J. Dairy Sci. 104:7071–7083
https://doi.org/10.3168/jds.2020-19796

Virtual fencing technology to intensively graze lactating dairy cattle. I: Technology efficacy and pasture utilization

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ABSTRACT

Virtual fencing is promoted as the next advancement for rotational grazing systems. This experiment compared the capacity of conventional temporary electric versus virtual fencing to contain a herd of 30 lactating dairy cows within the boundaries of their daily pasture allocation (inclusion zone). Cows were moved each day to a new rectangular paddock that was divided crosswise into an inclusion and exclusion zone by a single linear electric (first 10 d) or virtual (second 10 d) front-fence. A 3-d virtual fence training period separated the 2 treatments. Virtual fences were imposed using a precommercial prototype of the eShepherd virtual fencing system (Agersens Pty Ltd.). Neckband-mounted devices replaced the visual cue of an electric fence with benign audio cues, which if ignored were accompanied by an aversive electrical stimulus. Cows learned to respond to the audio cues to avoid receiving electrical stimuli, with the daily ratio of electrical to audio signals for individual cows averaging (± standard deviation) 0.18 ± 0.27 over the 10 d of virtual fence deployment. Unlike the electric fence, the virtual fence did not fully eliminate cow entry into the exclusion zone, but individual cows were generally contained within the inclusion zone ≥99% of the time. Pasture depletion within the inclusion zone reduced the efficacy of the virtual fence in preventing cows from entering the exclusion zone, but the magnitude of this effect was insignificant in practical terms (i.e., increased time spent in the exclusion zone by ≤28 s/h per cow). This highlights the potential for virtual fences to control grazing dairy cow movement even when pasture availability is limited (i.e., 1 kg of dry matter/cow above a target residual of 1,500 kg of dry matter/ha), but requires confirmation under longer and more complex virtual fencing applications. Within each treatment period, uniform daily pasture utilization (% of pasture consumed above a target residual of 1,500 kg of dry matter/ha) within inclusion zones indicates that cows did not avoid grazing near electric or virtual front-fences. Overall, this study demonstrated a successful simple application of this virtual fencing system to contain a herd of grazing lactating dairy cows within the boundaries of their daily pasture allocation.

Key words: automated technology, associative learning, cattle, paddock usage, resource availability

INTRODUCTION

Grazed pasture is generally the most cost-effective nutrient source in pasture-based dairy systems (Dillon et al., 2008), making it imperative to maximize annual pasture consumption (t of DM/ha) without unduly compromising individual cow performance (Peyraud and Delagarde, 2013). Achieving this requires rotational grazing systems that accurately allocate pasture to minimize wastage (over-allocation) or compromise pasture and cow performance (under-allocation; Fulkerson and Donaghy, 2001; Fulkerson et al., 2005; Roche et al., 2017). Virtual fencing is promoted as the next advancement for rotational grazing systems. It was first used to control the location of livestock in 1987 (Fay et al., 1989) and can be defined as an enclosure, barrier, or boundary without a physical fence (Umstatter, 2011). Virtual fencing offers the possibility for automation of grazing management in real time, enabling the implementation of complex grazing systems to improve pasture and cattle management (Anderson et al., 2014). Other advantages of virtual fencing systems over traditional electric fencing include reduced material and labor costs (Lee et al., 2007), and by reducing manual labor requirements, offer lifestyle improvements and enable more cognitive labor allocation to feedbase management (Anderson, 2007; Anderson et al., 2014). A potential application of virtual fencing is staggering pasture access as cows trickle back after milking to

Received October 15, 2020.
Accepted February 16, 2021.
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achieve more equitable pasture intake (kg of DM/cow) across the herd (Dias et al., 2019).

A recent advancement in virtual fencing is the eShepherd virtual fencing system (Agersens Pty Ltd.). This system uses licensed intellectual property developed by the Commonwealth Scientific and Industrial Research Organisation (Lee, 2006; Lee et al., 2007, 2009, 2010) and is being commercialized for cattle. Virtual fence location is assigned using global positioning system (**GPS**) technology and communicated to cattle using neckband-mounted devices. Neckband-mounted devices replace the visual cue of an electric fence with a benign audio cue, which, if ignored, is accompanied by an aversive electrical stimulation (Lee et al., 2018). Application of this stimuli sequence in response to animal behavior enables cattle to avoid receiving electrical cues by learning to stop moving or turn away from virtual fences when an audio cue is emitted (Lee et al., 2009).

Adoption of the eShepherd virtual fencing system into pasture-based dairy systems requires investigation. Pre-commercial prototypes of this system have been used to control the location of small groups ($n \leq 20$) of grazing dry cattle (Campbell et al., 2019a,b), even when virtual fences were moved (Campbell et al., 2017, 2020; Lomax et al., 2019). While such findings are encouraging, several factors may reduce the efficacy of the eShepherd virtual fencing system in controlling the location of grazing lactating dairy cows. Factors include the (1) higher stocking densities typical of pasture-based dairy systems (25–75 m^2/cow), increasing the probability of animals interacting with virtual fences; and (2) greater motivation of lactating versus dry cows to feed (Egea et al., 2019), with hunger suggested to challenge virtual fence efficacy (Verdon et al., 2020). Quantifying the effects of the eShepherd virtual fencing system on the uniformity of pasture utilization (% of pasture consumed above a target residual of 1,500 kg of DM/ha) is also required, as dry dairy cows have been observed avoiding areas near virtual boundaries (Lomax et al., 2019). Such research is imperative, as pasture consumption is a key profitability determinant (Savage and Lewis, 2005; Van Bysterveldt, 2005; Chapman et al., 2008).

This experiment compared the efficacy of conventional temporary electric versus eShepherd virtual fencing systems to contain a herd of 30 lactating dairy cows within the boundaries of their daily (24 h) pasture allocation (inclusion zone). A second objective was to determine if the efficacy of the virtual fence was subject to within day variation, with progression of time being a proxy for pasture/feed depletion by grazing. A final objective was to determine if use of electric versus virtual fencing changed the uniformity of pasture utilization within inclusion zones. Our companion paper (Verdon et al., 2021) presents data relating to dairy cow production and welfare.

MATERIALS AND METHODS

Ethical Statement

All procedures involving cattle were approved by the University of Tasmania Animal Ethics Committee (A0016943 and A0017449). After 23 d of fitting pre-commercial prototype eShepherd neckband-mounted virtual fence devices, the experiment was terminated (11 d early) due to the development of abrasions on the lower jaw of some cows. Skin abrasions have not been observed in other research or commercial trials using beef breed or nonlactating dairy cattle.

Site Description

This experiment was conducted during mid-spring (September 17 to October 10, 2018) at the Tasmanian Institute of Agriculture Dairy Research Facility (**TDRF**; 41°08′S, 145°77′E; 155.0 m above mean sea level), Elliott, northwest Tasmania, Australia. Daily cold stress index averaged (±SD) 972 ± 41 kJ/m^2 per hour, never reaching the upper threshold of 1,300 kJ/m^2 per hour (Bryant et al., 2007). Daily temperature humidity index values calculated using the NRC (1971) method averaged (±SD) 50 ± 3 and remained below 68, indicating cows were not heat stressed (Zimbelman et al., 2011).

