Phase [3]	2.30 **	0.039 / NA
	Phase [4]	3.64 ***	
	Phase [5]	2.67 ***	
Grazing	Period [2]	2.10 ***	
	Phase [2]	1.45 ***	
	Phase [3]	1.57 ***	
	Phase [4]	1.46 ***	
	Phase [5]	1.75 ***	0.005 / 0.007
	Treatment [VF] × phase [2]	1.36 *	
	Treatment [VF] × phase [4]	0.65 **	
	Treatment [VF] × phase [5]	0.65 **	
	Period [2] × phase [2]	1.75 ***	
	Period [2] × phase [3]	1.92 ***	
	(Treatment [vf] * period [2]) * phase [2]	0.56 *	
	(Treatment [vf] * period [2]) * phase [4]	1.58 *	
Lying	Phase [4]	0.36 **	0.004 / 0.008
	Phase [5]	0.56 *	
	Treatment [VF] * phase [4]	2.70 *	
Standing	Period [2]	0.48 ***	
	Phase [2]	0.69 **	
	Phase [3]	0.73 **	
	treatment [VF] × phase [4]	1.65 **	0.003 / 0.005
	treatment [VF] × phase [5]	1.60 **	
	period [2] × phase [4]	1.52 *	
	(Treatment [VF] × period [2]) × phase [4]	0.55 *	
Standing vigilant	Treatment [VF]	1.50 *	0.003 / 0.005
	Phase [5]	0.62 **	
Walking	Period [2]	0.67 *	
	Phase [4]	0.61 ***	
	Phase [5]	0.52 ***	0.001 / 0.002
	Treatment [VF] * phase [2]	0.60 **	
	Treatment [VF] * phase [3]	0.70 *	
	period [2] × phase [2]	0.51 ***	
	period [2] × phase [3]	0.59 **	
	(Treatment [VF] × period [2]) × phase [2]	2.52 ***	
FCM (general model)	Treatment [VF]	1.14 ***	
	Phase [5]	−0.31 *	0.168 / 0.438
	Time [pm]	0.45 ***	
	Treatment [VF] × period	−0.65 ***	
FCM (am only)	Treatment [VF]	1.75 ***	
	Treatment [VF] × phase [2]	−1.74 **	
	Treatment [VF] × phase [4]	−1.92 **	
	Treatment [VF] × period	−1.06 ***	0.110 / 0.439
	phase [4] × period	−0.60 *	
	(Treatment [VF] × phase [2]) × period	1.09 **	
	(Treatment [VF] × phase [4]) × period	1.18 **	
FCM (pm only)	Treatment [VF]	2.76 ***	
	Period	0.81 **	
	Treatment [VF] × phase [4]	−2.77 ***	0.259 / 0.619
	Treatment [VF] × period	−1.70 ***	
	(Treatment [VF] × phase [4]) × period	1.63 ***	
FCM (including period zero)	Period [1]	−0.28 *	0.069 / 0.311
	Period [2]	−0.61 **	
FCM (including period zero, am only)	Period [1]	−0.44 ***	0.090 / 0.365
	Period [2]	−0.70 **	

Abbreviations: FCM = Faecal cortisol metabolites; NA = not applicable.
* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.
Only significant effects are presented.
[1] The two 12-day periods were divided into five phases: phase 1: days one and two, phase 2: days three and four, phase 3: days five till seven, phase 4: days eight and nine, phase 5: days ten till twelve.

Success ratio and signal duration

Phase had a significant effect on the SR ($P < 0.001$; Table 2) and period did not. The SR increased from phase one to phase four and showed a slight decrease again in phase five (Table 3).

When examining differences between the types of acoustic signals, only phase had a significant effect on the signal duration ($P < 0.01$; Supplementary Table S1) and period and acoustic signal type did not. The signal duration decreased from phase two to phases three and four (Supplementary Table S3). The results of the individual analyses of the types of acoustic signals can be found in the supplementary material (Supplementary Tables S1 and S3).

