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Developing and applying precision animal farming tools for poultry behavior monitoring

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Developing and applying precision animal farming tools for poultry behavior monitoring

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Appropriate measurement of broiler behaviors is critical to optimize broiler production efficiency and improve precision management strategies. However, performance of different precision tools on measuring broiler behaviors of interest remains unclear. This dissertation systematically developed and evaluated radio frequency identification (RFID) system, image processing, and deep learning for automatically detecting and analyzing broiler behaviors. Then different behaviors (i.e., feeding, drinking, stretching, restricted feeding) of broilers under representative management practices were measured using the developed precision tools. The broilers were Ross 708 in weeks 4-8. The major findings show that the RFID system achieved high performance (over 90% accuracy) for continuously tracking feeding and drinking behaviors of individual broilers, after they were customized and modified, such as tag sensitivity test, power adjustment, radio wave shielding, and assessment of interference by add-ons. The image processing algorithms combined with a machine learning model were customized and adjusted based on the experimental conditions and finally achieved 85% sensitivity, specificity, and accuracy for detecting bird number at feeder and at drinkers. After adjusting labeling method and hyperparameter tuning, the faster region-based convolutional neural network (faster R-CNN) had over 86% precision, recall, specificity, and accuracy for detecting broiler stretching behaviors. In comprehensive algorithms, the faster R-CNN showed over 92% precision, recall, and F1 score for detecting feeder, eating birds, and birds around feeder. The bird trackers had a 3.2% error rate to track individual birds around feeder. The support vector machine behavior classifier achieved over 92% performance for classifying walking birds. Image processing model was also developed to detect birds that were restricted to feeder access. Broilers had different behavior responses to different sessions of a day, bird ages, environments, diets, and allocated resources. Reducing stocking density, increasing feeder space, and applying poultry-specific light spectrum and intensity were beneficial for birds to perform behaviors, such as feeding, drinking, and stretching, while using the antibiotics-free diet reduced bird feeding time. In conclusion, the developed tools are useful tools for automated broiler behavior monitoring and the measured behavior responses provide insights into precision management of welfare-oriented broiler production.

DEDICATION

I would like to dedicate this dissertation to my parents, my lover, my elder sisters and brother. Thank you for your love, encouragement, and support these years.

谨以此文献给我的父母，爱人，和哥哥姐姐。感谢你们这些年的挂念，鼓励和支持。特别想对我的爱人说，显芬，这些年你辛苦了，感谢你默默地支持着我，陪伴着我。

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CHAPTER I

PRECISION POULTRY FARMING: LITERATURE REVIEW

1.1 Introduction

Broiler production has undergone remarkable advancements over the past decades as poultry meat plays an indispensable role in efficient/affordable protein for human growth and development (Wahyono and Utami, 2018). In 2019, over 26 billion kg broilers were produced at a value of over 27 billion dollars (Figure 1.1) (USDA National Agricultural Statistics Service, 2020), which was nearly a 25% increase compared to those in 2009. Besides overall scales of the production, number of broilers per house also keeps increasing. A modern broiler house contains 40000-60000 birds in general (Mastyl, 2016) and up to 100000 broilers (Roger, 2018). Within such intensive production systems, it is even impossible for farmers to inspect individual poultry carefully on their daily basis, which they typically did for the backyard chickens in the past.

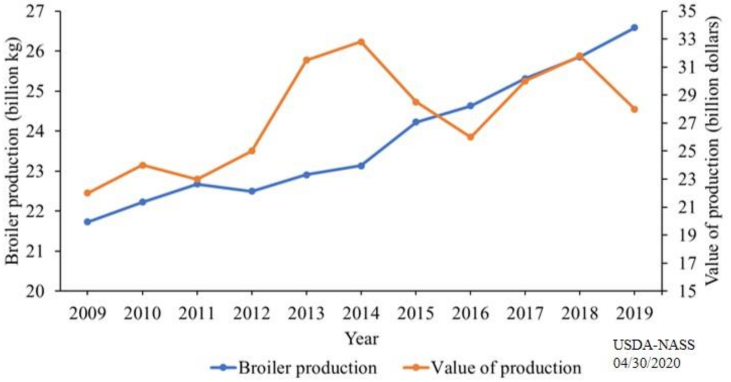

Figure 1.1 Broiler pounds produced and value of production, United States, 2009-2019

This figure was redrawn from USDA National Agricultural Statistics Service (2020).

Poultry in the intensive production systems is complex, individually different, time-varying, and dynamic (Berckmans, 2017). They can perform differently in different rearing systems and environmental conditions (Li et al., 2019a). Even in the same rearing system and environmental condition, individual poultry may respond to the surroundings differently (Oliveira et al., 2019). Even for the same poultry, its behavior patterns could change in different sessions of a day (Tolkamp et al., 2011). Poultry can also dynamically move to anywhere in a house (Febrer et al., 2006). These make the individual poultry inspection by humans difficult. Precision animal farming tools may play as “ears” and “eyes” to assist farmers in managing their farms, since they can tirelessly monitor chickens 24 hours a day and seven days a week and report any abnormalities, which could set early warnings for farmers and prevent the abnormalities from being worse (Berckmans, 2017).

The precision tools are not only needed for commercial purposes but also for behavior monitoring in academic research. Poultry behaviors contain critical information, which could better the facility design and animal-driven management for poultry production. For example, preening is a comfort behavior that chickens use their beaks to groom their feathers (Li et al., 2020a). If chickens have no access to feeders because of occupation by other birds, they could preen around the feeders to displace their frustration to the feeder resources, which is a sign of poor bird welfare (Appleby et al., 2004). Another example is poultry drinking. Drinking is critical to maintaining bird metabolism, and poultry use their beaks to touch nipple drinkers to get water in farms. If ambient temperature is extremely high, the chickens may spend more time drinking to reduce their heat stress (Lara and Rostagno, 2013). So, the performance of poultry drinking behaviors at different temperatures may tell us which temperature is better for poultry. To obtain poultry behavior information, the gold standard method is to observe birds manually. The method is precise to study single birds on small scales, but it’s time- and labor-consuming for obtaining sufficient data and studying multiple birds on large scales (Li et al., 2020b). Meanwhile, extraction of behaviors may be influenced by human bias because of different human experiences (Tuyttens et al., 2014). Furthermore, for some rarely performed behaviors, such as stretching behaviors, human observation may extract insufficient data for statistical analysis (Li et al., 2020a). Precision animal farming tools may overcome the disadvantages of human observation because they detect poultry behaviors automatically, objectively, and continuously (Li et al., 2019b).

The concept of precision livestock farming (PLF) was firstly proposed in the 1st European Conference on Precision Livestock Farming and the 4th European Conference on Precision Agriculture (Werner and Jarfe, 2003). The PLF is the use of technology to automatically monitor livestock, their products, and the farming environment in real time, in order to aid farm management, by supplying the farmer with relevant information on which to base management decisions, or by activating automated control systems (Werner and Jarfe, 2003). Livestock is commonly defined as domesticated animals raised for producing labor and commodities such as meat, egg, milk, fur, leather, and wool. According to the USDA definition, the livestock solely includes big domesticated animals, such as beef, swine, goat, and horse, and excludes domesticated birds (poultry) (Service, 2020). Therefore, to make the term more tailored in this dissertation, we use precision poultry farming or precision animal farming to replace the PLF.

Current precision tools for animal farming include, but are not limited to, sound technology, accelerometer, radio frequency identification (RFID) systems, image processing technology, and deep learning. They have pros and cons in different aspects, but their efficiency in poultry behavior monitoring has not been fully studied. We selected the latter three tools and systematically reviewed them in this chapter, which may provide insights into the choices of the three tools for poultry behavior monitoring.

1.2 Radio Frequency Identification System

An RFID system typically consists of data acquisition systems (DAQ, or PC), readers, antennas, and tags (Figure 1.2). The antennas are placed in positions of interest (e.g., nest box, feeder, drinker, etc.), and the RFID tags are attached to tested animals (e.g., neck, leg, back, etc.). Once the tested animals enter the detecting range of the antennas, the attached tags are energized by the electromagnetic field of the antennas. Then a uniquely coded signal is sent to the receiving reader that decodes the tag ID alongside the presence time, port number, etc.

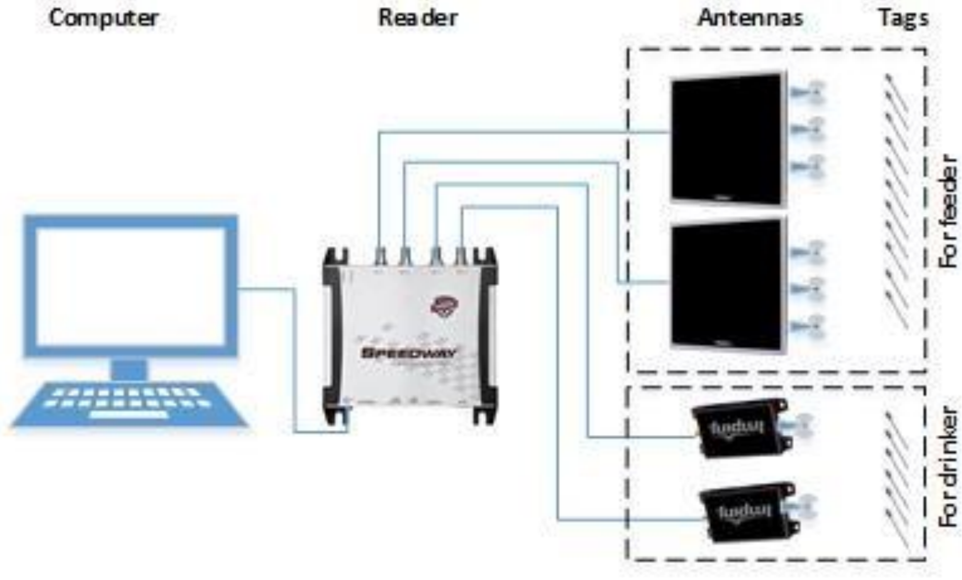

Figure 1.2 Schematic drawing of a radio frequency identification system

Radio frequency identification systems have strengths and weaknesses in different aspects (Siegford et al., 2016). They can be coupled with other systems to assist precision management.

For example, Tu et al. (2011) integrated an RFID system with body weight weighing stations and the system discerned individual turkeys entering the system and obtained feed conversion ratio and feeding behavior of individual turkeys. The system may further achieve precision feeding based on the body weights of turkeys entering the station. An RFID system can detect multiple individuals simultaneously, which measures the maximum usage of a tested resource (Oliveira et al., 2019). Additionally, there is no need for external power sources or battery for tags of passive RFID systems, which is opposite to other battery-based sensors (e.g., accelerometer). With appropriate set-up, RFID systems may continuously track the activities of individuals of interest across time and space with minimal intervention and disturbance. Despite the aforementioned advantages, RFID systems are rather expensive and complex to implement in poultry houses. The attached tags need frequent adjustment to avoid bird discomfort as poultry grow bigger and may lose during the test period (Li et al., 2019b). Furthermore, the sensitivity of the systems may be blocked by litter, metal materials, and animals (Siegford et al., 2016). These challenges limit RFID application in lab scales rather than commercial scales. If producers want to deploy this technology to their farms, they may need to consider these factors.

Current applications of RFID systems on poultry behavior monitoring are shown in Table 1.1. A majority of these applications are for laying hens. This lies in the fact that these laying hens are generally in cage-free housing systems and perform diverse behaviors and thus many efforts are dedicated to investigating the behaviors, indicating welfare status of birds in the housing systems. The RFID applications are also expanded to other types of poultry, such as broiler breeder, broiler, turkey, and duck. However, no research focuses on detecting broiler feeding/drinking behaviors, which are critical indicators for resource allowance and facility design. Factors in broiler production that are feeder/drinker type, stocking density, environmental conditions, rearing systems, and so forth may be different from those in previous research and affect detection results. Therefore, despite previous high performance on detecting various behaviors of poultry, development and evaluation of RFID systems on detecting broiler feeding/drinking behaviors are still needed in this dissertation.

Table 1.1 Applications of radio frequency identification systems on poultry behavior monitoring

Author (year)	Type of poultry	Measured behaviors	Performance (%, accuracy, sensitivity, specificity, etc.)
Li et al. (2017)	Laying hen	Feeding and nesting	85.7-98.5
Nakarmi et al. (2014)	Laying hen	Movement trajectories	95
Sales et al. (2015)	Laying hen	Compartment occupation	77.8-93.8
Thurner et al. (2008)	Laying hen	Ranging	97
Wang et al. (2019)	Laying hen	Perching	97.8-99.9
Pereira et al. (2008)	Broiler breeder	Resource utilization	——
Taylor et al. (2017)	Broiler	Ranging	——
Van der Sluis et al. (2020)	Broiler	Visits of antennas	82
Tu et al. (2011)	Turkey	Feeding	——
Bley and Bessei (2008)	Duck	Feeding	——

‘——’ means missing information in the reference.

1.3 Image Processing Technology

Image processing technology commonly consists of image/video acquisition systems and algorithms of recognizing animal behaviors of concern. For the former part, cameras are installed in animal houses to capture desired views, and then images/videos are continuously recorded in recorders for further processing. As for the latter part, it typically involves binarization and morphological operation for extracting regions of interest and models for making a prediction based on the extracted regions.

The technology is low-cost and algorithms can be embedded into some small processing units, such as Raspberry Pi. That is economically acceptable for farmers since cost efficiency is among their primary concerns (Figueiredo et al., 2003). The technology is non-invasive and requires no direct manipulations of animals, which is in contrast with sensing technologies (e.g., RFID, accelerometer, etc.). Bird activity can be recorded and processed with minimal human interference using this technology. Nevertheless, processing algorithms were subjective to the complexity of image background, environmental conditions, bird sizes, and bird postures, thus resulting in poor generalization to other settings. What's more, the technology may not be able to differentiate individual poultry in group settings and overlook individual variations within groups. These are challenges of image processing technology for commercial applications or behavior studies.

Table 1.2 shows different applications of image processing technology on poultry behavior monitoring. Different types of poultry were detected. For laying hens, different behaviors were classified with image thresholding and classification/template matching models; for broiler breeders, flock distribution and behavior classification were detected with thresholding and classification models as well; as for broilers, thresholding and morphological operations were used to evaluate flock distribution. In sum, thresholding and morphological operations were suitable for evaluating flock distribution, but additional classification models were also needed for classifying different bird behaviors. Although these algorithms achieved high performance in these applications, they were still needed to be developed and evaluated in detecting broiler feeding and drinking behaviors based on our own settings.

Table 1.2 Applications of image processing technology on poultry behavior monitoring

Author (year)	Type of poultry	Major Algorithm	Measured behaviors	Performance (%, accuracy, sensitivity, specificity, etc.)
Lao et al. (2012)	Laying hen	Binarization, Bayesian	Moving, drinking, etc.	54.0-100.0
Leroy et al. (2005)	Laying hen	Template matching	Standing, sitting, etc.	70- 96
Zaninelli et al. (2016)	Laying hen	Thresholding	Room presence	94.9-97.9
Nääs et al. (2012)	Broiler breeder	Blob explorer filter	Flock distribution	——
Pereira et al. (2013)	Broiler breeder	Contour detection, decision tree	Drinking, scratching, etc.	96.7
Guo et al. (2020)	Broiler	K-means clustering	Flock distribution	94.2-95.4
Novas and Usberti (2017)	Broiler	Otsu thresholding	Flock distribution	91.3-94.7
Figueiredo et al. (2003)	Broiler	Background subtraction	Flock distribution	82.3

'——' means missing information in the reference.

1.4 Deep Learning

Deep learning models have been widely used for speech recognition, text identification, computer vision, etc. In this dissertation, we mainly tested their performance on processing poultry-related images. Convolutional neural network (CNN), a deep learning technique, generally consists of input images, convolutional layers, pooling layers, fully connected layers, and output layers (Figure 1.3). The outputs include names of classes of interest, bounding box, and prediction probability. Although the fundamental of deep learning remains to be explored, the basic idea is to mimic operations of human brains, in which simple semantics (e.g., edges, corners) of images are extracted in low levels of convolution, while abstract semantics are inferred in high levels of convolution LeCun et al. (2015).

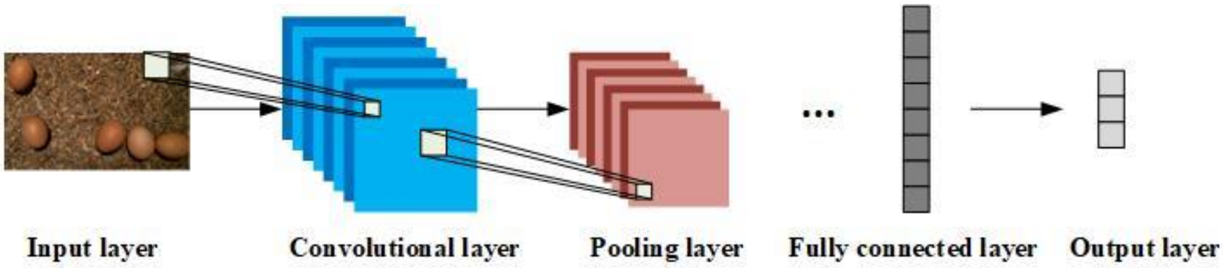

Figure 1.3 An example structure of a convolutional neural network

Deep learning is currently the most popular and powerful detection technique. It is widely applied for different domains and obtains decent detection performance. It can be generalized to different detecting environments, object shapes, object sizes, object number, object textures, etc. However, running a deep learning network is computationally expensive. As for some region-based networks (e.g., region-based CNN, faster region-based CNN, etc.), graphics processing units (GPU) are needed to boost detection performance and are expensive, which is not economically acceptable for farmers. Different network architectures are advantageous on specific applications, and thus networks need to be modified and verified before applications. The modifications include sizes of mathematical operations (e.g., convolution, pooling, and activation), connections schemes (e.g., plain stacking, inception, and residual connection), operational parameters (e.g., convolutional kernel size and kernel stride), and transfer learning dataset (e.g., ImageNet and

COCO). Expertise knowledge of machine learning is needed, which is not friendly for farmers who always want straightforward and simple tools.

Table 1.3 shows different applications of deep learning on poultry behavior monitoring. Different architectures of CNN generally had decent performance for detecting different types of poultry behaviors after trained with sufficient samples and fine-tuned with appropriate hyperparameters. Some research even combined other techniques (e.g., depth sensing) with CNN to optimize detection performance (Pu et al., 2018). Despite having decent performance in previous research, different CNNs still need fine-tuning in this dissertation to improve performance of detecting broiler behaviors.

