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The application of virtual fencing technology effectively herds cattle and sheep

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Abstract

Context. Herding and mustering procedures during livestock management can be time-consuming, labour intensive, and costly. The ability to gather animals virtually is an enticing notion but technology to do this is not widely commercially available.

Aims. The eShepherd® virtual fencing system being developed for cattle may be able to remotely herd animals. This system operates via global positioning system, and requires animals to wear a neckband device. Animals are trained to associate an audio tone with an electrical pulse to avoid a virtual boundary.

Methods. Experiments were conducted with cattle using pre-commercial prototypes of the automated virtual fencing neckbands, and with sheep using manually operated dog training collars implementing the same virtual fencing algorithm to explore the potential of this technology for herding, and optimal fence designs for herding success. In the first experiment, five groups of 12 cattle were moved down a 344 m paddock using three different fence placement designs.

Results. The most successful design for cattle herding was a back fence that followed behind the animals to prevent them from turning back in the wrong direction. The fences were manually activated by personnel based on the cattle movement. The same type of fence design was manually applied to two groups of six sheep to successfully herd them down a 140 m paddock in the second experiment.

Conclusions. All herding was highly dependent on the animal's own pace of movement as no signals were applied to 'push' the animals, the systems only prevented movement back in the wrong direction. The pre-commercial prototype of the automated eShepherd® device used is now obsolete and testing with updated versions would be needed to confirm its application for animal herding.

Implications. These preliminary trials indicate potential for virtual fencing technology to herd livestock, but technology improvements are required, and an automated device for sheep is not yet available.

Keywords: eShepherd®, herding, behaviour, animal husbandry, cattle, sheep, virtual fencing technology.

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Introduction

Herding and mustering of animals involves bringing them together in a group and moving them from place to place and is an integral part of livestock farming. These procedures can be time-consuming, labour-intensive, costly, and may have negative impacts on health and safety of both the animals and personnel (Connelly *et al*. 2005; Petherick 2006). The potential for animal gathering to be conducted virtually, thus reducing the time, cost, and labour involved, is an idea that has been entertained by multiple researchers proposing a variety of different potential methodologies; but no technology is yet readily commercially available (Anderson *et al*. 2014).

The limited available research with sheep has shown that individuals trained to approach audio and visual stimuli (beeping and flashing light) associated with food will lead naïve animals into target areas within a paddock (Taylor *et al*. 2011). In cattle, preliminary trials with experimental collar devices that played voice commands (Doniec *et al*. 2010) or unspecified audio sounds (Anderson *et al*. 2004) simulated to be directional (different attenuation on the left and right side), coupled with electric pulses to encourage movement, including gradations of aversiveness with increasing distance past the virtual barrier, have shown some success with moving cattle down a paddock or bringing cattle in from a grazing paddock (Anderson *et al*. 2004; Doniec *et al*. 2010). However, only small numbers of cattle (2–5 animals) have been tested with the directional virtual fence. It is possible that the complexity of this approach limits the ability of all animals in a herd to be able to learn the desired responses and this could have negative implications for animal welfare (Lee *et al*. 2018). Collar devices for cattle that play graduated sounds to indicate relative distance to a moving virtual barrier and using a rotating selection of sounds that are likely to be aversive to cattle (e.g. dog barking, tiger roaring, thunder, helicopter) have been proposed, although cattle appear to habituate to sound signals only (Butler *et al*. 2006). For mustering without a need for devices on animals, there is increasing interest in the possibility of using drones that play aversive sounds and that are themselves, perceived as a threat to the animals to stimulate moving away from the aerial vehicle (Gordon *et al*. 2018; Yinka-Banjo and Ajayi 2019). Other aversive stimuli emanating from drones such as an olfactory cue have been proposed to prod the animals in the desired direction (Gordon *et al*. 2018) but the research on the use of drones for herding is currently limited (Yinka-Banjo and Ajayi 2019).

Virtual fencing technology that is currently being commercialised by Agersens (Melbourne, Vic., Australia) is another potential system that may enable remote herding of livestock animals. The eShepherd® system incorporating patented IP developed by the Commonwealth Scientific and Industrial Research Organisation (Lee 2006; Lee *et al*. 2010) uses global positioning system (GPS)-enabled devices on cattle neckbands and a base station to activate virtual barriers to exclude cattle from specific areas. An audio cue as a warning tone is paired with an electrical pulse so that the animals can learn to respond to the audio cue alone and avoid receiving electrical stimuli (Campbell *et al*. 2018; Lee *et al*. 2009). There are no gradations of the applied audio or electrical stimuli. Research with the pre-commercial prototypes of these devices has demonstrated that beef cattle can be excluded from specific areas of pasture for up to 4 weeks (Campbell *et al*. 2019*a*) or environmentally sensitive areas for up to 6 weeks (Campbell *et al*. 2019*b*, 2020) using static fence lines. When fences are shifted across days within a paddock, cattle will adapt and move into previously excluded areas within a few hours (Campbell *et al*. 2017). Although there is high individual variation in learning of the virtual fence cues, all animals start showing responses to the audio cue alone within the first few days of exposure (Campbell *et al*. 2019*a*, 2019*b*, 2020). Although no equivalent automated neckband devices are currently available for sheep, the application of virtual fencing technology has been tested using manual dog training collars to demonstrate that sheep can learn to respond to the audio cue alone to avoid the electrical stimuli (Marini *et al*. 2018*a*), and they can be excluded from specified paddock areas (Marini *et al*. 2018*b*). However, the potential for the technology to herd cattle or sheep over short distances has not yet been tested. This application could be for producers needing to bring their animals into yards, or for shifting them to new paddocks remotely. A similar application of the technology could be applied for mustering purposes, but this would occur over much larger areas with extended timeframes (days vs hours). Thus, the objectives of this study were to assess whether virtual fencing technology (both automated or manually operated) could be used to herd cattle and sheep across short distances and what fence configurations were most effective.