Behaviour

The proportion for grazing was significantly affected by the interaction of treatment × period × phase ($P < 0.05$; Table 2). In phase two in period one, a significantly higher proportion was shown by the VF treatment (Table 4). In contrast, in period two, the PF treatment's proportion was significantly higher in phases two, three, and five (Table 4).

When analysing the lying behaviour, the interaction of treatment × phase proved to have a significant effect ($P < 0.05$; Table 2) with the PF treatments showing significantly lower proportions for lying in phase four than the VF treatments (Supplementary Table S4).

For standing vigilant, significant effects were found for treatment and phase (both $P < 0.05$; Table 2). The VF treatments spent significantly more time standing vigilant than the PF treatments (estimated means ± SE of proportions of scans of daily observation time: PF 0.0322 ± 0.00547, VF 0.0429 ± 0.00713). Furthermore, significantly higher proportions for standing vigilant were shown in phases one and four than in the other phases (Table 3).

When analysing the behaviours standing and walking, a significant effect of the triple interaction treatment × period × phase could be proven (standing $P < 0.05$, walking $P < 0.001$; Table 2). Differences in the proportion for standing could be detected in phase two in period one, where the PF treatment demonstrated significantly higher values than the VF treatment. On the other hand, in phase five in period two, significantly higher proportions for standing were calculated for the VF treatment (Supplementary Table S5). The VF treatment's proportion for walking was higher in phase two in period two, while the PF treatment showed significantly higher proportions for walking in phases two, three, and four (Supplementary Table S6).

Faecal cortisol metabolites

In the first calculation, where the general model was calculated, sampling time ($P < 0.001$), phase ($P < 0.05$), and the interaction treatment × period ($P < 0.001$) were significant (Table 2). The concentrations of FCMs were significantly higher in the pm samples (estimated means ± SE: 130.0 ± 14.5 ng/g) than in the am samples (estimated means ± SE: 81.0 ± 7.9 ng/g). The effect of phase is presented in Table 3 and shows a gradual decrease of the FCM concentrations from phase to phase. In period one, the concentration of FCMs was significantly higher for the VF treatment (goat group one; estimated means ± SE: VF 124.4 ± 18.1 ng/g, PF 83.6 ± 12.1 n g/g), while in the second period, the PF treatment (goat group one again; estimated means ± SE: VF 90.7 ± 13.2 ng/g, PF 117.0 ± 17. 1 ng/g) showed a significantly higher FCM concentration than the VF treatment.

When calculating separate models for the am and pm samples, in both cases, the interaction treatment × period × phase proved to be significant (am $P < 0.01$, pm $P < 0.001$; Table 2). In the mornings of period one, the VF treatment showed significantly higher FCM values in phases one and five, while in period two, the PF treatment had a significantly higher concentration in phase five (Table 5). A similar pattern was found for the pm samples, where the VF treatment showed significantly higher FCM concentrations in phases

Table 3
Results of Tukey's honestly significant difference tests (estimated means ± SE) for the target variables for which phase (phase 1: days one and two, phase 2: days three and four, phase 3: days five till seven, phase 4: days eight and nine, phase 5: days ten till twelve) was significant for virtually fenced goats, and in case of standing vigilant and FCM for virtually and physically fenced goats.

Target variable	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Success ratio	0.617 ± 0.0308^{a}	0.712 ± 0.0454^{ab}	0.796 ± 0.0279^{bc}	0.907 ± 0.0287^{c}	0.775 ± 0.0243^{b}
Standing vigilant	0.0442 ± 0.00526^{b}	0.0303 ± 0.00593^{a}	0.0272 ± 0.00538^{a}	0.0543 ± 0.00973^{b}	0.0356 ± 0.00663^{ab}
FCM – general model	121.8 ± 13.50^{c}	109.0 ± 11.72^{bc}	113.4 ± 15.72^{abc}	92.9 ± 10.02^{ab}	80.8 ± 9.73^{a}

Abbreviations: FCM = Faecal cortisol metabolites.
Superscript letters indicate significant differences between the phases for each variable ($P < 0.05$).