Experimental Design and Treatments

Two temporally separated 10-d treatments consisted of using conventional temporary electric versus virtual fencing to contain a herd of 30 lactating dairy cows within the boundaries of their daily pasture allocation (inclusion zone; Figure 1). Cows were milked twice daily (~0730 and ~1430 h local time) and following afternoon milkings (i.e., every 24 h) moved to a new perennial ryegrass (*Lolium perenne* L.)-based rectangular paddock containing a fresh pasture allocation. Walking distance of paddocks from the milking parlor averaged (±SD) 601 ± 352 m (range, 107 to 1,175 m).

Each paddock was bordered by a wire electric fence (mean voltage, 3.5 kV) and was divided crosswise into an inclusion and exclusion zone by a single linear front-fence (Figure 2). Inclusion zones had a mean (±SD) area of 3,371 ± 963 m^2, length of 100 ± 11 m, and width of 34 ± 9 m. Exclusion zones always represented >24% of total paddock area and had an average area and length of 2,224 ± 936 m^2 and 70 ± 23 m, respectively. During the 10 d of conventional temporary electric fencing

(T_0–T_1), front-fences consisted of a single strand of electrified poly-wire (model G72155, Gallagher Group Ltd.) supported by temporary posts (Speedrite SA023 Pigtails, Tru-Test Ltd.). During the final 10 d of the experiment (T_2–T_3), a virtual front-fence was imposed 24 h/d using a pre-commercial protype of the eShepherd virtual fencing system.

A 3-d virtual fence training period (T_1–T_2) separated the 2 treatments (Figure 1). Training was completed in a 2.2-ha paddock (length 240 m, width 91 m), which was divided crosswise by a single linear virtual front-fence so that the inclusion zone occupied 75% of the paddock. Pasture biomass within the inclusion zone remained above 1,800 kg of DM/ha and differed minimally within the exclusion zone (range, 2,013 to 2,055 kg of DM/ha). At the end of training, all cows had interacted with the virtual front-fence (i.e., received at least one audio cue).

Virtual fencing system hardware consisted of neckband devices (weight, 0.73 kg; dimensions, 170 mm length × 120 mm width × 59 mm height) and a solar-powered base station. At experiment commencement (T_0), trained and experienced Agersens staff fitted a neckband device on each cow that was mounted using nylon straps and maintained on top of the neck using a 1.4-kg hanging counterweight. Each neckband device used uncorrected GPS fixes to determine the cow's proximity to the virtual fence. Neckband devices were turned on for the entire experiment (T_0–T_3), with activation of the virtual fence (T_1–T_3) controlled by a cloud-based web interface that communicated fence location to neckband devices via a wireless radio frequency link (base station).

When a cow breached a virtual fence line (i.e., entered the exclusion zone), the neckband device emitted a distinctive but nonaversive audio cue within the animal's hearing range. No electrical stimulus was applied if the audio cue caused the cow to stop moving or turn away from the exclusion zone. If the cow continued moving into the exclusion zone, the neckband device delivered a short, sharp electrical pulse sequence in the kilovolt range that was lower in energy than an electric fence (exact values of electrical pulses are commercial and confidential). Stimuli sequences were repeated if the cow continued moving into the exclusion zone. Neckband devices logged the incidence (date and time) and duration of virtual fence line crossings (cows entering and exiting exclusion zones), audio cues, and electrical stimuli. Because grazing behavior can mimic a cow correctly responding to audio cues (i.e., movement forward followed by stopping at an audio cue), the algorithm controlling stimuli application contained a grazing function. The grazing function stipulated that if a cow gradually encroached on the exclusion zone, an electrical stimulus was applied after 3 consecutive audio cues. Similar to Campbell et al. (2019a), only one of these audio cues was counted in statistical analyses of stimuli data. Neckband devices ceased emitting all stimuli for a specified time if the cow became nonresponsive; that is, the cow received a specified number of electrical stimuli within a stipulated time frame or the cow was moving above a specified velocity (values are commercial and confidential).

Further virtual fence details are provided in the patent description (Lee, 2006; Lee et al., 2010).

Animals and Ration

The experimental herd consisted of 30 early-lactation multiparous (parity range 2–7) dairy cows (*Bos taurus* L.) that were naïve to virtual herding technology and of mixed age (mean ± SD; 5 ± 1 yr old) and breed (Friesian, Jersey, and Friesian × Jersey). Cows were selected to limit variation in DIM (mean ± SD; 46 ± 5 d), daily milk production (mean ± SD; 26 ± 3 L), live weight (mean ± SD; 474 ± 35 kg), and BCS (mean ± SD; 4 ± 0, 8-point scale). On the seventh day of the virtual front-fence treatment (T_2–T_3), cloprostenol (2 mL/cow of Ovuprost containing 500 μg of the active ingredient; Bayer Australia Ltd.) was intramuscularly injected into each cow as part of the TDRF breeding program. Clinical mastitis necessitated removal of 2 cows from the experiment on the second day of the virtual front-fence treatment. Another cow was removed on the last day

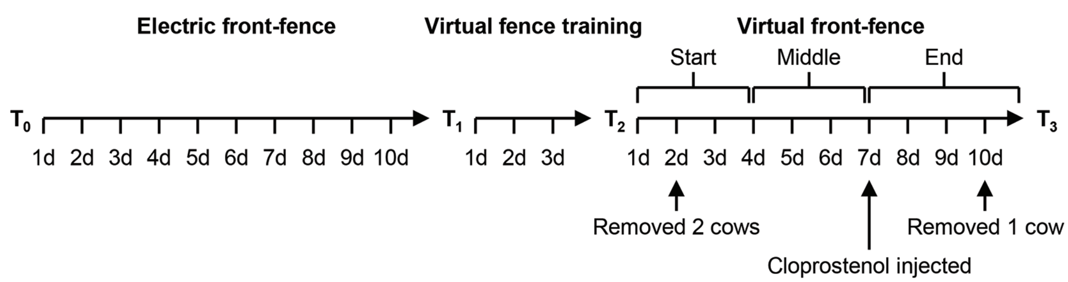

Figure 1. Schematic diagram of the experimental sequence, with T_0 to T_3 signifying key time points.

