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Research article

Evaluating virtual fencing as a tool to manage beef cattle for rotational grazing across multiple years

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ABSTRACT

Virtual fencing (VF) is a technology drawing attention for the management of grazing livestock under open-range conditions. This study investigated the use of VF collars to facilitate summer rotational grazing of beef cattle heifers and cow-calf pairs. Specifically, we evaluated the ability of cattle to initially learn and adapt to VF technology, and thereafter control their temporal and spatial use of pastures during the grazing season. Two years of rotational grazing were conducted using Nofence VF collars, with cattle also fitted with leg-mounted activity sensors. The first year involved yearling heifers naïve to VF, with the second year using the same animals as first-calf cows with calves. Heifers adapted to VF boundaries in 5–7 days, with an electrical pulse to audio cue ratio (E:A) of 17.9 % (±18.4) during training, decreasing to 5.2 % (±11.2) while rotational grazing. One year later, cows with prior VF experience had an E:A ratio of 1.6 % (±1.1 %) and 2.2 % (±1.6 %) during re-training and grazing, respectively. Cattle remained within VF boundaries more than 99 % of the time, though learning patterns varied by animal cohorts (age/reproductive groups), and among individuals. No associations were found between the number of VF stimuli and animal characteristics or performance. Animals with greater movement, as exhibited by step counts, experienced greater audio cues ($r_s \geq +0.087$), and as heifers, greater electrical pulses ($r_s = +0.21$). Stocking rate had a direct positive association with the frequency of audio cues ($r_s = +0.36$) and electrical pulses ($r_s = +0.25$) for cows, but not heifers. We conclude that cattle can readily learn and be compliant with VF boundaries, and that VF technology can be used to facilitate rotational grazing through the remote movement of cattle among virtual paddocks. Overall, these findings support VF's potential to enhance cattle management flexibility and control forage use, thereby providing an innovative 'fenceless' tool to balance ongoing pasture use with grassland sustainability.

1. Introduction

Globally, approximately 1.57 B cattle (FAO, 2024) rely on 2 B ha of grasslands (Mottet et al., 2017) to supply 39 % of their annual feed (Makkar, 2018). At the same time, grasslands are among the most threatened ecosystems, facing pressures from conversion to crop agriculture and invasive species (Boval and Dixon, 2012), overgrazing (O'Mara, 2012) and climate change (Piipponen et al., 2022). Grassland sustainability relies heavily on grassland management, particularly the spatio-temporal alignment of livestock grazing with ecosystem tolerance and recovery. Therefore, management of grazing cattle plays an important role in grassland sustainability, which typically includes relying on physical fences such as barbed wire, permanent electric, or temporary electric fencing to control cattle distribution in time and space. The type and amount of fencing installed can vary depending on management goals, resources at hand, and the preferred grazing system (Sheppard et al., 2015; Holley et al., 2020). Fence construction and maintenance represents a significant cost in the management of grazing cattle, especially when additional control is desired by the producer (Bishop-Hurley et al., 2007). Moreover, the inflexibility of physical fences limits the ability to respond to naturally changing conditions (Aaser et al., 2022), and negatively impacts wildlife movement and broader ecosystem structure (Jachowski et al., 2014).

Virtual fencing (VF) is an innovative technology proposed as an

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alternative to physical fencing that could reduce the infrastructure cost of cattle management, enhance the efficiency of beef production, and address specific environmental impacts of the cattle industry (Goliński et al., 2023; Hamidi et al., 2023). Several VF systems are in various stages of commercialization, including Nofence (Batnfjordsøra, Norway), Vence (San Francisco, CA, USA), eShepherd (Hamilton, New Zealand), Halter (Auckland, New Zealand), and Monil (Oslo, Norway). Virtual pasture boundaries are set by the application user and downloaded to collars, which uses a global navigation satellite system (GNSS), often referred to as global positioning system (GPS), to continuously track animal locations and administer a combination of audio cues (ACs) followed by electrical pulses (EPs) to train, then confine, animals to targeted inclusion (grazing) areas, which can be changed in real-time (Hamidi et al., 2024). Recent studies have shown that Nofence VF collars are able to perform well, even in northern temperate grasslands and during winter (Harland et al., 2025).

Animal training is an essential first step in VF system use (Umstatter et al., 2015; Hamidi et al., 2024). Cattle must learn to associate an AC with a subsequent EP, and thereby avoid the EP by retreating from a virtual boundary. Several studies have shown that cattle naïve to VF can learn to predict and control the incidence of EPs (Lee et al., 2009; Verdon et al., 2020; Hamidi et al., 2024), although a further understanding of how cattle learn to comply with VF is needed to optimize animal training and the practical benefits of VF. Additionally, it is necessary to investigate how cattle with prior VF experience react to the technology after an extended break between exposures. Within western Canada, approximately 76 % of beef cattle producers rely primarily on supplemental feeding as an alternative to grazing during the winter months from November to April (Sheppard et al., 2015), and this results in extended periods of time up to many months in duration where cattle would not experience VF boundaries.

Current applications of VF include specialized applications of controlled grazing, including the management of encroaching plants, creation of fuel breaks, and protection of sensitive ecological areas (Campbell et al., 2020; Log et al., 2022; Staahltoft et al., 2023; Boyd et al., 2022, 2023). Rotational grazing, a system that utilizes multiple paddocks that are alternately grazed and rested (Allen et al., 2011), is capable of providing substantial ecological and livestock production benefits (Teague et al., 2011; Roche et al., 2015), but factors such as increased infrastructure and labour can be barriers to its adoption (Wang et al., 2020). Use of VF may facilitate increased adoption of rotational grazing and other specialized management by offering greater control and flexibility in grazing, without the associated increase in permanent infrastructure and labour that is unavoidable with traditional fencing (Butler et al., 2006). Studies comparing VF and electric fencing on both sheep (Marini et al., 2022) and cattle (Campbell et al., 2019b) indicate that both methods are similarly effective for containing livestock. Cattle can be contained using VF within static grazing areas, and preliminary studies show cattle adapt well to changing boundaries, though success may depend on cattle behavior and pasture management (Campbell et al., 2017, 2019a, 2021; Verdon et al., 2021; Confessore et al., 2022). This highlights the importance of identifying those specific factors that affect cattle behaviour, and therefore, the success of VF systems.

While VF systems have garnered much interest among practitioners, gaps remain in our understanding of VF use. This includes understanding the trainability of cattle to VF platforms, how cattle adapt to VF over multiple growing seasons, and VF effectiveness for achieving control of cattle under classic rotational grazing. Many studies report successful cattle containment with VF, but fewer studies have examined responses of cows with calves. Boyd et al. (2022) reported that confinement of cows with uncollared calves was lower than that of cows without calves, and no studies appear to examine cattle responses to VF over successive years of grazing (e.g., first as heifers, and then transitioning to cows with offspring), as typically occurs at the farm level. This study explored the utility of VF to manage rotational grazing for beef cattle, first as heifers and then as first-calf cows, thereby approximating conditions representative of a commercial beef cattle operation. More specifically, we: 1) investigated whether heifers naïve to VF learn to comply with Nofence VF, and how first-calf cows with previous VF experience subsequently respond to VF stimuli after an extended break; 2) assessed whether VF can be used to contain heifers and cows with calves at side in virtual sub-pastures while rotational grazing; and 3) evaluated factors that may affect the practical success of VF technology.

2. Materials and methods

2.1. Study area

This investigation was conducted at the Roy Berg Kinsella Research Ranch (KRR), a University of Alberta research facility with a large-scale cow-calf cattle operation located in western Canada, approximately 150 km SE of Edmonton, Alberta (53°0′29.919″N, 111°30′57.833W). The ranch falls within the Aspen Parkland natural subregion and has a cool continental climate, with a mean temperature of 17 °C during July and 391 mm annual precipitation [Alberta Climate Information Service (ACIS) n.d.], of which 70 % falls during summer (May through September). The landscape is rolling hummocky moraine, and beef cattle graze on planted pastures that were once cultivated but have since been seeded to forages such as smooth brome (*Bromus inermis* L.), timothy (*Phleum pratense* L.), and alfalfa (*Medicago sativa* L.).