Methods

The experiments were approved by the CSIRO FD McMaster Laboratory Chiswick Animal Ethics Committee before the start of the experimental period (Animal Research Authority 18–06, 19–11). All trials were conducted on the CSIRO Chiswick site in Armidale across the period of May 2018 to August 2019. Pre-commercial prototypes of the eShepherd® neckbands were used in Experiment 1. Manually-operated Garmin dog training equipment was used for Experiment 2 (Garmin TT15 collar, and GPS hand-held unit Garmin Alpha 100, Garmin Ltd, Olathe, KS, USA).

eShepherd® neckbands

A pre-commercial prototype of the eShepherd® virtual system (Agersens, Melbourne, Vic.), which is now obsolete (it has since been updated), was used in the cattle trials and has been described previously (Campbell *et al*. 2019*a*, 2019*b*). With this system, cattle wore a neckband strap with a hanging counterweight (total weight ~1.4 kg) and a virtual fencing device (~725 g and 17 cm long × 12 cm wide × 14 cm high), positioned on the top of the animal's neck. The unit used GPS technology to monitor the animal's movement and a virtual fence boundary (separating inclusion versus exclusion zones), specified using GPS coordinates, was transmitted to the unit using a radio frequency link. When an animal approached the virtual fence boundary, the unit emitted a non-aversive audio tone within the animal's hearing range (precise specifications are commercial in confidence). Following the tone, if the animal stood still or turned away, no electrical pulse was applied. If the animal continued to move through the virtual fence boundary into the exclusion zone, the unit delivered a short, sharp electrical pulse sequence in the kilovolt range (values are commercial in confidence). This audio-pulse sequence was repeated if the animal walked through the fence line and continued into the exclusion zone. The virtual boundary was set at the same location for all animals; however, each animal wore a neckband device and stimuli applied past the virtual fence boundary while animals were in the exclusion zone were based on the individual's specific location. Thus, animals that were spatially separated within the exclusion zone each still received stimuli if they were moving farther into the exclusion zone. This could prevent re-grouping within the exclusion zone. To re-group without receiving stimuli, animals would need to turn around and head back into the inclusion zone as no stimuli were applied as the animal moved back in that direction. As a safety feature, if animal movement occurred above or below a specified velocity (values are commercial in confidence), stimuli were not applied. Additionally, if an individual animal received a certain number of pulse stimuli within a short time frame, the device entered standby mode and stimuli were not applied for a specified time frame (values of these parameters were available to the researchers but are commercial in confidence). The neckband algorithm also included a 'grazing function'. The natural behavioural pattern of grazing can mimic the correct response by the animal to the neckband cues of movement forward and stopping at an audio cue. Therefore, if an animal received three consecutive audio cues while still moving forward paired with stopping, an electrical pulse was applied. A base station set up adjacent to the trial paddock communicated with the neckbands and animal activity was monitored in real time through an online user-interface. All GPS and stimuli data were stored on a removable secure digital (SD) card for later download.

Experiment 1: automated neckbands on cattle

This trial used 60 Angus pregnant or dry cows who were naïve to virtual fencing and ~3–12 years of age with an average bodyweight of 642 kg ± 11.5 s.e. The animals were tested across five groups of 12 animals per group. A 6.15 ha grassed paddock (344 m long × 179 m wide) was used for the herding trials with animals kept in an adjacent paddock as needed during the experimental period. The yards for fitting and removing the devices were also adjacent to the experimental paddock. Cattle had *ad libitum* access to pasture and water in the experimental and holding paddocks. During herding, four water points were evenly placed along the length of the paddock on one side.

Each group of animals followed a similar experimental timeline but were exposed to different fence configurations during herding across three different designs as described in the following section (see 'Herding fence designs'). For each tested group, on Day 1, animals were restrained in a crush and fitted with pre-commercial eShepherd® prototype neckbands then moved into the experimental paddock. Animals were allowed full access to the available paddock area until a single virtual fence line was placed across the width of the paddock on Day 4 excluding ~50% of the paddock area. This single static fence line enabled the cattle to learn the audio and pulse cues and start showing responses to the audio cue only before they were exposed to dynamic fence lines that moved during the herding process. On Day 6 the fence line was deactivated, and cattle were moved to an adjacent holding paddock. On the morning of Day 7, cattle were moved into the top of the experimental paddock and herding commenced. Three different fence configurations were tested across the five groups (see 'Herding fence designs') with the duration of herding on that day dependent on the movement of the cattle. Herding was tested in an east–west direction (top to bottom of the paddock) on Day 7 and then the reverse direction on Day 8. Once herding down the length of the paddock was complete, the animals were held at the end of the paddock for 30 min by a single virtual fence line (approximate depth of the holding zone was 50 m). The trial for that day was then complete and the animals were moved back into the adjacent holding paddock overnight. Personnel were in the adjacent paddock for the duration of each herding event to manually set the virtual fences and observe cattle responses to the stimuli.