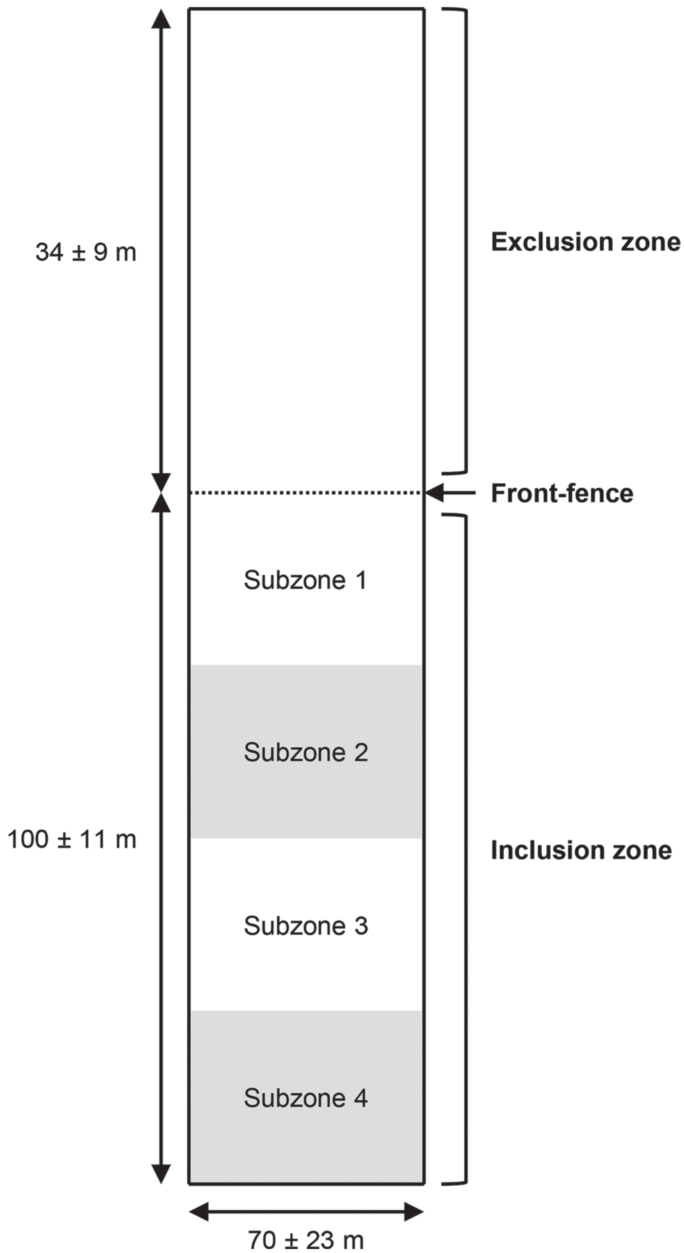

Figure 2. Diagrammatic overview of the paddock layout used to impose conventional temporary electric and virtual front-fence treatments. Pasture utilization within the inclusion zone was monitored in 4 distinct subzones of equal area (i.e., 25% of inclusion zone area).

of the virtual front-fence treatment due to the development of an abrasion.

Cows were fed to requirement (200 MJ/d) based on their known energy requirements (CSIRO, 2007), assuming pasture and supplementary concentrate energy densities of 12 and 12.5 MJ/kg of DM, respectively. Cows entered paddocks at an average (±SD) pregrazing pasture biomass of 2,864 ± 428 kg of DM/ha. Available pasture was allocated at 14.6 ± 1.4 kg of DM/cow per day and consisted of the following: DM, 16.8 ± 1.9%; CP, 21.1 ± 2.5% of DM; TDN, 70.4 ± 1.9% of DM; NDF, 38.7 ± 3.1% of DM; ADF, 21.3 ± 1.6% of DM; ether extract, 3.2 ± 0.4% of DM; starch, 1.7 ± 0.6% of DM; NSC, 15.2 ± 2.3% of DM; and estimated ME, 11.2 ± 0.4 MJ/kg of DM. Supplementary concentrate was initially fed at 1.8 kg of DM/cow per day in the milking parlor, which was equally split between morning and afternoon milking events, and consisted of the following: DM, 90.3%; CP, 14.2% of DM; TDN, 72.1% of DM; NDF, 19.1% of DM; ADF, 10.3% of DM; ether extract, 2.0% of DM; starch, 42.8% of DM; NSC, 47.2% of DM; and estimated ME, 11.6 MJ/kg of DM. Concentrate allocation was increased to 2.7 kg of DM/cow per day on the ninth day of the electric front-fence treatment (T_0–T_1) because the 7-d mean BW of a single cow had declined by 5% since experiment commencement. As this was the highest milk producing cow and both milk production and BW change across the herd was minimal (see Verdon et al., 2021), we suggest that this cow may have had an underlying health issue (subclinical ketosis). Water was provided ad libitum via water troughs within the inclusion zone.

Pasture Allocation and Utilization

Inclusion zone area (ha) was calculated by dividing daily herd pasture requirement (kg of DM/d) by the estimated grazeable pasture biomass (kg of DM/ha; i.e., pasture above a target postgrazing residual of 1,500 kg of DM/ha). In each paddock, pasture biomass was estimated from the average of 150 measurements of compressed pasture height taken with an electronic rising plate meter (Ag Hub F200, Farmworks Ltd.) in a zigzag transect. Within each inclusion zone, pasture utilization was estimated in 4 distinct subzones of equal area (i.e., 25% of inclusion zone area) that divided the inclusion zone lengthwise, with subzones 1 and 4, respectively, closest and farthest from the front-fence (Figure 2). Pasture utilization was calculated as total pasture consumed (kg of DM/ha; pregrazing minus postgrazing pasture biomass) divided by total grazeable pasture (kg of DM/ha). In each subzone, average pregrazing and postgrazing pasture biomass were estimated from the average of ≥50 measurements of compressed pasture height taken in a zigzag transect.

Measurements of compressed pasture height were converted into pasture biomass (kg of DM/ha) using a site-specific linear regression equation (Earle and McGowan, 1979). An initial calibration was completed before experiment commencement, and thereafter refined every 7 d during the experiment. Each calibration involved selecting 5 paddocks at different regrowth stages, with compressed pasture height measured in

20 randomly selected rectangular quadrant (0.09 m^2) samples/paddock. Pasture biomass was then calculated (kg of DM/ha) by harvesting herbage in each quadrant to ground level, which was dried to constant weight at 60°C in a fan-forced drying oven (Unitherm drying oven, S & T Engineering Company). At the end of the experiment, all data from quadrant samples with a pasture biomass between 500 and 4,500 kg of DM/ha were pooled to generate an overall equation:

$$\text{estimated pasture biomass (kg of DM/ha)} = 279.6 \times \text{compressed pasture height (cm)} + 181.8\ (P < 0.0001;\ \mathrm{R}= 0.6;\ \mathrm{n} = 537).$$

Data were pooled to better account for between and within paddock variation. Pooling was possible because (1) pasture remained in the same physiological state (vegetative) during the experiment and (2) data were collected over a short period (36 d) within a single season (spring).

Video Recordings

Video recordings of cow interactions with the electric front-fence were taken between morning and afternoon milking events (mean ± SD, 4.9 ± 0.6 h) on d 4, 6, and 9 of the electric front-fence treatment (T_0–T_1). Four cameras (Hero5, GoPro Ltd.) filmed the entire length of the front-fence, with cows identified by numbers sprayed on both of their sides (Tell Tail Aerosol, FIL). Video footage was viewed to obtain the number of cow interactions with the electric front-fence. Confirmation of electrical stimuli emitted by the electric front-fence was based on physical contact between the cow and fence followed by an adverse behavioral reaction (retreat from fence, shake head, cessation of previous activity along with a rapid postural change, jump, or vocalization; Verdon et al., 2020). These data were compared with the number of stimuli delivered to cows on comparable days and times by the virtual front-fence (see Verdon et al., 2021).