Table 1.3 Applications of deep learning on poultry behavior monitoring

Author (year)	Type of chicken	Architecture	Measured behavior	Performance (%, accuracy, recall, specificity, etc.)
Li et al. (2020a)	Laying hen	Mask R-CNN	Preening	84.3-95.8
Li et al. (2020b)	Laying hen	Faster R-CNN	Drinking	88.2-89.4
Lin et al. (2020)	Laying hen	Faster R-CNN	Drinking, movement	98.2
Lin et al. (2018)	Laying hen	ZF-net	Flock distribution, movement	——
Pu et al. (2018)	Laying hen	CNN	Flock distribution	99.2
Wang et al. (2020)	Egg breeder	YOLO V3	Mating, standing, feeding, etc.	86.9-94.7
Fang et al. (2020)	Broiler	Deep regression network	Movement	——

'——' means missing information in the reference. CNN is convolutional neural network; mask R-CNN is mask region-based CNN; and faster R-CNN is faster region-based CNN.

1.5 Objectives and Outlines of the Dissertation

The major objective of this dissertation was to develop and evaluate different precision animal farming tools (i.e., RFID, image processing, deep learning) for broiler behavior monitoring. The developed tools were used to detect different behaviors of broilers under representative management practices, which provide insights into precision broiler management.

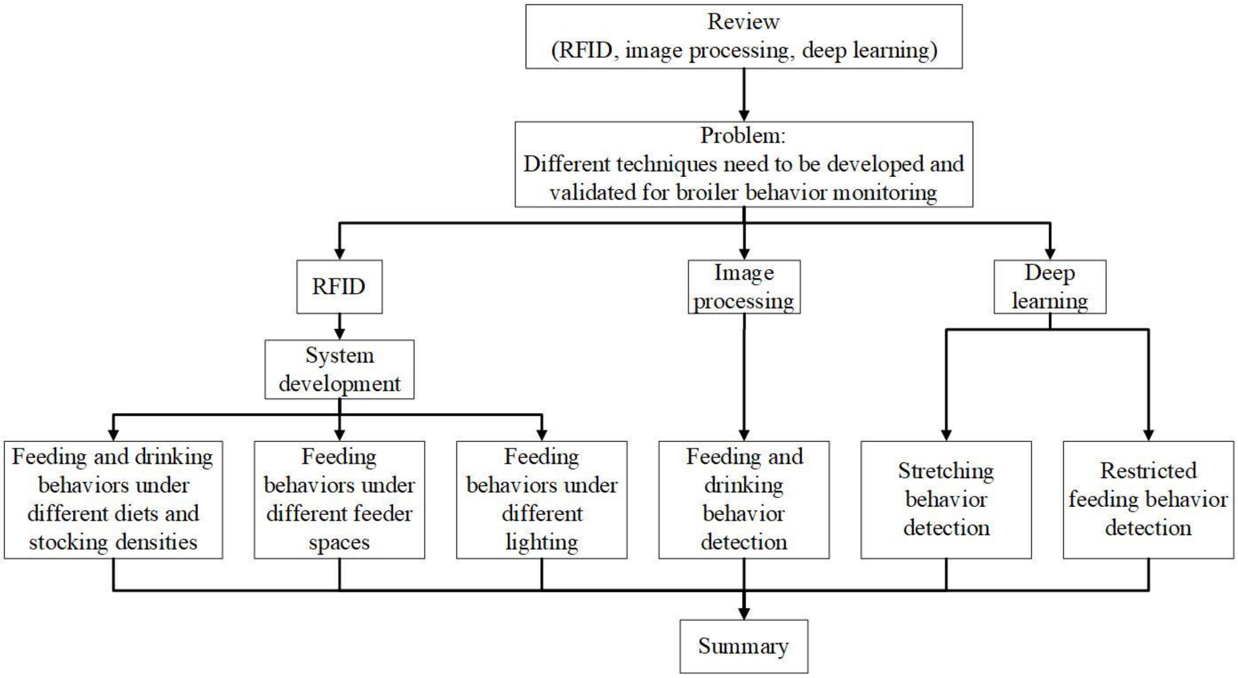

Figure 1.4 Overview of the structure of this dissertation

RFID is radio frequency identification.

Figure 1.4 shows an overview of the structure of this dissertation. The detailed objectives were:

- to review current techniques (i.e., RFID, image processing, deep learning) on poultry behavior monitoring (Chapter I).

- to develop an ultra-high frequency RFID system for monitoring broiler feeding and drinking behaviors (Chapter II).
- to detect feeding and drinking behaviors of broilers under different diets and stocking densities using the developed RFID system (Chapter III).
- to detect feeding behaviors of broilers under different feeder spaces using the developed RFID system (Chapter IV).
- to detect feeding behaviors of broilers under different lighting conditions using the developed RFID system (Chapter V).
- to detect feeding and drinking behaviors of broilers using image processing technology (Chapter VI).
- to detect stretching behaviors of broilers under different stocking densities using deep learning (Chapter VII).
- to detect restricted feeding behaviors of broilers under different stocking densities using deep learning (Chapter VIII).

Except for Chapter I, each chapter was an independent publication in different journals. The results from these chapters are summarized in Chapter IX and the conclusions provide hands-on suggestions on precision broiler management.

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CHAPTER II

RADIO FREQUENCY IDENTIFICATION SYSTEM FOR POULTRY BEHAVIOR MONITORING: SYSTEM DEVELOPMENT

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Li, G., Zhao, Y., Hailey, R., Zhang, N., Liang, Y., and Purswell, J. L. (2019). An ultra-high frequency radio frequency identification system for studying individual feeding and drinking behaviors of group-housed broilers. Animal, 13: 2060-2069. doi: 10.1017/S1751731118003440.

Abstract: Radio frequency identification (RFID) technology offers a solution to monitor behavioral responses of individual animals to various stimuli, which provides crucial implications on farm management and animal well-being. The objectives of this study were to (1) develop an ultra-high frequency radio frequency identification (UHF-RFID) system for monitoring feeding and drinking behaviors of individual broilers in group settings; and (2) validate the performance of the UHF-RFID system against video analysis in determining the instantaneous bird number (IBN) and time spent (TS) at feeder and drinker. The UHF-RFID system consisted of cable-tie tags, antennas, a reader, and a data acquisition (DAQ) system. The antennas generated electromagnetic fields where tags were registered by the DAQ system. A series of system evaluations and customizations were conducted to modified detecting ranges of the antennas, including tag sensitivity test, power adjustment, radio wave shielding, and assessment of interference by add-ons (e.g. plastic wraps for protecting antennas and an empty carton box for zoning out broilers) and feed/feeder. System validation was performed in two experimental rooms, each with 60 tagged broilers. The results showed that the max reading distances of tags from the same manufacturer were markedly different. Desired electromagnetic fields could be achieved by adjusting the supply power and by partially shielding antennas with customized stainless steel sheets. The protection materials and fully loaded feeder had little effect on electromagnetic fields of the antennas. The accuracies of the UHF-RFID system for determining IBN and TS were, respectively, 92.5±4.2% and 99.0±1.2% by the feeder antennas and 94.7±4.2% and 93.7±6.9% by the drinker antennas. It is concluded that the UHF-RIFD system can accurately detect and record feeding and drinking behaviors of individual broilers in group settings and thus being a useful tool for investigating impacts of resource allocations and management practices on these behaviors.

Keyword: poultry, behavioral detection, system setup, validation

2.1 Implications

The customized ultra-high frequency radio frequency identification (UHF-RFID) system can be used to track the feeding and drinking behaviors of individual broilers. The feeding and drinking behaviors of broilers can be used as indicators of bird health, resource utilization, and productivity problems, thus having critical welfare and economic implications on broiler production. The system customizations and validations presented in this study demonstrated standard procedures to improve accuracy of UHF-RFID systems for broiler behavioral monitoring.

2.2 Introduction

Assessments of poultry feeding and drinking behaviors help to understand bird utilization of feed and water resources, thus having critical economic and welfare implications for poultry industry (Gonyou, 1994; Prayitno et al., 1997). Previous studies have investigated poultry feeding and drinking behaviors as affected by management practices (Savory and Mann, 1999), environmental stimuli (May and Lott, 1994), and rearing systems (Tanaka and Hurnik, 1992). Of these studies, many recorded poultry behaviors through manual observation, e.g. identifying birds and behaviors visually by investigators. Manual observation is suitable for behavioral studies with small sample sizes; however, it becomes laborious and impractical as the sample size increases and multiple behavioral responses are required to be monitored simultaneously. Development of automatic systems that can accommodate large sample sizes and monitor multiple behaviors is warranted.

Some automatic monitoring systems have been developed for studying group-housed poultry behaviors. For example, weighing scale systems were used to monitor real-time feed and water consumptions (Lott et al., 1992; Puma et al., 2001). While these systems successfully recorded the feed and water uses of the entire group, they were not capable of monitoring behaviors of individual birds, therefore missing the information of individual variations within a group.

Radio frequency identification offers a solution to simultaneously monitor behaviors of multiple individual animals by registering the tagged animals entering electromagnetic fields of antennas (Maselyne et al., 2014; Sales et al., 2015). The commercially available antennas vary in size and shape and can be incorporated into existing animal production systems with proper modifications. Radio frequency identification systems have been used for automatically monitoring feeding and drinking behaviors of swine, turkeys, and laying hens, and have demonstrated high accuracy of sampling (Tu et al., 2011; Brown-Brandl et al., 2013; Maselyne et al., 2016; Li et al., 2017). Nakarmi et al. (2014) designed a RFID matrix and algorithms to track trajectory movements of individual laying hens, and register their feeding, drinking, perching and nesting behaviors.

Although RFID system has been employed for monitoring behaviors of many domestic animal species, it has not been developed for use in group-housed broilers in the open flooring housing system which is typical practice at US broiler commercial farms. The objectives of this study were to: (1) develop a UHF-RFID system for continuously monitoring feeding and drinking behaviors of individual broilers in group settings; and (2) validate the UHF-RFID system against video analysis in determining the instantaneous bird number (IBN) and time spent (TS) at feeder and drinker.

2.3 Materials and Methods

2.3.1 Ultra-high Frequency Radio Frequency Identification System

The UHF-RFID system consisted of four elements: tags, antennas, a reader and a data acquisition (DAQ) system (Figure 1.2). The antennas generated electromagnetic fields that registered uniquely coded RFID tags and the reader (IPJ-REV-420; TransTech Systems Inc., Wilsonville, OR, USA) subsequently transmitted IDs of the tags to the DAQ system. In animal tests, the tags were attached to the necks of birds (Figure 2.1), and antennas were placed closely to the areas of concern (i.e., underneath tube feeders and next to nipple drinkers). Cable-tie tags (PT-103; TransTech Systems Inc., Wilsonville, OR, USA) were used in this study because they were small and could be easily attached to birds (Oliveira et al ., 2016). A square antenna (TIMES-7 A6034S; Impinj Inc., Seattle, WA, USA) and a rectangular antenna (IPJ-A0303-000; Impinj Inc., Seattle, WA, USA) were selected to register feeding birds at the tube feeder and drinking birds at the nipple drinker, respectively. The UHF-RFID tags were manufactured by Technologies ROI LLC (SC, USA).

Figure 2.1 A Ross×Ross 708 broiler with a radio frequency identification tag on its neck

2.3.2 System Performance Tests

2.3.2.1 Variations in Tag Sensitivity

Cable-tie tags with the same manufacture specifications may be excited at different electromagnetic strengths or, in other words, be registered at different distances from an antenna. To understand the variations among tags and select those with similar sensitivities for the animal test, max reading distances (MRD) of cable-tie tags from a square antenna (TIMES-7 A6034S; Impinj Inc., Seattle, WA, USA) were determined using the procedures described below. The antenna was horizontally placed and provided with the power of 0.2 W. A cable-tie tag was placed at the center of the testing antenna. The tag was then moved perpendicularly up from the antenna until it could no longer be detected. At this moment, the distance between the tag and antenna was recorded as the MRD. At the MRD, the tag was rotated in the horizontal plane to make sure a true MRD. The way of tag positioning and rotating in this test simulated how a tagged bird approached to the feeder or drinker antenna (Figures 2.2c and 2.2d). The position and movement of tags were applied for the entire system performance tests. In this section, the MRDs of tags at the center of the antenna were determined. Basic descriptive statistical parameters (e.g., mean, standard deviation, and CV) were calculated to evaluate the variations among tags. To select tags with similar sensitivities for the animal test (or to remove the outliers), a method of inter-quartile range (IQR) was used (Tukey, 1977). The first quartile (Q_{25}) was the 25th percentile of the MRD data, and the third quartile (Q_{75}) was the 75th percentile of the MRD data. The IQR was defined as the difference between Q_{25} and Q_{75}. The lower and upper inner fences were defined by Q_{25}-(1.5×IQR) and Q_{75}+(1.5×IQR), respectively. The MRD data out of the lower and upper inner fences were treated as outliers. Tags with MRD data located within the inner fence were deemed similar in sensitivities and used in the animal test.

To observe the MRD difference of same tags, five additional tags (tag IDs: A359, A362, A372, A384, and A393) were randomly selected and the MRD of each of these tags was measured for three times. The MRDs of these tags held by wooden sticks were compared with those held by a hand to check the hand effect on the system performance tests. The MRDs of these five tags were tested when the tags were leaving and entering the electromagnetic field of the antenna. Due to the variations in tags, four tags with similar sensitivities were selected via the IQR method mentioned above and used for the following system performance tests.

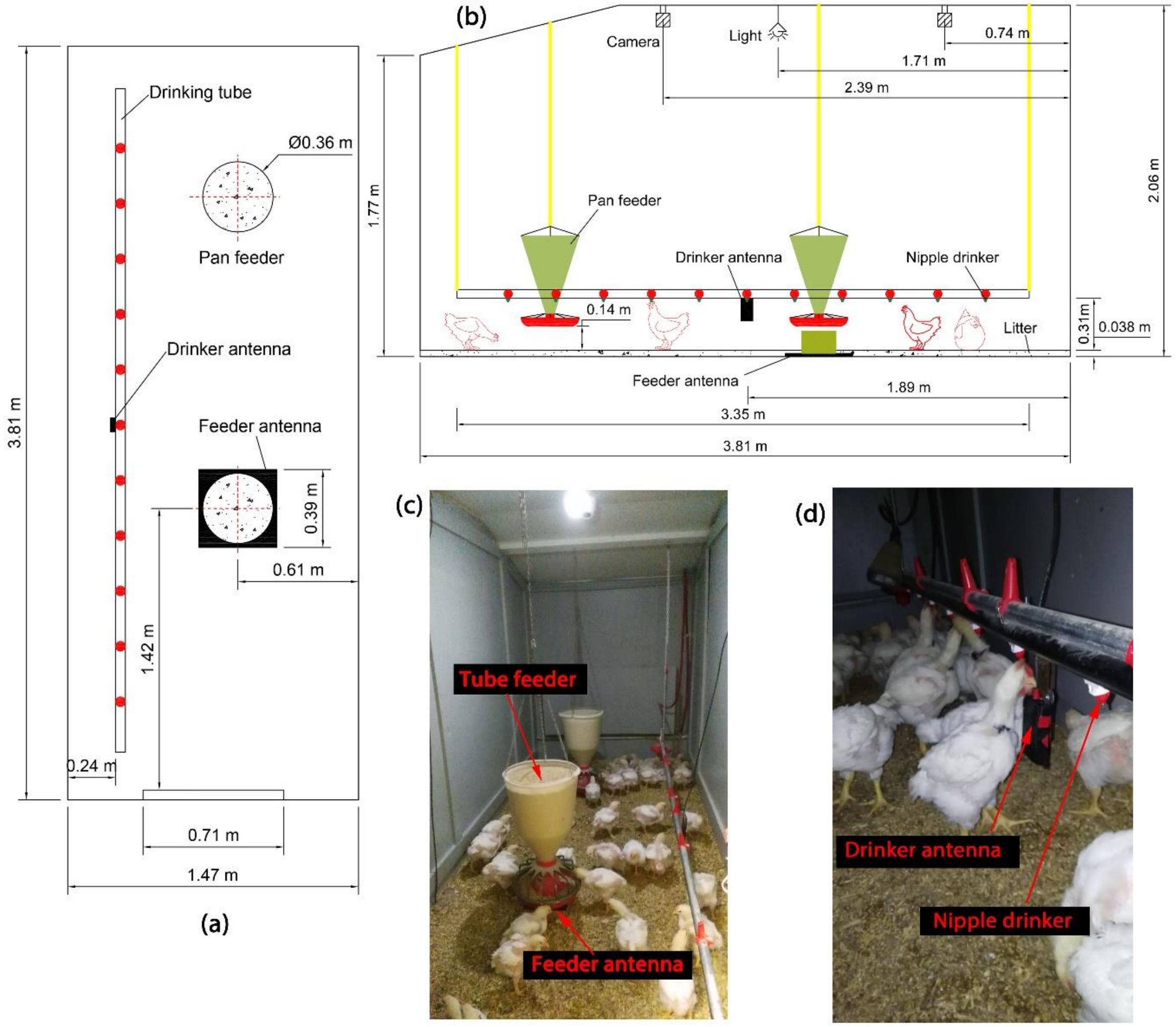


Figure 2.2 Schematic drawings and photos of the experimental room and antennas for the behavioral study

(a) top view; (b) side view; (c) a photo for the placement of the feeder antenna; (d) a photo for the placement of the drinker antenna

2.3.2.2 Effect of Steel Sheets on Electromagnetic Field of the Feeder Antenna

The square antenna was larger than the tube feeder (Figure 2.3), which produced areas of unconcern.

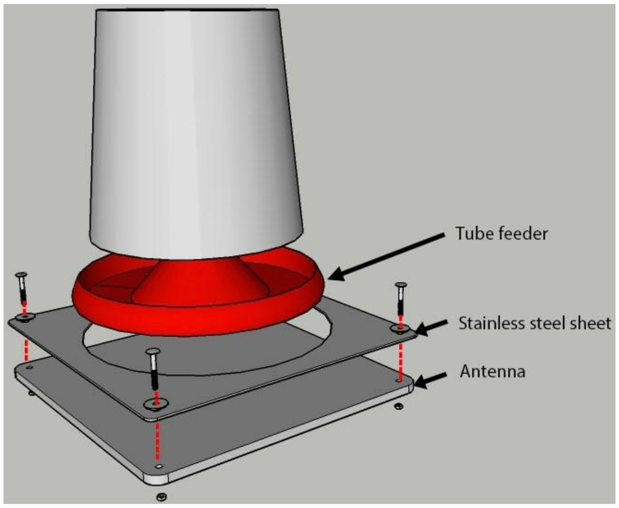


Figure 2.3 Schematic illustration of system setup for testing shielding effect of stainless steel sheet

Electromagnetic fields at the corners of a feeder antenna are blocked the steel sheet. Different diameters of the center opening were tested.