2.2. Study animals

Cattle examined were Kinsella Composite (KC) crossbred yearling heifers (n = 49) and two KC bulls in 2022, and a subset of these same animals returning in 2023 as 2-yr old first-calf cows (n = 39) with calves at foot aged 2–3 months as of June 1, 2023, and joined by three new KC bulls. These cattle have been uniquely developed at the KRR and are descendants of three synthetic lines, composed mainly of Angus, Charolais, Galloway, Hereford, Brown Swiss, Holstein, and Simmental, which were combined into one synthetic herd by 1994 (Berg et al., 2014). Heifers and cows averaged 371.6 (±20.2 SD) and 432.5 (±32.4 SD) kg head^{-1}, respectively, at the start of grazing. All cattle had originated from the property, and had no experience previously with electric fencing, with all fences comprised of four-strand barb wire.

All cattle handling and VF collar evaluations were conducted under animal ethics protocols approved by the University of Alberta Committee on Animal Care and Use (AUP #3850 and #4004), following guidelines of the Canadian Council on Animal Care (Canadian Council on Animal Care [CCAC], 2009). As part of a parallel study, animals were weighed every two weeks throughout each trial. Grazing took place within small pastures using an intensively-managed rotational system.

2.3. Nofence virtual fencing system

The Nofence VF system has been described previously (see Hamidi et al., 2024; Harland et al., 2025). Briefly, it is comprised of 1) an animal collar featuring bluetooth and mobile network receivers, a re-chargeable lithium ion battery, two (side-mounted) solar panels to facilitate recharging, and a GNSS receiver (Nofence Ltd., 2023); and 2) a mobile phone application that is used to remotely set parameters for virtual pastures, manage animal locations, and monitor collar performance. Network connection is necessary to upload virtual pasture information to collars and exchange messages and notifications between the mobile application (user) and collars (animal). The GNSS receiver provides location data to the collar system, which in turn, is compared to the programmed confinement boundaries and when appropriate, triggers ACs and EPs independent of mobile network connection. The collar uses an adjustable neck strap to remain on the animal. The total weight of the collar is 1446 g. The mobile phone application was used on a Google Pixel 6a phone by the first author, who monitored cattle and managed the VF system.

Details about the VF operation can be accessed from the Nofence Ltd. manual (2023) and Hamidi et al. (2024). Briefly, when an animal approaches the virtual boundary between the inclusion zone (where animals should be) and exclusion zone (where animals should not be), the collar plays a warning AC. The warning is a maximum of 82 dB and varies from a low-pitched tone to a higher-pitched tone. The velocity at which the animal is moving determines the rate at which the audio tone changes, with a total warning duration of 5–20 s depending on animal velocity and how quickly the animal responds. The AC ends when either 1) the animal turns around and the collar records a position that is 1 m away from where the warning was triggered, or 2) when the entire audio tone scale has been played. Once the audio warning is complete, if the animal has not turned away from the virtual boundary, an EP is administered. The delivered EP is between 1.5 and 3 kV, depending on environmental conditions, and the collar unit has a maximum stored power capacity of 0.2 J. If the animal continues into the exclusion zone despite the AC and EP, the collar will continue to deliver ACs and EPs; animals can receive a maximum of three warnings followed by EPs, after which they are considered escaped. Collars of escaped animals do not discharge further ACs or EPs but continue to track location. Once an escaped animal successfully returns to the inclusion zone their collar resumes normal operation. All interactions of the animal with the VF boundary are recorded on the collar, and transmitted to the Nofence server. Data were later downloaded in csv format for summary and analysis.

Nofence VF collars have two modes: operating and teaching. In operating mode animals must return to a location that is 1 m behind where the audio warning was triggered to end the audio warning. In teaching mode the warning is more easily switched off to support animal learning to control the EPs; for example, the audio warning will shut off if the animal moves their head or takes a few steps away from the boundary. While the most recent Nofence Ltd. operating manual (2023) does not describe specific criteria to switch from teaching to operating mode, the 2020 version states that the collar mode will automatically switch from teaching to operating once the animal has correctly responded to 20 audio warnings by avoiding the subsequent EP, which is corroborated by Hamidi et al. (2024). When animals wearing collars are moved to a new pasture, the collars automatically reset to teaching mode.

2.4. Rotational grazing trials

Cattle were confined within, and rotated between, virtual sub-pastures using Nofence VF technology during the summer of 2022 and 2023. Each trial was composed of two phases: training and rotational grazing. Rotational grazing was further divided into grazing periods - discrete periods of time during which animals were contained within sub-pastures delineated by VF within larger, physically fenced pastures (Fig. S1). To move cattle into a new virtual sub-pasture, a remote herding process was utilized. First, the leading edge of the VF boundary was moved forward to include the new pasture area, and as cattle naturally moved into the new area, the rear boundary was pulled in to complete the move. This process typically took less than 1 h to achieve, and often as little as 10 min. Virtual fences were deactivated and cattle were mustered and herded by ranch staff approximately every two weeks for weighing. Water was available *ad-libitum* in all trials, and consisted of dugouts or ponds. In two cases, sub-pasture VF boundaries were adjusted to allow for access corridors to water situated within adjacent sub-pastures that otherwise were protected from grazing; corridors were at least 55 m wide.

The first rotational grazing trial took place from June 24, 2022 to August 30, 2022, using 51 commercial KC cattle (49 yearling heifers and two breeding bulls) naïve to VF. The training phase was 11 days long with an average pasture size of 6.5 ± 3.1 ha, and composed of four progressive phases: i) an initial 24-h acclimation period during which collars were turned off; ii) a five-day period when collars were activated and virtual boundaries coincided with existing physical fences; iii) a two-day period when one virtual boundary was moved 50 m inward from the physical fence; and iv) a three-day period during which the virtual boundary was moved to exclude cattle from half the physical pasture area. Training was followed by a 56-day rotational grazing trial to test the capabilities of Nofence VF to confine heifers within and rotate them between designated inclusion zones (i.e., virtual sub-pastures). The average grazing period length, grazing area, and stocking rate were 7.3 ± 1.5 days, 4.7 ± 0.9 ha, and 2.4 ± 0.8 AUM ha^{-1}, respectively (see Table S2).

The second rotational grazing trial occurred from June 27 to August 16, 2023, with 39 of the original 49 heifers from Trial 1 returning as first-calf cows with calves at side, and thus with previous exposure to VF. Cows were joined by three KC bulls (naïve to VF), and all calves remained uncollared. A 6-h acclimation period was followed by a three-day re-training phase with an average pasture size of 7.2 ± 3.1 ha, where VF boundaries aligned with physical fences for one day, VF boundaries were moved inwards 50 m for one day, and then VF was used to exclude access to half of the pasture for a final day. This was followed by a 46-day rotational grazing period similar to that described in Trial 1. The average grazing period length, grazing area, and stocking rate were 6.1 ± 0.6 days, 3.7 ± 1.5 ha, and 2.6 ± 1.3 AUM ha^{-1}, respectively.

2.5. Cattle activity monitoring

All heifers and cows were fit with an IceQube + activity sensor (Peacock Technologies, Stirling, Scotland, UK) at the start of the grazing season. Activity sensors were placed on the lower left rear leg and collected continuous data on the proportion (%) of time cattle spent lying down and standing, as well as movement patterns through step counts in 15-min binned intervals. Here, we use only information on lying time (as lying and standing time are inversely related) and step counts to relate these behaviors to interactions with the VF boundary. Activity sensors were removed at the end of each grazing trial, and data downloaded for analysis.

2.6. Forage sampling

Standing forage was measured in each VF sub-pasture at the start and end of each grazing period to track changes in biomass and associated grazing pressure, a measure that quantifies the relationship between forage intake and the biomass available within a grazing area at a specific point in time (Allen et al., 2011). During 2022 and 2023, six and four samples, respectively, consisting of annual net primary production (ANPP), were harvested from within a 0.25 m^2 quadrat; sampling locations were randomly chosen, but stratified by topographic position to be representative of the pasture. Litter was discarded and broad-leafed plants (forbs) and graminoids were harvested. Vegetation was dried to a stable mass and weighed. Forage mass values were converted to kg ha^{-1} for statistical analysis.

2.7. Data processing and statistical analysis

All data processing and analyses were performed using the packages available in CRAN repository on R *software*, version 4.4.0 (R Core Team, 2024). Data from Nofence VF collars were compiled throughout training and rotational grazing. Collars transmit data via the mobile network to an online cloud, from which data were downloaded. As described in Staahltoft et al. (2023), collars report five types of messages. '*Warning*' and '*Zap*' messages were sent every time an animal received an AC or EP, respectively, and were used to count the number of VF stimuli cattle received. '*Status*' messages were sent whenever the fence or collar status changed and were used to count the number of escapes and their duration. '*Poll*' messages were received every 15 min and used in conjunction with *Warning, Zap,* and *Status* messages, to calculate the amount of time cattle were contained by VF boundaries. Data were checked for duplicates, and 0.28 % of data were removed. Outliers for all data were identified as observations more than four standard deviations away from the mean.