Statistical Analysis

Logistic regression was used to evaluate if cows learned to respond to the audio cues and avoid receiving electrical stimuli during the virtual fence training period (T_1–T_2). Similar analyses have previously been conducted for beef cattle (Lee et al., 2009; Campbell et al., 2018, 2019a) and sheep (Marini et al., 2018a,b). A data set was generated for each cow consisting of audio event number paired to the binary variable, event outcome. Event outcome was 0 if the audio cue was not followed by an electrical stimulus and 1 if it was followed by an electrical stimulus. Paired data sets for 26 of the 30 cows were analyzed by fitting a logistic regression curve to the data using the nonlinear least square function in the R statistical software package (version 4.0.0; https://www.r-project.org/). Omission of 4 animals resulted from 2 cows never receiving electrical stimuli during the virtual fence training, and neckband device logging failure for another 2 cows. A general logistic curve of the form

$$\pi = a + \frac{c}{1 + \exp\left[-b\left(x - m\right)\right]},$$

was fitted where π is the probability that the audio cue was followed by an electrical stimulus (i.e., event outcome is 1), a is the lower asymptote, $a + c$ is the upper asymptote, b is a slope parameter, and m is the point of inflection. A negative slope parameter indicates a reduction in the proportion of cows receiving electrical stimulus with repeated audio cue events. The upper asymptote is then the proportion of naïve cows receiving an electrical stimulus after their first audio cue, whereas the lower asymptote is the proportion of cows still receiving electrical stimulus after a learning period. The midpoint of the curve between the upper and lower asymptotes is the point of inflection, which is the mean number of audio events required for half of the herd to respond to audio cues alone. As no constraints were applied when fitting the logistic curve, asymptotes could be outside of the meaningful range of 0 to 1 and the slope parameter could exceed 0.

Boxplots were used to describe the distribution of data collected across all cows and virtual front-fence treatment days (T_2–T_3) for time spent in the exclusion zone/cow per 24-h day, count of audio cues and electrical signals received/cow per 24-h day, and ratio of electrical to audio signals/cow per 24-h day. Generalized linear mixed models (GLMM) in the SPSS statistical software package (SPSS Version 26.0, SPSS Inc.) were used to analyze the time spent in the exclusion zone and count of both audio and electrical signals expressed on an hourly basis. For each daily (24 h) pasture allocation, data analyzed were restricted to the first 4 h of paddock time following both afternoon and morning milking events, hereafter termed grazing period 1 and 2. This decision was made on the basis that pasture availability would be greater in grazing period 1 (cows first entry into the paddock) and thus this assessment could be used to determine the effects of pasture availability on virtual front-fence efficacy. Comparison between grazing periods was permitted by cows being in a similar state at the start of both grazing periods (i.e., cows had recently been milked and received concentrate). Diurnal effects on grazing behavior were also considered, with cows due for a major grazing bout at the start of both grazing periods (Supplemental Figure S1, https://figshare.com/articles/figure/Grazing_bouts_tiff/14214392).

Analyses included individual cows as the unit of analysis and the fixed effects of grazing period (1 or 2), hour since entry into paddock (1, 2, 3, or 4) and day block [start (d 1–3), middle (d 4–6), and end (d 7–10)] and their 2- and 3-way interactions. Only hours that cows were present in the paddock for ≥45 min were retained, resulting in the omission of data collected during the final hour of the second grazing period on d 2 of the virtual front-fence treatment (T_2–T_3). An additional 16 full missing days of data across 2 cows (i.e., 8 d/cow) and one partial missing day of data for one cow resulted from neckband device logging failure and removal of 3 cows due to health conditions (Figure 1). Days were clustered into day blocks to account for changes as cows adjusted to grazing with the virtual front-fence, with the end period nominated to take account for any behavioral change resulting from the cloprostenol injection (Figure 1).

All analyzed variables were assessed for normality using a combination of visual methods (quantile-quantile plots and histograms) and the Shapiro-Wilks normality tests. Time in the exclusion zone underwent a $y = \log_{10}(x + 1)$ transformation before analysis so that residual variation was homogeneous between grazing periods and day blocks. Logarithmically transformed time in the exclusion zone data was analyzed with a normal distribution and identity link. A Gaussian distribution and identity link were used for data relating to the count of both audio and electrical signals, as data sets were skewed toward larger positive values. As these distributions exclude data equal to zero, all zero cases were entered as 0.000001 before analysis. Each GLMM accounted for repeated observations of cow over hour, grazing period, and day block with a scaled identity or first-order autoregressive matrix covariance, based on the structure with the lowest Akaike information criteria scores. Nonsignificant interactions were removed from the model so that the main effects could be better interpreted.

A linear regression modeling framework was used to analyze pasture utilization data for both the electric and virtual front-fence treatments, which included a random effect for each unique cluster of paddocks situated within close geographical proximity, thus obtaining temporal replication for each front-fence treatment. Diagnostic plots of model residuals were examined to assess validity of modeling assumptions, such as adhering to the Gaussian distribution and homogeneity. However, no transformation was required. Main effects of front-fence treatment (electric vs. virtual front-fence), day of front-fence treatment (0–10), inclusion subzone (1–4), and their interactions were included in the analysis. Nonsignificant terms were removed from the model. The PROC MIXED and PROC PLM functions in SAS for Windows Release 9.3 (SAS Institute Inc.) were used for analysis and post hoc tests, respectively.

Unless otherwise stated, differences discussed are significant at $P < 0.05$.

RESULTS

Learning the Virtual Fence (T_1–T_2)

Figure 3 shows the logistic curve used to model the relationship between the proportion of cows receiving an electrical stimulus following an audio cue and audio event number during the virtual fence training period (T_1–T_2). The logistic model fitted the data well until the ninth audio event (i.e., observed proportions of cows receiving electrical stimulus after an audio cue were close to the fitted line; Figure 3). Concurrent increases in audio event number and the spread of observed proportions resulted from fewer cows interacting with the virtual fence, which increased the error associated with observed proportions. The logistic model showed that cows on average required 3 audio events (point of inflection, 3.12) to form an association between audio cues and electrical stimulus and approximately 5 audio events to complete the learning period. Over the learning period the percentage of cows receiving an electrical stimulus following an audio cue significantly declined from 65% (upper asymptote, 0.65) for naïve cows to 32% (lower asymptote, 0.32) for trained cows ($t_{(215)} = 2.28$, $P = 0.02$). Once the lower asymptote was reached, the number of cows testing the virtual fence and therefore receiving audio cues rapidly declined.

Electric Versus Virtual Front-Fence Efficacy

Cows were never visually observed in the exclusion zone over the 10-d electric front-fence treatment (T_0–T_1). Neckbands registered cows entering the exclusion zone on average (±SD) 3.3 ± 2.9 times/cow per 24-h day over the virtual front-fence treatment (T_2–T_3), but this equated to an average (±SD) duration of only 5 ± 15 min/cow per 24-h day or 0.4 ± 1.3% of time spent in the paddock (Figure 4a and b). On 90% of occasions cows spent ≤12 min/24-h day in the exclusion zone (≤1.00% of paddock time), with 50% of observations ≤0.4 min/cow per 24-h day (≤0.03% of paddock time).