To create an electromagnetic field at the space of interest directly above the feeder pan, radio waves emitted from corners of the square antenna needed to be shielded. Because stainless steel sheets can effectively block the wave emission from antennas (Sales et al., 2015), 1.5-mm-thick stainless steel sheets with different sizes of center openings were fabricated and their shielding effects on the electromagnetic field at the corners of the feeder antenna were investigated. The tested steel sheets had the same dimension (40×40 cm, L×W) as the antenna, but differed in the diameters (46, 43, 41, 38, and 36 cm) of the center openings (Table 2.1). They were bolted to the feeder antenna during the test. Based on the results of section 2.2.2.1, four tags with similar sensitivities in the acceptable MRD range were randomly selected for this test. The four tags (each measured for three times and the same in the following) were used to test the MRD at the shielded corners of the feeder antenna at four power settings (Table 2.1). The tags were held for 3 to 5 s at the MRD for each measurement. The steel sheets with all opening sizes were initially tested at 1.0

W, the maximal power setting. The steel sheet with a 36-cm-diameter center opening shielded the electromagnetic field most effectively and appropriately, therefore its shielding effect was fine-tuned at other power settings of 0.8, 0.6 and 0.5 W.

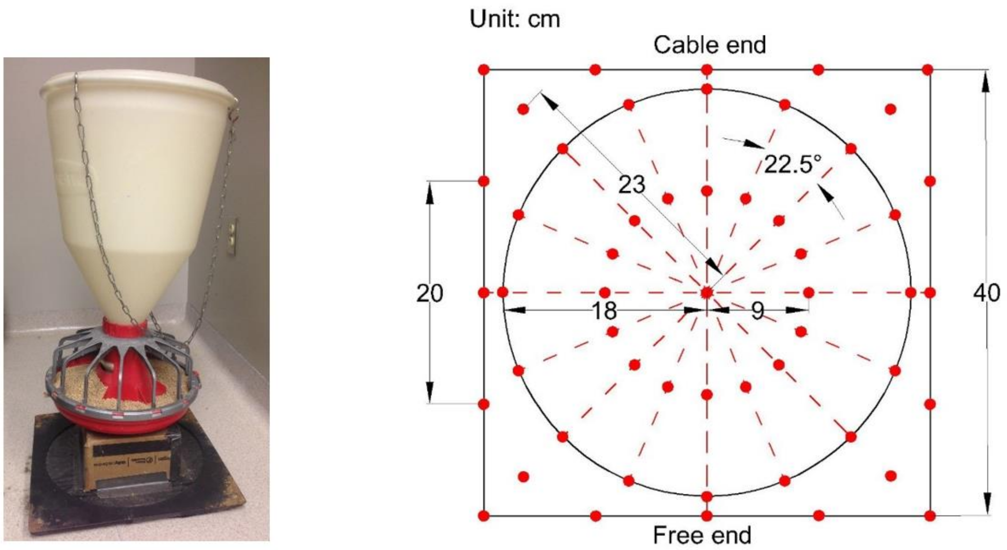
Table 2.1 Power settings and center opening diameters for the shielding effect testing

Diameter of center opening (cm)	Power setting (W)
46	1.0
43	1.0
41	1.0
38	1.0
36	1.0
36×2*	1.0
36	0.8
36	0.6
36	0.5

* Two layers of steel sheets with 36-cm center opening. The tested materials are stainless steel sheets and feeder antennas.

2.3.2.3 Effect of Other Add-ons and Feed/feeder on Electromagnetic Field

In the animal test, the feeder antenna was protected with plastic wraps and placed on the litter floor and ~14 cm below the hanging feeder. An empty carton box was placed in the gap between the antenna and the feeder to prevent birds staying underneath the feeder (Figure 2.4a).



(a) (b)

Figure 2.4 Details of electromagnetic field testing of customized feeder antenna

(a) System setup of electromagnetic field test for the feeder antenna; and (b) top view of the feeder antenna and test points indicated by red dots.

The four testing scenarios are shown in Table 2.2. The plastic wrap is one layer. The empty carton box is 21.5×20.6×17.4 cm (L×W×H). The feeder is either empty or fully loaded. Supplying power of the antenna was set to 1.0 W. Max reading distances of four tags were determined at the three different points near the center of the antenna for each scenario. Plastic wraps were also used to protect the drinker antenna, and MRDs of four tags above the drinker antenna with or without plastic wraps were determined through the same method as that for the feeder antenna.

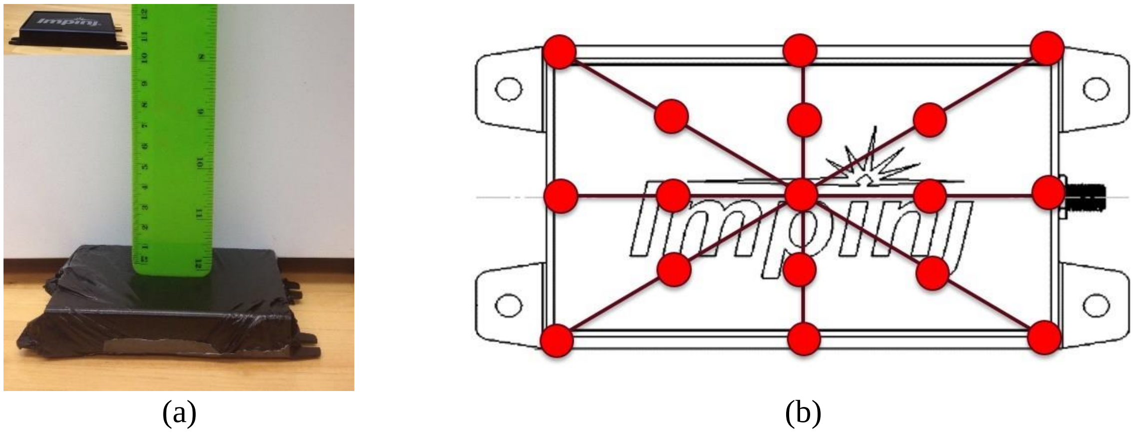
Table 2.2 Scenarios for the shielding effect testing

Scenario	Items
1	Without plastic wrap, carton box, and feeder
2	With plastic wrap only
3	With plastic wrap and carton box
4	With plastic wrap, carton, and fully loaded feeder

The plastic wrap is one layer, the carton box is empty, and the feeder is either empty or loaded.

2.3.2.4 Electromagnetic Fields of Antennas

Electromagnetic fields of the feeder and drinker antennas were measured with all add-ons and a fully loaded feeder, which simulated the system setup in the validation tests. For the feeder antenna, the MRDs of four tags were determined at 53 points above the antenna (Figure 2.4). For the drinker antenna, the MRDs of four tags at 17 points above the antenna were determined (Figure 2.5). The power settings were 0.8 W for the feeder antenna and 1.0 W for the drinker antenna. The MRD data were interpolated to produce electromagnetic fields of the antennas in a 3D coordination using Matlab (R2014b; MathWorks, Natick, MA, USA). In addition to the testing points indicated in Figures 2.4 and 2.5, some extra fields beyond the borders of both antennas were also tested. However, the signal in those fields was weak (MRD was ~1 to 2 cm) and unstable. Therefore, only the fields right above both antennas were presented in this study.


(a)

(b)

Figure 2.5 Details of electromagnetic field testing of customized drinker antenna

(a) System setup of electromagnetic field test for the drinker antenna; and (b) top view of the drinker antenna and test points indicated by red dots.

2.3.3 Validation of the Ultra-high Frequency Radio Frequency Identification System

2.3.3.1 Housing, Animals, and Management

Two experimental rooms were used for the UHF-RFID system validation, and each measured 3.81 m long, 1.47 m wide, and 2.06 m high (Figure 2.2). Each room was equipped with two 36-cm-diameter tube feeders and 11 nipple drinkers. Pine shavings (~4-cm thick) were used as the bedding material. A dimmable LED light bulb was installed at the center of the ceiling. Light intensity at bird level was adjusted according to typical practices at commercial broiler farms. In each room, the wrapped square antenna was placed on the litter floor below one of the suspending tube feeders. An empty carton box was placed in the gap between the feeder and antenna. A drinker antenna was attached to a bracket mounted to one of the nipple drinkers. See Figure 2.2 for details of the system setup. All procedures were approved by the USDA-ARS Institutional Animal Care and Use Committee at Mississippi State.

One hundred and twenty Ross×Ross 708 broilers at 28 days of age were equally allocated to the two experimental rooms (60 birds each). A tag was tied, like a collar, to the neck of each bird (Figure 2.1). Only tags within the acceptable MRD range based on IQR method were used for the test. To minimize discomfort, tag collars were loose enough to tuck in an index finger. Tagged broilers were inspected on a daily basis. The size of collars was regularly adjusted to avoid discomfort (e.g., panting, choking, etc.). Standard broiler diets were supplied. Water and feed were provided *ad libitum*. Lighting schedule was 16-h lighting and 8-h darkness (ON at 0500 h and OFF at 2100 h). During the test period of the experiment, the daily temperature and relative humidity at bird level were maintained at 20.7±2.0 °C and 64±6% (mean±SD), respectively.

2.3.3.2 Data Collection

The UHF-RFID system continuously registered broilers at feeder and drinker. The data were exported as the text documents (.txt) and then processed in Excel using Visual Basic for Applications. Broiler behaviors at the tube feeder and nipple drinker with antennas were videotaped using two high-definition cameras (Vandal Proof IR Dome Camera; Backstreet 248 Surveillance, LLC., Salt Lake, UT, USA) installed at the ceiling of each experimental room. The video files (2 frame per second, or 2 fps) were saved as AVI format in the network video recorder. All frames of the video files were extracted using Free Video to JPG Converter (ver. 5.0). Numbers of broilers in these frames were manually counted and compared with those registered by the UHF-RFID system.

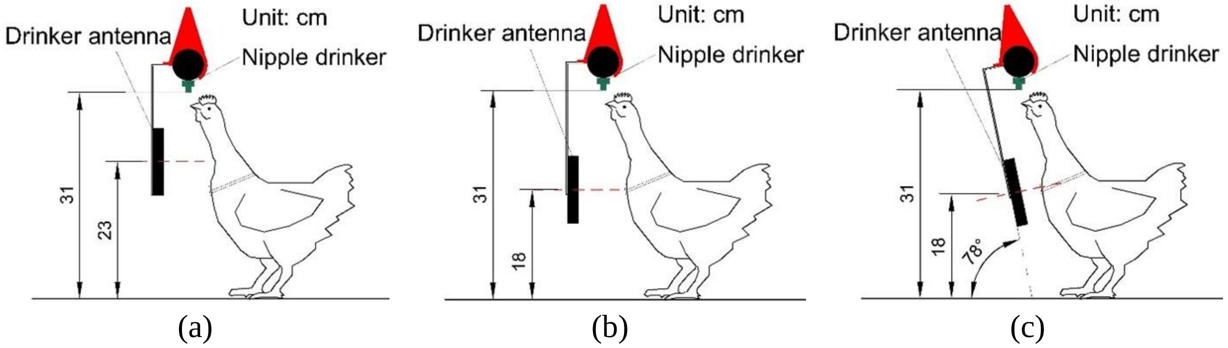
2.3.3.3 Duration of Intermittent Withdrawal from a Feeder/Drinker in a Continuous Feeding/Drinking event

In a continuous feeding/drinking event, a bird could shortly withdraw from the feeder/drinker for swallowing based on manual observation (Li et al., 2017). This yielded reading gaps in continuous feeding/drinking events. The duration of intermittent reading gaps was determined via a histogram analysis of feeding and drinking events in 10 video episodes (Li et al., 2017). The time gaps between two adjacent readings of 10 individual birds were determined. Then a histogram of the time gaps was generated and analyzed. A duration that yielded 95% coverage of the RFID readings in the histogram was used to fill the time gaps.

2.3.3.4 System Validation

The broilers at feeder and drinker detected by the UHF-RFID system were compared to those observed manually in images. A broiler was identified as ‘at feeder/drinker’ when it was eating/drinking, or when it stood at the feeder/drinker and its head directed to the feeder/drinker.

The validation tests of drinking behaviors were performed with three different antenna placements (i.e., vertical placement at 23-cm height, vertical placement at 18-cm height, and tilting placement at 18-cm height) (Figure 2.6).



(a) (b) (c)

Figure 2.6 Placements of antennas in validation tests for drinking behaviors

(a) Vertical placement at 23 cm height; (b) vertical placement at 18 cm height; and (c) tilting placement at 18 cm height

Each placement was tested for 2 days. As we wanted to spread the validation periods within and across days, rather than focusing on a specific day and time, 2 min of every 2 h (0600, 0800, 1000, 1200, 1400, 1600, 1800, and 2000 h) in the 16 lighting hours were selected. Total 55 2-min videos were collected in a 7-day period (in the 7th day, seven videos were selected for the validation). These videos were then converted to 13200 frames for the validation. Li et al. (2018) also reported that broilers spent average 1.3 to 2.0 min for single feeder visit registered by the UHF-RFID system. Therefore, 2-min episodes were enough to cover these behaviors for the validation purpose. In the 2-min periods, the IDs of feeding and drinking birds recorded by RFID system at 1-s intervals were summarized. Based on that information, we determined the IBN at feeder/drinker in each second and the overall TS at feeder/ drinker of each bird. These RFID data were compared with the visual observation data for determining the accuracy. It did not affect the validation at all if some birds already started feeding/drinking at the beginning of the 2 min or did not complete feeding/drinking at the end of the 2 min.

The equations for calculating the accuracy are shown as follows:

(1) For IBN:

$$Accuracy[\%] = \frac{N}{M} \times 100 \tag{2.1}$$

where *N* is number of seconds when RFID could register correct number of birds at feeder/drinker; and *M* is the total number of seconds in 2 min.

(2) For TS

$$Accuracy[\%] = \frac{TSRFID}{TSM} \times 100 \tag{2.2}$$

where *TSRFID* and *TSM* are the *TS* detected by the RFID system and by human observation in 2-min videos, respectively. Time spent is the sum of bird number at feeder/drinker in 2-min videos.

2.3.3.5 Example Continuous Behavioral Monitoring

Numbers of birds at a feeder (out of two feeders) and at a drinker (out of 11 drinkers) were presented from 0912 to 1012 at 35 days of bird age. These results indicated that the system could continuously monitor group-reared birds at feeder/drinker. To elaborate that the system could also continuously monitor the individual behaviors, seven randomly-selected birds with unique IDs (A005, A007, A012, A021, A023, A029, and A045) at feeder and the other seven birds (A002, A028, A034, A049, A050, A057, and A088) at drinker were also presented within the same hour.

2.3.4 Statistical Analysis of Results

One-way ANOVA with LSD post-hoc analysis was used to compare the MRDs of tags above the antennas as affected by a hand vs. wooden sticks, leaving vs. entering the electromagnetic field, center opening sizes of the steel sheets, supplying powers, add-ons and feed/feeder. The statistical analysis was conducted in Statistical Analysis Software (SAS 9.3; SAS Institute Inc.). All data were analyzed using PROC GLM statement. The effects were considered significant at a probability level of 0.05. The root mean square error (RMSE) was also provided to quantify the differences between values predicted by the model and the values observed.

$$Y_{ij} = \mu + \alpha_i + \varepsilon_{ij} \tag{2.3}$$

where Y_{ij} is the measured max reading distance; μ is the overall mean; α_i is the main effect of diameters of opening and power, or the main effect of the add-ons; and ε_{ij} is the random error for the model.

2.4 Results

2.4.1 Variations in Tag Sensitivity

Max reading distances of 50 cable-tie tags were determined above the center of a square antenna. The mean±SD of MRD was 50.1±4.6 cm (Figure 2.7). The first quartile (Q_{25}), the third quartile (Q_{75}), the 1.5×IQR, the upper inner fence and the lower inner fence were 48.3, 53.3, 7.5, 61.0 and 40.6 cm, respectively. In Figure 2.7, one tag ((48, 60.1), tag ID and MRD) is above upper inner fence and four tags ((3, 40.5), (4, 38.1), (5, 38.1) and (37, 39.3)) are below lower inner fence. These tags were treated as outliers. After excluding these tags, the mean of MRD±SD was 50.8±3.0 cm with a CV of 5.9%. Max reading distances of five extra tags held by a hand were 64.0±1.0 cm for A359, 55.7±1.5 cm for A362, 54.3±1.5 cm for A372, 46.7±1.5 cm for A384, and 47.7±1.5 cm for A393. Max reading distances of these tags held by wooden sticks were 67.3±0.6 cm for A359, 55.0±1.7 cm for A362, 58.0±1.0 cm for A372, 47.0±1.0 cm for A384, 46.7±1.2 cm for A393. The mean MRDs of these five tags held by a hand and wooden sticks were 53.7±6.6 and 54.8±8.0 cm

(*P*=0.25, RMSE=0.10). The mean MRDs of these five tags leaving and entering the field were 52.8±7.8 and 53.2±8.1cm, respectively (*P*=0.33, RMSE=0.10).

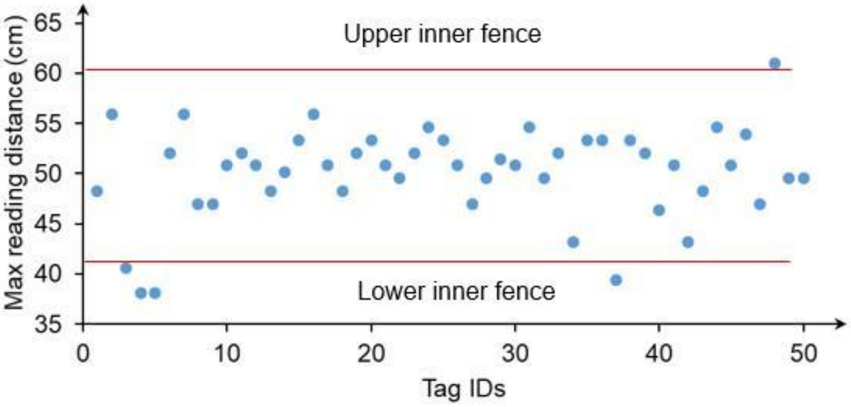


Figure 2.7 Max reading distances of 50 cable-tie tags above an antenna at power of 0.2 W Upper and lower inner fences are indicated as horizontal red lines.

2.4.2 Shielding Effect of Steel Sheet on Electromagnetic Field

Figure 2.8 shows the mean MRDs of four tags at the shielded corners of the feeder antenna covered by the stainless steel sheets with different opening sizes at four power settings. At 1.0 W, the MRDs were similar when the antenna was covered by sheets with center opening sizes of 41 to 46 cm. The MRDs were significantly reduced for opening sizes of 36 and 38 cm, indicating better shielding effects by these sheets. An extra layer of an identical sheet to the existing one with a 36-cm-diameter opening provided no additional shielding effect on radio waves, because the MRDs were similar (31.1±0.9 cm for one layer vs. 30.5±0.3 cm for two layers). Reducing the input power to 0.8 W was an effective way to minimize the MRD to 13.5±1.3 cm for the sheet with a 36-cm-diameter opening. At the power of 0.6 and 0.5 W, the MRDs were further reduced (5.1±1.1 and 2.3±0.2 cm, respectively). The P-value and RMSE were <0.0001 and 0.46, respectively. Based on our field measurements, the average height of tags attached to 28-day-old standing broilers was

~18 cm. In this study, power was set to 0.8 W and one layer of metal sheet with a 36-cm-diameter center opening was used in the animal tests. In this section, the signal shielding at the corners was the main objective. It was not necessary to test the full grid because only electromagnetic field at the corners need to be blocked to avoid registering birds nearby the feeder without eating. The full-grid electromagnetic fields of shielded antennas were determined in a latter step.