2.7.1. Virtual fence data

Data on VF use were compiled as the number of EPs and ACs received by each animal per day, with approximately 2.3 % of data removed as outliers. The E:A ratio was computed as the number of EPs divided by the number of ACs received by cattle (no. head^{-1} day^{-1}). Audio cue duration was averaged per head per day, and approximately 0.12 % of data were removed as outliers. The distribution of VF stimuli data was inspected using the *fitdistrplus* package (Delignette-Muller and Dutang, 2015) and visually through histograms, and was observed to fit a Poisson distribution. The proportion of time that cattle spent within intended VF inclusion zones, reported as the inclusion zone frequency (IZF), was compiled per head per day using methods in Staahltoft et al. (2023). The number and duration of escapes were summarized and presented as raw data due to their small sample size.

Throughout both trials there were instances of planned (e.g., animal handling, field tours) and unplanned (e.g., removing cattle from incorrect pastures) human disturbances that impacted cattle behaviour. For the purposes of this study, all collar and activity sensor data were excluded for: 1) handling and weighing events; 2) periods when cattle needed to be moved independent of the VF trial; and 3) anomalous disturbance events, such as field tours and a single severe summer storm in 2022. Bulls were excluded because of their small sample size, one heifer was removed from the study during the training phase because of handling difficulties when weighing, and data for another was removed because of a VF collar connection malfunction. Once data were removed, VF stimuli counts were standardized over the hours of data inclusion per day. Training phase records were excluded for any summaries or analyses that did not require training data, as indicated.

2.7.2. Cattle learning and individual behaviour

Means and standard deviations of the number of EPs and ACs (no. head^{-1} day^{-1}) and the E:A ratio, along with the mean and standard error of AC duration, are reported for the training and rotational grazing phases of each trial, including by cohorts in each trial. The ability of cattle, both naïve to and experienced with VF, to learn to avoid crossing VF boundaries was investigated through the change in EPs, ACs, and the E:A ratio over time, where a decrease in EPs and the E:A ratio indicated associative learning took place (Aaser et al., 2022; Hamidi et al., 2024). Means and standard deviations of daily EPs, ACs, and E:A ratios were presented graphically to visualize changes over time. Data on ACs, EPs, and E:A ratios were summed over each of the training and rotational grazing periods for each animal. All three values were compared between training and rotational grazing using the Wilcoxon signed rank test for paired, non-parametric data. To further represent the change in VF stimuli over time, sums of EPs and ACs for each animal were plotted over five distinct time periods for each trial, including the following: training period (11 days in 2022 and 3 days in 2023), the first 14 days of rotational grazing, the middle period of rotational grazing (28 days in 2022 and 19 days in 2023), the last 14 days of rotational grazing, and for the entirety of rotational grazing. The number of ACs, EPs, and the E:A ratios for heifers in 2022, and cows with calves in 2023, were also compared using Wilcoxon signed rank tests and visualized using scatterplots.

To evaluate individual animal responses to VF exposure, cattle in each trial year were ranked by the total number of EPs they received from most to fewest (Table S1). Data were then graphed and inspected to reveal groupings of VF behaviour both as heifers and cows, with cattle subsequently categorized into high stimuli (HS), moderate stimuli (MS) and low stimuli (LS) cohorts (reviewed in Section 3.1). These cohorts describe the number of EPs and ACs received per head relative to the other individuals. Differences in EPs, ACs, and E:A ratios received by cattle between cohorts, were investigated using a Kruskal-Wallis rank sum test for non-parametric data. Significant Kruskal-Wallis results were followed by *post-hoc* pairwise comparisons using a Dunn's test from the R package *FSA* (Ogle et al., 2023).

2.7.3. Virtual fencing and rotational grazing

The effectiveness of VF for containing cattle within virtual sub-pastures was investigated using IZF, the number of escapes (total and frequency per animal and day), and the duration of escapes. Animal performance metrics of average daily gain (ADG) and pregnancy rate were included to assess the productivity of cattle while under the influence of VF. The mean IZF (no. head^{-1}) for training and rotational grazing periods were compared using Wilcoxon signed rank tests. A Kruskal-Wallis rank sum test followed by a Dunn's test was used to investigate whether the likelihood of being outside of the VF inclusion zone during rotational grazing, as well as cow and calf ADG and cow pregnancy rate, differed between cohorts. Spearman rank correlations from the R package *rstatix* (Kassambara, 2023) were used to investigate associations between cow and calf ADG and pregnancy rate of individual animals, and the EPs, ACs, and E:A ratios received throughout the rotational grazing trials. The Mann-Whitney U test for unpaired, non-parametric data was used to compare the number of EPs and ACs received by pregnant and non-pregnant cattle, excluding data from the training phase.

2.7.4. Factors affecting virtual fence outcomes

Behaviour metrics and select cattle characteristics were used to investigate possible factors associated with the behavioural variation observed between individuals within a VF system. Spearman's rank correlation was used to assess relationships between EPs and ACs, the E:A ratio, and AC duration, against both step counts and lying times. Means and standard deviations of behaviour are presented.

Stocking rate and grazing pressure were used to investigate possible effects of grazing management strategies on VF success. Stocking rate, which describes the number of animals utilizing a specific area of land over a specified time (Allen et al., 2011), was calculated as animal-unit-months (AUM) of cattle per hectare for each grazing period, and is representative of the aggregate forage use within a grazing period (Bedell, 1998). In contrast, grazing pressure is an instantaneous relationship between forage demand and forage mass available in a specific land area being grazed (Allen et al., 2011). Grazing pressure was calculated for each rotational grazing period as the forage demand of the herd with bulls included, computed from live animal weight (derived from the most recent weight measure) and expected forage intake, divided by the forage mass available in the VF sub-pasture. Forage intake was assumed to be 2 % of bodyweight for heifers and bulls, and 2.4 % of bodyweight for lactating cows (Agriculture and Food, 2008). An estimated bodyweight was calculated whenever a scheduled weighing session did not fall within a grazing period. Furthermore, in 2023 calves were included in the calculation of forage demand, with the assumption that calves of median frame size, nursing at median milk yield, each consume approximately 2 kg day^{-1} of dry matter at 4 months age and 3.6 kg day^{-1} of dry matter at 5 months age (Fox et al., 1988). Spearman's rank correlation tests were used to investigate relationships between cattle stocking rates and grazing pressure, with observed EPs and ACs, E:A ratios, and AC duration, for each of the heifer and cow cohorts. Data used were the VF stimuli values summed per head over each grazing period. Summary statistics describing the grazing periods, stocking rate, grazing pressure, forage supply and utilization are presented in Table S2.

3. Results

3.1. Cattle learning of the virtual fence system

The E:A ratio exhibited by heifers during 2022 declined over the course of training and rotational grazing (Table 1; Fig. S2). Compared to day one, the first day of training, the mean E:A rate per day for heifers decreased 15.9 % by day three, 55.4 % by day five, and 93.6 % by day 11 (Fig. S2) - the first day of rotational grazing. Heifers experienced a much lower E:A ratio while rotational grazing than during training (Table 1), which reflected a combination of a lower EP rate and increased AC rate during the rotational period (Fig. 1). Heifers also had a shorter duration of exposure to ACs during the rotational grazing phase when they occurred (Table 1).

One year later, these same animals exposed to VF as cows had markedly different responses. First, while the VF stimuli received by cows still fluctuated (Figs. S3–C), it was at a sharply reduced level relative to the year prior (i.e., Figs. S2–C). Second, the E:A ratio exhibited by cows was relatively low during the re-training phase (Table 1), primarily due to consistently low exposure to EPs (Fig. 1). Despite this, E:A ratios experienced by cows demonstrated a small increase once into the rotational phase (Table 1), primarily due to a doubling of the EP exposure rate (Fig. 1). Cows also experienced a longer duration of the AC (i.e., warning sound) when they occurred while rotational grazing (Table 1).

We found there were three different response patterns evident among animals (Table 2; Fig. 2) to the VF system. Cattle could be categorized into VF behaviour cohorts based primarily on the number of

Table 1
Summary and descriptive statistics for the time cattle spent within inclusion zones, number of escapes, and virtual fence (VF) stimuli received by heifers and cows. Data are summed as VF stimuli and time spent within inclusion zones (no. head^{-1} day^{-1}) and were compared between training and rotational grazing phases within each year using a Wilcoxon signed-rank test for paired, non-parametric data. Means with different letters differ (P < 0.05). Escapes and escape duration are compiled for each grazing trial phase.