Table 4
Results of Tukey's honestly significant difference test (estimated means ± SE) for the parameter grazing. The interaction treatment × period × phase was significant when comparing virtually (VF) and physically (PF) fenced goats over two periods.

Phase	Period 1		Period 2	
	Treatment	Estimated means ± SE	Treatment	Estimated means ± SE
1	PF	0.685 ± 0.0338^{a}	PF	0.820 ± 0.0244^{a}
	VF	0.721 ± 0.0316^{a}	VF	0.786 ± 0.0275^{a}
2	PF	0.759 ± 0.0291^{a}	PF	0.920 ± 0.0132^{b}
	VF	0.836 ± 0.0225^{b}	VF	0.876 ± 0.0185^{a}
3	PF	0.773 ± 0.0268^{a}	PF	0.932 ± 0.0108^{b}
	VF	0.807 ± 0.0241^{a}	VF	0.884 ± 0.0165^{a}
4	PF	0.761 ± 0.0289^{a}	PF	0.833 ± 0.0226^{a}
	VF	0.710 ± 0.0323^{a}	VF	0.805 ± 0.0251^{a}
5	PF	0.792 ± 0.0256^{a}	PF	0.870 ± 0.0243^{b}
	VF	0.747 ± 0.0291^{a}	VF	0.796 ± 0.0346^{a}

Superscript letters indicate significant differences between the treatments per phase (phase 1: days one and two, phase 2: days three and four, phase 3: days five till seven, phase 4: days eight and nine, phase 5: days ten till twelve) and period ($P < 0.05$).

Table 5
Results of Tukey's HSD honestly significant difference tests (estimated means ± SE) for the separate calculations of morning (am) and midnight (pm) faecal cortisol metabolite (FCM) samples. The interaction of treatment × period × phase was significant (am $P < 0.01$, pm $P < 0.001$) when comparing physically (PF) and virtually (VF) fenced goats over two periods.

Phase	Period 1		Period 2	
	Treatment	Estimated means ± SE	Treatment	Estimated means ± SE
1 (am)	PF	68.8 ± 13.12^{a}	PF	111.8 ± 25.65^{a}
	VF	136.9 31.41^{b}	VF	76.7 ± 14.22^{a}
2 (am)	PF	82.1 ± 15.67^{a}	PF	88.8 ± 16.26^{a}
	VF	85.6 ± 15.68^{a}	VF	95.0 ± 17.61^{a}
3 (am)	PF	76.5 ± 16.94^{a}	PF	94.9 ± 22.69^{a}
	VF	96.4 ± 22.10^{a}	VF	89.6 ± 20.55^{a}
4 (am)	PF	78.9 ± 13.24^{a}	PF	70.5 ± 13.24^{a}
	VF	75.5 ± 14.20^{a}	VF	75.9 ± 14.27^{a}
5 (am)	PF	45.4 ± 8.30^{a}	PF	93.1 ± 17.26^{b}
	VF	87.8 ± 17.06^{b}	VF	43.6 ± 8.47^{a}
1 (pm)	PF	97.3 ± 20.6^{a}	PF	218.5 ± 48.2^{b}
	VF	279.6 ± 57.3^{b}	VF	114.3 ± 25.2^{a}
2 (pm)	PF	95.7 ± 20.3^{a}	PF	133.0 ± 28.2^{a}
	VF	238.4 ± 50.5^{b}	VF	97.2 ± 20.6^{a}
4 (pm)	PF	102.8 ± 21.8^{a}	PF	124.0 ± 27.4^{a}
	VF	95.2 ± 21.0^{a}	VF	107.2 ± 22.0^{a}

Superscript letters indicate significant differences between the treatments per phase (phase 1: days one and two, phase 2: days three and four, phase 3: days five till seven, phase 4: days eight and nine, phase 5: days ten till twelve) and period ($P < 0.05$).

one and two of the first period, while in the second period, the FCM values of the PF treatment were significantly higher in phase one (Table 5).