Cows received fewer aversive electrical stimuli when an electric versus virtual front-fence was used. Video recordings taken between morning and afternoon milking events on 3 d of the electric front-fence treatment only captured one instance of a cow receiving an electrical stimulus, which was effective (i.e., cow received no further stimuli). Comparable recordings over the virtual front-fence treatment captured 13 instances of cows receiving electrical stimulus (spread across 11 cows) and 91% of these instances were effective (see Verdon et al., 2021). Audio cues outnumbered electrical stimuli, indicating cows generally responded to the benign audio cues alone and avoided receiving electrical stimuli (Figure 4c). Over the 10-d virtual front-fence treatment, cows on 90% of occasions received ≤8 audio cues and ≤2 electrical stimuli/cow per 24-h day, whereas cows on 50% of days received no electrical stimuli. Omission of additional grazing function audio cues increased the overall ratio of electrical to audio signals for the experimental herd over the entire 10-d virtual fence treatment (T_2–T_3) from 0.14 to 0.22. Daily ratio of electrical to audio signals for individual cows averaged (±SD) 0.18 ± 0.27 and was 0 on 50% of occasions and seldom exceeded 0.5 (90th percentile; Figure 4d).

Statistical analyses of data logged during the virtual front-fence treatment (T_1–T_2) were restricted to the 2 distinct 4-h grazing periods following twice daily milking events. Grazing period only affected the time cows spent in the exclusion zone at the start and end of the 10-d virtual front-fence treatment (Table 1). At these times, cows spent an average of 18 to 28 fewer seconds in the exclusion zone during the first hour of grazing period 1 than grazing period 2. Effects of grazing period on the number of audio cues received by cows were explained by the interactions of day block × grazing period ($F_{2,633} = 4.276$, $P = 0.014$) and grazing period × hour since entry into the paddock ($F_{3,633} = 5.198$, $P = 0.001$; Table 2). Only at the start of the virtual front-

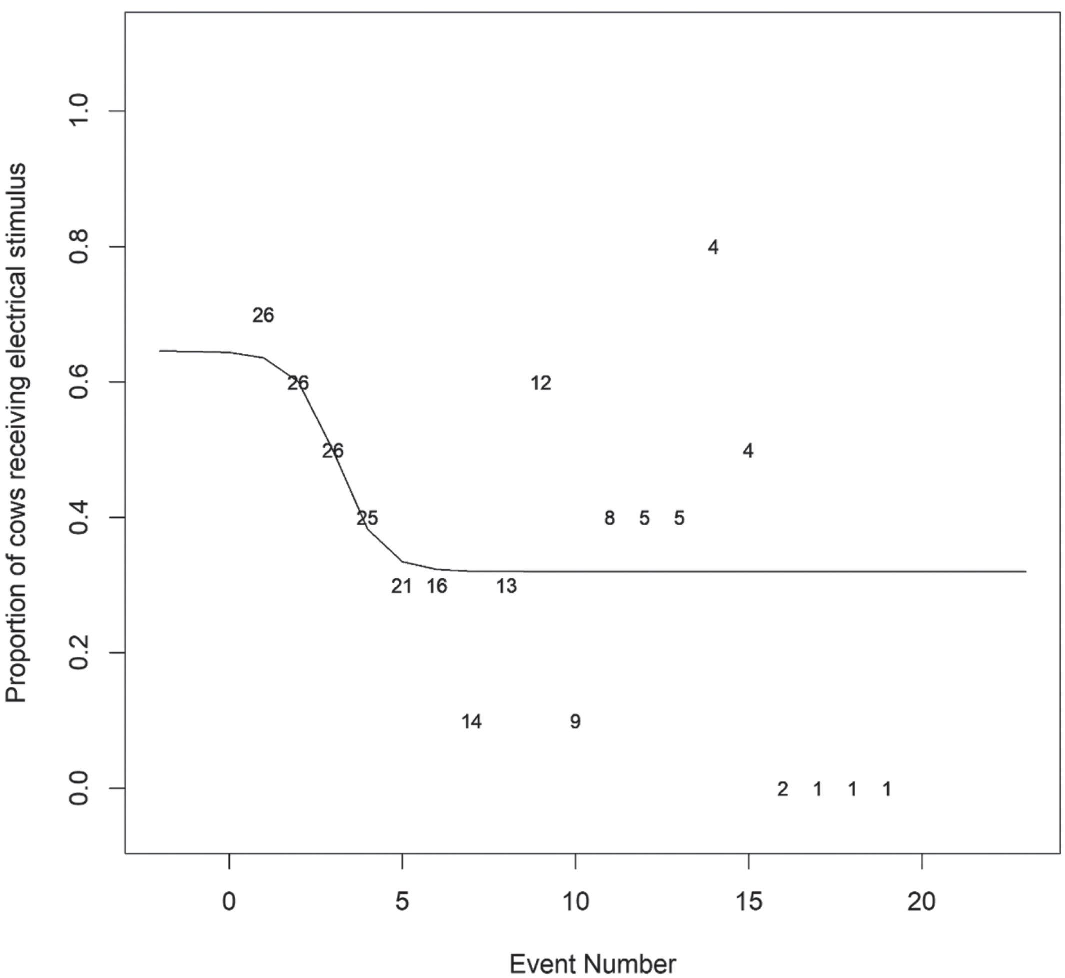

Figure 3. Logistic regression curve for the relationship between the proportion of cows receiving an electrical stimulus following an audio cue and audio event number. The curve was generated from data collected over all 3 d of the virtual fence training period (time points T_1–T_2) for 26 of the 30 cows. Numerals are the number of cows receiving an audio cue for each audio event.