Year & Animal Class (no)	2022 Heifers (49)		2023 Cow/calf Pairs (39)	
Trial Phase (number of days)	Initial training (11)	Rotational grazing (56)	Re-training (3)	Rotational grazing (47)
Virtual Fence Compliance				
Mean (±SD) IZF[a] (%)	99.6 (±2.3)^{A}	99.8 (±1.1)^{A}	99.9 (±0.7)^{A}	99.7 (±2.5)^{A}
Escapes, total (no)	23	32	3	39
Escapes (no. head^{-1} day^{-1})	0.043	0.012	0.026	0.021
Cattle escaped (% of herd)	22 (44.9 %)	21 (42.9 %)	2 (5.1 %)	22 (56.4 %)
Mean (±SD) escape duration (min)[b]	114.8 (±91.8)	74.9 (±218.2)	1.4 (±0.7)	137.1 (±235.2)
Virtual Fence Stimuli				
Mean (±SD) EP[c] (no. head^{-1} day^{-1})	1.8 (±1.8)^{A}	0.76 (±1.3)^{B}	0.26 (±0.58)^{A}	0.52 (±0.94)^{B}
Mean (±SD) AC[d] (no. head^{-1} day^{-1})	11.1 (±7.9)^{A}	17.3 (±21.1)^{B}	13.4 (±11.8)^{A}	34.1 (±41.5)^{B}
Mean (±SD) E:A[e] ratio (%)	17.9 (±18.4)^{A}	5.2 (±11.2)^{B}	1.6 (±4.2)^{A}	2.1 (±5.7)^{B}
Mean (±SEM) AC duration (sec head^{-1} event^{-1})	7.7 (±0.1)^{A}	6.0 (±0.05)^{B}	4.0 (±0.1)^{A}	6.4 (±0.06)^{B}

[a] IZF: inclusion zone frequency, describing the proportion of overall time cattle spent within inclusion zones.
[b] Mean escape duration: is the average time that lapsed when an animal moved outside the target containment area, before returning to the sub-pasture.
[c] EP: electrical pulse.
[d] AC: audio cue.
[e] E:A ratio: the frequency of time that an EP was delivered when an AC occurred.

EPs, and secondarily on the number of ACs (Fig. 2, Figs. S2, S3; Table S1) received over the course of each trial. More specifically, 1) high stimuli (HS) cattle consistently received either a higher number of EPs, or a moderate to high number of EPs together with numerous ACs relative to other cattle; 2) moderate stimuli (MS) cattle received a moderate to high count of ACs but only low to moderate EPs; while 3) low stimuli (LS) cattle were those that received low numbers of both EPs and ACs (Table 2, Table S1; Figs. 2 and 3). Heifers and cows within the HS group received an average of twice as many EPs and ACs while rotational grazing, in comparison to MS and LS cattle (Table 2; Fig. 2, Figs. S2, S3). Notably, there were no significant differences in E:A ratio among cohorts, for both heifers and cows (Table 3), although this response remained variable within each cohort. Across all cattle, the smallest number of animals were consistently found within the HS cohort, at 14 % and 13 % of heifers and cows, respectively. Heifers within the HS cohort had greater EPs than the other cohorts, both while training and rotational grazing (Table 3). Moreover, similar to the data for heifers one year prior, rates of EPs were higher for HS cows compared to both the MS and LS cows, particularly while rotational grazing (Table 3; Figs. S3–A). In addition, HS cows received more ACs than MS and LS cows at that time (Table 3), and experienced distinct periods of high and low numbers of ACs (Figs. S3–B). Ten heifers did not return for the 2023 trial, and of the remaining 39 animals, 50 %, 77 %, and 50 % of HS, MS, and LS heifers, respectively, were categorized to the same behavioral cohort as cows in 2023, with a total of 67 % of animals being categorized as the same cohort in both years (Table S1).

The number of EPs received while rotational grazing differed between the same animals as heifers and cows, being lower for cows (mean ± SEM; heifers = 0.76 ± 0.09 EPs head^{-1} day^{-1}, cows = 0.53 ± 0.05 EPs head^{-1} day^{-1}; P = 0.02). In contrast, the mean number of ACs received while rotational grazing was greater for cows than as heifers the year prior (mean ± SEM; heifers = 17.2 ± 2.2 ACs head^{-1} day^{-1}, cows = 34.4 ± 5.2 ACs head^{-1} day^{-1}; P < 0.001), as were E:A ratios (mean ± SEM; heifers = 0.052 ± 0.003, cows = 0.021 ± 0.002; P < 0.001). When EPs, ACs, and E:A ratios were presented graphically for the same heifers and cows (Fig. 3), the MS and LS heifer groups in 2022 received similar numbers of EPs upon return to the VF system in 2023, while HS heifers received fewer EPs upon return in 2023 (Table 3, Fig. 3-A). In contrast, both HS and MS heifers received more ACs upon return in 2023 than in 2022, while LS heifers remained the same (Fig. 3-B). Finally, all animals exhibited lower or similar E:A ratios in 2023 compared to 2022 (Fig. 3-C).

3.2. Cattle containment and performance

Heifers and cows were consistently moved between virtual paddocks using virtual herding in both years, with a total of 15 successful moves conducted. Both heifers and cows with uncollared calves at side spent more than 99 % of their time within the target VF inclusion zones during both rotational grazing trials (Table 1), and heifers tended to escape for shorter durations (~1.25 h) compared to cows (>2 h) while rotational grazing. A limited number of all animals escaped each year (≤22 % of the herd), with relatively few animals demonstrating repeat escapes; only 3 heifers (6.1 %) and 5 cows (12.8 %) escaped more than twice. Additionally, all cattle that escaped returned to the inclusion area on their own without the need of human intervention. Three of 49 heifers (1 MS and 2 LS) and four of 38 cows (all MS; the pregnancy status of one cow was not recorded in 2023) were found to be non-pregnant during pregnancy checks in late fall of each year following VF exposure (Table 4). The number of EPs and ACs received by each animal, and the E:A ratio experienced by cows and heifers, were not correlated with ADG, calf ADG (2023 only), or pregnancy rate (P > 0.05).