The third calculation, which analysed the influence of time and therefore included period zero, demonstrated that, regardless of using the am and pm data or solely the am data, the period had a significant effect (both $P < 0.01$; Table 2). In both cases, the FCM concentrations were significantly lower in period two than in periods zero and one (Fig. 5). There was an additional significant difference between the first two periods with the highest FCM values in period zero, when using only the am data (Fig. 5A).

When testing for fundamental differences in the FCM levels of the two goat groups, no significant effect was found ($P = 0.84$).

Standing herbage on offer

For standing herbage on offer, sample time ($F_{1\ 133} = 4.673$, $P = 0.032$) and the interaction of period × treatment proved to be significant ($F_{1\ 133} = 14.433$, $P = 0.0002$). Standing herbage on offer was higher pregrazing than postgrazing (estimated means ± SE: pregrazing 112.1 ± 3.04 g DM/m^2, postgrazing 96.4 ± 3.04 g DM/m^2). In period one, no difference between the treatments was found (estimated means ± SE: VF 98.0 ± 4.08 g DM/m^2, PF 104.7 ± 4.08 g DM/m^2), while in period two, the standing herbage on offer was greater in the paddock of the VF treatment than in the one of the PF treatment (estimated means ± SE: VF 120.4 ± 4.08 g DM/m^2, PF 93.9 ± 4.08 g DM/m^2; Fig. 6).

Discussion

This study aimed to investigate goats' learning when first introduced to a VF training protocol. Additionally, the behaviour and FCMs were analysed and compared with the data of physically fenced goats, what makes this the first study to examine the stress level of virtually fenced goats.

Escapes

The two big breakouts in this study occurred in the last third of period one, while the 36 escapes in the group of naïve goats in Eftang et al. (2022) happened during the first 3 days. We, therefore, suspected that the varying strength of the GPS signal or the mobile phone coverage could be responsible, as this was also discussed for the escapes of experienced goats in Eftang et al. (2022). Furthermore, the kids could have played a role, as they were not virtually fenced and had full access to the whole paddock and ran ahead of their dams. Boyd et al. (2023) found VF for cows with calves was only half as efficient in confining than for dry cows without offspring. However, many studies with cattle or sheep reported high−efficiency values for VF (e.g., Campbell et al., 2020; Langworthy et al., 2021; Marini et al., 2022) or even no escapes at all (Marini et al., 2018a; Hamidi et al., 2022; Eftang et al., 2023; Fuchs et al., 2024) when every animal was collared.

Learning

A problem we faced was the 46 cases in which an animal did not receive a signal in one day, as it was not possible to calculate a SR. Since we did not unconditionally agree with the idea of defining these cases as successes, as it was done before (Eftang et al., 2022 and 2023), we focussed on removing them to influence the results as little as possible. The calculation of the other two approaches (success or failure) showed, however, that the outcomes varied only slightly from each other. Nevertheless, it should be discussed how it is to be assessed when an animal does not interact with the virtual fence, especially if this happens repeatedly. Circumstances like the paddock size and herbage availability, social facilitation and, thus, imitating the behaviour of group members (Keshavarzi et al., 2020), and the animals' individuality need consideration. A possible connection with the previous receipt of electric pulses was not analysed in this study but could give an indication of how seriously the electric pulses influenced the goats and their spatial grazing behaviour. Location learning and the associated avoidance of areas close to the virtual boundary were described in sheep (Brunberg et al., 2016) and cows (Lomax et al., 2019; McSweeney et al., 2020) but stayed unobserved in other studies (for cattle: Campbell et al., 2017 and 2019 and 2020; Hamidi et al., 2022; for sheep: Marini et al., 2018a and 2022).

