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Goats are able to adapt to virtual fencing; A field study in commercial goat herds on Norwegian farms

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A B S T R A C T

Virtual fencing technology has been developed over the last decades with the goal of giving farmers a flexible fence solution especially for remote rangeland. The latest technology is based on the use of Global Positioning System (GPS), mobile phone networks and internet applications. During the autumn of 2017 a field study was performed on eight commercial goat farms in Norway by using the Nofence virtual fencing technology. The main aim of the study was to describe the ability of goats to adapt to virtual fencing with three different sets of conditions. The first condition consisted of six groups with a total of 53 goats naïve to virtual fencing, that were introduced to and enclosed by a virtual fence. The second consisted of ten groups with a total of 92 goats already accustomed to virtual fencing being held on their regular pasture enclosed by a virtual fence. The third condition consisted of four groups with a total of 45 goats accustomed to virtual fencing that were moved to or given new rangeland areas enclosed by a virtual fence. All sets of conditions lasted for five days, and the number of audio cues and electric stimuli were automatically registered for all individual animals. A success ratio was calculated based on these measures. All variables were analyzed using a Generalized Linear Mixed Model with either a Poisson or Binomial distribution. The number of escapes were also registered. For the naïve goats, the mean number of audio cues and electric stimuli per goat were reduced from day one to day five, while the success ratio increased. On day one, 22 goats escaped whereas on day four and five no goats escaped. For the accustomed goats, the success ratio was significantly higher than that for the naïve goats, but not different from accustomed and moved. The total number of escapes in this condition was 7. For accustomed and moved, the success ratio was similar to the accustomed goats, but there was large variation across days, also in the number of audio cues. Escapes were only registered in one of the groups. We concluded that goats could adapt to and be confined by virtual fencing in commercial herds, but there were large individual variations as well as variation between groups regarding the number of audio cues and electric stimuli received.

1. Introduction

Virtual fencing is a relatively new technology in commercial use that makes it easier to utilize large pasture areas and remote rangeland. The latest versions of virtual fences use Global Positioning System (GPS) technology and can be easily controlled via an application. Indeed, new accessible pasture areas can be defined within seconds on the farmers' smartphone and transferred via the mobile network to the collars on the animals. The animals are controlled by audio cues and weak electric stimuli to prevent them from leaving the pasture.

In the early 1970's, Peck (1973) patented a virtual fencing system aimed at dogs and cats. Fay et al. (1989) tested the same system on goats and concluded that the system could contain goats in the predefined area, but a few goats were unable to adapt. During the 90's several others developed virtual fencing patents, including Brose (1990), Aine (1992), Rose (1996, 1994), and Quigley (1995). All these previous patents were based on a wire in the ground, but in the end of the 1990's, Marsh (1999) patented the first fenceless system for controlling farm animals based on GPS-technology. During the last decade, more patents and commercial solutions have been issued based on GPS-technology, like eShepherd, Halter, Vence and Nofence.

Fencing livestock by this type of system creates new opportunities and better control of the animals. However, concerns about welfare aspects have been raised, mainly related to stress and discomfort, but also of the animals' ability to learn to avoid the electric stimuli.

A recent review article by Lee and Campbell (2021) reported about

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already applied and possible future methods assessing welfare in cattle and sheep in relation to virtual fencing. The ability of each individual to learn the system is an important factor to reduce stress. Already in 2009 Lee et al. (2009) looked at cattle's associative learning ability to virtual fences when hearing a neutral audio cue before the aversive electric stimuli. They found a higher percentage of correct avoiding behaviors (turning, backing up or stopping), as a response to the audio cue the more sessions animals took part in, suggesting the ability to learn. The results of Umstatter et al. (2015) showed that a virtual fence prevented a herd of ten cows from crossing the established virtual boundaries, while their general and lying behavior remained unchanged, and the authors concluded that the animals learned the fencing system and were not stressed. Effects of virtual fencing on goats have so far been studied only by Fay et al. (1989).

In Norway, goats are normally kept on large rangeland areas during summer (June to September), fenced or free ranging. Goats are known for their ability to climb as well as their high cognitive skills, which makes it challenging to contain them. Free-ranging animals may cause disputes when they enter unassigned grazing areas, and even causing traffic accidents. Virtual fences could be a solution to these challenges, in addition they can prevent both wild and farm animals getting stuck in physical fences.