Herding fence designs

Three different herding fence designs were trialled but with varying numbers of replicates based on their observed success and impact on the animals. Design 1 was a single line back fence across the paddock width that followed behind the group of animals. This was manually activated via the online user interface by observers who were present in the paddock adjacent to the experimental herding paddock during the trial period. A series of six fences divided the paddock with each fence sequentially activated based on the movement of the group of cattle down the paddock. The first fence was activated when either all of the cattle, or the majority of the group (one or two animals were sometimes spatially separated from the main herd) had moved at least 50 m down the length of the paddock. This series of 'back fences' that were activated behind the animals prevented them from turning around and moving back up the paddock to their starting location. The fence did not 'push' the animals as signals were only given to animals that turned back in the opposite direction to the intended herding destination. This design was repeated with four groups, totalling seven replicates of this design.

Design 2 had the same series of fences as in Design 1; however, initially, the group of animals was manually split ~100 m in distance by personnel in the field to simulate a herd of cattle that may not all be in close proximity when a virtual herding line needed to be set. The first virtual line was set in between the two subgroups of six animals. This design aimed to test whether the animals that were in the exclusion zone would re-join the animals in the inclusion zone and whether 50% of the herd in the inclusion zone was sufficient to attract the 50% of the herd in the exclusion zone. This design was tested on one group with only one replicate as it was logistically difficult to manually separate the group and simulate a spread-out grazing group of animals in the experimental setting.

Design 3 employed a series of double fences that were aimed at keeping the animals in a tighter group. The cattle had both a back fence that prevented them from moving back up the paddock in the opposite direction, as well as a fence in front that prevented the herd from spreading out down the direction of travel. Animals were placed in the paddock and a front fence was activated; the back fence initially was the physical back fence of the paddock. When the first animal at the front of the group received signals at the front fence, it was deactivated, and a new front fence was activated farther down the paddock. The back fence was shifted farther down when all or the majority of the group had moved into the new inclusion area. This 'inching' forward of the double fence allowed the animals 75 m space when both the front and back fence were activated, and this opened up to 150 m of space when a new front fence was activated before shifting the back fence farther down. These space allowances were tested with one group across one replicate. However, observations indicated this amount of space did not achieve the aims of keeping the group tightly together and thus the second replicate for the same group (in the opposite direction the following day) allowed 50 m of space which opened up to 75 m of space. This spacing was trialled across one replicate for the same group.

The eShepherd® pre-commercial prototype system that was used when these trials were conducted from May to July 2018 required personnel to manually activate and deactivate specific fences that were drawn into the online user-interface prior the trial commencing. The reporting time between the neckbands and the base station was every 6 min, i.e. every 6 min each neckband connected with the base station to receive a fence update. A reporting time could sometimes be missed due to connectivity issues; thus, a single neckband could take up to 12 min to receive a fence update. This reporting time resulted in individual animals not all receiving the updated fence position simultaneously. This version of the eShepherd® system has now been superseded and communication speeds within the system have been improved.

Experiment 2: manual collars on sheep

Twelve 1-year-old Merino ewes who were naïve to virtual fencing signals were trained as a single group to the cues in sheep holding yards (4×10 m) for 3 min each day over 3 days. The sheep required the wool around their neck to be clipped before fitting of collars before each training period. During the virtual fencing training, one end of the sheep yard was sectioned off using the virtual fence (exclusion zone). If the sheep walked towards the virtual fence, they received an audio cue (70–80 dB, 2.7 kHz) for ~2 s. If they did not alter their behaviour after their 2 s audio cue, they received an immediate electrical stimulus set to level 4 out of a possible 18 (<1 s, 320V, 20 µs, with 16 pulses delivered per second, with no resistance). The 'grazing algorithm' was also implemented if sheep kept moving forward following three consecutive audio cues. When not undergoing training, the sheep were provided with water *ad libitum* and kept together on pasture.