The evaluation of the SR in this study showed an increase close to one, which is the highest possible value, in phase four and a slight decrease again in phase five. Other studies (Eftang et al.,

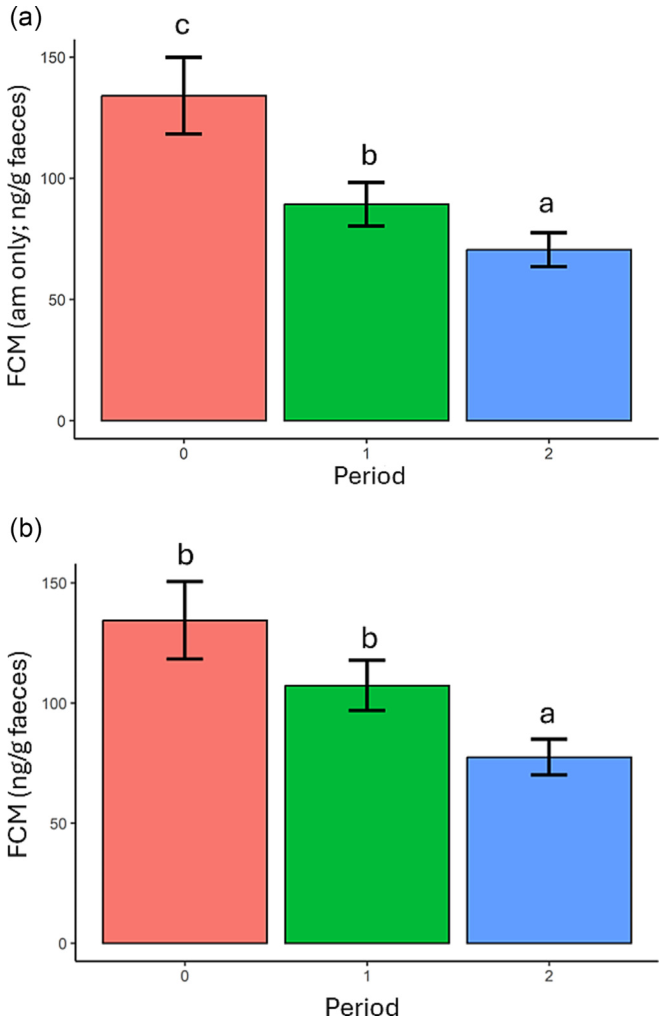

Fig. 5. Estimated means ± SE of FCM (faecal cortisol metabolite) concentrations of virtually and physically fenced goats over 3 periods. In a) only data from am (morning) samples were used, while in b) data from am and pm (midnight) sampling were incorporated. Letters indicate significant differences between the periods ($P < 0.05$).

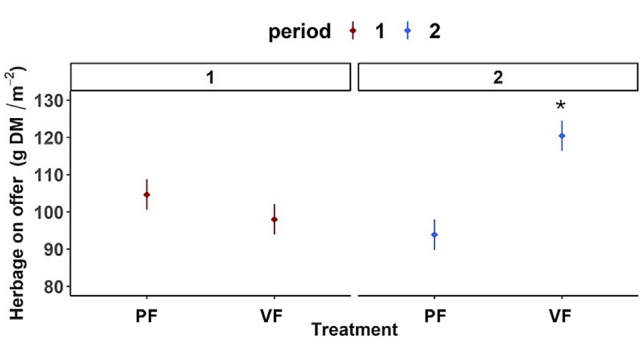

Fig. 6. Estimated means ± SE of herbage on offer of virtually (VF) and physically (PF) fenced goats over two periods. In period one (red), no significant difference could be proven, while in period two (blue), herbage on offer was significantly higher for VF than for PF ($P < 0.05$; marked with an asterisk).

2022 and 2023; Hamidi et al., 2024) presented fluctuations in the SR too. We divided the study days into phases to increase comparability, since phase two and phase four showed a certain similarity (1st 2 days with the novel virtual fence), as did phases three and five (3 days when goats should have come accustomed to the virtual fence). When comparing the SR of phases two and four, the obvious significant difference indicated that the goats were able to handle the boundary shift in phase four appropriately. A similar result was found in Hamidi et al. (2024).