Nofence AS (Batnfjordsøra, Norway) has since 2011 developed a GPS-based virtual fencing system, which today is the only commercially available for small ruminants. In 2017, the Norwegian Food Safety Authority initiated a pilot trial in commercial herds to gain better knowledge regarding animal welfare when using virtual fencing in practice.

The aim of the study was to compare how goats in commercial herds, with three different levels of experience: (1) naïve to virtual fences, (2) accustomed to virtual fences or (3) accustomed to virtual fences and moved to a new rangeland area, adapted to virtual fencing. We predicted that animals with previous experience with virtual fencing would know how to avoid electric stimuli, and hence have a higher success ratio than naïve goats. We also predicted that gaining access to a new pasture would decrease the success of avoiding electric stimuli the first days, compared to accustomed goats browsing on their regular pasture. Furthermore, we expected that day of study would influence the success ratio for naïve goats as an effect of learning.

2. Materials and methods

2.1. The virtual fencing system

The virtual fencing system used in this study was based on GPS-technology. The collars were the hardware C prototype from Nofence (Fig. 1), developed for goats, and patented in Norway as well as the US. The collar hung under the neck of the goat from two chains with a leather strap at the top. There were solar panels on three sides for charging the batteries. Coordinates for the virtual boundary were defined by the farmers on a smartphone or tablet and were transferred to the animals' collars via the mobile network.

When an animal crossed the virtual boundary, the collar began to vibrate (1–2 s), at the same time as an audio cue started (Fig. 2). The audio cue (2–4.2 kHz) consisted of a tone scale that started at the lowest tone and lasted for a minimum of five seconds and a maximum of twenty seconds, depending on the speed of the animal across the virtual boundary. When the animal turned around upon hearing the audio cue, the tone scale was played in reverse until the animal was back inside the pasture area and the audio cue stopped. If the animal did not turn around as a response to the audio cue, it received an electric stimulus in the neck region (1.5 kV, 0.1 J, 0.5 s duration), after the highest tone was reached. If the animal continued to cross the virtual boundary, the audio cue and electric stimulus were repeated a maximum of two times, after which the animal was registered as escaped. Once registered as escaped, the farmer received a push notification on the mobile application, the collar went into tracking mode and the mechanism for vibration, audio cue and electric stimuli was deactivated. When the animal returned to the pasture area, the system was reactivated automatically, and the farmer received a push notification informing that the animal was back inside the virtual fence again.

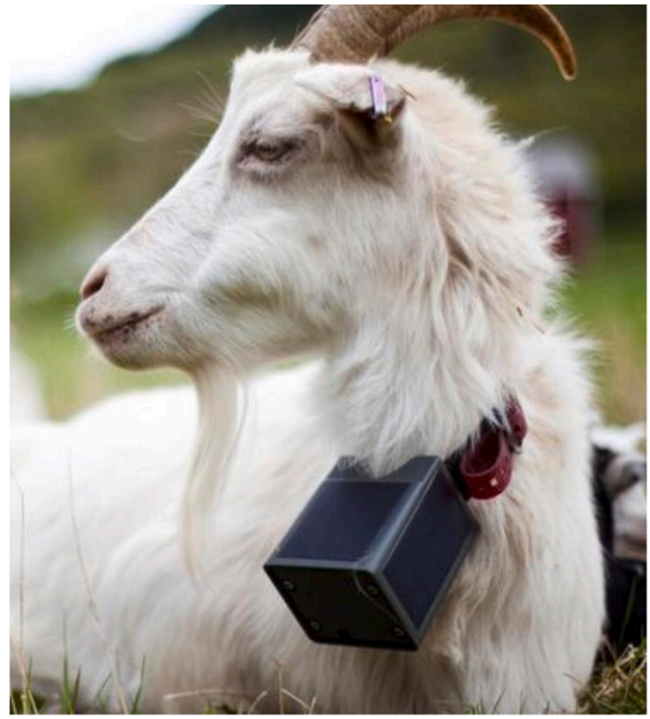

Fig. 1. A goat wearing the virtual fencing technology from Nofence, Hardware C collar (http://nofence.no).

Collar data (date, time, audio cues, electric stimulus, escapes and GPS-coordinates) was transferred from the collars via Global System for Mobile (GSM) to Nofence's server, where it was extracted to MS Excel.

2.2. Selection of farms

The study was conducted during September and October of 2017 and included seven farms in the mountainous areas of the west coast of Norway and one in the south-eastern region. The farms were selected based on their proximity to logistic support, as there was a need for assistance from Nofence with the equipment during the start-up. All the farmers were contacted in advance and a trained observer with a master's degree in animal science visited the animals on their pastures on the first day of the study, together with technical assistant from the equipment provider. The pasture sizes were estimated based on digital map data (for an overview about pasture sizes per goat in each group, see Supplementary material, Table S1).