On Day 5, the 12 sheep were split into two groups of six and each sheep was marked on their flank with numbers and patterns using stock paint (Si-Ro-Mark, Cox Agri, County Durham, UK) to be visually distinct. Herding occurred over 4 days, with each group undergoing herding over 2 consecutive days. On the morning of each herding day, the six sheep were fitted with the Garmin collars and then herded across a 0.56 ha paddock (40×140 m, water was available at both ends of the paddock) using Design 1 as described for the cattle trials (see 'Herding fence designs'), which implemented the single back fence. The single virtual fence sequentially followed behind the sheep (set at specific lines every 20 m) as they moved down the paddock across the day. Once the group of sheep reached the final inclusion zone (40×20 m), they were held there with the back fence for 30 min before being herded back to the other end of the paddock. A total of seven herding replicates were carried out across the two groups with Group 1 starting on the eastern side of the paddock on Day 1, and on the western side of the paddock on Day 2; the reverse was implemented for Group 2. Only one replicate was carried out for Group 1 on Day 1 as the animals started moving up the paddock but then stayed only part way up for ~1 h before continuing to move to the end of the paddock. As the animals were believed to be less likely to be active in the afternoon, the trial was terminated after the single replicate. During the herding trials, personnel were in the adjacent paddock for the duration to manually implement the virtual fence and observe sheep responses to the stimuli. All administered signals were manually recorded at the time of application and time-stamped GPS data were downloaded from the electronic devices at the end of each day.

Data

In summary for the automated herding trials with cattle (Experiment 1) there were seven replicates of Design 1, one replicate of Design 2, and two replicates of Design 3. For Experiment 2, there were seven replicates of Design 1 with sheep. The GPS data per animal from each experiment were compiled in SQL Server software (Microsoft 2012). Spurious points outside the experimental paddock resulting from GPS drift were removed and all available locational data for each herding day were plotted as longitudinal and/or latitudinal data across time using the 'ggplot2 package' (Wickham 2016) in R (R Core Team 2015). For Experiment 1, the audio and electrical stimuli cue data were summarised per animal and averaged across both the training period and each herding design to show the proportion of total administered cues that were audio signals. The cue data were also summarised across each herding design for Experiment 1 to show the total number of audio and pulse signals received. Cue data were missing from three animals across three replicates of Design 1 due to errors in data storage. The cue data were not statistically analysed due to the unequal number of replicates among designs. The means of audio and electrical cues across the training period and all herding replicates are presented for Experiment 2 with sheep as well as the proportion of total administered cues that were audio signals. The reports on the outcomes of each herding trial are primarily qualitative based on visual observations of the group behaviours with summary statistics of the administered cues.

Results

Experiment 1: automated neckbands on cattle

Across all five tested groups, the mean proportion ($\pm$s.d.) of total administered cues that were audio signals during the training period was 0.77 ± 0.07 (range: 0.66 to 1.00). This indicates that all individuals were learning to respond to the audio cue alone to avoid the exclusion zone (a proportion of 0.5 would indicate every audio cue was followed by an electrical pulse and animals were not learning). The mean ($\pm$s.d.) proportion of total cues that were audio cues for each herding design did vary but overall were similar to the proportions observed during the training period: Design 1 proportion: 0.81 ± 0.13; Design 2 proportion: 0.77 ± 0.05; Design 3 proportion: 0.75 ± 0.04.

The GPS plots of the animal movement across time (Fig. 1) indicate the varying movement trajectories of the groups, their degree of cohesion, and the duration of herding. For the majority of the time, the cattle stayed as a group in their movement down the paddock (see Fig. 1, e.g. plots Groups 1*a*, *b*, 5*a*, *b*) but some individuals did spatially separate out such as in plots Groups 2*b*, 3*b*, and 4*b* (Fig. 1). These plots illustrate that herding is highly dependent on the behaviour of the group. On some days, the group of animals walked down to the end of the paddock and were held by the final fence with minimal to no interactions with the back fence as they did not turn around in direction. These herding patterns were observed for Design 1 and total herding duration on these occasions was ~1 h or less (Fig. 1, plots Groups 1*a*, 4*b*, and 5*a*, *b*). If the animals turned back in direction, then the duration of herding was extended. Consequently, the cues received by animals varied across different designs with the most audio and pulse cues received by animals exposed to Design 3 with both the