Another parameter that can provide information about the learning process of the animals is the signal duration, as it reflects how fast the animal responds to the acoustic signal. An inexperienced animal would probably not respond immediately to the acoustic signal, which would result in a longer signal duration. In this study, a general decrease in the signal duration over time may suggest a successful association of the acoustic signal and electric pulse. To date, the signal duration has only been analysed in a multipart experiment with Nofence collars and Limousin cattle (Confessore et al., 2022) and in a study with lactating dairy cattle and the New Zealand-based Halter system (Verdon et al., 2024). In both studies, a decrease in the signal duration over time was reported, similar to our findings.

Summarising the results on the signals, the increase in the SR and decrease in the signal duration generally suggest that goats learned to associate the acoustic signal and the electric pulse by avoiding the latter. In Eftang et al. (2022), the SR of naïve goats that were continuously virtually fenced over 5 days increased significantly, proving the successful avoidance of the electric pulse. However, Fay et al. (1989) pointed out that not every animal might be suitable to be virtually fenced, as the learning capabilities and individuality of each animal need to be acknowledged (Lee and Campbell, 2021).

Behaviour

The comparative behavioural analysis was intended to detect differences between the goats which could be caused by the VF system and associated stress (Lee and Campbell, 2021). The results for the main activity of grazing showed no consistent effect of the treatment, as the proportions for grazing differed between the periods. Goats in the VF treatment were observed grazing for a higher proportion in phase two of period one, which could be a natural variation across time as it was not repeated in the second period. The significantly higher proportion for grazing of the goats in the PF treatment in period two could have been influenced by the standing herbage on offer, which was significantly lower in the PF paddocks than in the VF paddocks. It is known that a reduced feed availability leads to an increase in grazing time in livestock (reviewed by Hughes and Reid, 1951; Allden and McDWhittaker, 1970; Gibb et al., 1999). In both periods, it was goat group one to show higher grazing proportions, regardless of the fence system. This goat group contained a higher number of lactating goats. During lactation, animals increase their feed intake and adjust their diet composition (Clutton-Brock et al., 1982; Pulido et al., 2001; Mellado et al., 2005) due to a higher energy demand. These factors, combined with the absence of consistent significant differences, suggest that there was no influence of the fencing system at all. In studies with dairy cows (McSweeney et al., 2020; Verdon et al., 2021a), some deviations in the grazing behaviour could be detected, while in a study with sheep, the percentage of grazing did not significantly differ between phases with and without a virtual boundary (Eftang et al., 2023).

When analysing the lying behaviour, a significantly lower proportion was found for the PF treatment in comparison to the VF treatment in phase four. Less lying in this phase could have been caused by the fence shift and the associated new piece of accessible pasture, which was directly visible for the goats in the PF treatments only. Therefore, the PF goats might have spent more time grazing than lying, especially, since the standing herbage on offer was significantly unevenly distributed in period two. However, the analysis of the grazing behaviour did not show any significant differences between VF and PF for phase four. In a review of Wilms et al. (2024), no effect of the VF system on the lying time of beef and dairy cattle could be calculated and Eftang et al. (2023) could not find any significant differences in the lying behaviour of sheep between phases with and without a virtual boundary. In Marini et al. (2018a), sheep showed significantly less lying after the removal of the virtual boundary compared to a previous control period (without virtual fence), likely due to the increased pasture availability after the restriction of the virtual fence was lifted.

Vigilance behaviour includes an interruption of the current activity and a head lift to allow checking of the surroundings to detect predators, observe conspecifics or locate food, depending on the context (reviewed by Quenette 1990). Vigilance was validated as an indicator of fear and anxiety in several species, including cattle (Welp et al., 2004) and sheep (Lee et al., 2016; Monk et al., 2023) and its frequency is increasing with potential threat (Hochman and Kotler, 2007; Shi et al., 2010).