2.3. Animals and conditions

The animals were followed for five days, and all adult animals in the groups were equipped with collars, as recommended in the user manual, while kids younger than 4 months were not. Some of the goats were used to wearing a collar, and an adaptation period was not considered necessary as the goats did not appear to respond to wearing the collars, neither its weight.

The goats in each group were from the same farm and herd. No individuals were introduced into an already established group. A few of the groups were moved to a new pasture area prior to the introduction of the virtual fence, so an adaptation period of minimum two-days was given to ensure all groups were familiar to their pasture area. This was

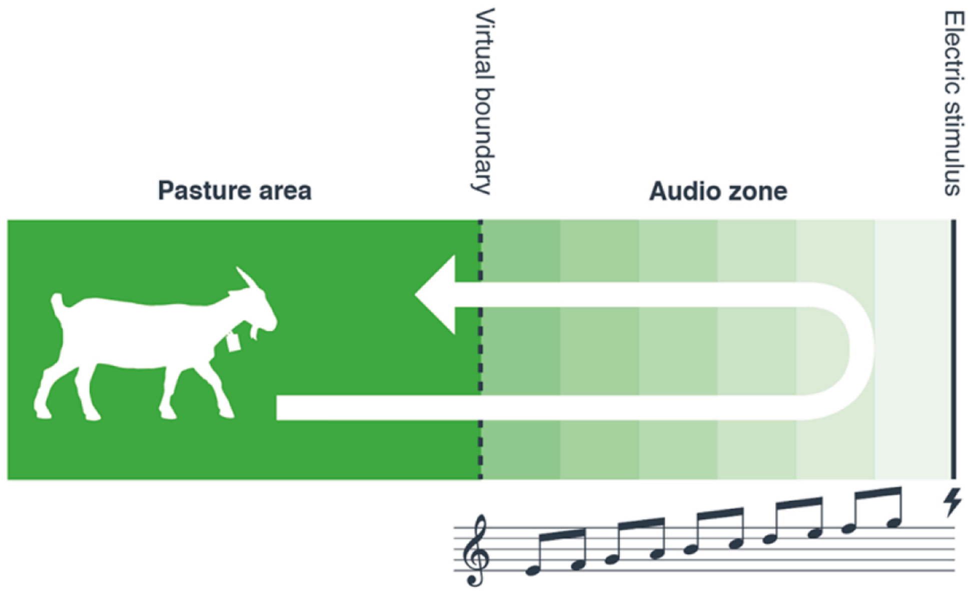

Fig. 2. The collar started to vibrate and play an audio cue when the goat crossed the virtual boundary. If the goat did not turn upon hearing the highest tone, an electric stimulus was given (http://nofence.no).

not the case for the accustomed and moved groups (3.1–3.4) that was followed from day one at their new pastures. All groups were kept on pastures that covered the animals' nutritional needs, so no additional forage was provided.

2.3.1. Naïve: goats naïve to virtual fencing

The condition included six groups of goats from five different farms. A total of 53 goats were introduced to a virtual fence for their first time. The groups consisted of five to sixteen goats, either of Kashmir ($n = 48$) or Boer breed ($n = 5$), aged four months to six years. The pastures were mainly rangeland, and the mean size of the area was 2600 m^2/goat, (range: 500–5700 m^2/goat). The number of virtual boundaries varied from providing a boundary on only one side of the pasture to enclosing the entire pasture, and there was a large difference between the groups in the length of the virtual boundary. For five of the groups, the virtual boundary was set in front of an existing electric fence with a minimum distance of 40 m apart, as recommended by Nofence.

2.3.2. Accustomed: goats accustomed to virtual fencing

The condition included ten groups of goats from eight different farms for a total of 92 goats. The groups consisted of four to twenty goats, either of Kashmir ($n = 65$) or Boer breed ($n = 27$), aged four months to eight years old. The goats' previous experience with virtual fencing varied from five days to more than two years and were therefore considered to be accustomed to virtual fencing. The pastures were mainly rangeland, and the mean size of the area was 4000 m^2/goat (range: 350–15,000 m^2/goat). Four of the pastures were fenced partly by a permanent fence and partly by a virtual fence, whereas six pastures were fenced by a virtual fence only.