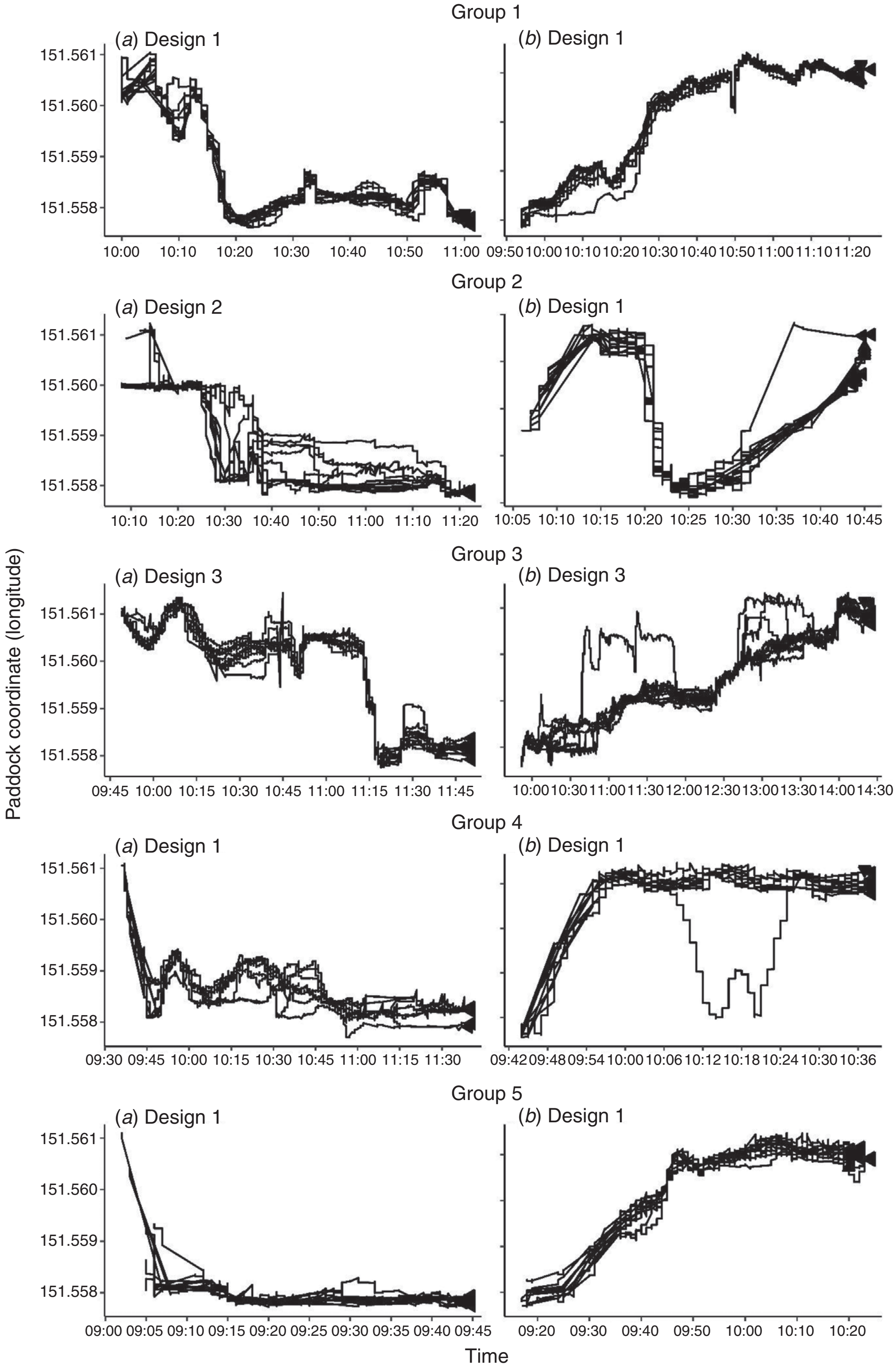

Fig. 1. GPS plots of longitude across time for five groups of cattle (12 animals/group) across three different herding designs (see 'Herding fence designs'). All herding trials conducted are displayed in the figure where each plot represents one replicate of a specific herding design with replicate numbers varying among the designs. Each line within the plots represent a single animal's movement along the paddock length with deviations indicating the individual(s) turned around to move in the opposite direction. The plots on the left portray travel down the paddock (east–west direction) and the plots on the right portray travel back up the paddock the following day (west–east direction). Note the variation in time for each *x*-axis. All animals were held for 30 min at the end of the paddock once they successfully reached this target destination.

front and back fences (Design 1 mean audio ± s.d.: 8.36 ± 9.99, mean pulse ± s.d.: 2.97 ± 4.11; Design 2: mean audio ± s.d.: 13.08 ± 7.51, mean pulse ± s.d.: 4 ± 2.89; Design 3: mean audio ± s.d.: 33.21 ± 17.02, mean pulse ± s.d.: 10.83 ± 6.29).

Comparisons between herding designs were limited by the difference in the number of replicates carried out but each replicate was informative to understanding the varying cattle responses to the moving virtual fences. Design 2 was only tested once as it was logistically difficult to manually separate the group of animals and it was concluded that the artificial testing environment did not adequately reproduce a scenario where animals might be naturally separated while grazing. However, a split-herd scenario where some animals were in the inclusion zone and some were in the exclusion zone did occur during this replicate of Design 2 when some animals turned around in the opposite direction before one of the back fences was able to be set for all individuals. Observations during this split herd scenario of behavioural signs of agitation in the cattle (e.g. turning in circles, head tossing) suggested that the situation was confusing and stressful to the animals. Because individuals in the exclusion zone received signals at their specific location (see 'Methods' section for the 'eShepherd® neckbands' description) each animal received signals in a different place when they were spatially spread out. This resulted in a conflict between receiving signals and wanting to join herd members. If the cattle turned to walk down to the inclusion zone then no signals were applied, but there was limited incentive to make this directional choice when herd mates were within the exclusion zone. When this occurred during the trial, observers noted the cattle appeared to be in distress which resulted in them freezing in their current location for a period of ~30 min (see Fig. 1 plot Group 2*a* from 10:40 to 11:10 hours and Fig. 2) until the animals started moving again and walked back into the inclusion zone. These observations resulted in no additional testing of an intentionally split herd.