3.3. Factors affecting virtual fence outcomes

The duration of ACs experienced by heifers in 2022 was negatively

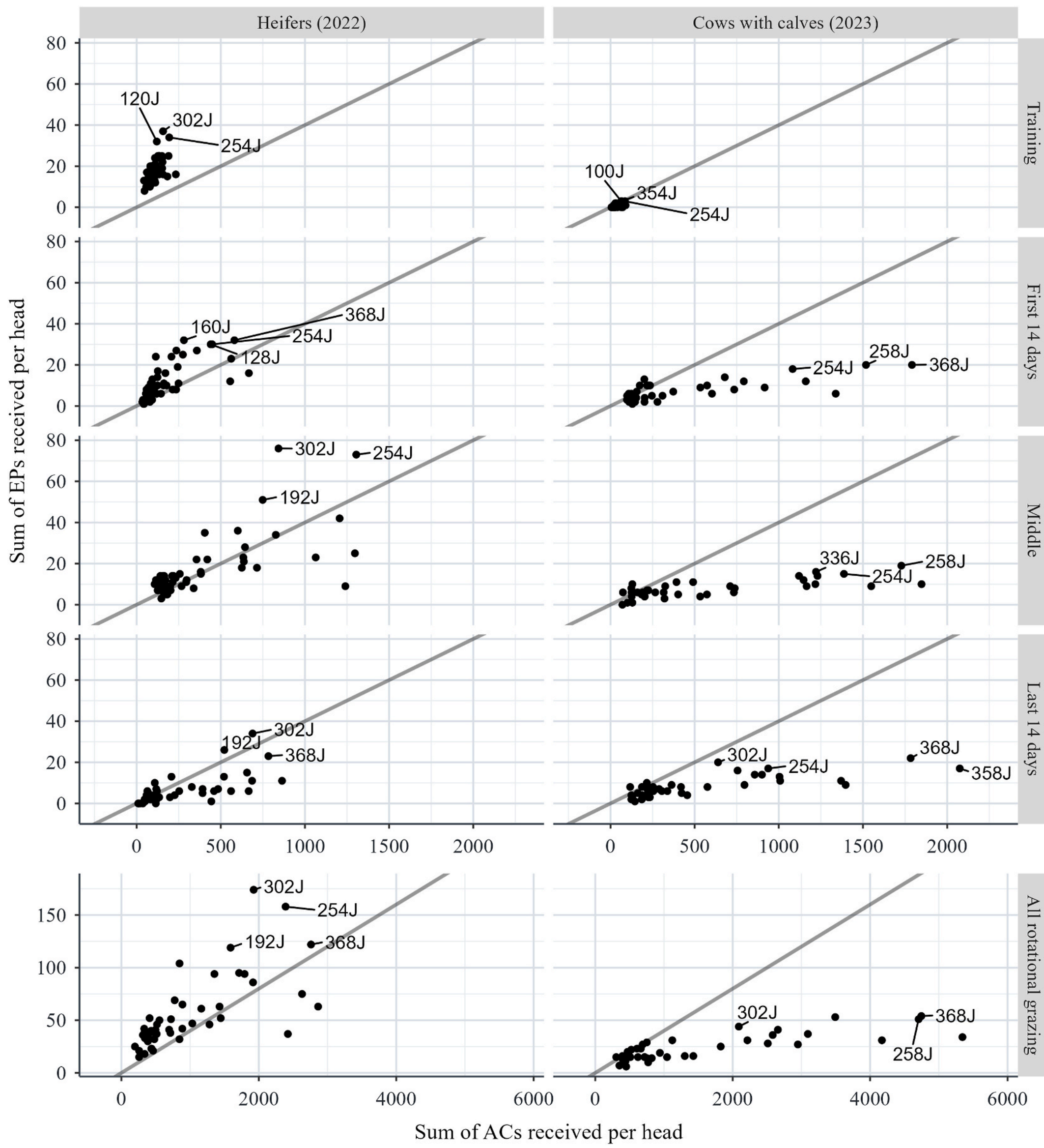

Fig. 1. Comparison of the number of electrical pulses (EP) and audio cues (ACs) received by each animal, summed over consecutive time periods throughout each phase of the grazing trial. The grey line represents a frequency where electrical pulses were received 4 % of the time that an audio cue was received. Individual animals that received the three highest numbers of warnings in each time period are labelled.

Table 2
Mean characteristics of cattle virtual fence (VF) behavioural cohorts, detailing the proportions of each group in relation to the total number of animals in the herd, percentage of total EPs and ACs received, and the average number of ACs and EPs received (no. head^{-1}).

Year & Animal Class (no)	2022 Heifers (49)			2023 Cow/calf Pairs (39)		
Trial Length (d)	67			50		
Cohort	High stimuli	Moderate stimuli	Low stimuli	High stimuli	Moderate stimuli	Low stimuli
Number of cattle (% of herd)	7 (14.3 %)	20 (40.8 %)	22 (44.9 %)	5 (12.8 %)	23 (59.0 %)	11 (28.2 %)
Virtual fence stimuli						
EPs[a] received (% of total)	32.5	40.9	26.5	26.2	59.0	14.9
Mean (±SD) EPs received (no. head^{-1})	124.0 (±28.8)	55.6 (±16.0)	30.9 (±7.7)	48.8 (±5.3)	23.5 (±7.9)	13.5 (±3.9)
ACs[b] received (% of total)	28.3	52.0	19.7	29.4	59.5	11.1
Mean (±SD) ACs received (no. head^{-1})	1862 (±564)	1229 (±697)	379 (±79)	3550 (±1072)	1647 (±1267)	444 (±80)

[a] EPs: electrical pulses.
[b] ACs: audio cues.

correlated with cattle stocking rate ($r = -0.13$, $P < 0.001$), but was positively correlated with grazing pressure ($r = +0.24$, $P < 0.001$). Neither stocking rate nor grazing pressure of heifers were associated with the number of EPs or ACs received per head during each grazing period, or the E:A ratio ($P > 0.05$). The stocking rate of cows with calves during 2023 was positively correlated with EPs and ACs received, AC

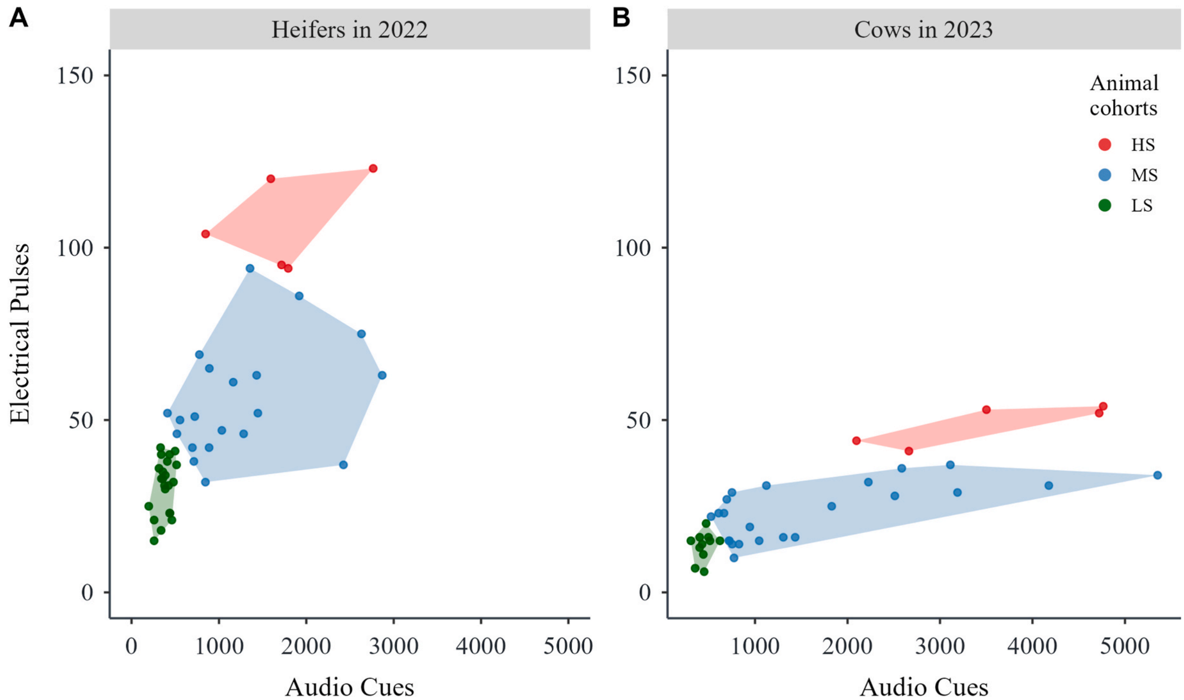

Fig. 2. Overview of the relationship between electrical pulses and audio cues received by each of A) heifers during 2022, and B) the same animals as cows one year later during 2023. Individual cohorts are highlighted as groups of animals with similar likelihood of interacting with the virtual fence, and are denoted as either low stimuli (LS), moderate stimuli (MS) or high stimuli (HS).

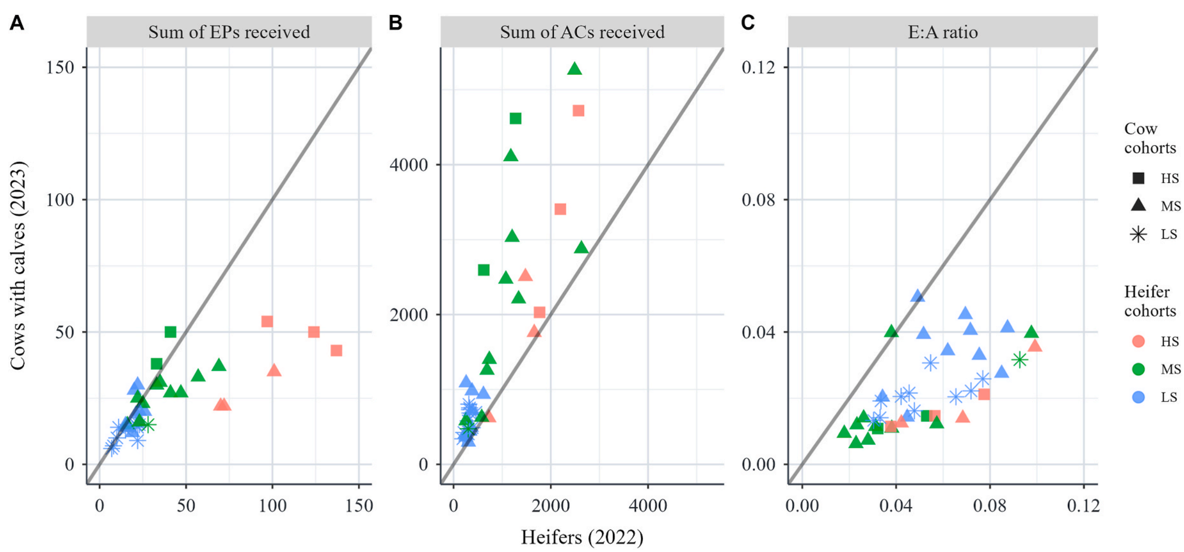

Fig. 3. Comparison of the total number of virtual fence stimuli received by the same animals as heifers in 2022 (x-axis) and one year later as cows in 2023 (y-axis), including for A) electrical pulses (EP), B) audio cues (ACs), and C) the ratio of electrical pulses to audio cues (E:A). All data are stimuli received per head while rotational grazing. High stimuli (HS), moderate stimuli (MS), and low stimuli (LS) cohorts for heifers are identified using different colors, and for these same animals one year later as cows using different types of symbols.

duration, and the E:A ratio (r = +0.36, +0.25, +0.25, and +0.33 respectively, $P < 0.001$). Similarly, grazing pressure from cows was positively correlated with EPs, AC duration, and the E:A ratio (r = +0.094, +0.093, and +0.29 respectively, $P < 0.05$).