2.3.3. Accustomed and moved: goats accustomed to virtual fencing, exposed to a new rangeland area

The condition included four groups of goats from four different farms for a total of 45 goats that were accustomed to virtual fencing and exposed to a new rangeland area. Groups consisted of five to twenty goats of either Kashmir ($n = 25$) or Boer breed ($n = 20$), aged four months to eight years old. Their previous experience with the system varied from five days to more than two years. The pastures were mainly rangeland, and the mean size of the area was 2600 m^2/goat (range: 1400–3950 m^2/goat). In two of the pastures there were partly a permanent fence and partly a virtual fence whereas the two other pastures were fenced by a virtual fence only.

2.4. Technical issues

Some of the collars had technical issues. These appeared to be mainly collars running out of battery, collars that did not connect with the mobile network and hence could not download the pasture area, or collars that stopped reporting, which all caused insufficient data records. Data from 11.3 % (6/53) of the naïve goats, 16.3 % (15/92) of the accustomed goats, and 17.8 % (8/45) of the accustomed and moved goats were excluded from further analyzes due to insufficient data records caused by technical issues. For the number of animals and functioning collars in each group, see Table S1 in the Supplementary material. As the technical issues were discovered after the study was finished, the animals with nonfunctional collars stayed in the groups with the other goats as normal.

2.5. Ethical consideration

As the virtual fencing technology was already introduced at some farms in Norway at the time of the present study, the Norwegian Food Safety Authority initiated the pilot study as part of a documentation process of the technology. The study was not approved the traditional way, as it was developed together with the authorities without assigning any specific approval number. The procedures applied in the study were in concordance with the management practices as well as the Norwegian animal welfare regulations. The animals were closely monitored during the study, both daily at the farm, as well as in the mobile application by both the farmers and the technical team in Nofence. No individuals were removed from the study due to welfare issues.

2.6. Statistics

This field study describes the goats' response, measured by number of audio cues, electric stimulus, and escapes, when kept within virtual fences. Statistical analyses were conducted in R (version 3.6.3, R Core Team, 2021). For data exploration, data manipulation and descriptive statistics, dplyr (Wickham et al., 2018), tidyverse (Wickham, 2017) and pastecs (Grosjean et al., 2018) packages were used. For comparative statistics, including post-hoc tests, car (Fox and Weisberg, 2019), lme4 (Bates et al., 2015), lmerTest (Kuznetsova et al., 2017) and emmeans

(Lenth, 2020) packages were applied. The graphs were created with ggplot2 package (Wickham et al., 2022).

Escapes were too rare for statistical comparison; therefore, only descriptive values of these occasions are given in this paper.

The number of audio cues was compared between conditions and days in a generalized linear mixed model (GLMM) with Poisson distribution. Day (as covariate) and conditions were regarded as independent variables, and their interaction was also included in the model. Group was added as a random factor to control for group effect and repetitions. During the pairwise post-hoc comparisons, day was regarded as a factor with five levels and the Tukey-method was applied to correct for multiple comparisons.

Success was defined as "not receiving an electric stimulus upon hearing an audio cue" (number of audio cues-number of electric stimuli). The success ratio was calculated as success divided by the sum of number of audio cues per day per individual (and so could vary between 0 and 1).

$$Success \quad ratio = \frac{Number \quad of \quad audio \quad cues - Number \quad of \quad electric \quad stimuli}{Number \quad of \quad audio \quad cues}$$

Many of the animals did not receive any audio cues some of the days (15.3 % of naïve goats, 16.6 % of accustomed goats, and 20.0 % of accustomed and moved goats). It was also considered a success "not hearing an audio cue" as the animals did not receive any electric stimuli (Success ratio = 1). To compare conditions with variable experience, we used a generalized linear mixed model (GLMM) with a binomial distribution (with logit link). The success ratio was used as a dependent variable, while day and condition were included as independent variables (separately, as their interaction was found not to be significant and so removed from the final model). Group was used as a random factor. Pairwise post-hoc comparisons were corrected for multiple comparisons with the Tukey-method. For indication of learning within condition, similar GLMM were run with day as an explanatory variable and group as a random factor separately for each condition.

3. Results

3.1. Audio cues

Large individual as well as group differences regarding the number of audio cues were registered. As seen in Table 1, mean number (± SE) of audio cues per animal per day on group level varied between 0.7 (± 0.2) and 39.8 (± 6.6), with an overall mean of 9.4 (± 0.7).