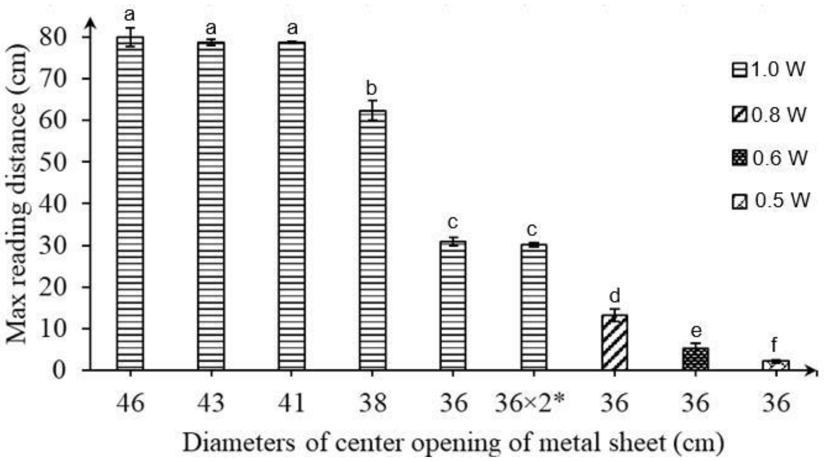


Figure 2.8 Arithmetical mean maximum reading distances of radio frequency identification tags at corners of the feeder antenna

The feeder antennas were shielded by stainless steel sheets with different opening sizes at four power settings. * Two layers of steel sheets with 36-cm-diameter center openings. Means with different letters on the top of bars are significantly different at *P* <0.05 (*n*=4).

2.4.3 Effect of Other Add-ons and Feed/Feeder on Electromagnetic Field

Figure 2.9 shows the MRDs of tags above the feeder antenna with and without plastic wraps, carton box, and feed/feeder. The mean MRDs±SD were 82.3±0.9 cm for the feeder antenna without all add-ons and feed/feeder, 81.9±1.2 cm for the antenna with protective plastic wraps, 81.5±2.5 cm for the antenna with wraps and a carton box, and 81.3±1.2 cm for the antenna with all add-ons and a fully loaded feeder. The P–value and RMSE are 0.47 and 0.25, respectively. The mean MRDs numerically reduced as more add-ons were used, but the difference was not statistically significant. The mean MRD of tags above the drinker antenna with and without plastic wraps are 6.3±2.4 and 6.1±1.5 cm, respectively, and the difference is not significant (*P*=0.34, RMSE=0.19). The results indicated little effect on electromagnetic field of the antennas by these add-ons and feed/feeder. Based on the observation, the box worked fine during the one-week testing. We did not test for an extended period, but there should be other simple alternatives if the carton box is not last long. In this section, the interference effect of radio waves by the add-ons and feed/feeder was the main concern. It was enough to select a few representative testing points for this objective. Therefore, three different points near the center of the antennas were selected for the test. Electromagnetic fields of the shielded antennas were determined in a latter step.

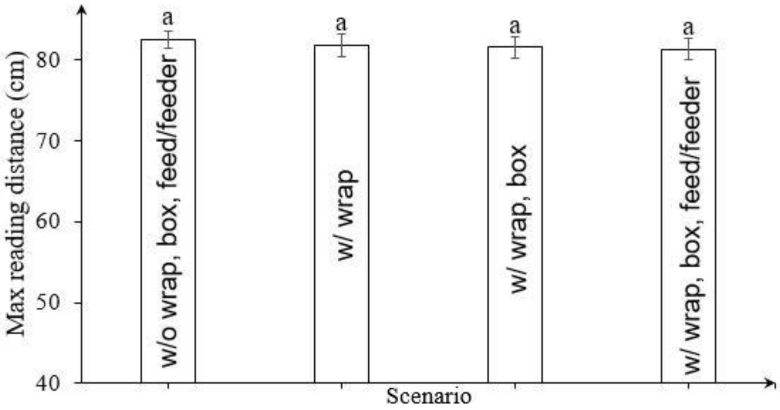


Figure 2.9 The maximum reading distances of radio frequency identification tags above a feeder antenna

The feeder antenna was with or without protective plastic wraps, a carton box, and feed/feeder at power of 1.0 W. Means with the different letters on the top of bars are significantly different at *P*<0.05 (*n*=4). 'w/o' and 'w/' in the figure mean 'without' and 'with', respectively.

2.4.4 Electromagnetic Field of Antennas

With the same setup as in the validation tests, electromagnetic fields of feeder and drinker antennas are delineated in Figure 2.10. Each point at the colorful dome surface represents the measured or interpolated MRD of RFID tags above the corresponding projection point of an antenna placed in x-y plane. For the feeder antenna, the MRDs were 51.2±5.2 cm for the center area and 12.6±1.3 cm for the corners, respectively (Figure 2.10a). Such an electromagnetic field is reasonable to register the eating broilers and ignore those walking by the feeder without eating. The MRD at the center of the drinker antenna was 6.2±0.3 cm (Figure 2.10b). However, the mean MRD at the corners of the drinking antenna was 2.5±0.3 cm, which could not be sufficient to register a drinking broiler. The result implies the need for strategic placements (e.g., the tilting placement) of drinker antennas in order to maximize the chance for registering drinking broilers.

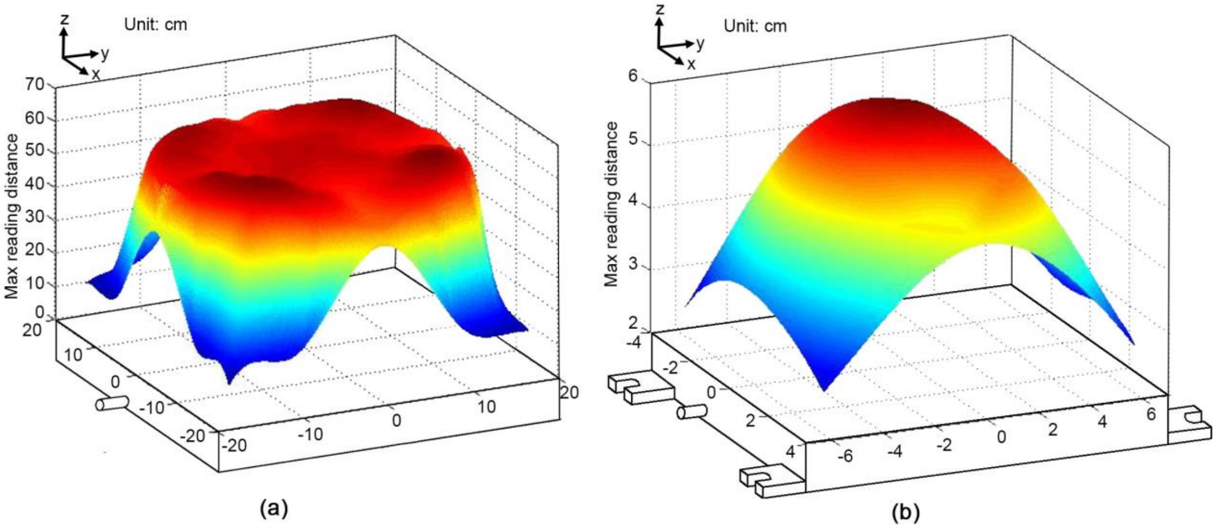


Figure 2.10 Electromagnetic fields of the customized feeder and drinker antennas

(a) A feeder antenna (with one-layer stainless steel sheet with a 36-cm-diameter center opening, plastic wraps, a carton box, and a fully loaded feeder at 0.8 W); and (b) a drinker antenna (with protective plastic wraps at 1 W).

2.4.5 Duration of Intermittent Withdrawal from a Feeder/Drinker in a Continuous Feeding/Drinking Event

Figure 2.11 shows coverage of RFID reading gaps at different intervals for including two gapped RFID readings in one behavioral event. A threshold of 20 s for inclusion of RFID data in a single feeding/drinking behavior provided, respectively, 94.7% and 96.0% coverage of the data collected by the UHF-RFID system. In other words, ~95% of the intermittent withdrawal (or swallowing) behaviors lasted for less than 20 s.

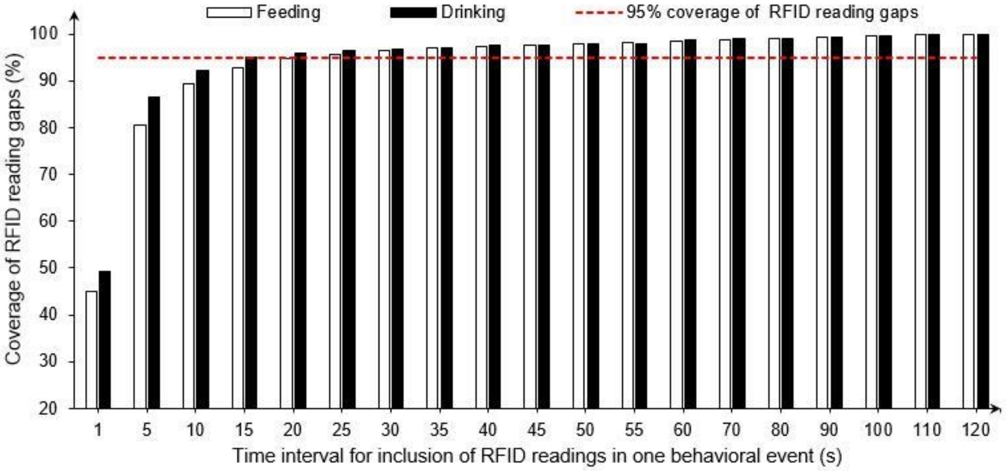


Figure 2.11 Coverage of radio frequency identification (RFID) reading gaps vs. time interval for including two gapped RFID readings in one behavioral event

2.4.6 Accuracy of the Ultra-high Frequency Radio Frequency Identification System

The UHF-RFID system was accurate in monitoring broiler feeding behaviors. The mean accuracies were 92.5% for IBN and 99.0% for TS at feeder (Table 2.3). The accuracy of the UHF-RFID system for drinking behaviors was affected by placements of the drinker antenna. Specifically, the mean accuracies of IBN and TS at drinker were, respectively, 77.2% and 68.4% for the vertical placement at 23 cm height, 89.8% and 73.1% for the vertical placement at 18 cm height, and 94.7% and 93.7% for the tilting placement at 18 cm height.

Table 2.3 Accuracy of the UHF-RFID system registering feeding/drinking behaviors

Behaviors	Accuracy (mean±SD (%))	
	IBN	TS
Feeding	92.5±4.2	99.0±1.2
Drinking		
Vertical placement at 23cm height	77.2±19.5	68.4±21.3
Vertical placement at 18cm height	89.8±10.8	73.1±27.3
Tilted placement at 18cm height	94.7±4.2	93.7±6.9

IBN is instantaneous bird number at feeder/drinker; and TS is time spent at feeder/drinker.

2.4.7 Continuous Behavioral Monitoring by the Ultra-high Frequency Radio Frequency Identification System

Figure 2.12a shows the number of broilers at one tube feeder (out of two feeders) and one nipple drinker (out of 11 drinkers) from 0912 to 1012 on 35 days of bird age in one experimental room. Broilers spent overall 336.7 bird-min at feeder and 34.3 bird-min at drinker, respectively, within the hour. Seven randomly-selected tag birds (A045, A029, A023, A021, A012, A007, and A005) were used to test the monitoring performance of the feeder antenna (Figure 2.12b). Another seven tags birds (A002, A028, A034, A049, A050, A057, and A088) were selected to test the performance of the drinker antenna as well (Figure 2.12c). The results show individual broilers exhibited different feeding/drinking pattern within this hour. The average and 95% confidence interval for TS were 11.8±6.1 min at feeder and 2.8±1.7 min at drinker, and 7.2 to 16.3 min at feeder and 1.6 to 4.1 min at drinker for these seven individual birds during this hour.

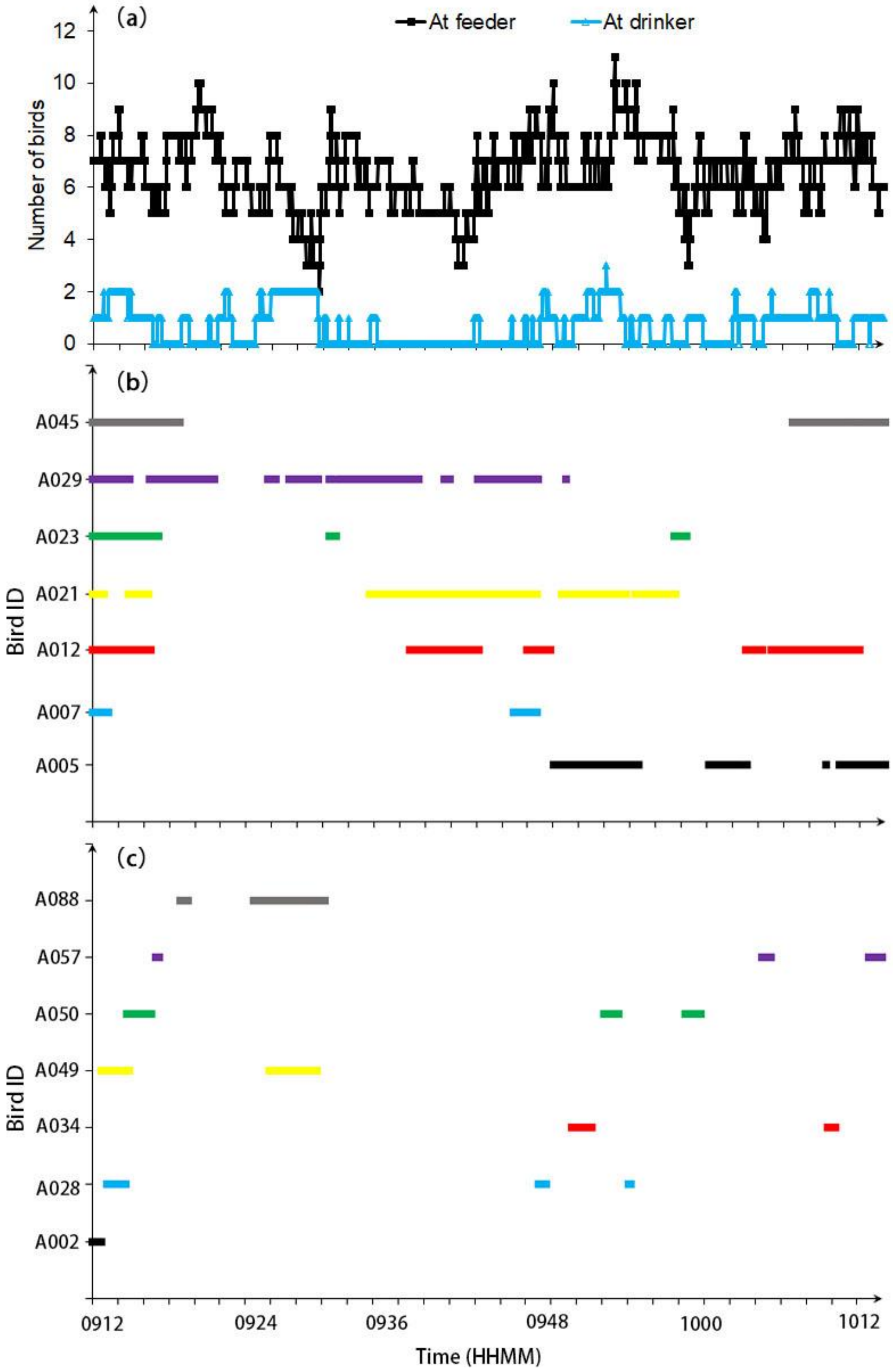
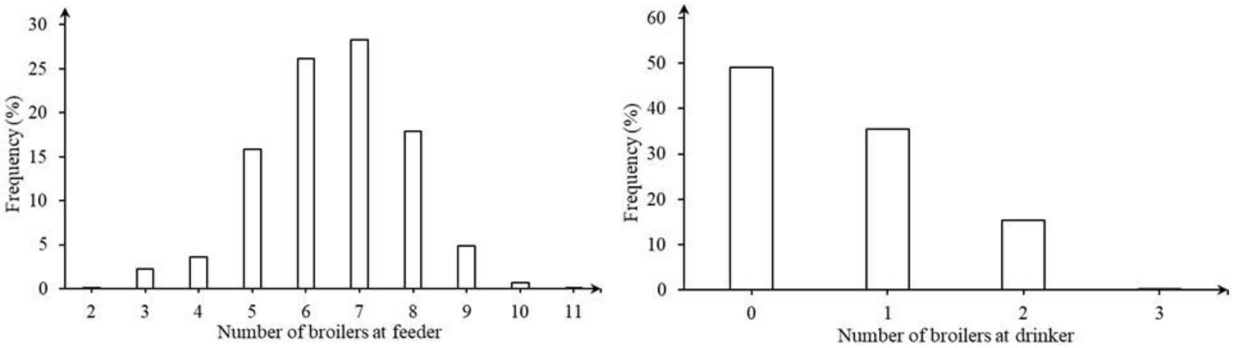


Figure 2.12 Example continuous behavioral monitoring from 0912 to 1012 h

The bird age is 35 day old. (a) The number of birds out of 60 testing birds at feeder and drinker; (b) seven randomly selected birds at feeder; and (c) seven randomly selected birds at drinker.

Figure 2.13 shows the distribution of bird numbers simultaneously presenting at feeder and drinker in the hour. At any time during this 1-h period, 2 to 11 broilers stayed at feeder and 0 to 3 broilers were at drinker. The tube feeder was designed with 14 feeding slots which, however, were never occupied by 14 broilers. Eighty eight percent (88%) of the time the feeder was used by five to eight broilers (Figure 2.13a). The events of three birds being at drinker simultaneously accounted for less than 0.1% of the time. The scenario of no bird using the drinker took up most of the time (49.1%) in this hour (Figure 2.13b).



(a) (b)

Figure 2.13 Frequency distribution of different number of eating/drinking birds

The testing period is 0912 to 1012 h on 35 days of age. (a) Frequency distribution of number of birds eating simultaneously; and (b) frequency distribution of number of birds drinking simultaneously.

2.5 Discussion

2.5.1 Max Reading Distances of Tags

With five extra tags, the SD of MRD for the same tags was 1 to 2 cm, whereas the SD of MRD for different tags was 7 to 8 cm. Therefore, the tag variations were mainly caused by different tags rather than by measurement differences. During the test, the zip-tie end of the tag (Figure 2.1) was held by a hand to minimize the hand effect on the readings. Max reading distances of the five tags held by wooden sticks were compared with those held by a hand, but little difference was noticed between these two methods. Therefore, the hand had little effect on the results. Significant variations of commercial tags with the same manufacturing specification indicated the user to verify the tags before using them for animal tests. Common method (e.g., IQR method in this case) was recommended to select the tags with similar sensitivities, which could minimize reading bias caused by tag variations.