In this study, the VF treatments showed a significantly higher proportion for standing vigilant than the PF treatments. It is thus likely, that being virtually fenced has led to a higher vigilance in the respective goat group, possibly due to an increased level of insecurity, anxiety, or fear after having experienced electric pulses. Additionally, the acoustic signals could have triggered attention and events of standing vigilant per se.

The proportions for standing vigilant were also significantly higher in phases one and four. In phase one, where the goats were experiencing the acoustic signals and the electric pulse for the first time, the latter triggered an initial fear response (as intended; Lee and Campbell, 2021) and, subsequently, a higher proportion for standing vigilant. When the virtual boundary was shifted in phase four, a SR close to one implies that the goats were able to avoid the electric pulse in most cases. Still, the higher proportion for standing vigilant indicates that the goats were experiencing insecurity, maybe due to the VF signals from conspecifics discovering the new VF line. A potential influence on the vigilance of the goats could have been the extent of the kids' accessible area. The kids of the VF treatments were not restricted by the VF boundary and could therefore, access the area beyond it and move away further from their dams than the physically fenced kids, which were restricted by the physical fence. However, mountain goats with kid at foot did not show more vigilance behaviour (Hamel and Côté, 2008).

This is the first VF study investigating vigilance behaviour and the results suggest it to be a promising indicator related to the affective state of animals in a VF system. More research is necessary to evaluate whether VF increases the vigilance of goats longlasting and under other conditions (e.g. without kids).

No clear influence of the VF system could be proven for the proportions for standing and walking, with different significant effects in various phases. In cattle (Campbell et al., 2017; Verdon et al., 2021a; Hamidi et al., 2022) and sheep studies (Marini et al., 2018a; Eftang et al., 2023), no apparent significant impact of the virtual fence on the time standing and walking (Eftang et al., 2023) was reported.

Faecal cortisol metabolites

Cortisol metabolites have been analysed in VF studies before, especially in faeces of cattle (Campbell et al., 2019; Hamidi et al., 2022; Sonne et al., 2022). However, this is the first study to use FCMs as a stress parameter in goats and to take samples once or twice a day to create a comprehensive stress profile. Similar to other studies (Campbell et al., 2019; Hamidi et al., 2022; Wilms et al., 2024), we could not detect a clear influence of the VF treatment on FCMs but a significant effect of time. The FCM concentrations decreased significantly from phase to phase, as it was observed in Campbell et al. (2019) and Hamidi et al. (2022), reflecting the animals' habituation to the daily experimental procedures in both periods. Furthermore, the significant decrease from period to period when calculating with the base values of period zero shows the animals' general habituation to the handling and the performing persons over the entire experiment. In addition, FCM values may have started at a higher level due to changes in group composition shortly before the experiment, as regrouping was shown to be reflected in higher FCMs in goats for several weeks (Waiblinger et al., 2010). It was noticed, that when significant differences between treatments occurred, the higher values were always found in the same goat group (group one), regardless of the fencing system applied. As reviewed by Palme (2019), the social environment and individual differences influence FCM concentrations. However, the analyses of differences between the two goat groups during the baseline phase could not prove a significant result. This may be explained by either a quicker establishment of a stable social hierarchy after regrouping and thus, lower social stress and FCM concentrations in group two, or a group with treatment interaction (i.e. the two groups reacting differently to the treatment), or only chance differences during the experimental phase.

The significantly higher values of the pm samples are probably due to the handling (Kearton et al., 2019) at noon, as peak concentrations of FCM were measured between 11.3 and 15 h (mean: 13 h) after the acute stressor by Kleinsasser et al. (2010). Besides, it occurred in both groups and, therefore, independently of the fencing treatment. To get a more precise answer to whether the VF system actually caused stress, the faecal sampling should have taken place between two and four am, to follow the timetable presented by Kleinsasser et al. (2010). Nevertheless, the drop in FCM concentrations until morning sampling contradicts a permanently increased stress level as far as assessable with FCMs.