While condition in itself had no effect on audio cues ($\chi^2 = 0.1462$, df = 2, $P = 0.9295$, naïve: 5.49 ± 0.50, accustomed: 12.93 ± 1.31, accustomed moved: 6.95 ± 0.81), day ($\chi^2 = 168.0564$, df = 1, $P < 0.0001$) and interaction day x condition ($\chi^2 = 57.9337$, df = 2, $P < 0.0001$) had a significant effect. The number of audio cues decreased over time (mean ± SE, day 1: 11.47 ± 1.64; day 2: 9.64 ± 1.43; day 3: 11.07 ± 1.56; day 4: 6.71 ± 1.50; day 5: 7.95 ± 1.37).

For naïve goats, there was a drop in audio cues from day 1 to day 2, and day 3 to day 4. Day 5 had higher numbers again, while day 3 was not significantly different from day 2 and day 4. For accustomed goats, there was a drop from day 1 to day 2, and the number of audio cues remained at the same level afterwards, with no significant difference between days 2 and 5. Accustomed and moved goats showed a different pattern. After low numbers of audio cues on day 1, there was an increase on day 2, and again an increase from day 2 to day 3. The number of audio cues dropped on day 4 to the lowest level and increased again on day 5 as shown in Fig. 3. Within the same day, there was no difference between the conditions.

3.2. Electric stimuli

Mean number (± SE) of electric stimuli per animal per day varied

Table 1
Overview of conditions, groups, number of animals with functioning collars, registered audio cues, electric stimuli and escapes. Naïve groups: 1.1–1.6, accustomed groups: 2.1–2.10, accustomed and moved groups: 3.1–3.4.

Condition. Group	No. of collars	No. of audio cues[a] Mean (± SE)	Range of audio cues[b]	No. of electric stimuli[a] Mean (± SE)	Range of electric stimuli[b]	Total escapes[b]
1.1	5	1.0 (± 0.2)	3–7	0.2 (± 0.1)	0–3	0
1.2	12	1.7 (± 0.3)	3–16	0.4 (± 0.1)	0–5	0
1.3	10	8.1 (± 1.1)	20–112	2.3 (± 0.4)	3–27	17
1.4	4	4.3 (± 1.2)	16–29	1.6 (± 0.6)	6–9	8
1.5	3	13.2 (± 5.1)	35–83	5.5 (± 2.9)	11–38	7
1.6	13	7.3 (± 0.6)	23–50	1.5 (± 0.2)	4–15	4
2.1	5	17.4 (± 2.6)	58–182	0.5 (± 0.1)	1–3	0
2.2	11	39.8 (± 6.6)	7–754	0.9 (± 0.2)	0–20	0
2.3	4	2.2 (± 0.5)	6–17	0.1 (± 0.1)	0–1	0
2.4	8	3.3 (± 0.5)	1–32	0.2 (± 0.1)	0–1	0
2.5	6	1.7 (± 0.4)	3–19	0.1 (± 0.1)	0–1	0
2.6	7	17.2 (± 2.6)	39–184	0.7 (± 0.2)	0–8	0
2.7	7	2.5 (± 0.5)	2–38	0.3 (± 0.2)	0–6	2
2.8	13	19.3 (± 3.3)	27–316	1.3 (± 0.2)	0–13	5
2.9	5	0.7 (± 0.2)	1–5	0.1 (± 0.1)	0–1	0
2.10	11	3.0 (± 0.5)	2–29	0.4 (± 0.1)	0–4	0
3.1	6	7.6 (± 1.1)	30–61	0.4 (± 0.1)	0–4	0
3.2	12	3.3 (± 0.5)	5–27	0.4 (± 0.1)	0–3	0
3.3	15	11.1 (± 1.8)	21–165	1.6 (± 0.3)	3–17	18
3.4	5	2.4 (± 0.6)	0–22	0.2 (± 0.1)	0–3	0

[a] Per goat per day.
[b] During the five days period for the entire group.