During the test, a tag was placed to the neck of each bird (Figure 2.1). The broilers felt uncomfortable at the first 3 h after the tag placement. Then they got used to the tags and could eat and drink normally based on daily inspection by the caretaker. The collar size required adjustments to avoid discomfort (e.g., panting, choking, etc.) as the broilers grew, but it was doable for the lab test.

2.5.2 Duration of Intermittent Withdrawal from a Feeder/Drinker in a Continuous Feeding/Drinking Event

The 20-s threshold was used to fill the time gaps in the RFID readings when characterizing feeding and drinking behaviors. Li et al. (2017) used a time threshold of 30 s for feeding and nesting behaviors of laying hens. A shorter time threshold of 20 s was identified in this study, possibly because broilers were motivated to eat fast, thus a reduced swallowing time compared to laying hens (Bizeray et al., 2002a).

2.5.3 Accuracy of the Ultra-high Frequency Radio Frequency Identification System

Accuracies for the vertical antenna placements were relatively low because the drinker antenna failed to register drinking birds outside its detection range. Based on our measurement, the distance between the tags and vertically-placed drinker antenna could be greater than 8 cm which was beyond the detection range (6 cm) of the antenna. Tilting the support bracket and the antenna toward the drinking broilers profoundly increased the accuracy of the UHF-RFID system.

Misidentification of drinking broilers may occur when a bird approached the drinker from sides of the antenna, which was more likely to happen when multiple birds try to drink simultaneously at the same drinker. Tags may occasionally turn to the backside of the bird necks, which resulted in failure in tag detection by the drinker antenna and should be avoided through regularly checking of the tags.

The sensitivity, specificity, accuracy, and precision, which were described in Adrion et al. (2018) for evaluating the system performance, are not relevant in our study because of two reasons. First, we were working with a large group of broilers (60 birds/pen), which made it difficult/impossible to visually identify individual birds and compare them with RFID data. Second, the tube feeder/drinker and our RFID system were designed for a group of broilers eating/drinking simultaneously, rather than individual feeder/drinker space like for pigs reported by Adrion et al. (2018). Therefore, the accuracy in this study referred to Li et al. (2017). It reflected the chance of the RFID system to recognize the correct number of birds at feeder/drinker.

Li et al. (2017) developed an UHF-RFID system in the enriched colony housing system for detecting the feeding and nesting behaviors of individual laying hens. The accuracies of the UHF-RFID system were 92.1±6.4% for feeding behaviors and 91.4±1.7% for nesting behaviors. Sales et al. (2015) detected hen transitions between environmentally controlled chambers using a RFID system, and reported that the accuracies were 91.0±2.6% for total TS in chambers and 85.8±8.0% for TS per visit. Thurner et al. (2008) developed the high frequency transponder system to register the laying behaviors of individual hens in the floor rearing system. Of 374 visits to the nest boxes, 89.8% were correctly registered. The accuracies of the UHF-RFID system developed in this study (92.5% to 99.0% for feeding behaviors; 93.7% to 94.7% for drinking behaviors) were comparable or higher than those reported previously. The set-up of the UHF-RFID system worked for the broilers from 28 to 35 days of age. We believe the system works for older broilers (up to nine weeks old) as well, because the electromagnetic fields of the antennas may well cover the locations of tags attached to older feeding/drinking broilers through proper system adjustments. For younger broilers (e.g. <1 week old), the system may not work as it is hard to attach tags to the birds. Additional system validation is recommended for broilers at other ages.

2.5.4 Continuous Behavioral Monitoring by the Ultra-high Frequency Radio Frequency Identification System

Based on the 1-h sample data, the capacities of the feeder and drinker were not fully utilized. Compared to other studies that recommended 54 to 75 birds/feeder (Newberry and Hall, 1990; Dozier et al., 2005) and 7 to 13 birds/drinker (Bizeray et al., 2002b; Dozier et al., 2005), the broilers were provided with more feeding and drinking resources in this study, i.e., 30 birds/feeder and 6 birds/drinker. In this study, not all feeders and drinkers in the experimental room were mounted with RFID antennas. This setup served the major objective well, which was validation of the accuracy of the UHF-RFID system. When diurnal feeding and drinking rhythms of individual broilers are of interest, it can be readily achieved by expanding the UHF-RFID system to all feeders and drinkers. Overall, the UHF-RFID system is a useful tool for investigating individual broiler behaviors and resource allocation in group settings.

2.6 Conclusions

An UHF-RFID system for monitoring feeding and drinking behaviors of individual group-housed broilers was developed and tested. Tag sensitivity and modified electromagnetic fields of the feeder and drinker antennas were investigated. The UHF-RFID system was validated in two experimental rooms with 120 broilers. The results show significant sensitivity variations among tags, thus the tags with similar sensitivities should be selected for animal tests. The electromagnetic fields at the corners of the feeder antenna (40×40cm) could be effectively shielded by covering the antenna using one layer of the stainless steel sheet with a 36-cm-diameter center opening. Protective plastic wraps, a carton box, a fully loaded feeder had little effect on the electromagnetic field of the feeder antenna. The accuracies of the UHF-RFID system for determining IBN and TS were 92.5±4.2% and 99.0±1.2% for the feeder, and 94.7±4.2% and 93.7±6.9% for the drinker, respectively. Drinker antennas required adjustment to minimize distance to the tagged broilers while drinking in order to achieve greater accuracy. The UHF-RIFD system successfully registered feeding and drinking behaviors of individual broilers in group settings with high accuracy, and thus is a useful tool for investigating the impacts of resource allocations and management practices on broiler behaviors.

2.7 Acknowledgements

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2.8 Declaration of Interest

The authors confirm that there are no known conflictions of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

2.9 Ethics Statement

All procedures were approved by the USDA-ARS Institutional Animal Care and Use Committee at Mississippi State.

2.10 Software and Data Repository Resources

None of the data were deposited in an official repository.

2.11 Supplementary Material

To view supplementary material, please visit https://doi.org/10.1017/S1751731118003440

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CHAPTER III

RADIO FREQUENCY IDENTIFICATION SYSTEM FOR POULTRY BEHAVIOR MONITORING: EFFECTS OF STOCKING DENSITY AND DIET ON BIRD FEEDING AND DRINKING BEHAVIORS

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Li, G., Zhao, Y., Purswell, J. L., Chesser Jr, G. D., Lowe, J. W., and Wu, T. L. (2020). Effects of antibiotic-free diet and stocking density on male broilers reared to 35 days of age. Part 2: feeding and drinking behaviours of broilers. Journal of Applied Poultry Research, 29: 391-401. doi: 10.1016/j.japr.2020.01.002.

Abstract: The U.S. broiler industry is trending toward antibiotic-free (ABF) production because of increasing concerns on antimicrobial resistance in human medicinal treatments. Given the differences in performance observed between ABF diets and conventional diets, changes in feeding and drinking behaviors may result. The objective of this study was to characterize feeding and drinking behaviors of male broilers fed with ABF diet vs. diet containing antibiotic growth promoter (AGP diet) under 4 stocking densities (SD), that is 27 (27SD), 29 (29SD), 33 (33SD), and kg·m^{-2} (39SD). Resource allowances ranged from 50 to 72 birds per tube feeder (with 14 feeder slots) and 11 to 12 birds per nipple drinker. Behaviors of 15 broilers in each treatment combination were monitored continuously at 30 to 35 D of age using an ultra-high frequency radio frequency identification system. The results show that feeding time (62.7 min·bird^{-1}·D^{-1}) and feeder visits (52 times·bird^{-1}·D^{-1}) of broilers with ABF diet were significantly less ($P \leq 0.02$) than birds with AGP diet (85.1 min·bird^{-1}·D^{-1} and 62 times·bird^{-1}·D^{-1}). Bird drinking behaviors were similar among treatments ($P \geq 0.10$). Coefficient of variation of the behaviors was not significantly different among treatments ($P \geq 0.09$), suggesting unaffected flock uniformity of these behaviors by diet and SD. Feeder and drinker utilization ratios were less than 40% at any diet and SD levels, indicating sufficient resource allowances. It is concluded that 1) changes in diet and management may alter certain behaviors of broilers and 2) the results offer benchmark behavioral data for standardization of resource allowances toward efficient, welfare, and healthy broiler production.

Keyword: broiler, stocking density, antibiotic-free, behavior, radio frequency identification system

Primary Audience: live production, scientist, veterinarian

3.1 Description of Problem

In U.S. broiler production, diets containing antibiotic growth promoter (AGP) have been widely used to treat clinical diseases, to prevent and control diseases, and to improve general performance of birds (Smith, 2011). However, the long-term application of AGP may be attributed to incidence of antibiotic resistant bacteria that are harmful to human health and cause increasing public concern (Piva et al., 2001). As such, some food chain companies have committed to reduce the use of antibiotics in broiler production and, where possible, provide antibiotic-free (ABF) products (Wattles, 2017). It has been reported that use of ABF diets compromises broiler feed efficiency/conversion and increases disease incidence and mortality (Smith, 2011; Emborg et al., 2001). Therefore, current ABF broiler production is typically associated with additional management strategies such as reducing stocking density (SD) to alleviate the above-mentioned negative effects (Cervantes, 2015).

Stocking density influences a broad spectrum of aspects in broiler production, spanning from management, profitability, productivity, and animal well-being to bird health (Feddes et al., 2002; Sørensen et al., 2000; Andrews et al., 1997; Dozier 3rd et al., 2005). Stocking density is typically defined as overall body weight allowance per unit area. Different associations/institutes have different recommendations on SD. For instance, National Chicken Council (2017) recommended the maximal SDs of 32, 37, 42, and 44 $kg \cdot m^{-2}$ for broilers targeting market weights of <2.0, 2.0 to 2.5, 2.5 to 3.4, and >3.4 kg, respectively. European Commission (2018) reported a SD of <33 $kg \cdot m^{-2}$ for European broiler production. Global Animal Partnership (2017) stated that SD could not exceed 29 $kg \cdot m^{-2}$ for Step 1 in the welfare rating program. In general, high SD may restrict bird movement, impede air flow, and increase litter moisture and microbial growth, thus impairing broiler production performance and well-being (Dozier 3rd et al., 2005; Bessei, 2006).

To improve ABF production, one of the alternatives is to rear ABF broilers under low SDs in commercial farms (Cervantes, 2015). Tsiouris et al. (2015) compared intestinal lesions under 2 SDs of 15 and 30 bird·m^{-2} with ABF diets and found that the birds reared at the higher SD had higher gross lesion score in the intestine. Ravindran et al. (2006) examined the influence of SDs and dietary zinc bacitracin on broiler performance, meat quality, and welfare. They found that feed conversions were similar between 32 and 40 kg·m^{-2} yet worse at 48 kg·m^{-2}, when zinc bacitracin was not used. They concluded that a SD lower than 40 kg·m^{-2} was recommended for broiler production with ABF diets. Although effects of diet and SD on broiler production performance, physiology, and well-being have been previously investigated, their effects on bird feeding and drinking behaviors are not well understood.

Feeding and drinking behaviors are 2 of the most important indicators for animal well-being and health (Hart, 1988). Previous studies have investigated poultry feeding and drinking behaviors as affected by feeding schedules (Savory and Mann, 1999), lighting conditions (Li et al., 2018), and rearing systems (Tanaka and Hurnik, 1992); however, there is a lack of experimental information regarding to broiler behavioral responses with different diets and SDs. In addition, an appropriate tool is important to obtain behavioral information. An ultra-high frequency radio frequency identification (UHF-RFID) system was developed and validated previously by our team (Li et al., 2019), and it can accurately monitor behaviors of individual broilers. As the Part 2 of a series of publications from a cooperative project, this study was to investigate the feeding and drinking behaviors of individual broilers with 2 diets (AGP vs. ABF) and at 4 SDs (27, 29, 33, and 39 kg·m^{-2}, or “27SD”, “29SD”, “33SD”, and “39SD”, respectively) using a UHF-RFID system. The other 2 companion publications focus on diet and SD effects on production performance (Part 1) and bird physiology (Part 3).

3.2 Materials and Methods

3.2.1 Housing, Animals, and Management

The experiment was conducted in the USDA Poultry Research Unit at Mississippi State, United States. A total of 952 Ross × Ross 708 male broilers were obtained from a commercial hatchery and randomly distributed to 16 pens, each of which was adjusted to a total area of 3.9 m^2 (3.0 m long and 1.3 m wide) and equipped with one tube feeder and several drinkers. The diameter of the tube feeder was 36 cm, and one feeder had 14 feeder slots. Room temperature, light intensity, and photoperiod were adjusted according to the schedules in Table 3.1. Rearing period was 0 to 35 D of bird age. Feed and water were provided *ad libitum*. Birds were provided with a commercial-type corn–soy diet formulated to meet the requirements of National Research Council (1994), which were previously described by Dozier III et al. (2007). Play sand was used as inert filler in the ABF diet. All procedures in this experiment were approved by the USDA-ARS Institutional Animal Care and Use Committee at Mississippi State.

Table 3.1 Air temperature and lighting settings at different bird ages

Day of age	Temperature (°C)	Photoperiod (L:D)	Intensity (lux)
0-3	32	23L:1D	32
4-6	31	23L:1D	32
7	29	23L:1D	32
8-13	29	20L:4D	10
14-20	27	20L:4D	10
21-27	24	20L:4D	10
28-35	21	16L:8D	5

‘L:D’ means number of hours for lighting vs. number of hours for darkness.

3.2.2 Treatments

The treatment combination for each pen is shown in Table 3.2. The AGP diet contained 2 additives of *salinomycin* and *bacitracin* at manufacture’s recommended levels, whereas the ABF diet did not contain any antibiotics. Used litter was obtained from AGP and ABF commercial farms and then placed in respective diet treatment pens. Pens with AGP and ABF treatments were partitioned to avoid cross contamination of litter. The range of SD treatments were selected according to recommendations of National Chicken Council (2017), European Commission (2018), and Global Animal Partnership (2017) to represent the practices in current commercial production or proposals for future production. The SDs were based on a 2-kg market weight which represents the average live body weight of <2.8 kg that has a large market share of ~54% in U.S broiler production (U.S. Department of Agriculture, 2019).

Table 3.2 Treatment assignment in different pens

Pen #	Diet	Density ($kg \cdot m^{-2}$)	Bird #	Feeder #	Drinker #	Pen #	Diet	Density ($kg \cdot m^{-2}$)	Bird #	Feeder #	Drinker #
1	AGP	39	72	1	6	9	ABF	27	50	1	4
2	AGP	29	54	1	5	10	ABF	39	72	1	6
3	AGP	33	62	1	5	11	ABF	33	62	1	5
4	AGP	27	50	1	4	12	ABF	29	54	1	5
5	AGP	33	62	1	5	13	ABF	33	62	1	5
6	AGP	39	72	1	6	14	ABF	27	50	1	4
7	AGP	27	50	1	4	15	ABF	29	54	1	5
8	AGP	29	54	1	5	16	ABF	39	72	1	6

AGP is the antibiotic grow-promoting diet. ABF is the antibiotics-free diet. Litter for AGP and ABF diets were obtained from the commercial AGP and ABF farms. The diameter of the feeder is 36 cm and each feeder has 14 feeder slots. "#" indicates number.

3.2.3 Behavioral Data Acquisition System

A UHF-RFID system was used to monitor feeding and drinking behaviors of individual broilers. The system consisted of 16 feeder antennas (TIMES-7 A6034S; Impinj Inc., Seattle, WA), 80 drinker antennas (IPJ-A0303-000; Impinj Inc., Seattle, WA), 240 tags (PT-103; TransTech Systems Inc., Wilsonville, OR), 3 hubs (IPJ-A6001-000; Impinj Inc., Seattle, WA), 3 readers (IPJ-REV-420; Impinj Inc., Seattle, WA), and 3 Python-based data acquisition systems.

Within each pen, 1 feeder antenna was placed underneath the suspending feeder (Figure 3.1a), 1drinkerantennawas mounted to each nipple drinker (Figure 3.1b), and 15 birds were randomly selected and tied with collar tags (Figure 3.1c). When a bird with a unique tag ID entered the electromagnetic field of feeder/drinker antennas, it was registered by the system. Data were recorded at a 1-sec interval and saved into.csv files every 30 min. Based on previous validation, the accuracies for monitoring feeding and drinking behaviors of broilers through the UHF-RFID system were above 92 and 94%, respectively (Li et al., 2019).

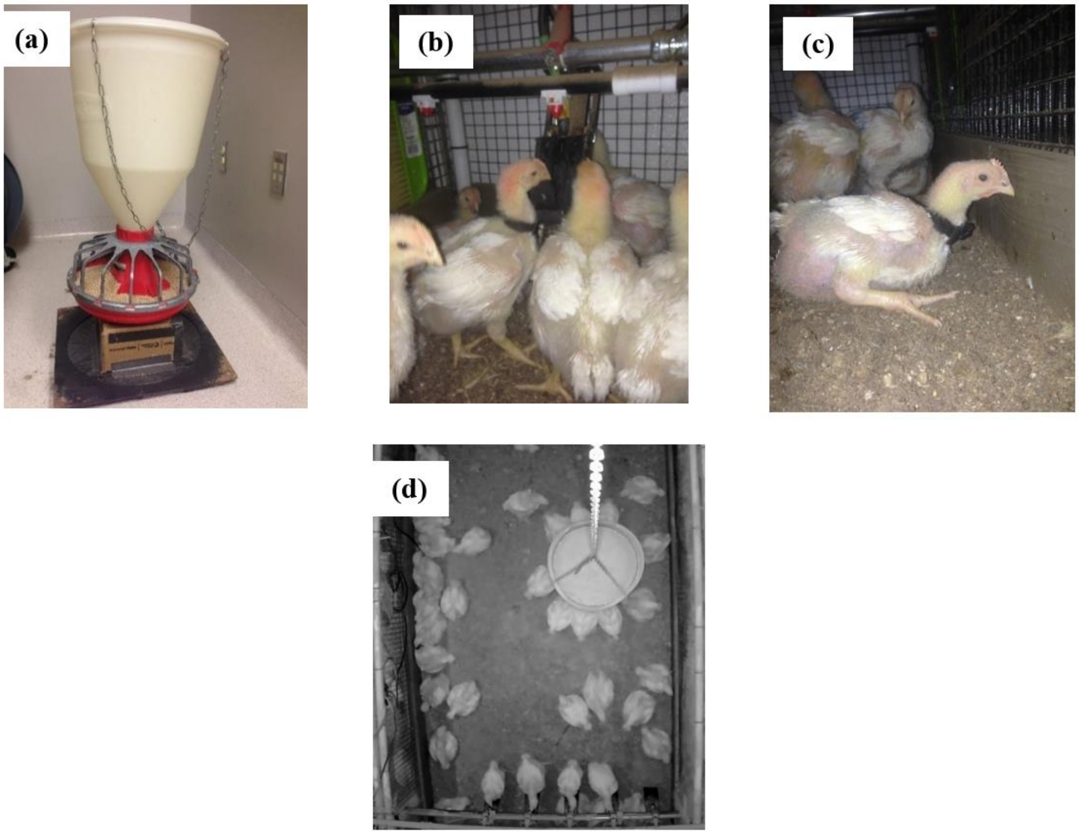

Figure 3.1 Photos of system setup for the experiment

(a) A feeder antenna underneath a suspending tube feeder; (b) a drinker antenna attached to drinking line; (c) a broiler attached with a collar tag; and (d) top view of a pen

3.2.4 Behavioral Responses and Definitions

The tagged birds in each pen were selected for behavioral test from 30 to 35 D of bird age. In a continuous feeding/drinking event, a bird may temporarily withdraw from a feeder/drinker for ingesting, which could not be registered by the UHF-RFID system. To correct the miss-identification of feeding/drinking behaviors, gaps of 2 consecutive RFID readings that spanned 20 s or less were filled. Based on previous validations, the 20-sec threshold could cover 95% of RFID reading gaps induced by the intermittent ingesting behaviors (Li et al., 2019). After filling the time gaps, time spent and visit frequency of the feeing/drinking events were summarized for each bird.