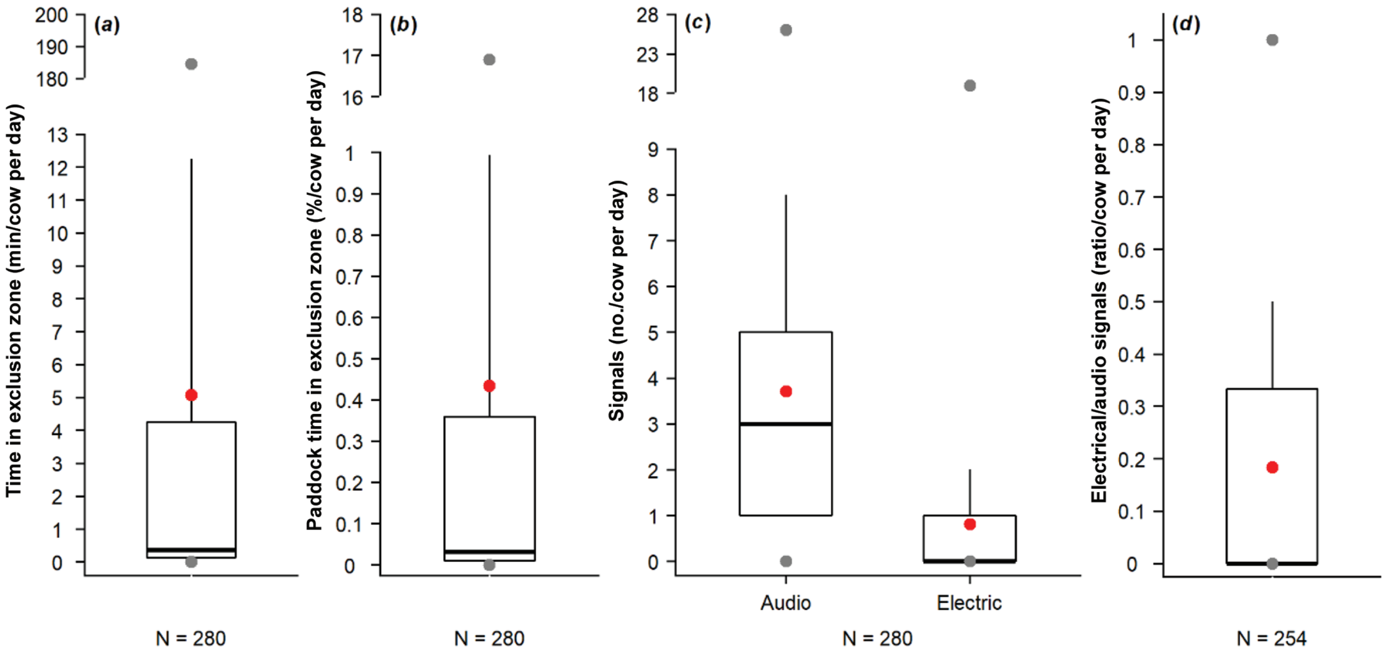

Figure 4. Boxplots show the distribution of neckband data collected across all cows and each 24-h day of the virtual front-fence treatment (time points T_2–T_3) for (a) minutes spent in the exclusion zone/cow per 24-h day, (b) % of paddock time in the exclusion zone/cow per 24-h day, (c) number of audio and electrical signals received/cow per 24-h day, and (d) ratio of electrical to audio signals/cow per 24-h day. Lines represent median values (50th percentile), boxes represent 25th and 75th percentiles, and whiskers represent 10th and 90th percentiles. Points show the mean (red circles) and both maximum and minimum values (gray circles).

fence treatment did the number of audio cues received by cows significantly differ between grazing periods, averaging 0.1 and 0.2 audio cues/h per cow in the first and second grazing periods, respectively. Cows also received 0.2 to 0.3 fewer audio cues/h in the first and fourth hour of the first compared with the second grazing period. Grazing period did not affect the number of electrical stimuli received by cows ($F_{1,13}$ = 1.217, P = 0.289; Table 3).

Pasture Utilization

Within each front-fence treatment, daily pasture utilization was consistent within inclusion zones and across experimental days (main effects of inclusion subzone and day of experiment were nonsignificant).

Greater daily pasture utilization was achieved during the electric versus virtual front-fence treatment (front-fence treatment, $F_{1,16}$ = 5.90, P = 0.03), averaging 95.8 versus 71.2%, respectively. Accordingly, pasture consumption within the inclusion zone was higher during the electric versus virtual front-fence treatment (13.1 vs. 11.7 kg of DM/cow per day). Despite this, the lower average ME content of pasture during the electric versus virtual front-fence treatment (11.1 vs. 11.5 MJ/kg of DM) combined with less average concentrate consumption (1.98 vs. 2.7 kg of DM/cow per day) resulted in cows achieving similar total energy intakes (168 vs. 165 MJ/cow per day).

DISCUSSION

Our study showed single linear virtual fence lines being successfully used to divide rectangular paddocks crosswise and restrict a herd of 30 lactating dairy cows to the portion containing their daily (24 h) pasture allocation (inclusion zone). While the virtual front-fence did not eliminate cow entry into the exclusion zone, as did the conventional temporary electric front-fence, individual cows were generally contained within the inclusion zone ≥99% of the time. This is comparable with results from previous studies evaluating the efficacy of the virtual fence to contain small herds of grazing beef and dry dairy cattle (n = 6–20) within the boundaries of pasture allocations (Campbell et al., 2017, 2019a,b, 2020; Lomax et al., 2019). Unlike these previous studies, cows in our study were exposed to higher stocking densities and more regular changes in virtual fence location (daily paddock change; i.e., conditions more closely resembling the anticipated application of virtual fencing in intensive grazing systems). Cows initially received more audio cues when they first entered a new paddock, suggesting that the daily changes in paddock and resultant virtual front-fence location reduced en-

Table 1. Interaction of day block × grazing period × hour since paddock entry[1] for the time spent by cows in the exclusion zone (s/h per cow)[2]

Day block	Hour since paddock entry	Grazing period 1	Grazing period 2
Start	1	3.07 (0.23 ± 0.09)^{A,b}	30.61 (0.77 ± 0.15)^{A,a}
	2	0.13 (0.04 ± 0.02)^{B,a}	17.38 (0.29 ± 0.12)^{BC,a}
	3	2.48 (0.15 ± 0.07)^{AB,a}	10.24 (0.31 ± 0.11)^{B,a}
	4	0.18 (0.04 ± 0.03)^{B,a}	0.21 (0.05 ± 0.03)^{C,a}
Middle	1	18.99 (0.62 ± 0.12)^{A,a}	42.02 (0.55 ± 0.16)^{A,a}
	2	8.87 (0.34 ± 0.11)^{AB,a}	16.19 (0.17 ± 0.11)^{B,a}
	3	7.76 (0.40 ± 0.11)^{B,a}	15.19 (0.40 ± 0.13)^{AB,a}
	4	9.35 (0.16 ± 0.10)^{B,a}	42.52 (0.40 ± 0.15)^{AB,a}
End	1	3.23 (0.26 ± 0.08)^{BC,b}	21.10 (0.69 ± 0.14)^{A,a}
	2	2.47 (0.20 ± 0.07)^{C,a}	2.28 (0.11 ± 0.07)^{C,a}
	3	8.91 (0.54 ± 0.10)^{B,a}	7.54 (0.30 ± 0.10)^{B,a}
	4	25.63 (0.88 ± 0.13)^{A,a}	35.65 (0.74 ± 0.17)^{A,a}

[A–C]Means followed by the same letter are not significantly different ($P \geq 0.05$); uppercase letters indicate comparisons within day block × grazing period combinations.

[a,b]Means followed by the same letter are not significantly different ($P \geq 0.05$); lowercase letters indicate comparisons within day block × hour since paddock entry combinations.

[1]$F_{6,656} = 2.332$, $P = 0.031$.

[2]Day blocks divided the 10-d virtual front-fence treatment (T_2-T_3) into start (d 1–3), middle (d 4–6), and end (d 7–10) periods. Analysis of data logged during each 24-h pasture allocation (day) was restricted to the 2 distinct 4-h grazing periods following twice-daily milking events. Pasture availability was distinctly higher in grazing period 1 than 2 (cows' first and second entry into the paddock). Raw values are presented for biological meaning (referenced in text), with LSM ± SEM shown in parentheses. Least squares means were generated from y = $\log_{10}$(X) transformed data.

vironmental predictability and created a challenging environment for testing the virtual fence (Lee et al., 2018). Cows may have also been more motivated to cross the virtual front-fence than in the abovementioned previous studies, particularly during the second period of their daily pasture allocation, due to the high energy requirements of early lactation (CSIRO, 2007). Subsequently, it is promising to see that the virtual front-fence effectively contained the experimental herd within the inclusion zone without compromising cow production metrics (e.g., milk yield and live weight; Verdon et al., 2021).