Design 3 was observed to also be less successful than Design 1. On the days where the double fence was trialled, the herding duration extended up to 4 h (Fig. 1). Observations in the paddock indicated that including the front fence hindered the animal movement more than intended because of the neckband reporting times. Because it took up to 12 min for the fence to be deactivated for all animals once the first animal reached it, the animals turned away from the front fence as well as the back fence. Personnel in the field interpreted that animals were uncertain of expectations of their movement direction which coincided with the animals

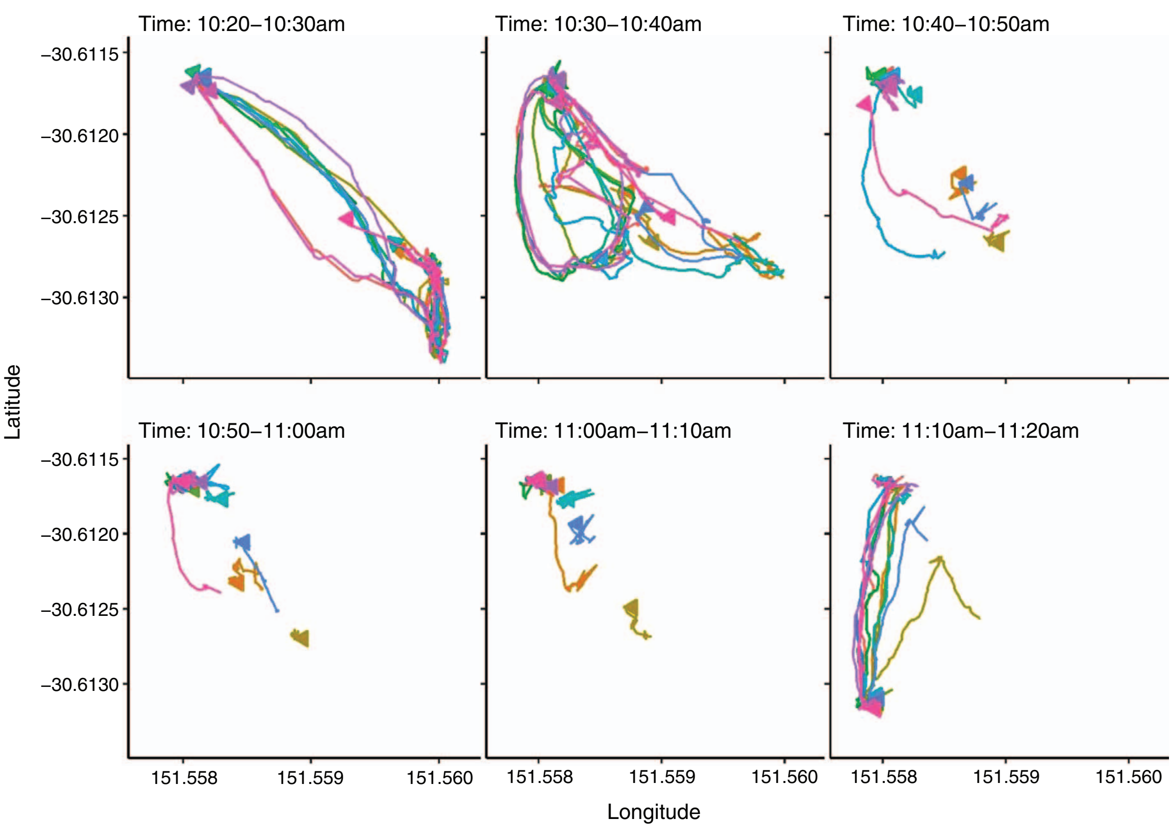

Fig. 2. GPS plots of latitude and longitude across 10 min intervals for individual animals within Group 2 for a portion of their herding trial during the single replicate of 'Design 2' (plot 'a' in Fig. 1 and see 'Herding fence designs'). These plots display cattle movement during a period where animals were separated in the paddock with some individuals in the exclusion zone and some in the inclusion zone which resulted in the animals ceasing movement (see from 10:40 until 11:10 hours) until all animals walked down into the inclusion zone (see 11:10–11:20 hours). Each colour represents an individual animal with the arrow indicating direction of movement.

lying down for ~1 h at the half-way point in the paddock (see from 11:30 to 12:30 hours for Group 3*b*, Fig. 1). Animals did not lie down during any other herding replicate. Faster fence update times would be needed for this type of fencing design to work for herding purposes.

Experiment 2: manual collars on sheep

Across the single group of 12 animals, the mean proportion (±s.d.) of total administered cues that were audio signals during the training period was 0.68 ± 0.08 (range: 0.57 to 0.8), indicating all individuals were learning to respond to the audio cue alone to avoid the exclusion zone (a proportion of 0.5 would indicate every audio cue was followed by an electric pulse).

Sheep were able to react to a single back fence without displaying any adverse behaviour (e.g. excessive running, attempting escapes). The small group of six sheep were able to be moved up and down the test paddock in the same day and were successfully held at either end of the paddock without breaking through the fence. However, in the last replicate on Day 2 for Group 1, the sheep lay down part way back up the paddock and remained there for 2 h before the trial was terminated (Fig. 3). The amount of time it took to herd the group across the paddock varied from 10 min to approximately 1 h depending on the motivation of sheep to either graze or walk (Fig. 3). The GPS plots show the cohesion of the group when walking through the paddock (Fig. 3).