According to previous observation (Li et al., 2019), broilers rarely ate and drank during a dark period; therefore, feeding/drinking behaviors of broilers were analyzed only for the lighting period (0100-1700, 16 h). Feeding and drinking behaviors for individual birds were summarized into daily time spent at feeder (DTSF), hourly time spent at feeder (HTSF), daily time spent at drinkers (DTSD), hourly time spent at drinkers (HTSD), daily number of feeder visit, daily number of drinker visit (DNDV), duration per feeder visit, and duration per drinker visit. Details of behavioral definitions are provided in Table 3.3. Mean values and coefficient of variation (CV, in %) of all behavioral responses were calculated for each pen.

Table 3.3 The behavioral responses and definitions

Behavioral responses	Definition
Daily time spent at feeder (DTSF, min·bird^{-1}·D^{-1})	Overall time spent at a tube feeder within a day
Daily time spent at drinkers (DTSD, min·bird^{-1}·D^{-1})	Overall time spent at nipple drinkers within a day
Daily number of feeder visit (DNFV, times·bird^{-1}·D^{-1})	Number of visit to a tube feeder within a day
Daily number of drinker visit (DNDV, times·bird^{-1}·D^{-1})	Number of visit to nipple drinkers within a day
Duration per feeder visit (DFV, min·bird^{-1})	DTSF/DNFV
Duration per drinker visit (DDV, min·bird^{-1})	DTSD/DNDV
Hourly time spent at feeder (HTSF, min·bird^{-1}·h^{-1})	Overall time spent at a tube feeder within each hour throughout a day
Hourly time spent at drinkers (HTSD, min·bird^{-1}·h^{-1})	Overall time spent at nipple drinkers within each hour throughout a day

3.2.5 Feeder and Drinker Utilizations

Feeder and drinker utilization ratios (FUR and DUR) were used to evaluate the intensity of usage of these resources by broilers in each treatment. Lower FUR and DUR values mean fewer utilizations of a feeder and a drinker. Equations 3.11 and 3.2 show the calculations of FUR and DUR.

$$FUR = \frac{Bird\ minutes\ at\ feeder}{Total\ feeder\ slot\ minutes} \times 100\% = \frac{DTSF \times bird\ number}{Lighting\ minutes \times feeder\ slot\ number} \times 100\% \tag{3.1}$$

$$DUR = \frac{Bird\ minutes\ at\ drinkers}{Total\ drinker\ slot\ minutes} \times 100\% = \frac{DTSD \times bird\ number}{Lighting\ minutes \times\ drinker\ number} \times 100\% \tag{3.2}$$

where bird number is 50 for 27SD, 54 for 29SD, 62 for 33SD, and 72 for 39SD; lighting minutes are 960 min·D^{-1} (60 min·h^{-1} × 16 h·D^{-1}); feeder slot number is 14 for all treatments; and drinker number is 4 for 27SD, 5 for 29SD, 5 for 33SD, and 6 for 39SD.

3.2.6 Statistical Analysis

Treatments were arranged in a 4 × 2 factorial design, with 4 levels of SD and 2 levels of diets. Main effects of SD and diet were represented by 4 and 8 replicate pens, respectively, and yielded 2 replicate pens for interaction. Effects of diet, SD, and their interaction on all behavioral responses were analyzed with ANOVA using PROC MIXED in SAS (SAS 9.3, SAS Institute Inc., Cary, NC). Treatment means and mean CV were separated using Fisher's least significant difference with PDMIX800 (Saxton, 1998), with significance considered at $P \leq 0.05$.

3.3 Results

3.3.1 Average of Behavioral Reponses

The average behavioral responses of 15 individual birds in each pen are shown in Table 3.4. Overall, broilers spent average 51.2 to 90.2 min (3.6–6.3% of 24 h) at feeder and 22.7 to 32.7 min (1.6–2.3% of 24 h) at drinkers. Resource visits ranged from 48 to 64 feeder visits·bird^{-1}·D^{-1} and 42 to 54 drinker visits·bird^{-1}·D^{-1}. For each visit, birds spent 1.0 to 1.4 min at feeder and 0.5 to 0.7 min at drinkers. Feeding time, feeder visit, and duration per feeder visit were higher with AGP than with ABF ($P \leq 0.04$). There was no significant difference between the 2 diets for all drinking behavioral responses ($P \geq 0.22$). Generally, broilers performed similar feeding and drinking behaviors among all SDs ($P \geq 0.10$). No significant interactive effects were observed ($P \geq 0.30$).

Table 3.4 The mean behavioral responses of broilers reared with two diets and at four stocking densities

Treatment	DTSF (min·bird^{-1}·D^{-1})	DNFV (times·bird^{-1}·D^{-1})	DFV (min·visit^{-1})	DTSD (min·bird^{-1}·D^{-1})	DNDV (times·bird^{-1}·D^{-1})	DDV (min·visit^{-1})
Diet						
AGP	85.1^{a}	62^{a}	1.3^{a}	28.3	46	0.6
ABF	62.7^{b}	52^{b}	1.2^{b}	26.6	46	0.6
SEM^{1}	4.0	2	0.06	1.4	2	0.03
Stocking density (SD)						
27SD	79.9	59	1.3	30.1	52	0.6
29SD	78.3	58	1.3	25.4	45	0.6
33SD	68.9	56	1.2	25.3	42	0.6
39SD	68.6	54	1.2	28.8	44	0.7
SEM^{2}	5.6	3.1	0.08	2.0	2	0.04
Interaction						
AGP-27SD	90.2	64	1.4	27.6	49	0.6
AGP-29SD	84.3	59	1.4	27.3	45	0.6
AGP-33SD	79.9	63	1.2	27.9	42	0.7
AGP-39SD	86.0	61	1.4	30.3	46	0.7
ABF-27SD	69.5	53	1.3	32.7	54	0.6
ABF-29SD	72.3	58	1.2	23.6	44	0.5
ABF-33SD	57.9	50	1.1	22.7	43	0.5
ABF-39SD	51.2	48	1.0	27.4	43	0.7
SEM^{3}	7.9	4	0.11	2.9	3	0.05
P-value						
Diet	<0.01	0.02	0.04	0.50	0.76	0.22
SD	0.39	0.75	0.51	0.30	0.10	0.30
Diet × SD	0.58	0.51	0.62	0.40	0.66	0.30

AGP=antibiotic growth-promoting diet; ABF=antibiotics-free diet; DTSF=daily time spent at feeder; DNFV=daily number of feeder visit; DFV=duration per feeder visit; DTSD=daily time spent at drinkers; DNDV=daily number of drinker visit; DDV=duration per drinker visit. 27SD, 29SD, 33SD, and 39SD mean the stocking densities of 27, 29, 33, and 39 kg·m^{-2}.

[a,b] Values within the same column that lack of a common superscript differ significantly ($P \leq 0.05$).

[1] Standard error for main effect of diet (*n*=8).

[2] Standard error for main effect of stocking density (*n*=4).

[3] Standard error for interaction effects (*n*=2).

3.3.2 Feeder and Drinker Utilization with Two Diets and at Four Stocking Densities

The results show that FUR and DUR values were 28 to 38% and 29 to 39%, respectively (Figure 3.2). The FUR and DUR values were higher with AGP than with ABF. Higher FUR values associated with higher SDs, whereas the highest DUR value (39%) was found at the lowest SD that is 27SD.

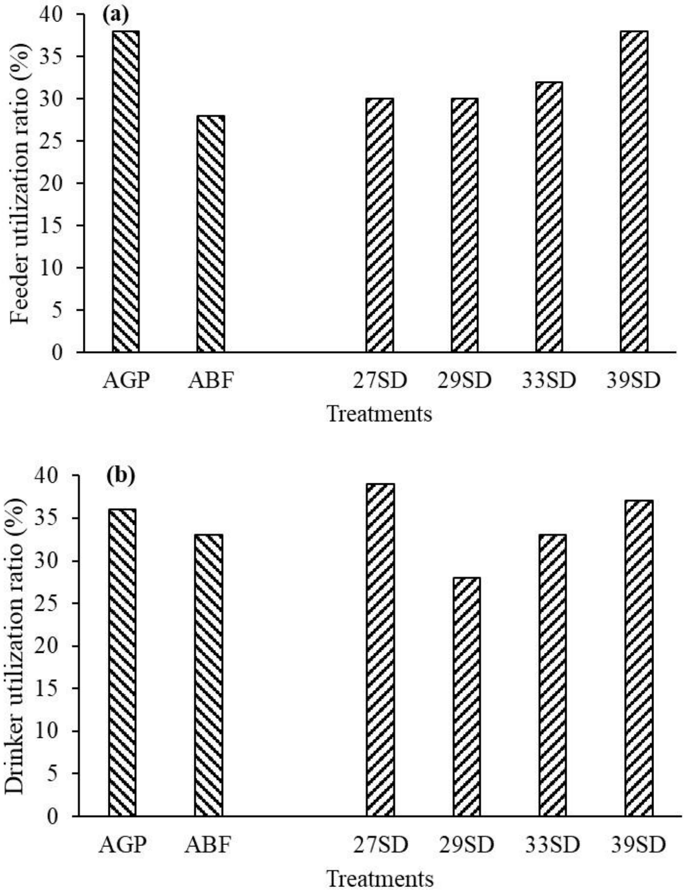

Figure 3.2 Feeder and drinker utilization ratios with 2 diets and at 4 stocking densities

(a) Feeder utilization ratio among treatments; and (b) drinker utilization ratio among treatments. AGP, diet containing antibiotic growth promoter; ABF, antibiotic-free diet; SD, stocking density; 27SD, SD of 27 kg·m^{-2}; 29SD, SD of 29 kg·m^{-2}; 33SD, SD of 33 kg·m^{-2}; 39SD, SD of 39 kg·m^{-2}.

3.3.3 Coefficient of Variations of Behavioral Responses

Table 3.5 shows the CVs of behavioral responses of 15 individual birds in each pen. The CVs were 23.9 to 66.3% for all behavioral responses. Diet, SD, and their interaction did not affect the CVs of all of the feeding and drinking behavioral responses ($P \geq 0.09$).

Table 3.5 The coefficient of variation of behavioral responses of broilers reared with two diets and at four stocking densities

Treatment	DTSF (%)	DNFV (%)	DFV (%)	DTSD (%)	DNDV (%)	DDV (%)
Diet						
AGP	55.2	30.4	39.8	39.9	35.6	30.5
ABF	59.4	34.8	36.4	40.7	38.3	29.4
SEM[1]	3.7	3.3	1.8	1.9	1.0	2.2
Stocking density (SD)						
27SD	58.9	35.3	40.1	38.3	37.2	27.5
29SD	58.7	31.6	41.4	42.8	35.3	33.2
33SD	58.7	34.8	35.0	41.5	38.1	29.7
39SD	52.9	28.6	35.9	38.6	37.1	29.5
SEM[2]	5.2	4.7	2.5	2.7	1.4	3.1
Interaction						
AGP-27SD	52.4	33.5	40.1	40.7	39.1	28.5
AGP-29SD	51.1	23.9	44.1	41.0	34.0	33.1
AGP-33SD	65.3	37.9	37.6	38.7	34.8	33.9
AGP-39SD	51.0	26.0	37.5	39.3	34.6	26.6
ABF-27SD	64.4	37.1	40.1	35.8	35.5	26.6
ABF-29SD	66.3	39.3	38.7	44.6	36.6	33.2
ABF-33SD	52.0	31.6	32.4	44.3	41.5	25.4
ABF-39SD	54.8	31.1	34.2	37.9	39.5	32.4
SEM[3]	7.3	6.7	3.6	3.8	2.0	4.4
P-value						
Diet	0.45	0.38	0.21	0.75	0.09	0.71
SD	0.81	0.73	0.28	0.64	0.59	0.62
Diet × SD	0.30	0.49	0.87	0.54	0.14	0.45

AGP=antibiotic growth-promoting diet; ABF=antibiotics-free diet; DTSF=daily time spent at feeder; DNFV=daily number of feeder visit; DFV=duration per feeder visit; DTSD=daily time spent at drinkers; DNDV=daily number of drinker visit; DDV=duration per drinker visit. 27SD, 29SD, 33SD, and 39SD mean the stocking densities of 27, 29, 33, and 39 kg·m^{-2}.

Values within the same column that lack of a common superscript differ significantly ($P \leq 0.05$).

[1] Standard error for main effect of diet (*n*=8).

[2] Standard error for main effect of stocking density (*n*=4).

[3] Standard error for interaction effects (*n*=2).

3.3.4 Hourly Behavioral Responses among All Treatments

Figure 3.3 shows HTSF (Figure 3.3a) and HTSD (Figure 3.3b). Overall, a broiler spent average 4.3 ± 0.9 min at feeder and 1.5 ± 0.4 min at drinkers in each hour throughout a day. In general, HTSF and HTSD among all treatments gradually decreased from the lights ON until 13:00 during the 6 testing days. All hourly behavioral responses gradually increased after 13:00, peaked at 11:30, and decreased again within 1 h before the lights OFF.

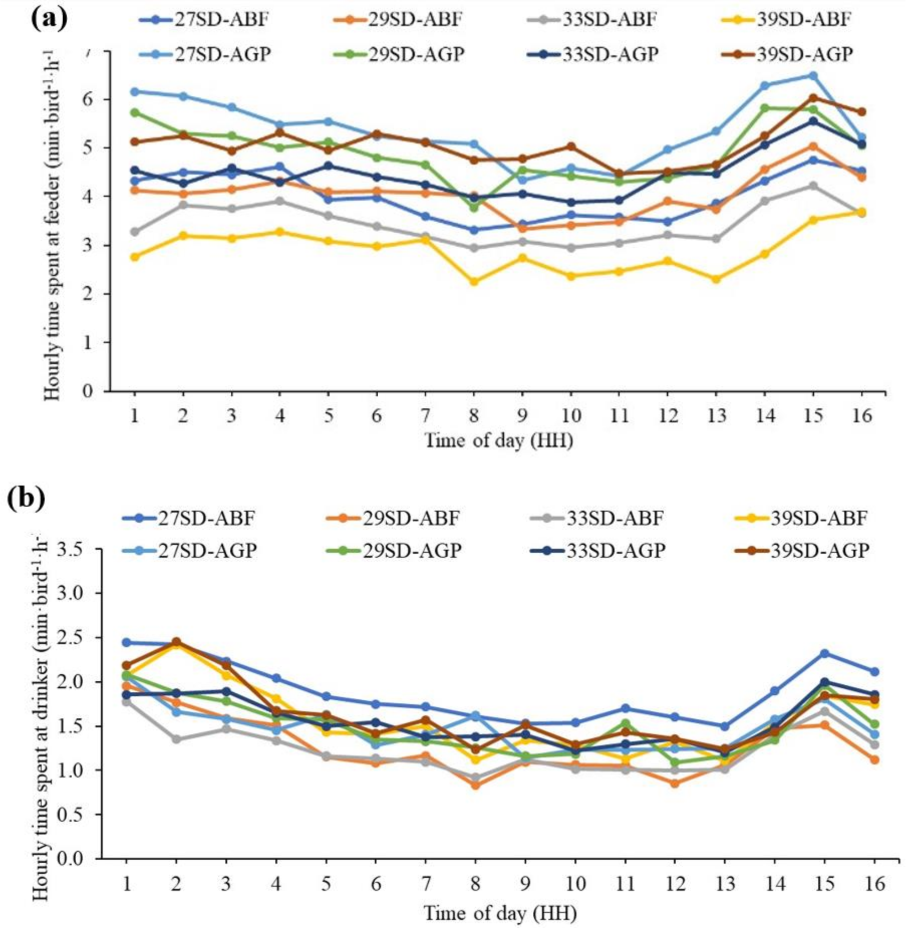

Figure 3.3 Hourly behavioral responses throughout a day

(a) Hourly time spent at feeder; and (b) hourly time spent at drinkers. Each point is the mean of 14 observations. AGP=antibiotic growth-promoting diet; ABF=antibiotics-free diet; SD=stocking density; 27SD=SD of 27 kg·m^{-2}; 29SD=SD of 29 kg·m^{-2}; 33SD=SD of 33 kg·m^{-2}; 39SD=SD of 39 kg·m^{-2}

3.4 Discussion

3.4.1 Interaction Effects of Diet and Stocking Density on the Behavioral Responses

The interaction effects of diet and SD were not observed for the means and CVs of all of the behavioral responses. Ravindran et al. (2006) observed diet-by-SD interaction effects on the production parameters (e.g., feed conversion rate) of broilers. The term of interaction refers to how the effect of one explanatory factor on the response depends on levels of another explanatory factors (Fitzmaurice, 2000). Thus, our results show that behavioral responses of broilers at different SDs did not rely on diet types. It should be noted that given experimental pen being experimental unit, each combined treatment only had 2 replications. More replications are recommended to consolidate conclusion of the interaction effects.

3.4.2 Overall Behavioral Responses

The DTSF and DTSD were lower than those reported by Li et al. (2018) (DTSF was 138–162 min·bird^{-1}·D^{-1}) and by Newberry et al. (1988) (DTSD was 36–60 min·bird^{-1}·D^{-1}). Compared with the study of Li et al. (2018), the feeder allowance (4–5 birds per feeder slot in the current study vs. 2 birds per feeder slot in the previous study) and bird age (30–35 D of age vs. 35–40 D of age) may cause the discrepancy of feeding time. Compared with the study of Newberry et al. (1988), the difference of drinking time may be affected by light intensity (5 lux vs. 6 and 180 lux), bird type (Ross × Ross 708 broilers vs. Peterson × Arbor Acre broilers), drinker allowance (11–12 birds per nipple drinker vs. 7 birds per nipple drinker), etc.