Cows received fewer aversive electric stimuli from the electric versus virtual front-fence. This may have

Table 2. Audio cues received by cows (no. of audio cues/h per cow) during the virtual front-fence treatment (time points T_2–T_3)[1]

Item[2]	Start	Middle	End	
Day block × grazing period				
Grazing period 1	0.09 (−0.01 ± 0.04)^{B,b}	0.23 (0.25 ± 0.05)^{A,a}	0.26 (0.23 ± 0.03)^{A,a}	
Grazing period 2	0.21 (0.21 ± 0.04)^{A,ab}	0.21 (0.22 ± 0.04)^{A,b}	0.21 (0.28 ± 0.05)^{A,a}	
	Hour 1	Hour 2	Hour 3	Hour 4
Grazing period × hour since paddock entry				
Grazing period 1	0.26 (0.26 ± 0.05)^{B,a}	0.12 (0.12 ± 0.02)^{A,b}	0.23 (0.26 ± 0.06)^{A,a}	0.14 (−0.00 ± 0.05)^{B,b}
Grazing period 2	0.44 (0.44 ± 0.08)^{A,a}	0.07 (0.07 ± 0.03)^{A,c}	0.15 (0.15 ± 0.03)^{A,b}	0.18 (0.28 ± 0.05)^{A,a}
	Hour 1	Hour 2	Hour 3	Hour 4
Day block × hour since paddock entry				
Start	0.34 (0.32 ± 0.07)^{AB,a}	0.08 (0.08 ± 0.03)^{A,b}	0.13 (0.13 ± 0.03)^{B,b}	0.05 (−0.14 ± 0.08)^{C,c}
Middle	0.44 (0.44 ± 0.09)^{A,a}	0.13 (0.12 ± 0.03)^{A,c}	0.19 (0.25 ± 0.06)^{A,b}	0.12 (0.12 ± 0.04)^{B,c}
End	0.28 (0.28 ± 0.05)^{B,b}	0.08 (0.09 ± 0.03)^{A,c}	0.25 (0.23 ± 0.05)^{AB,b}	0.31 (0.43 ± 0.06)^{A,a}

[A–C]Means followed by the same letter are not significantly different ($P \geq 0.05$); uppercase letters indicate comparisons within columns.

[a–c]Means followed by the same letter are not significantly different ($P \geq 0.05$); lowercase letters indicate comparisons within rows.

[1]Day blocks divided the 10-d virtual front-fence treatment into start (d 1–3), middle (d 4–6), and end (d 7–10) periods. Analysis of data logged during each 24-h pasture allocation (day) was restricted to the 2 distinct 4-h grazing periods following twice-daily milking events. Pasture availability was distinctly higher in grazing period 1 than 2 (cows' first and second entry into the paddock). Raw values are presented for biological meaning (referenced in text), with LSM ± SEM shown in parentheses.

[2]Day block × grazing period: $F_{2,633} = 4.276$, $P = 0.014$. Grazing period × hour since paddock entry: $F_{3,633} = 5.198$, $P = 0.001$. Day block × hour since paddock entry: $F_{6,633} = 6.158$, $P = 0.000$.

resulted from cows longer period of habituation to electric versus virtual fencing (mean ± SD, 4.9 ± 1.3 yr vs. 3 ± 0 d, respectively). Cows being visually dominant learners (Uetake and Kudo, 1994) may have also found it easier to learn to associate the visual cue of an electric fence with aversive electrical stimuli than the audio cue provided by the virtual fence. Indeed, McSweeney et al. (2020) found that cows interactions with a virtual fence increased when visual fence location indicators were removed. Despite this, cows learned to respond to audio cues alone and avoided receiving electrical stimulus, with the percentage of cows receiving electrical stimulus following an audio cue declining from 65 to 32% over the 3-d virtual fence training period (T_1–T_2). While this decline indicates learning occurred, comparable values reported for beef breed heifers were lower, equaling 34 and 19% at the start and end of the learning period (Campbell et al., 2019a). Possible reasons for these differences may include the higher stocking rate in our study increasing the probability of animals interacting with the virtual fence (McDonald et al., 1981; McKillop and Sibly, 1988) and greater nutritional requirements (i.e., impetus to cross the fence) of lactating dairy cows versus virgin heifers (CSIRO, 2007). Values reported by both studies were lower than reported for a group of beef breed heifers that were individually trained to the virtual fencing system (Campbell et al., 2018). This may indicate a degree of social learning in our study, as has been observed for cattle learning to associate the visual cue of standard electric fencing with aversive electric stimuli (McDonald et al., 1981; McKillop and Sibly, 1988). Anecdotally, video footage taken during the virtual front-fence treatment (T_2–T_3) captured instances of multiple cows moving away from the virtual front-fence after a single cow received stimuli. Social learning may explain why in our study, 2 cows never received electrical stimuli during the virtual fence training and 38% of cows responded to audio cues alone on their first interaction with the virtual fence. Alternatively, cows may have found audio cues alone aversive.

Over the virtual front-fence treatment (T_2–T_3), daily ratios of electrical to audio signals for individual cows averaged 0.18 and seldom exceeded 0.5, indicating cows were primarily contained within inclusion zones by audio cues alone. Similar results have been reported for beef cattle in studies where additional audio cues associated with activation of the grazing function were not omitted (Campbell et al., 2017). In our study, removal of these additional audio cues increased the overall ratio for the virtual front-fence treatment from 0.14 to 0.22. Taken together, results show dairy cows can be trained to the virtual fencing system and once trained respond to audio cues as or more effectively than beef cattle. This could be partly attributed to dairy cows' intensive prior exposure to electric fencing, which facilitated more rapid associative pairing of audio and electrical stimuli in a feed attractant trial (Verdon et al., 2020).

Pasture depletion reduced the efficacy of the virtual front-fence, but the magnitude of this effect was small. Cows spent an average of 18 to 28 s longer in the exclusion zone during the initial hour of the first compared with the second grazing period. This may be attributed to the reduced availability of pasture within the inclusion zone upon cows' second postmilking entry, which combined with their high desire to graze (Sheahan et al., 2013), would have made ungrazed pasture within the exclusion zone a desirable feed attractant. Indeed, feed attractants are known to increase the motivation of cattle to test standard electric fences (McDonald et

Table 3. Electrical stimuli received by cows (count of electrical stimuli/h per cow) during the virtual front-fence treatment (time points T_2–T_3)[1]

Fixed effect[2]	Level	Value
Day block	Start	0.04 (0.03 ± 0.01)^{B}
	Middle	0.05 (0.05 ± 0.01)^{A}
	End	0.03 (0.06 ± 0.01)^{A}
Grazing period	Grazing period 1	0.03 (0.04 ± 0.01)
	Grazing period 2	0.05 (0.05 ± 0.01)
Hour since paddock entry	Hour 1	0.08 (0.09 ± 0.02)^{A}
	Hour 2	0.02 (0.02 ± 0.01)^{B}
	Hour 3	0.04 (0.05 ± 0.01)^{A}
	Hour 4	0.03 (0.02 ± 0.01)^{B}

^{A,B}Means followed by the same letter are not significantly different ($P \geq 0.05$).