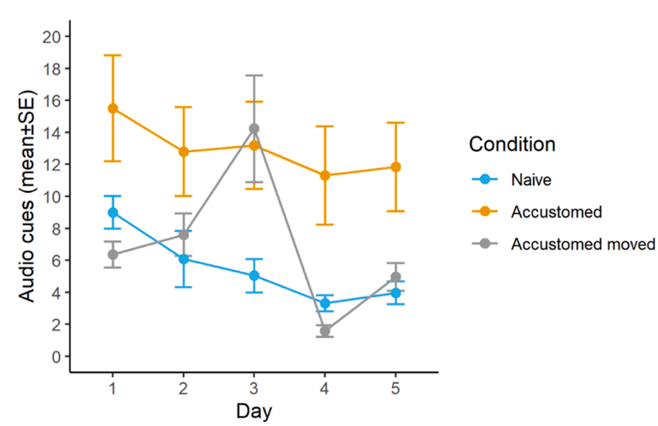

Fig. 3. Daily variation in audio cues among the three study conditions (Condition P > 0.05, Day P < 0.0001, Condition * Day P < 0.0001; post-hoc: no difference between conditions within day on any day).

between 0.1 (± 0.1) to 1.6 (± 0.3) among groups, with an overall mean of 0.9 (± 0.1). In sum, 28 animals did not receive any electric stimuli during the study period (5/47 of naïve goats, 20/92 of accustomed goats and 3/37 of accustomed and moved goats). The maximum number of electric stimuli given to an individual during the period was 38 (one animal in group 1.5).

3.3. Escapes

Of the naïve goats, there were 36 individual escapes among four of the six groups during the five-day period. All the escapes happened within the first three days. Most incidents of escapes occurred when all goats or larger parts of the group escaped at the same time. After a few of the escape episodes the animals were led back into the pasture area by stockmen, but in most cases the animals returned by themselves. The number of escapes was reduced from 22 on day 1 to 11 on day 2, and 3 escapes on day 3. On day 4 and day 5 there were no escapes. Among all groups of accustomed goats, the total number of escapes was 7 for the entire period. In all cases the animals returned to the pasture by themselves.

For the accustomed and moved goats, escapes were only observed in group 3.3 where the total number of individual escapes was 18 for the five-day period. On the first day, 1 goat escaped, but on the second day 15 goats escaped, of which two of the goats escaped twice. After this, there were no more escapes.

3.4. Success ratio

As shown in Figs. 3 and 4, both condition ($\chi^2 = 31.06$, df = 2, $P = 0.0007$) and day of observation ($\chi^2 = 7.11$, df = 1, $P = 0.007$) had significant effects on the success ratio in goats. Naïve goats had lower success ratio (0.813 ± 0.017) compared to accustomed goats (0.913 ± 0.008, $z = -4.931$, $P < 0.0001$) and accustomed and moved goats (0.913 ± 0.012, $z = -3.676$, $P = 0.0007$), while accustomed and moved goats had comparable levels of success ratio ($z = 0.190$, $P = 0.9803$). The success ratio increased with time in general. For naïve goats, the success ratio increased over time ($\chi^2 = 6.3017$, df = 1, $P = 0.01206$), while days did not have any significant effect in the other conditions (accustomed $\chi^2 = 2.4368$, df = 1, $P = 0.1185$; accustomed and moved $\chi^2 = 0.047$, df = 1, $P = 0.7856$).

4. Discussion

To ensure good animal welfare when using virtual fencing, it is important that all animals are able to learn how to respond when

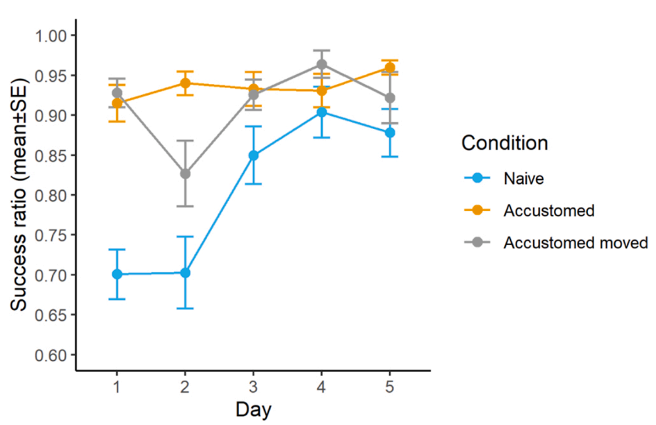

Fig. 4. Success ratio (mean ± SE) in the three study conditions on the different study days (Condition $P < 0.0001$, Day $P = 0.009$, Condition * Day $P < 0.05$; post-hoc: Naïve vs Accustomed $P < 0.0001$, Naïve vs Accustomed and moved $P = 0.002$, Accustomed vs Accustomed and moved $P > 0.05$).