To assess stress comprehensively, a combination of behavioural and physiological indicators is necessary (Terlouw et al., 1997; Palme, 2012). The increased vigilance in the VF treatments suggests higher levels of insecurity and possible anxiety or fear; however, this is not reflected in elevated FCM concentrations.

Limitations of the study and prospects

Problems during the implementation of this study were caused by technical issues on the 1st day (loose batteries) and an unreliable GPS signal. It was not specifically evaluated but the collar activation after leaving the stable (with GPS–inhibiting shelter beacons) took longer on some days, what could have played a role in the two outbreaks, as mentioned above.

The scan sampling of behaviour using a short interval of instantaneous recording proved to be sufficiently sensitive to detect differences in vigilance, despite the risk of missing behaviours of short duration by this method (Martin and Bateson, 2007). However, it does not allow associating this behaviour with the emitted acoustic signals. The allocation of the behaviour to the location within the paddock relative to the distance to the VF boundary was not possible due to the unreliable GPS signal. Both aspects should be considered in the future.

For further studies, we would recommend utilising larger goats to ensure a reliable signal transmission, as long as there is no suitable collar for smaller goats. Furthermore, it would be interesting to see if a more domesticated goat breed would react differently to the VF signals. We also suggest using a study design that allows a longer pasture access and excludes non-collared goats (e.g. kids) to rule out unwanted distractions. Excessive standing herbage on offer should be prevented to encourage the animals to test and interact with the virtual boundary to facilitate the learning process.

A longer study duration would allow identifying possible long-term effects of the technology on goats and, when comparing groups of animals, the conditions should be as equal as possible to increase comparability between the groups. Overall, more research on virtually fenced goats is necessary to, first, confirm the goats' ability to learn the VF system and rule out adverse effects on animal welfare. Secondly, to test the technology in the practical application to verify its potential for e.g. grazing of alpine or mountain pastures.

Conclusion

The analyses revealed no apparent negative effect of the VF system on most of the goats' basic behaviours and FCM concentrations, as certain variations could also be explained by external circumstances like the kids. Furthermore, signs of successful learning were found, what makes the technology potentially usable for applications like alpine grazing. However, a higher occurrence of vigilance behaviour suggests insecurity and potential fear or anxiety in virtually fenced goats, but a possible influence of the kids cannot be excluded. Future research needs to confirm this study's results, ideally including vigilance and further indicators of the affective states of goats.

Supplementary material

Supplementary Material for this article (https://doi.org/10.1016/j.animal.2024.101413) can be found at the foot of the online page, in the Appendix section.

Ethics approval

This study was approved by the Department of Agricultural Education and Agricultural Law of the Office of the Tyrolean Provincial Government (LW_LR-4022/210-2021).

Data and model availability statement

None of the data were deposited in an official repository. The data and models that support the findings of the study are available from authors upon request.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) did not use any AI and AI-assisted technologies.

Author ORCIDs

LW: https://orcid.org/0009-0007-4277-8813.
DH: https://orcid.org/0000-0001-5273-7862.
MH: https://orcid.org/0000-0002-1150-2845.
MK: https://orcid.org/0000-0001-6284-4506.
RP: https://orcid.org/0000-0001-9466-3662.
JI: https://orcid.org/0000-0002-8010-9238.
SW: https://orcid.org/0000-0003-3565-4306.
ME: https://orcid.org/0000-0003-2255-9035.

CRediT authorship contribution statement

L. Wilms: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis. **D. Hamidi:** Software, Formal analysis. **C.H.U. Lüntzel:** Investigation. **M. Hamidi:** Software, Formal analysis. **M. Komainda:** Writing – review & editing, Formal analysis. **R. Palme:** Writing – review & editing, Resources. **J. Isselstein:** Writing – review & editing. **S. Waiblinger:** Writing – review & editing, Resources, Methodology, Conceptualization. **M. Egerbacher:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of interest

None.

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