During herding a total of 68 audio cues and 28 electrical pulses for Group 1 and 40 audio cues and 21 electrical pulses for Group 2 were administered. The mean proportion (±s.d.) of audio cues for the two groups was 0.70 ± 0.07 for Group 1 and 0.66 ± 0.07 for Group 2.

Discussion

This study aimed to test the application of virtual fencing technology to herd small groups of cattle or sheep (≤12 animals) across short distances (<400 m) using either pre-commercial automated eShepherd® neckbands for the cattle or manual electronic collars for sheep implementing the same signal algorithm. The technology trains the animals to stop or turn away at an audio cue to avoid receiving an electrical stimulus and virtual boundaries separate ‘inclusion’ from ‘exclusion’ zones. Different fence configurations were applied to cattle with the most successful fence being a back

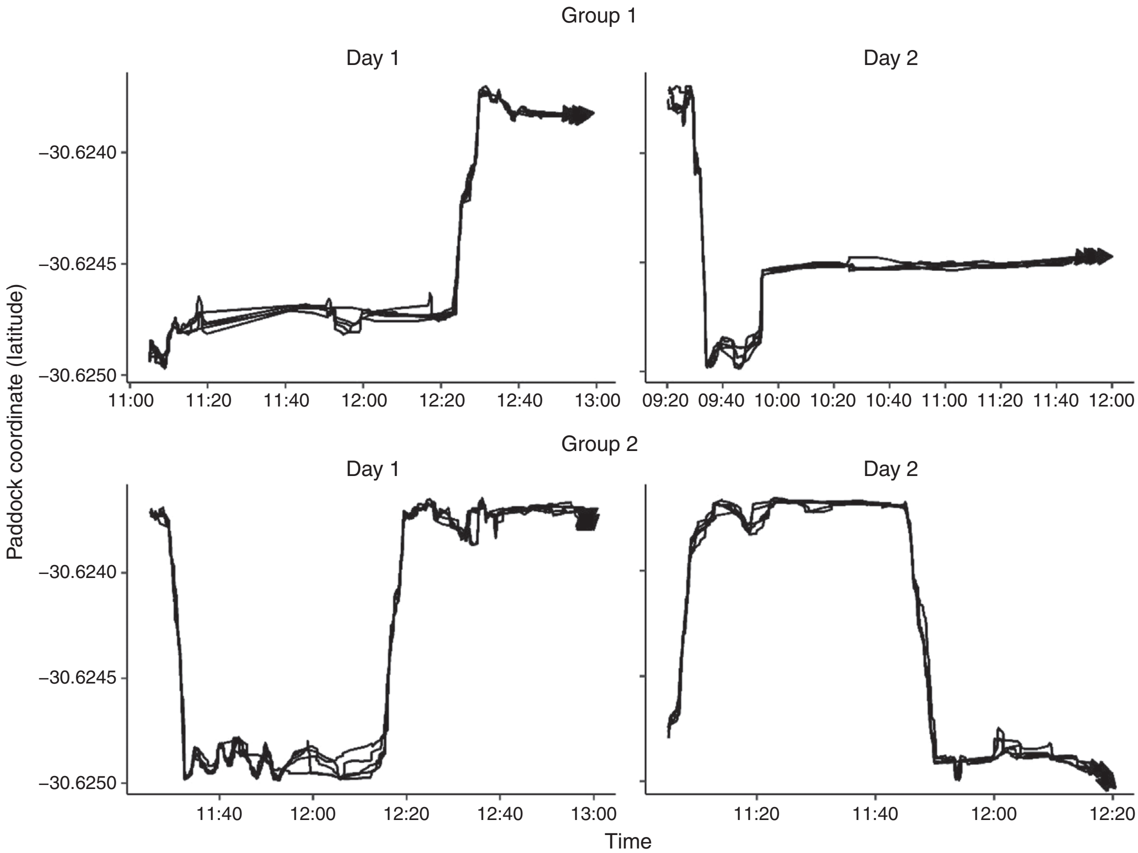

Fig. 3. GPS plots of latitude across time for two groups of sheep (six animals/group), using the single back fence method to herd sheep across a paddock. Group 1 started on the eastern side of the paddock on Day 1 (single replicate only) and on the western side on Day 2 (see ‘Experiment 2: manual collars on sheep’ for further details). The opposite pattern was implemented for Group 2. All sheep were held for 30 min at the end of the paddock once they successfully reached this target destination (displayed as a horizontal line in the plots) before being herded back through the paddock again. Each plot displays two herding replicates. On Day 2, Group 1 lay down part way back up the paddock and the trial was terminated after 2 h.

fence that was set behind the animals as they moved down the paddock to prevent them from moving back in the opposite direction. This back fence was also confirmed to work for herding sheep. The versions of the automated cattle neckbands used in this study are now obsolete and subsequent upgrades may greatly improve the success of the eShepherd® system for herding but this requires further investigation.