No differences in animal step counts or lying time were observed among stimuli groups, for either heifers or cows ($P > 0.05$). The rate of EP and AC exposure, along with the E:A ratio, were all positively related to increasing step counts in heifers during 2022 (r = +0.21, +0.33, and +0.096, all $P < 0.05$), with no association evident between AC duration and step counts ($P > 0.05$). In contrast, lying times of heifers were unrelated to VF interactions ($P > 0.05$). For cows one year later, higher step counts were associated with a greater number of ACs (r = +0.087, $P < 0.05$) and AC duration (r = +0.082, $P < 0.05$), but remained unrelated to EPs and the E:A ratio ($P > 0.05$). Cow lying times were positively related to the number of ACs experienced in 2023 (r = +0.11, $P < 0.05$), but not other VF interactions.

Table 3
Virtual fence (VF) compliance and VF stimuli data compared between cohorts throughout the training and rotational grazing phases during each of 2022 and 2023. Cohorts were compared within each year using a Kruskal-Wallis (K-W) rank sum test for non-parametric data, followed by a Dunn's test for pairwise comparisons. Cohort means within a period and year having different letters differ, $P < 0.05$. Descriptive statistics for escape numbers and durations are presented.

Year & Animal Class (no)	2022 Heifers (49)				2023 Cow/calf Pairs (39)			
Cohort & Animals (no)	High Stimuli (7)	Moderate Stimuli (20)	Low Stimuli (22)	K-W *P* - value	High Stimuli (5)	Moderate Stimuli (23)	Low Stimuli (11)	K-W *P* - value
Training Period Summary								
Training Period Length (d)	11				3			
Virtual fence stimuli								
Mean (±SD) EP[a] (no. head^{-1} day^{-1})	2.7 (±2.2)^{A}	1.8 (±1.7)^{B}	1.5 (±1.6)^{C}	$P < 0.001$	0.6 (±1.1)	0.2 (±0.5)	0.2 (±0.4)	*NS*
Mean (±SD) AC[b] (no. head^{-1} day^{-1})	14.4 (±9.7)^{A}	12.5 (±8.3)^{A}	8.7 (±6.0)^{B}	$P < 0.001$	23.2 (±16.1)^{A}	13.6 (±11.6) ^{AB}	8.5 (±5.8)^{B}	$P = 0.02$
Mean (±SD) E:A[c] ratio	20.3 (±16.7)	17.3 (±17.8)	17.7 (±19.4)	*NS*	1.7 (±3.5)	1.7 (±4.8)	1.2 (±2.9)	*NS*
Virtual fence compliance								
Mean (±SD) IZF[d] (%)	99.4 (±2.7)	99.6 (±2.2)	99.6 (±2.2)	*NS*	99.4^{A} (±1.9)	100 (±0.0)^{B}	100 ^{AB} (±0.2)	$P = 0.009$
Number of escapes	5	8	10	–	10	0	0	–
Mean (±SD) ESC[e] duration (min)	98.5 (±99.8)	122.5 (±96.5)	116.8 (±93.6)	–	1.4 (±0.7)	NA	NA	–
Rotational Grazing Period Summary								
Rotational Period (d)	56				47			
Virtual fence stimuli								
Mean (±SD) of EP (no. head^{-1} day^{-1})	2.0 (±2.1)^{A}	0.7 (±1.2)^{B}	0.4 (±0.8)^{C}	$P < 0.001$	1.1 (±1.3)^{A}	0.5 (±0.9)^{B}	0.3 (±0.7)^{C}	$P < 0.001$
Mean (±SD) of AC (no. head^{-1} day^{-1})	35.9 (±28.4)^{A}	21.6 (±22.5)^{A}	7.0 (±6.1)^{B}	$P < 0.001$	80.4 (±54.1)^{A}	33.9 (±39.3)^{B}	13.5 (±12.5)^{B}	$P = 0.003$
Mean (±SD) E:A ratio	6.7 (±8.6)	4.8 (±10.5)	5.1 (±12.6)	*NS*	1.4 (±1.9)	2.2 (±5.6)	2.0 (±6.8)	*NS*
Virtual fence compliance								
Mean (±SD) IZF (%)	99.73 (±1.42)	99.82 (±1.07)	99.81 (±1.08)	*NS*	99.75 (±1.76)	99.67 (±3.09)	99.88 (±1.04)	*NS*
Number of escapes	10	14	8	–	4	28	7	–
Mean (±SD) ESC duration (min)	116 (±283)	79 (±233)	15 (±11)	–	153 (±238)	149 (±260)	80 (±118)	–

[a] EP: electrical pulse.
[b] AC: audio cue.
[c] E:A ratio: the frequency of time that an electrical pulse was delivered when an audio cue occurred.
[d] IZF: inclusion zone frequency, describing the proportion of total time cattle spent within inclusion zones.
[e] ESC: escape event.

Table 4
Cattle production parameters summarized by behavioral cohorts for each of the heifers and cows with calves at foot. Cohorts were compared within each year using a Kruskal-Wallis rank sum test for non-parametric data. None of the performance metrics differed among cohorts, $P > 0.05$.

Year & Animal Class (no)	2022 Heifers (49)				2023 Cow/calf Pairs (39)			
Cohort & Group Size (no)	High stimulus (7)	Moderate stimulus (20)	Low stimulus (22)	Kruskal-Wallis *P*-value	High stimulus (5)	Moderate stimulus (23)[b]	Low stimulus (11)	Kruskal-Wallis *P*-value
Number of cattle pregnant (%)	7 (100 %)	19 (95 %)	20 (91 %)	*NS*	5 (100 %)	18 (82 %)	11 (100 %)	*NS*
Mean (±SD) cow ADG[a] (kg d^{-1})	0.62 (0.19)	0.56 (0.13)	0.54 (0.16)	*NS*	0.46 (0.19)	0.47 (0.30)	0.51 (0.23)	*NS*
Mean (±SD) calf ADG (kg d^{-1})	NA	NA	NA	NA	1.13 (0.11)	1.13 (0.16)	1.07 (0.12)	*NS*

[a] ADG: average daily gain.
[b] One cow in 2023 did not have a pregnancy status recorded.

4. Discussion

4.1. Behavior of heifers naïve to virtual fencing

Heifers naïve to VF technology learned to navigate VF boundaries using ACs to avoid EPs. The mean number of EPs received by heifers was lower during rotational grazing than training, while the mean daily E:A ratio declined throughout the training phase and into rotational grazing, and the overall mean E:A ratio during rotational grazing was visually lower than during training. In essence, a marked 'learning curve' was evident from the decrease in the mean daily E:A ratio over time (see Figs. S2–C), and highlights that most naïve heifers learned to avoid receiving EPs by day 5 of VF exposure.

These results are consistent with previous VF studies reporting a decrease in the number of EPs and the E:A ratio during successive days after VF deployment. Although the lengths of learning periods vary, several investigations report that learning occurred after two to six days of continuous VF exposure (Campbell et al., 2017; Lomax et al., 2019; Verdon et al., 2021; Confessore et al., 2022). One study even reported that 40 min of training spread over four VF test events was sufficient to observe learning (Colusso et al., 2020), while another reported a two-week learning period (Aaser et al., 2022), and yet another did not report a specific learning period but indicated that the number of EPs and the E:A ratio decreased over time (Staahltoft et al., 2023). Learning period length also may depend on the individual animals' capacity to learn, results supported here, and thus, individual learning should be tracked to determine sufficient training time (Hamidi et al., 2024).