3.4.3 Behavioral Responses at Different Stocking Densities

The SDs tested in this study were selected based on recommendations by industry trade associations and animal welfare groups. We found that broiler feeding and drinking time, feeder and drinker visits, and duration per visit were similar across the SDs from 27 to 39 kg·m^{-2}. At SD levels (34 vs. 40 kg·m^{-2} at a 2-kg market weight) similar to our tested range, Hall (2001) did not find significant difference in the broiler feeding and drinking time neither. Interestingly, Simitzis et al. (2012) assessed a lower-than-recommended SD at 12.6 kg·m^{-2} and reported that broilers visited feeders and drinkers more frequently at such an SD than a recommended SD of 27 kg·m^{-2}. These studies collectively indicate that SD would only affect feeding and drinking of broilers when it is set far below the recommended range. As for the message to broiler producers, our results show that the same resource allowances can be applied for the SD recommendations by National Chicken Council, European Commission, and Global Animal Partnership, without affecting the bird feeding and drinking behaviors.

3.4.4 Utilization of Feeder and Drinker

The resource allowances were 4 to 5 birds per feeder slot and 11 to 12 birds per nipple drinker in this study, which met the requirement of commercial settings (Aviagen Ross, 2015). The FUR and DUR were 28 to 39%, which means that feeder slots and nipple drinkers were not fully used in all treatments. Therefore, current resource allowances might be more than sufficient. However, it should be noted that the FUR and DUR should not be the sole parameters to judge the sufficiency of resource allowances. During the experiment, we occasionally noticed some broilers attempted to access the available feeder slots and drinkers but failed because of competitions with other birds. These frustration feeding and drinking behaviors should be also considered when determining an appropriate resource allowance that aims to improve bird welfare and production efficiency (Duncan and Wood-Gush, 1972; Sirovnik et al., 2018).

3.4.5 Behavioral Response Differences of Individual Birds

The CVs of behaviors reflect individual behavioral differences, and higher CVs commonly indicate poor group uniformity (Estévez et al., 1997; Kostal et al., 1992). The CVs of daily feeding and drinking time were similar between 2 diets and among all SDs, indicating that the group uniformity of broilers was not affected neither by diets nor by current group sizes (50, 54, 62, and 72 $\text{bird}^{-1}\cdot\text{group}^{-1}$). Estévez et al. (1997) found that the CVs of body weight for individual broilers were similar across group sizes of 50 to 200 $\text{broilers}\cdot\text{group}^{-1}$. Uniform body weight among broilers in their group settings suggested that birds could get equivalent resources in large groups (50 or more birds), which may be helpful for group uniformity.

3.4.6 Hourly Behavioral Responses

Hourly behavioral analysis helps to examine temporal broiler feeding and drinking behaviors throughout a day. Broilers showed peaks of feeding and drinking behaviors after the lights ON and before the lights OFF among all treatments. These 2 peaks were also reported by Li et al. (2018). The former peak may be caused by no food and water intake during long-term darkness, and the latter peak may be stimulated by the prediction of darkness (Savory, 1980). Owing to more feeding and drinking behaviors during these 2 periods, evaluation of the sufficiency of feeder and drinker should focus on these periods.

3.5 Conclusions and Applications

We investigated feeding and drinking behavior of broilers fed with AGP/ABF diets and under four SDs and obtained the following conclusions.

1. No interaction effect of diet and SD was observed for behavioral responses.

2. Male broilers at 30 to 35 D of age spent less time in feeding when fed with ABF diet than AGP diet. Broilers fed with either diet spent similar time in drinking. Feeder allowance could be reduced when diet is changed from AGP to ABF.

3. All feeding and drinking behaviors of broilers were similar among SDs (27-39 $kg\cdot m^{-2}$). A lower SD may not necessarily stimulate broiler feeding and drinking.

4. At all treatments and resource allowances tested in this study, feeders and drinkers were never fully used (feeder and drinker utilization ratios, 40%). Feeder utilization ratios were higher with AGP and at higher SD, whereas drinker utilization ratios were also higher with AGP yet the highest at the lowest SD that is 27 $kg\cdot m^{-2}$.

3.6 Acknowledgments

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3.7 Conflict of Interest Statement

The authors did not provide a conflict of interest statement.

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CHAPTER IV

RADIO FREQUENCY IDENTIFICATION SYSTEM FOR POULTRY BEHAVIOR MONITORING: EFFECTS OF FEEDER SPACE ON BIRD FEEDING BEHAVIORS

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Li, G., Zhao, Y., Purswell, J. L., and Magee, C. (2020). Effects of Feeder Space on Broiler Feeding Behaviors. Poultry Science, 100(4): 101016. doi: 10.1016/j.psj.2021.01.038.

Abstract: Providing adequate feeder space in broiler production is important to ensure bird performance and well-being; however, the effect of feeder space on the behavioral responses of broilers remains unclear. The objective of this research was to investigate feeding behaviors of broilers provided with four feeder spaces, i.e. 2.3 cm/bird with one feeder (2.3FSO); and 2.3, 4.6, and 6.9 cm/bird with three feeders (2.3FST, 4.6FST, and 6.9FST, respectively). Sixteen identical pens, each with 45 broilers (Ross 708, mixed sex), were used to accommodate the four feeder space treatments. Feeding behaviors were continuously monitored from week 4 to week 8 using ultra-high frequency radio frequency identification systems. Number of feeder slots per feeder was 14 at 2.3FSO, 5 at 2.3FST, 9 at 4.6FST, and 14 at 6.9FST. The results show that the daily feeding time and number of feeder visits for broilers at 2.3FST were similar as those at 4.6FST and 6.9FST, but higher than those at 2.3FSO ($P<0.01$). The feeder utilization ratio was the highest at 2.3FST, indicating the feeder being used most efficiently under the treatment than under other treatments ($P<0.01$). Coefficient of variations (33.0-65.1%) of the feeding behavioral responses were similar among the treatments, suggesting similar group uniformity of feeding behaviors of individual broilers ($P\geq0.06$). Feeders among all treatments may not be fully utilized, because for most of the time, less than six birds chose to eat simultaneously at a more-than-five-slot feeder in all treatments. Given the same feeder space, increasing feeder amount can accommodate more birds to eat simultaneously. The outcomes of this study provide insights into improvement of feeder design and management for broiler production.

Keyword: broiler, feeder space, feeding behavior, radio frequency identification system

Nomenclature			
2.3FSO	2.3 cm/bird feeder space with one feeder	DTSF	Daily time spent at feeder
2.3FST	2.3 cm/bird feeder space with three feeders	FSO	Feeder space with one feeder
4.6FST	4.6 cm/bird feeder space with three feeders	FST	Feeder space with three feeders
6.9FST	6.9 cm/bird feeder space with three feeders	FUR	Feeder utilization rate
ANOVA	One-way analysis of variance	HNFV	Hourly number of feeder visit
ARS	Agricultural Research Service	HTST	Hourly time spent at feeder
CV	Coefficient of variation	SAS	Statistical Analysis Software
DFV	Duration per feeder visit	UHF-RFID	Ultra-high frequency radio frequency identification
DNFV	Daily number of feeder visit	USDA	United States Department of Agriculture

4.1 Introduction

The United States is the largest broiler producer in the world with over 9 billion broilers produced in 2018 at a value of 31.7 billion dollars (USDA National Agricultural Statistics Service, 2019). Broilers need to access feed to meet their daily nutrient requirement. Adequate feeder space that allows birds to eat at will is important for efficient and welfare-oriented broiler production. Insufficient feeder space may cause competition, aggression, and frustration among hens and downgrade their well-being (Sirovnik et al., 2018), while excessive feeder space leads to inefficient resource utilization for hens (Oliveira et al., 2019). Feeder spaces of 1.2-5.1 cm/bird for typical US broiler production have been recommended by governmental agencies, breeding companies, and scientific institutes (Table 4.1). However, little research has been conducted to validate these space recommendations through continuous monitoring of broiler feeding behaviors which are crucial indicators of feeder usage (Li et al., 2019). With the assistance of precision agricultural tools, researchers are now able to monitor feeding time, feeder visit frequency, and feeding location of individual birds in group settings of small-scale pens (Li et al., 2020a; Oliveira et al., 2019). Understanding the abovementioned feeding behavioral responses to different feeder spaces could provide insights to broiler feeder design and management.

Table 4.1 Feeder space recommendations for broilers from different sources

Recommendation (cm/bird)	Number of birds per feeder	Bird age (weeks)	Diameter of the tube feeder (cm)	Reference
1.2-2.1	45-80	—	30	USDA Animal and Plant Health Inspection Service (2013)
1.6	65	—	33	Canadian National Farm Animal Care Council (2016)
1.3-1.8	70-100	—	40	European Commission Health & Consumer Protection Directorate-General (2000)
1.5-2.1	50-70	—	33	Cobb (2018)
1.7	70		38	Aviagen (2015)
2.5	—	1	—	SASSO (2018)
3.8	—	2-3	—	SASSO (2018)
5.1	—	3-8	—	SASSO (2018)

'—' indicates information not to be provided in the reference.

Earlier research examined feeder spaces mostly from broiler production standpoints. In general, decreasing feeder spaces from 6.1 to 1.9 cm/bird did not compromise growth rate, body weight, body weight uniformity, feed consumption, feed conversion, and mortality (Hansen and Becker, 1960; McCluskey and Johnson, 1958; Reed and Ringrose, 1960). As broiler genetics, nutrition, and management have been improved, more recent studies showed inadequate feeder space (e.g., less than 2.0 cm/bird) may lower body weight but not impair feed conversion rate (Lemons and Moritz, 2015; Malone et al., 1980). When provided with the feeder space of 1.47 cm/bird (one feeder per pen) and 2.94 cm/bird (two feeders per pen), broilers of the former feeder space had less but more severe leg defects (gross skeletal defects in the hip-leg-foot region) (Wilson et al., 1984). As the concerns of animal welfare keep growing, recent studies started to examine the agonistic behaviors (e.g., head pecks, steps, pushes, threats, and chases) as affected by the feeder spaces and reported that the agnostic behaviors may be reduced by increasing feeder spaces from 2.4 cm/bird to 3.6 cm/bird (Olukosi et al., 2002). Oliveira et al. (2019) reported that no significant differences among the feeder spaces of 12.0, 9.5, and 8.5 cm/hen were detected in daily time spent at feeder and maximum percentage of hens feeding simultaneously, and inter-hen variability in daily time spent at feeder was observed, indicating the behavioral repertoire and time budget of individual animals to be various greatly. However, little research has been conducted to examine effects of feeder space on feeding behavior responses of group-housed broilers.

Our previous study has demonstrated an ultra-high frequency radio frequency identification (UHF-RFID) system and data analysis algorithms that can continuously register broilers at feeders and report the feeding behaviors of individual broilers (Li et al., 2019). With the help of the UHF-RFID system, the objective of this research was to investigate feeding behaviors of individual broilers (weeks 4 to 8) at four feeder spaces (2.3 cm/bird with one fully open tube feeder shared by 45 broilers in a pen, 2.3FSO; and 2.3, 4.6, and 6.9 cm/bird with three fully open or partially blocked tube feeders shared by 45 broilers in a pen abbreviated as 2.3FST, 4.6FST, and 6.9FST, respectively, Figure 4.1). The four selected feeder spaces represent a good coverage of the recommended range in Table 4.1. As a part of a series of publications from a cooperative project, this study only focused on the feeding behaviors, while the other publications focused on the feeder space effects on production performance and bird physiology.

4.2 Materials and Methods

4.2.1 Housing, Animals, and Management

The experiment was conducted in the USDA-ARS Poultry Research Unit at Mississippi State, USA. A total of 720 broilers (Ross 708, mixed sex) was obtained from a commercial hatchery and randomly distributed to 16 identical pens with 45 birds per pen. Sixteen pens yielded four replicates per feeder space treatment (total four treatments) and were placed in the middle of a house to control variations of ventilation and lighting. They were separated equally into two sides, and birds at the same sides could have visual contact through the wire fence. Each pen measured 323 cm long and 137 cm wide and was equipped with one or three tube feeders. The tube feeder was 33 cm in diameter with 14 7.3-cm-wide feeder slots. Room temperature, light intensity, and light program were adjusted following the schedule shown in Table 4.2. Caretakers inspected the birds daily and removed the abnormal birds, such as lame birds that were unable to walk to feeders. Therefore, the tagged birds were those without leg issues. Broilers were kept in pens from day of hatch to 56 days of age and provided with corn-soy diets *ad libitum* (National Research Council, 1994). Diet ingredients were previously described by Dozier 3rd et al. (2005). All procedures in this experiment were approved by the USDA-ARS Institutional Animal Care and Use Committee at Mississippi State (license number: 19-3).

Table 4.2 Air temperature and lighting conditions

Week of age	Day of age	Temperature (°C)	Light program (L:D)	Intensity (lux)
Week 1	1-3	32	23L:1D	30
Week 1	4-7	31	23L:1D	30
Week 2	8-13	29	20L:4D	10
Week 3	14-20	27	20L:4D	10
Week 4	21-27	24	20L:4D	10
Weeks 5-8	28-54	21	18L:6D	5

‘L:D’ means number of hours for lighting vs. number of hours for darkness.

4.2.2 Experimental Treatments

The four feeder space treatments were 2.3 cm/bird with one feeder per pen and 2.3, 4.6, and 6.9 cm/bird with three feeders per pen (Figure 4.1). The feeder space treatments were achieved by granting birds access to all (for 2.3FSO and 6.9FST) or partial (for 2.3FST and 4.6FST) feeder slots (Figure 4.1). A few feeder slots of tube feeders for 2.3FST and 4.6FST were filled with sand

and blocked using partition plates. The sand could stabilize the hanging feeder and block electromagnetic emission of the RFID antenna, thus avoiding false detection. The reason that we used three feeders was to ensure that available floor space per bird was equal among the treatments (2.3FST, 4.6FST, and 6.9FST), while the single feeder pen was essentially a negative control (2.3FSO). Number of feeder slots per feeder was 14 at 2.3FSO, 5 at 2.3FST, 9 at 4.6FST, and 14 at 6.9FST. Number of total available feeder slots was 14 at 2.3FSO, 15 at 2.3FST, 27 at 4.6FST, and 42 at 6.9FST.

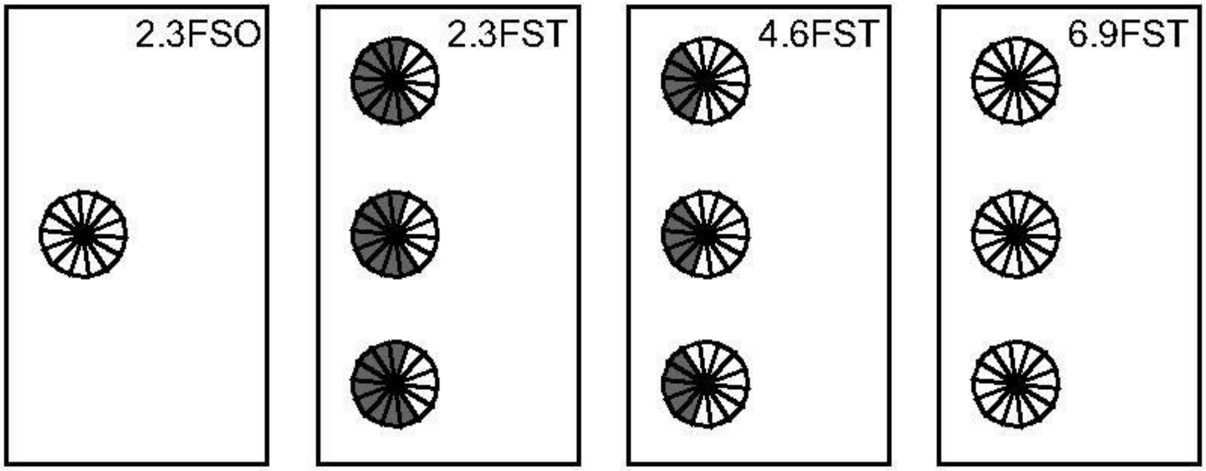

Figure 4.1 Illustration of the experimental pens and treatments

Round objects are feeders. Dark gray areas of the feeders represent blocked feeder slots and white areas represent open feeder slots. 2.3FSO = 2.3 cm/bird feeder space with one fully open feeder shared by 45 birds in a pen; 2.3FST = 2.3 cm/bird feeder space with three partially blocked feeders shared by 45 birds in a pen; 4.6FST = 4.6 cm/bird feeder space with three partially blocked feeders shared by 45 birds in a pen; 6.9FST = 6.9 cm/bird feeder space with three fully open feeders shared by 45 birds in a pen.

4.2.3 Behavioral Data Acquisition System

A UHF-RFID system was used to monitor feeding behaviors of individual broilers. The system consisted of 40 antennas (TIMES-7 A6034S; Impinj Inc., Seattle, WA, USA), 360 tags

(PT-103; TransTech Systems Inc., Wilsonville, OR, USA), three hubs (IPJ-A6001-000; Impinj Inc., Seattle, WA, USA), three readers (IPJ-REV-420; Impinj Inc., Seattle, WA, USA), and three Python-based data acquisition systems. The antennas were placed underneath tube feeders as described in our previous study (Li et al., 2019). All 45 birds in four pens (one pen per treatment) and 15 birds in each of the remaining 12 pens (three pens per treatment) were tagged. A total of 360 birds were tagged. The light-weight RFID tags (less than 5 grams for each) were placed using one simple-interrupted full-thickness throw of non-absorbable nylon suture (Ethilon size 1), attaching the tag to the skin on midline of the ventral neck, approximately 1 inch from the bottom beak. Tags were applied by the attending veterinarian with care to avoid the underlying structures of the neck, as an experienced caretaker gently restrained the bird as for a blood draw. As this minor procedure is analogous to a blood draw, no anesthetics were applied. Besides, before the study, a pilot study with 20 birds being sutured was conducted. Based on 14-day observation, only a couple of birds were observed preening around the tags soon after placement and after that there was seemingly no significant attention paid to them. What's more, our previous test showed that performance (feed consumption and conversion) of birds wearing tags was similar as those without tags. Therefore, the suturing tag method should be suitable for the behavior study. The system registered birds eating at all feeders continuously. The tag IDs, feeding time, and feeder codes were saved into .csv files and processed in Microsoft Excel using Visual Basic for Application. The previous study reported a greater than 92% accuracy for monitoring broiler feeding behaviors through the UHF-RFID system (Li et al., 2019). Except for the operation of the RFID tags, we followed the similar set-ups with the previous study, therefore, the registration accuracy should be similar with the previous study as well.

4.2.4 Behavioral Responses and Definitions

Birds were tagged on day 24, and their behaviors were continuously monitored through day 54. In a continuous feeding event, a bird may temporarily withdraw from a feeder/drinker for swallowing, which cannot be registered by the UHF-RFID system. To correct the misidentification of feeding behaviors, the gaps of two consecutive RFID readings that spanned 20 sec or less were filled. The 20-sec threshold could cover 95% of the RFID reading gaps induced by the intermittent swallowing behaviors (Li et al., 2019). After filling the time gaps, time spent and visit frequency for the feeding event were summarized for all tagged birds.