The automated neckbands available at the time of the study had slow communication times between the device and base station resulting in new fences not being applied to the animals for up to 12 min. These were limitations of the technology at the time, and observations in the paddock indicated this hindered the success of herding as individual animals varied in when their own device was updated and they could also travel a substantial distance while waiting for a new fence to be activated. The small paddock sizes used in our study were a challenge for the long fence update times, but these slow times may have had minimal consequence if animals were being mustered over large distances and longer periods of time. Furthermore, all fences were manually activated by personnel out in the paddock observing the animal movement. Necessary improvements in the technology for short-term herding to be successful would include faster fence update times and automated detection of animal location and activation of new fences. An automated algorithm that is able to apply signals to target animals separated out from the main herd may also result in more successful herding over shorter time periods as it would keep animals in a tighter group. Although the eShepherd® system has been upgraded since the period of this study, the new system has not been verified for animal herding over short distances.

In this study, the single back fence preventing movement back in the opposite direction was the most successful, but it relied on the animal's own pace of movement. The algorithm trains the animals to turn away at the audio cue and there is no signal that pushes them from behind. An advantage of this approach is that it is simple, once animals learn the association between the audio cue and the electrical pulse, they do not need to learn anything additional for herding to occur. In other proposed herding devices, an electrical pulse has been applied to encourage the animals to begin moving (Doniec *et al*. 2010), which improves the speed and success of the herding event, but this would not be appropriate to apply for the eShepherd® system as it involves learning the opposite response to the cues. The variation in cognitive and learning abilities of all animals within a herd is important to consider when applying aversive stimuli such as electrical pulses, and the more complex the process, the less likely that all animals will be able to learn. If animals are not able to learn, this can result in long-term negative states such as helplessness (perception that an animal's actions have no relationship with the outcome) and hopelessness (perception that all actions result in a negative outcome) with serious implications for animal welfare as highlighted by Lee *et al*. (2018). Potentially, an additional adverse audio cue could be applied to initiate movement (Butler *et al*. 2006; Umstatter *et al*. 2013), but it is likely the animals would rapidly become habituated to this cue resulting in no change in behaviour in response to its playback (Butler *et al*. 2006). Animals have been shown to learn to ignore novel cues if they are not associated with important consequences through the process of habituation (McGreevy and Boakes 2007).

It is uncertain from this study how animals may respond if the herding path was one that animals were accustomed to and they were experienced with the application of the back fence. For example, if dairy cattle were regularly brought in for daily milking, the herding back fence may act as prompt to instigate movement along a known trajectory, but this remains to be tested. The back fence was successful for herding over small distances and it is likely this type of fence could also be applied to mustering animals across much larger distances. Previous application of the technology showed animals moved into new areas as a virtual fence gradually increased the size of the inclusion zone over a period of days (Campbell *et al*. 2017), and it is likely it would also work if the inclusion zone was gradually reduced in size over a period of several days. Although the application of both a front and back fence did not appear to be conducive to moving animals in this study, it could be suitable for strip grazing purposes.

During the herding trials, the animals generally acted as a coordinated group in their movement trajectories, which is typical for both cattle and sheep (Ramseyer *et al*. 2009*a*, 2009*b*). This was both a benefit and a hindrance and the technology must account for the social dynamics to minimise negative impacts on the animals. Both cattle and sheep show social facilitation in their responses to the virtual fencing signals (Keshavarzi *et al*. 2020; Marini *et al*. 2020). Herding was sometimes of short duration if the animals followed each other down the paddock (see Figs 1, 3). But if there was a conflict between receiving electric stimuli and wanting to re-group with herd mates as seen during one of the automated cattle herding trials (see Fig. 2), this could result in elevated stress for the animals and unsuccessful herding. From this trial it is unclear what proportion of animals may need to already be in the inclusion zone to attract the remainder of the animals if a fence is activated within a herd's spatial distribution (cf. behind the entire herd). This may also be dependent on social bonds between animals split across the inclusion and exclusion zones rather than related solely to animal numbers. However, preliminary observations do suggest simple fence configurations that do not intentionally divide a herd may be best applied to ensure the animals can learn what movement trajectory is desired of them, especially in a social setting. A more complicated herding fence that is box-shaped, for example, and gradually reduces in size to restrict the animals to one small area of a paddock may be difficult to learn as animals would be receiving signals on multiple sides which may be confusing and thus could not be implemented as a low-stress automated technique. This likely contributed to the poor success of the front and back fence where animals were expected to rapidly move into an area that they were previously excluded from. Immediate deactivation of the front fence following the first interaction would likely increase the speed of herding when using both a back and front fence. Further testing of different automated algorithms with updated eShepherd® devices is warranted to confirm the best method for cattle herding. It is likely similar methods could then be applied to sheep if an automated device is able to be developed.

In conclusion, virtual fencing technology shows potential for herding cattle and sheep over short distances but relies on the animal's own movement and thus durations can vary substantially. A simple back fence to prevent the animals moving back in the undesired direction may be the most successful option but further testing with an updated eShepherd® system is required to verify the capabilities for automated herding. Automated virtual fencing devices are still needed for sheep, but in principal, the same technology may also be able to herd this livestock species.

Conflicts of interest

Agersens provided ongoing support during the trials but had no role in the interpretation of results and decision to publish. Dana Campbell is an Associate Editor of Animal Production Science but was blinded from the peer-review process for this paper.

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