hearing the audio cue to avoid the electric stimuli. Thorpe (1963) defined learning as "that process which manifests itself by adaptive changes in individual behavior as a result of experience". Based on this statement as well as the theory of operant conditioning, we predicted that goats naïve to virtual fencing would learn how to avoid electric stimuli within the five days period. This was supported by a significant increase of success in avoiding electric stimuli during the period, which indicated an associated adaptive response to the audio cue. Several studies on cattle (Bishop-Hurley et al., 2007; Kearton et al., 2020a, 2020b; Quigley et al., 1990; Umstatter et al., 2015), sheep (Jouven et al., 2012, 2019) and one on goats (Fay et al., 1989) have also indicated that animals can learn a virtual fencing system and successfully be confined. However, other studies on sheep could not confirm this (Brunberg et al., 2017, 2015), which result was probably influenced by the study design and technological challenges. As a result of learning, we also predicted that the day of study would have an effect on the success of avoiding electric stimuli, and we registered a significant effect of day for naïve goats. There was an increased success ratio throughout the period as the animals learned how to respond to the audio cue. For the two other conditions there was no effect of day regarding the success ratio, however, there was an effect of day on the number of audio cues for all the three conditions. We assume that the increase in audio cues without similar change in electric stimuli indicates that the audio cue in itself is a neutral stimulus. This change in time may be associated with increased browsing at the boundary after a period of avoidance and as such indicate a decrease in stress level and increase in perceived controllability over the system. The accustomed goats moved to a new pasture showed a comparable success to accustomed goats at their regular pasture. This is an indication that goat do not simply form association between the place and aversion but generalize the learned reaction to the audio cue to new places. It seems that accustomed goats that are moved have learned the virtual fencing system and quickly adapt to new pastures. This is important insight in terms of practical use, for example using the technology for rotational grazing.

Predictability and controllability are of high importance in accordance with the animals` experience of stress, which again is one of the major concerns when using aversive stimuli in animal husbandry. As the animals were introduced to the audio cues and electric stimuli the first times, their perceived predictability and controllability of the situation was probably low (Lee et al., 2018), but as they learned to associate the neutral audio cue to the aversive electric stimuli and their own response, the predictability and the controllability increased. Recent studies focusing on the welfare aspects of learning a virtual fencing system have also highlighted the importance of predictability and controllability (Kearton et al., 2020a, 2020b; Marini et al., 2019). Ewes that received an audio cue in advance of the electric stimulus showed a tendency to decreased reaction, such as ear flick to the electric stimuli over time compared with ewes that only got electric stimulus without preceding audio cue (Marini et al., 2019).

When comparing the results from the three conditions, we found that naïve goats received the least number of audio cues and escaped most during the five-day period. The reason for the high number of escapes being the goats' lack of experience to respond by turning around when they received their first audio cues and electric stimuli. It was also observed that if a group of goats approached the virtual boundary for the first time, and the animal in front ran forward in response to the electric stimulus, the rest of the group followed in the same direction. This was the main reason why several animals escaped at the same time. But, even in these groups, the goats learned to turn when hearing the audio cue with only a few contacts with the electric stimuli. In one of the experienced groups that was exposed to a new pasture, there were also a high number of escapes. In that group, 25 % of the collars had technical issues, due to poor mobile phone coverage in the area, which probably caused the large variation between days for accustomed and moved goats.

Variation in group size and animal density, as well as the length of the virtual boundary may explain some of the large between group variation. Fencing out attractive environments like houses, gardens, hilltops, pastures of better quality and water edges, seemed to increase the likelihood of an increased number of audio cues and electric stimulus, compared to pastures with less attractive areas outside the fence. In two groups of naïve goats, there were individuals that had been climbing the physical fences and escaping on a nearly daily basis before our study. When these animals got their virtual fence activated, they had a higher incidence of escapes compared to their groupmates, but they stopped escaping from the pastures within the first two days. In addition, this field study was conducted on ten different farms, so that environmental conditions such as pasture quality and size, weather conditions, management, as well as the animals' age and breed varied and thus contributed to the large variation between groups. As the learning process may be influenced both by number of exposures to audio cues and electric stimuli, and motivation to leave the fenced area, learning curves may be affected by environmental conditions.