It is notable that the 'learning curve' observed for heifers in the current study was interrupted by a sudden, short-lived spike in the E:A ratio on day 8 (Figs. S2–C), which coincided with the first incidence that a VF boundary did not overlap with a physical fence during training. Hamidi et al. (2024) reported a similar phenomenon where the only time a heifer escaped across a VF boundary occurred when a physical fence was removed from the VF boundary. In the present study, it is possible that the learned association between EPs and ACs made by heifers during the training phase was initially confounded by the visual cue of the physical fence, such that when the visual cue of the fence was removed, heifers may not have recognized the AC as the conditioned stimulus. This phenomenon appeared to be short lived, however, as by day 9 heifers were again avoiding EPs, such that EPs were at similar levels to those seen prior to day 8. Considering the temporary nature of the E:A ratio increase observed in the present study, and similar to the absence of further escapes reported by Hamidi et al. (2024), these results collectively demonstrate that heifers were able to avoid EPs by responding to ACs without the assistance of visual cues, which is supported by similar conclusions drawn by early VF research (Lee et al., 2007, 2009). Ultimately, the results discussed above lead to the conclusion that the naïve beef heifers observed in this study learned to navigate a VF system within five days, although their learning was enhanced by additional time and the ability to experience ACs that did not coincide with a physical fence.

4.2. Behavior of cows with prior virtual fence experience

Heifers from the 2022 trial returned to a VF grazing system in 2023 as cows with uncollared calves at side, after a 300-day period since their last exposure to VF. As the effects of prior VF experience and uncollared offspring are confounded, the results of this study should be interpreted within this context and not as a direct comparison of different cattle age classes. Despite the presence of calves, cows successfully minimized EPs from the first day of the re-training period and throughout the subsequent rotational grazing period. Of note is that cows received fewer EPs per day than they did as heifers, and the E:A ratio was approximately half of what they experienced during their first exposure to VF. As a result, in 2023 there was no clear 'learning curve' as compared to the year prior when the E:A ratio declined markedly over time for the naïve heifers. Equally important perhaps, the low E:A ratio in 2023 occurred despite an increase in ACs, suggesting that cows were further adapting to the VF system as time went on.

While the current study observed the persistence of the AC and EP association over time, such that cattle avoided receiving EPs upon hearing ACs 300 days after their last exposure to VF, other research has not reported similar findings. Verdon and Rawnsley (2020) initially trained heifers naïve to VF at six, nine, and 12 months of age, then re-exposed those heifers to a VF system at 22 months, and compared the behaviour of re-exposed heifers to others that were initially trained at 22 months. They reported that previous training had no effect on the behaviour of heifers that were later re-exposed to VF, with heifers failing to retain their associative learning. This inconsistency between studies could be due to differences in the number of AC-EP pairing events. In the current study, naïve heifers were continuously exposed to VF for 67 days, and individuals experienced a range of 30–124 EPs (i.e. AC-EP pairing events) per head. In contrast, Verdon and Rawnsley (2020) exposed naïve heifers to VF stimuli via four training sessions held over the course of only two days, during which heifers interacted with the fence an average of 10–15 times in total, receiving an EP in 70 %–90 % of these interactions, meaning that heifers experienced an average of only 7 to 13.5 AC-EP pairing events. We postulate that the limited number of AC-EP pairing events experienced by heifers in Verdon and Rawnsley (2020) resulted in a weak or incomplete association between ACs and EPs. Notably, the association between a conditioned stimulus (AC) and the conditioned response (flight or freeze) has been shown to be persistent across time, particularly if the last experience of the conditioned stimulus was paired with the unconditioned stimulus (EP) (Malone, 1990). This means that after a period without VF exposure cattle should react to the AC and avoid the EP provided there was an established AC-EP association, and an AC was paired with an EP before the break from VF exposure. This suggests that cattle could be better 'primed' for success after a break from VF exposure by ensuring that they experience a sufficient number of AC-EP pairing events prior to the conclusion of the initial VF exposure, as was the case here for heifers during the first year of study.

In any case, it is important to understand how cattle react to VF after an extended break from VF use, and that practitioners recognize how to minimize the amount of re-training necessary. Many beef cattle producers in Canada do not graze their cattle for some or all of the winter due to cold temperatures and a build up of snow (Sheppard et al., 2015). It is likely that producers who wish to use VF for grazing management in this region will go weeks or months without exposing their cattle to VF stimuli between grazing periods. The time and labour required to enclose cattle in a small paddock, progressively change VF boundaries, and observe cattle during training, highlights that the training period is one of the most resource intensive aspects of VF use. Information on how much re-training is required, and the best practices while re-training, including potential insight into how to 'prime' animals in preparation for the next grazing season, could assist producers in implementing this new technology. The results of this study on the persistence of the AC-EP association over 300 days are encouraging, though more research on the nature of the association over time is needed.

4.3. Virtual fencing and rotational grazing

Within the context of the pastures and rotational grazing strategies utilized in this study, both naïve heifers and experienced cows with uncollared calves were successfully contained within targeted grazing areas by VF. It has been documented that heifers, steers, dry cows, and lactating dairy cows can be effectively contained by static VF boundaries for over 99 % of the time while grazing (Lomax et al., 2019; Campbell et al., 2020; Langworthy et al., 2021; Boyd et al., 2022; Fuchs et al., 2024). Despite its success in many cases, VF has not been universally effective. Verdon et al. (2021) reported a containment failure when attempting to use VF to keep cattle within designated inclusion zones. The authors attributed this failure to the experimental design, which involved concurrent trials with multiple groups of cattle placed in close proximity. The resulting social interactions of animals may have compromised subsequent containment success.

Rotational grazing of cattle using VF requires that animals respond to ACs rather than simply "learn the location" of each virtual boundary, and thus allow them to actively adapt to dynamic VF boundaries. Previous studies have shown that cattle learn to react to ACs rather than depending solely on visual cues or a boundary "location" to avoid EPs (Campbell et al., 2017; Marini et al., 2018). Heifers and cow-calf pairs in the current study displayed this ability as they could be effectively 'herded', albeit passively, between sub-pastures every four to eight days using VF technology in moves that took less than an hour. We also noted two unique VF applications of cattle management (Harland, 2024). First, in one instance where cattle were moved to the wrong pasture after weighing, the VF system was used to progressively move cattle to the correct location approximately 700 m away using a series of three moves in VF boundaries, which took less than 2 h to complete. Second, where sub-pastures had limited water supply, we maintained access to water using corridors to adjacent water sources, which the cattle consistently adhered to, providing high flexibility in grazing management. These results are supported by other research demonstrating that VF can be used to passively herd cattle and sheep over short distances, strip graze dairy cows, and holistically graze bull calves (Marini et al., 2018; Colusso et al., 2021b; Campbell et al., 2021; Staahltoft et al., 2023). The VF management in these examples is similar to the virtual herding method adopted by the current study, where herding and rotation between sub-pastures relied on the animals' own movement and the subsequent changing of front and/or rear VF boundaries to prevent movement in the wrong direction.

Few studies have directly addressed the ability of VF to contain cow-calf pairs in comparison to those utilizing steers or females unaccompanied by offspring. There are 11.8 million beef cattle in Canada, 80 % of which graze on 18.5 million hectares of grassland, accounting for 30 % of the total farm area in Canada (Sheppard et al., 2015; Statistics Canada, 2022, 2024a). Many beef operations in Canada raise cow-calf pairs (Statistics Canada, 2024a), and it is reasonable to assume that producers who wish to use VF will place collars on cows and leave offspring uncollared. The user manual from Nofence Ltd. (2023) states that a VF collar must be placed on every adult animal in a herd, but also that an animal must have sufficient mental development to understand the VF system, suggesting that VF is not appropriate for young calves. We observed that cows with calves at side escaped more times than they did the year prior as heifers; despite this, VF was more than 99 % effective at containing cows, even when calves were able to freely leave the inclusion area. Our containment rate of lactating cows was generally greater than that observed by Boyd et al. (2022), where cows with calves were less successfully contained (80.6 %) relative to cows without calves (98.5 %), a discrepancy that increased as time passed within the grazing period. Of note is that we are unable to draw direct comparisons between the effectiveness of VF in the heifer and cow trials due to study design and resource limitations, which led to confounding effects of VF experience and the presence of uncollared offspring. Ultimately, the high IZF reported here during the 2023 cow-calf trial indicates cows were effectively contained despite the presence of uncollared calves, and this is supported by Nyamuryekung'e et al. (2023) who concluded that nursing Brangus cows could learn and be contained by VF despite having uncollared offspring. More research on the impact that uncollared offspring have on cows within a VF system will help shed light on best management practices for the use of VF on cow-calf pairs.