[1]Day blocks divided the 10-d virtual front-fence treatment into start (d 1–3), middle (d 4–6), and end (d 7–10) periods. Analysis of data logged during each 24-h pasture allocation (day) was restricted to the 2 distinct 4-h grazing periods following twice-daily milking events. Pasture availability was distinctly higher in grazing period 1 than 2 (cows' first and second entry into the paddock). Raw values are presented for biological meaning (referenced in text), with LSM ± SEM shown in parentheses.

[2]Day block: $F_{2,281} = 4.994$, $P = 0.007$. Grazing period: $F_{1,13} = 1.217$, $P = 0.289$. Hour since paddock entry: $F_{2,673} = 13.983$, $P = 0.000$.

al., 1981), with hunger suggested to challenge the efficacy of virtual fences (Verdon et al., 2020). The small magnitude of the declining pasture availability effect on virtual front-fence efficacy highlights the potential for virtual fences to control grazing dairy cow movement even when pasture availability is limited (i.e., 1 kg of DM/cow of grazeable pasture), but requires confirmation under longer and more complex virtual fencing applications. This conclusion is further evidenced by the fact that the number of electrical stimuli received by cows did not differ between analyzed grazing periods, while the number of audio cues was only slightly higher in the grazing period following cows' second versus first entry into a pasture allocation.

Greater daily pasture utilization was achieved when an electric rather than virtual front-fence was deployed (95.8 vs. 71.2%, respectively), but the inclusion zone area adjacent either front-fence was grazed as much as any other inclusion zone location. This indicates cows did not avoid grazing near the virtual front-fence over the 24-h allocation. Similar studies using GPS data have found that small herds of beef cattle (n = 6–10) contained by a single virtual front-fence utilized the entire inclusion zone (Campbell et al., 2017, 2019a,b). However, these studies failed to account for the proportion of time cattle spent in different inclusion zone areas. Lomax et al. (2019) created a GPS location time-budget for a herd of dry dairy cows (n = 12) contained by a virtual fence, which showed underutilization of the inclusion zone area adjacent the virtual fence. Comparable observations were made from studies using virtual fences to prevent individual dairy cows and beef heifers from accessing a feed attractant (Campbell et al., 2018; Lomax et al., 2019). It is conceivable that in our study, cows also spent less time near the virtual front-fence, but achieved comparable pasture utilization to other inclusion zone locations by increasing bite rate, mass, or both (Allden and McDWhittaker, 1970). This may have also been the case for the electric front-fence, as previous research has shown grazing within close proximity to a wire fence was reduced by electrification of the wires (Teixeira et al., 2017). Alternatively, cows may have refrained from accessing the inclusion zone area adjacent either front-fence until pasture in the remaining inclusion zone was significantly depleted. Such questions will be the focus of a future publication.

Directly attributing the lower pasture utilization achieved within the inclusion zone during the virtual front-fence treatment to the technology per se is limited by the temporal separation of front-fence treatments and the absence of herd level replication. Logistic difficulties often make such replication in large pasture-based dairy studies impractical (Bransby, 1989; Oksanen, 2001). Despite these pasture utilization differences, cows achieved similar total energy intakes during virtual and electric front-fence treatments (165 vs. 168 MJ/cow per day), so that milk yield and liveweight remained stable (Verdon et al., 2021). Similar energy intakes resulted from the higher ME content of the pasture on offer during the virtual relative to electric front-fence treatment (11.5 vs. 11.1 MJ/kg of DM, respectively), which combined with the greater average concentrate consumption (2.7 vs. 1.98 kg of DM/cow per day), may have offset the decline in estimated pasture DMI (11.7 vs. 13.1 kg of DM/cow per day). Cows impetus to increase energy intake during the virtual front-fence treatment may have been reduced by the abrasions incurred from the neckbands. As abrasions progressively developed during the experiment, we suggest abrasions would have had a greater effect on grazing behavior of some cows during the virtual front-fence treatment that followed the electric front-fence treatment. Evidence is provided by the reduced time that cows spent grazing during the later stages of the virtual versus electric front-fence treatment (Verdon et al., 2021). Development of abrasions suggests the eShepherd prototype used in this experiment required modification before being repurposed from extensively grazed beef cattle to intensively grazed dairy cattle, owing potentially to neck profile and grazing behavior differences.

CONCLUSIONS

Our study showed single linear virtual fence lines being successfully used to divide rectangular paddocks crosswise and restrict a herd of 30 lactating dairy cows to the portion containing their daily (24 h) pasture allocation (inclusion zone). Cows learned to respond to audio cues alone and avoid receiving aversive electrical stimuli. Reductions in pasture availability as the inclusion zone was progressively grazed reduced the efficacy of the virtual fence in containing cows within the inclusion zone, but the magnitude of this effect was small and insignificant in practical terms. This highlights the potential for virtual fences to control grazing dairy cow movement even when pasture availability is limited (i.e., 1 kg of DM/cow above a target residual of 1,500 kg of DM/ha), but requires confirmation under longer and more complex virtual fencing applications. While cows achieved lower pasture utilization with the virtual versus electric front-fence, uniform pasture utilization was achieved within inclusion zones, indicating that cows did not avoid grazing near the virtual fence over 24-h allocations. Longer term studies using the virtual fencing system to impose more complex grazing regimens are needed to evaluate the value proposition of virtual fencing for intensive grazing-based dairy farming systems.

ACKNOWLEDGMENTS

The authors gratefully acknowledge funding provided by the Australian Government Department of Agriculture, Water and the Environment as part of its Rural R&D for Profit Programme. eShepherd virtual fencing system support was provided by Sally Haynes, Charlton Honig, Poppy McBain, Cameron Ralph, Andrew Ryder, and Bronwyn Stevens (Agersens Pty Ltd., Melbourne, VIC, Australia). Assistance with R software coding was provided by Jason Scott (Tasmanian Institute of Agriculture, University of Tasmania, Burnie, Tas., Australia). Logistic regression analysis was completed by Danila Marini (University of New England, Armidale, NSW, Australia). Manuscript revisions provided by Ray King (Dairy Australia Ltd., Melbourne, VIC, Australia). Technical assistance was provided by Nathan Bakker, Steven Boon, Steven Emmett, Carlton Gee, Desmond McLaren, Bradley Millhouse, Benjamin Noble, Amy Potter, Oliver Radford, Thomas Snare, and Avril Stewart (Tasmanian Institute of Agriculture). The authors acknowledge the useful insights gained from discussions with Michael Tarbath (Fruit Growers Tasmania Inc., Hobart, Tas., Australia). The authors declare no conflicts of interest.

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