However, the variation in the number of audio cues and success ratio were found to be large not just between, but also within groups. The large individual variation may be explained by a difference in risk taking behaviors. A virtual fencing study by Jouven et al. (2012) grouped ewes into three according to their behavior upon hearing the audio cue, namely number of turns under the training procedure and its change with time. They identified: 1) "followers", characterized by few audio cues and turns with low variation in time, 2) "easy learners", characterized by having many turns at the beginning decreasing over time and 3) "challengers", increasing their turns during the experiment. Indeed, browsing at the virtual boundary may give a fitness advantage, since the grazing pressure is lower and the access to resources is plentiful compared to within the virtual fence after a few days. Individuals browsing at the boundary received a high number of audio cues, but few electric stimuli and therefore had a high success ratio, which indicated that they had adapted well to the system. This coincides with the "Challengers" profile defined in the study by Jouven et al. (2012), characterized by many audio cues. At the same time, Nawroth et al. (2017) raised the hypothesis that observable differences in learning or cognitive skills may be due to individual differences in preference for environmental cues rather than general learning abilities. Another explanation could be that some variation is caused by the fact that some goats are more eager to learn by observing and possibly following others and learn by social learning more preferably than individually. Although goats were found to prefer individual information over social learning in some experiments (e.g., Baciadonna et al., 2013; Briefer et al., 2014; De Rosa et al., 1995), they showed social learning from humans in a spatial task (Nawroth et al., 2016) and followed the gaze of group mates to find food (Kaminski et al., 2005). The "followers" may have learned how to respond when hearing the audio cue by observing other animals. Lambs observing their experienced mothers using or naïve mothers learning a virtual fence did not differ in cues delivered when learning themselves (Kearton et al., 2020b). Individuals with little contact with the virtual boundary were also observed in Marini et al. (2019)'s studies.

A last factor possibly influencing robustness of results, especially the between group variation, is challenges associated with technical issues. The maturity of the technology at the time of earlier studies also seemed to influence on the results, as technical challenges have been registered in several previous studies (Brunberg et al., 2017, 2015; Tiedemann et al., 1999).

Technical issues were registered in 15.3 % of the collars in our study. In groups with a high percentage of technical issues, it was observed that goats with functioning collars tried to follow animals with nonfunctioning collars out of the pasture, and thus received a higher number of audio cues and electric stimuli. The ratio of collared and naïve sheep was also found to have a profound effect of success earlier (Jouven et al., 2012; Marini et al., 2020). When Quigley's patent, based on an ear tag, was tested in 1992 in a two-trial study on cattle, they found a high rate of correct responses (93 %) in the first trial, but a lower success rate of correct responses (67 %) in the second trial interpreted as being due to technical issues (Tiedemann et al., 1999). In other studies, some ewes were observed not to show any reaction to the electric stimuli given (Brunberg et al., 2017, 2015; Tiedemann et al., 1999). This could indicate that the delivery of the electric stimuli did not work properly, that the voltage was not high enough, or that wool could have acted as an insulator if not removed. A recent study performed by Marini et al. (2019) showed that all sheep were sensitive to electric stimuli.

5. Conclusions

We concluded that goats could learn to successfully avoid electric stimuli and be confined by a virtual fence. Goats naïve to virtual fences adapted to the system within a few days, and hence could avoid electric stimuli (increased success ratio), however the learning curve may be influenced by environmental factors and be variable between groups of animals as well as individuals. Goats accustomed to virtual fences moved to new areas adapt to the new pasture earlier, and hence, the virtual fencing system builds associations between audio cue and electric stimuli and does not purely conditions for place avoidance. This is important insight in terms of practical use and indicates that virtual fences can be used both on regular grazing areas as well as in rotational grazing. Well-functioning collars also seemed to be an important factor to reduce the number of audio cues and electric stimuli.

CRediT authorship contribution statement

Each author declares substantial contributions through the following: (1) the conception and design of the study, or acquisition of data, or analysis and interpretation of data, (2) drafting the article or revising it critically for important intellectual content, Please indicate for each author the author contributions in the text field below. Signatures are not required. (1)(2) Silje Eftang, (1)(2) Judit Vas, (1)(2) Øystein Holand, (1)(2) Knut Egil Bøe.

Conflict of interest

S.E. was at the time of the study employed by the Norwegian University of Life Sciences. At the time of the scientific writing, she was employed by Nofence, as an industrial PhD-candidate. These studies were funded by the Norwegian Research Council and Nofence. They had no role in the design of the studies, in the collection, analyses, or interpretation of data; neither in the writing of the manuscript, nor in the decision to publish the results.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Silje Eftang was at the time of the study employed by the Norwegian University of Life Sciences. At the time of the scientific writing, she was employed by Nofence, as an industrial PhD-candidate. These studies were funded by Nofence AS and the Norwegian Research Council. They had no role in the design of the studies, in the collection, analyses, or interpretation of data; neither in the writing of the manuscript, nor in the decision to publish the results.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.applanim.2022.105755.

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