The favorable containment of animals within targeted grazing areas is an indication of VF success. However, it is also important to consider possible impacts of VF on animal performance when assessing this technology. While we were not able to compare performance metrics to a non-VF control, results of this study indicate that within each herd there were no negative associations between the number of VF stimuli received and key cattle performance parameters, including pregnancy rate, ADG, and calf ADG. Pregnancy rates in both trials were the same as, or better than, the average Alberta provincial benchmark of 86 % from 2018 to 2022 (Agriculture and Irrigation, 2024). This is consistent with most other research reporting that VF had no affect on ADG and live weight gain (Verdon et al., 2021; Vandermark, 2023; Wilms et al., 2024), milk yield and milk cortisol levels in dairy cattle (Fuchs et al., 2024), and fecal cortisol metabolites in cattle (Campbell et al., 2019b); however, the latter study did observe one cohort of cattle exposed to VF that had lower weight gain than animals confined with electric fence instead.

4.4. Individual variation in behaviour

While all cattle tested were able to learn and adapt to the VF system, high variation was nevertheless observed in the number of ACs and EPs received by individual heifers and cows with calves (Figs. 1–3; Fig. S4). This is consistent with other studies reporting that specific individuals may be more likely to interact with the VF (i.e., receive an AC) than others, and that the E:A ratio received by cattle depends on the animal (Campbell et al., 2018, 2019b; Lomax et al., 2019; Aaser et al., 2022). In this study, the HS cohort was composed of animals more likely to interact with the VF boundaries and receive an EP, similar to the animals identified as "leaders" of VF interactions in other studies (Campbell et al., 2019a; Keshavarzi et al., 2020). Cattle in the MS cohort were more likely to interact with VF boundaries, but remained less likely to receive EPs, while cattle in the LS cohort were least likely to interact with the VF boundaries in general, and also were less likely to receive an EP when they did.

Interestingly, two-thirds of cattle were classified as the same cohort in both years of the grazing trials, suggesting that characteristics specific to each animal played a role in how, and how often, cattle interacted with VF boundaries. Differences in the number of ACs received by cattle may be related to how animals were spatially distributed. Many factors affect cattle distribution and therefore their likelihood of interacting with VF boundaries, which include personality or temperament, social position, age, the presence of offspring, nutritional status, and activity levels (Campbell et al., 2018; Ramos et al., 2021). Bolder animals may be more likely to explore their environment, and therefore encounter VF boundaries more often, while cautious cattle may avoid receiving ACs by observing the behaviour of, and VF stimuli received by, their bolder counterparts (Keshavarzi et al., 2020; Colusso et al., 2020). In the current study cattle within each trial were similar in age, production status (gestating or lactating), and the presence or absence of offspring, suggesting that these were unlikely to cause the variation in ACs among individuals.

Results of this study also showed that step counts and motion indices were positively correlated with the number of ACs received by both heifers and cows. This suggests that more active animals may have been more likely to interact with VF boundaries, and is supported by Staahltoft et al. (2023), who found a moderate, positive correlation between activity and the total number of ACs received by each bull calf in a rotational grazing system. In contrast, other studies have concluded that VF has little to no impact on resting or walking behaviour, and therefore the connection between animal activity and VF interactions should be further investigated (Hamidi et al., 2022; Vandermark, 2023; Wilms et al., 2024; Fuchs et al., 2024), particularly because any increase in animal movement may be caused by interactions with the VF.

The likelihood of an animal receiving an EP following an AC depends on the saliency of the AC, the strength of the association between ACs and EPs, and the reactivity of that animal to an AC. Cattle that have not interacted often with the VF boundary may not have a strong association between ACs and EPs, whereas cattle that receive more ACs typically have had more opportunities to experience an AC-EP pairing event. This is supported by the higher numbers of total ACs received over the course of each trial being associated with a decrease in the daily average EPs and total E:A ratios, and is consistent with the notion that cattle readily adapt to VF through a combination of classical and operant conditioning (Lee et al., 2009). The strength of the reaction of each animal to the AC and whether they are more likely to 'flee' or 'freeze' may also affect how likely they are to receive an EP. Further research should address nuanced relationships between the reactivity of cattle to un-paired ACs and EPs, and their interactions with VF boundaries after training, including the role of activity budgets and associated animal disposition, especially given the wide variation in responses found here among individual animals, which in most cases continued over the course of multiple years.

Although VF has been found to be highly successful at managing cattle distribution, insight into the factors affecting the number of VF boundary interactions and EPs received by individual cattle may help producers select cattle that are likely to be successful within a VF system. While we observed increased VF stimuli (EP and AC) among animals in relation to greater step counts (heifers) and reduced lying times (cows), it is difficult to know whether these VF interactions are an inherent response to animal disposition and activity, or vice-versa. Interestingly, Campbell et al. (2019b) reported reduced lying times in cattle exposed to VF boundaries as compared to electrical fencing. Temperament and personality are already criteria used to breed and cull cows, and understanding how these factors influence behaviour under VF may allow producers to select animals that can be contained by, and adapt to, VF systems. Finally, producers may be able to use data about the number of VF interactions each cow experiences to assess their behaviour within VF systems, and remove cattle that are not well suited to the technology.

4.5. Effects of grazing management factors

Stocking rate and grazing pressure both had an association to cattle interactions with VF boundaries. Stocking rate had a moderate positive association with AC and EP frequency, and grazing pressure had a weak positive association with EP frequency for cows with calves in 2023, although neither were correlated with ACs or EPs for heifers in 2022. Stocking rate can influence the spatial distribution of cattle by leading to more rapid forage depletion, thereby causing animals to spread out in search for forage, which in turn, could increase the number of times they interact with a VF boundary. Increases in stocking rate are known to lead to enhanced competition for resources and more aggressive interactions among cattle (Teixeira et al., 2017), as well as an increase in grazing pressure, which may increase the motivation of cattle to find areas of pasture with more available forage. Both factors may decrease the saliency of ACs in the face of competing motivation, explaining the relationships between stocking rate, grazing pressure, and EPs received, especially by cows during 2023. Higher stocking by cows in 2023 than heifers in 2022 may also explain the increased importance of stocking during the second year.

These results are consistent with prior studies indicating that while feed attractants, restricted feed rations, and increased grazing pressure are generally associated with more VF boundary interactions, VF still contains cattle within target inclusion zones (Campbell et al., 2018, 2020; Colusso et al., 2021a, 2021b), including across a wide range of stock densities and differential biomass utilization levels (Jero et al., 2025). Vandermark (2023) reported similar containment rates of steers using VF across most stocking rates (light, moderate, and heavy), with the exception of a heavy stocking rate in 2022 following a period of drought that reduced forage quantity and quality. Further research should investigate the effects of a wider range of stocking on VF success, including in combination with different grazing systems. Ultimately, despite the effects that grazing pressure and stocking rate had on increasing cattle interactions with VF boundaries, VF remained effective at containing cattle to inclusion zones in both years of this investigation.

5. Conclusions

This study demonstrated that heifers naïve to VF technology were able to learn to comply with VF boundaries within five to seven days, and that the learned associations between audio cues and electrical pulses persisted for 300 days without continuous VF exposure. While there was a high degree of variation in individual animal behaviour under VF, this technology could be successfully used to virtually herd heifers and cows among paddocks while rotationally grazing, even with the presence of uncollared calves. Importantly, there was no evidence that VF stimuli were associated with cattle production parameters. Further opportunities of research include the effects of higher stocking rates on VF success, the influence of temperament and other intrinsic factors, and the possibility that herds of livestock may be controlled by using VF collars on a specific subset of animals. Ultimately, the potential management flexibility of VF, and therefore efficient resource utilization, means this technology could be revolutionary for cattle industries by providing a low cost, highly flexible approach to manipulate where, when and how often cattle graze any given grassland. Additionally, the utility of VF technology will depend on access to high quality information about best practices for selecting animals, training, and deployment of VF to address specific producer goals.

CRediT authorship contribution statement

Alexandra J. Harland: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Francisco J. Novais:** Writing – review & editing, Visualization, Methodology, Formal analysis, Data curation. **Carolyn J. Fitzsimmons:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **John S. Church:** Writing – review & editing, Conceptualization. **Gleise M. da Silva:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Maria C. Londono-Mendez:** Writing – review & editing, Data curation. **Edward W. Bork:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors have no competing interests and nothing to declare.

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Appendix. ASupplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.125166.

Data availability

Data will be made available on request.

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