Broilers rarely eat during the dark period (Li et al., 2020b), therefore, feeding behaviors of broilers were analyzed only during the photoperiod. Feeding behaviors for individual birds were summarized into daily/hourly time spent at feeder (DTSF/HTSF), daily/hourly number of feeder visits (DNFV/HNFV), duration per feeder visit (DFV), and feeder utilization rate (FUR). Mean values and coefficient of variation (CV) of these behavioral responses were calculated for each pen. The CVs of behaviors reflect behavioral differences of individual broilers, and a lower CV indicates a better group uniformity (Li et al., 2020b). The abovementioned behavioral responses were summarized using three days of data every week from weeks 5 to 8 and then averaged in each week. Because the light program, light intensity, and temperature set point in week 4 were different from the following weeks, data in week 4 were not included in these behavioral analyses. Details of behavioral responses are provided in Table 4.3.

Table 4.3 The behavioral responses and definitions

Behavioral responses	Unit	Definition
Daily time spent at feeder (DTSF)	min·bird^{-1}·d^{-1}	Overall time spent at feeder(s) per pen within a day
Daily number of feeder visits (DNFV)	times·bird^{-1}·d^{-1}	Number of visits to feeder(s) per pen within a day
Duration per feeder visit (DFV)	min·visit^{-1}	DTSF ÷ DNFV
Hourly time spent at feeder (HTSF)	min·bird^{-1}·h^{-1}	Overall time spent at feeder(s) per pen within an hour
Hourly number of feeder visits (HNFV)	times·bird^{-1}·h^{-1}	Number of visits to feeder(s) per pen within an hour
Feeder utilization rate (FUR)	%	DTSF×45 ÷ (lighting minutes × number of total available feeder slots)

Number of total available feeder slots is 14 at 2.3FSO, 15 at 2.3FST, 27 at 4.6FST, and 42 at 6.9FST. The lighting minutest is 1200 in week 4 and 1080 in weeks 5-8.

Simultaneous feeding birds were determined for the four pens with all birds tagged and examined using data of week 4 because of the least tag loss. Figure 4.2 shows the cumulative lost tags from days 24 to 57, and average 1-2 tags were lost daily.

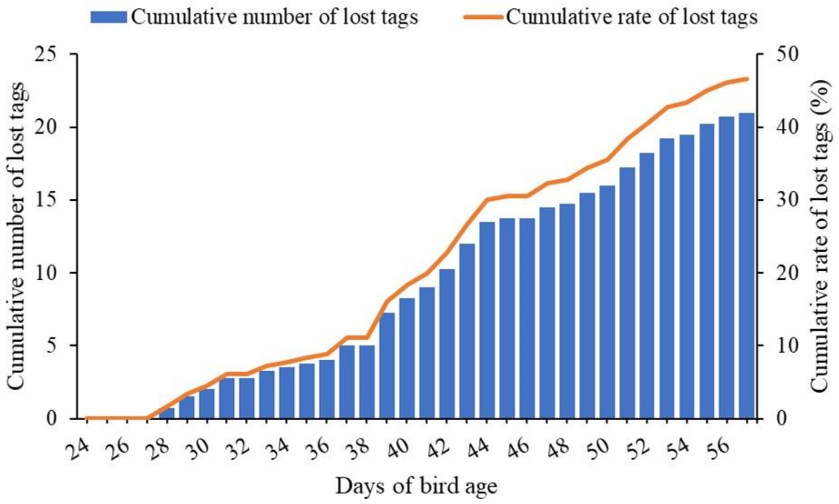

Figure 4.2 Cumulative lost tags from days 24 to 57

Each data point is the average of the four pens with 45 tagged birds.

4.2.5 Statistical Analysis

The effect of feeder space on the mean and CV of DTFS, DNFV, DFV, and FUR was examined using data of weeks 5 to 8 in 16 pens (Equation 4.1). The experimental unit was the treatment pen in each week. Broilers may perform the feeding behaviors differently in days, therefore, the data in days were averaged weekly to reduce day variations.

$$Y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijk} \tag{4.1}$$

where Y_{ijk} is the behavioural response of concern; μ is the least square means of the behavioural response; α_i is the feeder space, $i = 2.3\text{FSO}, 2.3\text{FST}, 4.6\text{FST}, 6.9\text{FST}$; β_j is the bird ages, $j = 5, 6, 7, 8$; $(\alpha\beta)_{ij}$ is the interaction effect of feeder space and bird age; and ε_{ijk} is the random error. Bird age was taken as categorical variable.

With the data from the four pens having 45 tagged birds in week 4, we compared the frequencies of numbers of birds simultaneously eating at one feeder or in a pen. Percentage data (i.e., FUR, CV, frequency of simultaneously feeding birds) were arcsine transformed into degrees before statistical analysis, and the resultant values were back transformed into percentage. The abovementioned statistical analyses were conducted with ANOVA using PROC MIXED statement in the Statistical Analysis Software (SAS 9.3, SAS Institute Inc.). Fixed effects in the model were feeder space and bird age treatments, and random effects were not included in the model. Least squares mean comparisons of the behavioral responses were conducted using Fisher’s least significant difference with PDMIX800 (Saxton, 1998), with significance considered at *P*≤0.05.

4.3 Results

4.3.1 Daily Feeding Behavioral Responses

4.3.1.1 Average of Daily Feeding Behavioral Responses

The average feeding behavioral responses of broilers are shown in Table 4.4. Overall, broilers spent average 72.4-144.4 min at feeders daily, translating into 5.0-10.0% of a day. The broilers visited the feeder for 73-125 times per day and stayed at the feeder for 0.8-1.6 min per visit. Feeder space and bird age had significant effects on DTSF, DNFV, and FUR ($P<0.01$), while their interaction did not significantly affect any behavioral responses ($P\geq0.15$). Due to that, we did not include interaction data in Table 4.4. The broilers at 2.3FSO spent less time at feeder and visited feeder less frequently than the broilers at other feeder space treatments ($P<0.01$), while no difference of the two responses was observed among treatments with three feeders per pen. Feeder utilization rate was the highest for the 2.3FST treatment (FUR=31.1%, $P<0.01$). Feeding time, number of feeder visits, and FUR decreased as the broiler age increased ($P<0.01$), while duration per feeder visit was not significantly different among the feeder space treatment ($P=0.15$).

Table 4.4 Broiler feeding behaviors at different feeder spaces and bird ages

Treatment	DTSF (min·bird^{-1}·day^{-1})	DNFV (times·bird^{-1}·day^{-1})	DFV (min·visit^{-1})	FUR (%)
Feeder space				
2.3FSO	73.7^{b}	73^{b}	1.1	21.5^{b}
2.3FST	113.2^{a}	122^{a}	0.9	31.1^{a}
4.6FST	119.1^{a}	114^{a}	1.5	18.0^{c}
6.9FST	119.6^{a}	118^{a}	1.0	11.5^{d}
SEM[1]	4.7	3	0.3	0.01
Bird age				
Week 5	144.4^{a}	125^{a}	1.2	27.6^{a}
Week 6	128.7^{b}	119^{a}	1.6	24.5^{b}
Week 7	80.0^{c}	97^{b}	0.8	15.2^{c}
Week 8	72.4^{c}	85^{c}	0.8	14.1^{c}
SEM[2]	4.6	3	0.4	0.01
P-value				
Feeder space	<0.01	<0.01	0.50	<0.01
Bird age	<0.01	<0.01	0.15	<0.01
Feeder space × Bird age	0.15	0.78	0.55	0.73

DTSF=Daily time spent at feeder; DNFV=Daily number of feeder visits; DFV=Duration per feeder visit; FUR=Feeder utilization rate; 2.3FSO=2.3 cm/bird feeder space with one fully open feeder shared by 45 birds in a pen; 2.3FST=2.3 cm/bird feeder space with three partially blocked feeders shared by 45 birds in a pen; 4.6FST=4.6 cm/bird feeder space with three partially blocked feeders shared by 45 birds in a pen; and 6.9FST=6.9 cm/bird feeder space with three fully open feeders shared by 45 birds in a pen.

^{a,b,c} Values within the same column that lack of a common superscript differ significantly ($P \leq 0.05$).

[1] Standard error for the effect of feeder space (*n*=16 pens).

[2] Standard error for the effect of bird age (*n*=16 pens).

4.3.1.2 Coefficient of Variations of Daily Feeding Behavioral Responses

The CVs of feeding behavioral responses of the tagged broilers in each pen are shown in Table 4.5. The CVs were 43.1-65.1% for DTSF, 33.0-39.8% for DNFV, and 38.6-46.1% for DFV. The CVs of all feeding behaviors responses were similar among the treatments ($P \geq 0.06$). The CVs of DTSF and DNFV significantly increased as broilers got older ($P \leq 0.05$), and the CVs of DFV were similar across all bird ages ($P = 0.21$).

Table 4.5 The coefficient of variation of broiler feeding behaviors at different feeder spaces and bird age

Treatments	DTSF (%)	DNFV (%)	DFV (%)
Feeder space			
2.3FSO	50.3	37.3	44.2
2.3FST	57.0	35.2	42.7
4.6FST	62.3	37.4	46.1
6.9FST	56.2	37.0	38.6
SEM[1]	0.10	0.03	0.05
Bird age			
Week 5	43.1^{c}	33.0^{b}	41.4
Week 6	53.2^{b}	34.6^{b}	43.9
Week 7	64.2^{a}	39.6^{a}	42.9
Week 8	65.1^{a}	39.8^{a}	43.3
SEM[2]	0.10	0.03	0.05
P-value			
Feeder space	0.06	0.77	0.09
Bird age	<0.01	0.01	0.85
Feeder space × Bird age	0.88	0.76	0.94

DTSF=Daily time spent at feeder; DNFV=Daily number of feeder visits; DFV=Duration per feeder visit; 2.3FS =2.3 cm/bird feeder space with one fully open feeder shared by 45 birds in a pen; 2.3FST=2.3 cm/bird feeder space with three partially blocked feeders shared by 45 birds in a pen; 4.6FST=4.6 cm/bird feeder space with three partially blocked feeders shared by 45 birds in a pen; and 6.9FST=6.9 cm/bird feeder space with three fully open feeders shared by 45 birds in a pen.

[a,b,c] Values within the same column that lack of a common superscript differ significantly ($P \leq 0.05$).

[1] Standard error for the effect of feeder space (*n*=16 pens).

[2] Standard error for the effect of bird age (*n*=16 pens).

4.3.1.3 Frequency of Duration per Feeder Visit

Figure 4.3 shows the frequency distribution of duration per feeder visit at four feeder spaces and four bird ages. Overall, broilers showed similar patterns of duration per feeder visit across the four feeder spaces and bird ages. The frequencies exponentially decreased as the durations increased. The frequency of <60 sec, 60-120 sec, 120-180 sec, 180-240 sec, and >240 sec for each feeding event were 67.7-77.5%, 11.1-15.6%, 4.3-6.8%, 2.3-3.8%, and 4.8-6.0% across all feeder spaces and bird ages.

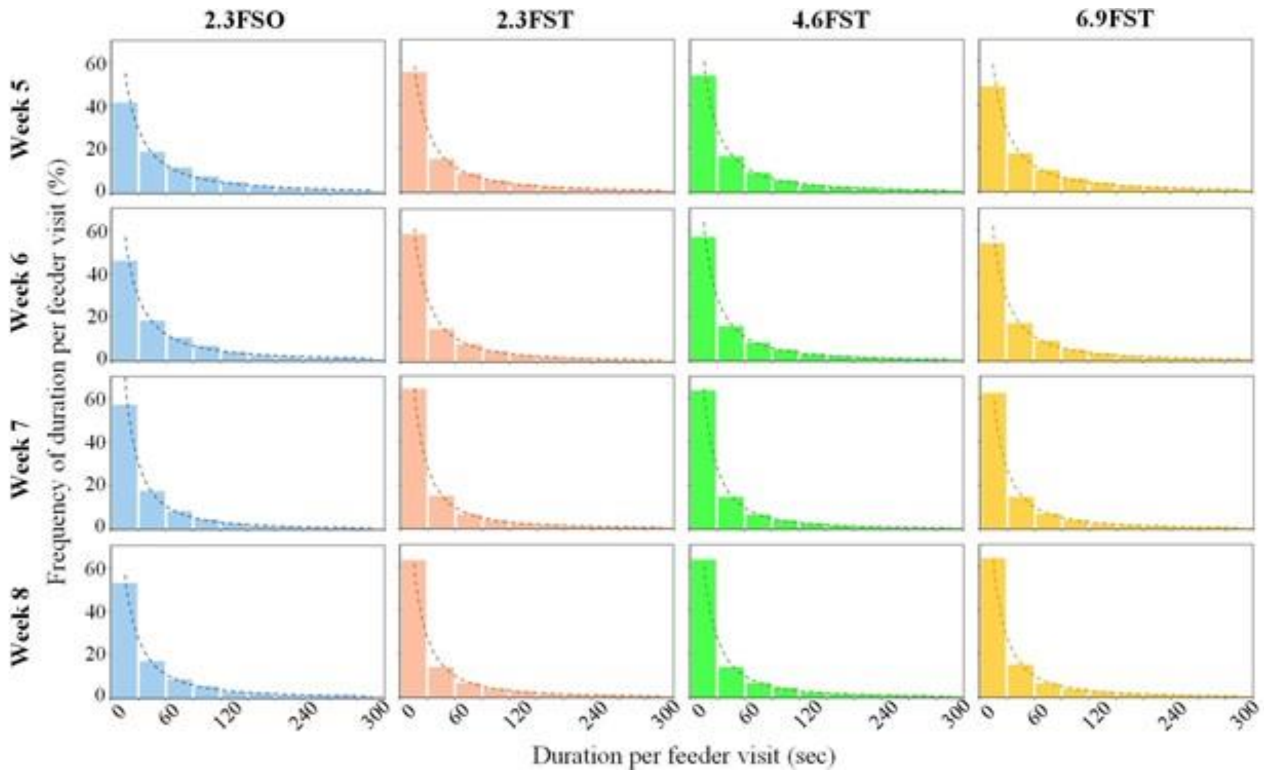

Figure 4.3 Frequency distribution of feeding duration per feeder visit with four feeder spaces and at four bird ages

2.3FSO=2.3 cm/bird feeder space with one fully open feeder shared by 45 birds in a pen; 2.3FST=2.3 cm/bird feeder space with three partially blocked feeders shared by 45 birds in a pen; 4.6FST=4.6 cm/bird feeder space with three partially blocked feeders shared by 45 birds in a pen; 6.9FST=6.9 cm/bird feeder space with three fully open feeders shared by 45 birds in a pen.

4.3.2 Hourly Feeding Behavioral Responses

Figure 4.4 shows the hourly feeding time and number of feeder visits under the four feeder spaces and at the four bird ages. Overall, broilers ate for 4.2±1.3 min at 2.3FSO, 7.1±1.6 min at 2.3FST, 6.1±1.6 min at 4.6FST, and 6.4±2.2 min at 6.9FST within each hour of a day. Broilers visited the feeders for 4±1 times at 2.3FSO, 7±1 times at 2.3FST, 6±1 times at 4.6FST, and 6±1 times at 6.9FST. Broilers ate consistently throughout the lighting period.

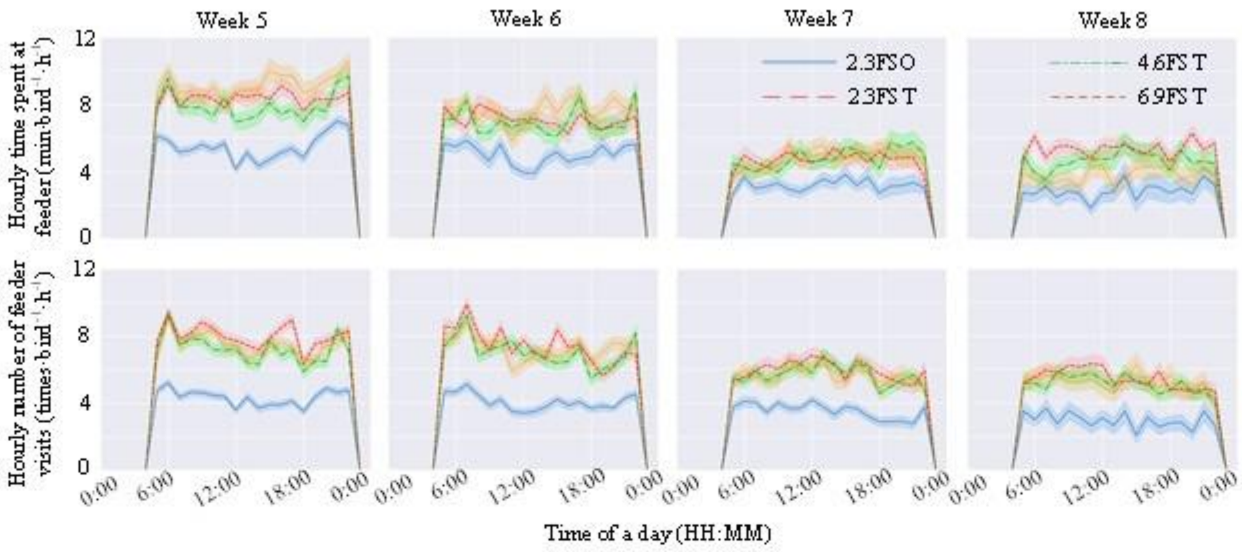

Figure 4.4 Hourly time spent at feeder and hourly number of feeder visits with the four feeder spaces and in the four bird ages

2.3FSO=2.3 cm/bird feeder space with one fully open feeder shared by 45 birds in a pen; 2.3FST=2.3 cm/bird feeder space with three partially blocked feeders shared by 45 birds in a pen; 4.6FST=4.6 cm/bird feeder space with three partially blocked feeders shared by 45 birds in a pen; 6.9FST=6.9 cm/bird feeder space with three fully open feeders shared by 45 birds in a pen. Lights ON at 5:00 am and OFF at 22:00.

4.3.3 Simultaneous Feeding Birds

Figure 4.5 shows the frequency of number of simultaneous feeding bird at a feeder or in a pen with the treatments. The data in this section was reported for week 4 only. The feeder of the 2.3FSO treatment pen was simultaneously used by two broilers for majority of time (19.9%), while the feeder of other treatment pens was mostly used by no broiler (38.3-58.4%). The frequency distributions of simultaneous feeding bird numbers at a feeder were similar among the 2.3FST, 4.6FST, and 6.9FST treatments. For the most time, the feeders in a pen were simultaneously used by 2 broilers at 2.3FSO, 0 at 2.3FST, 1-2 at 4.6FST, and 2-3 at 6.9FST. For 94.2-99.9% of the time, less than six birds chose to eat simultaneously at a feeder, and less than 10 birds ate simultaneously in a pen. The maximum numbers of birds simultaneously feeding at a feeder were

13 at 2.3FSO, 9 at 2.3FST, 10 at 4.6FST, and 12 at 6.9FST. The maximum numbers of birds simultaneously feeding in a pen were 13 at 2.3FSO, 18 at 2.3FST, 19 at 4.6FST, and 20 at 6.9FST.

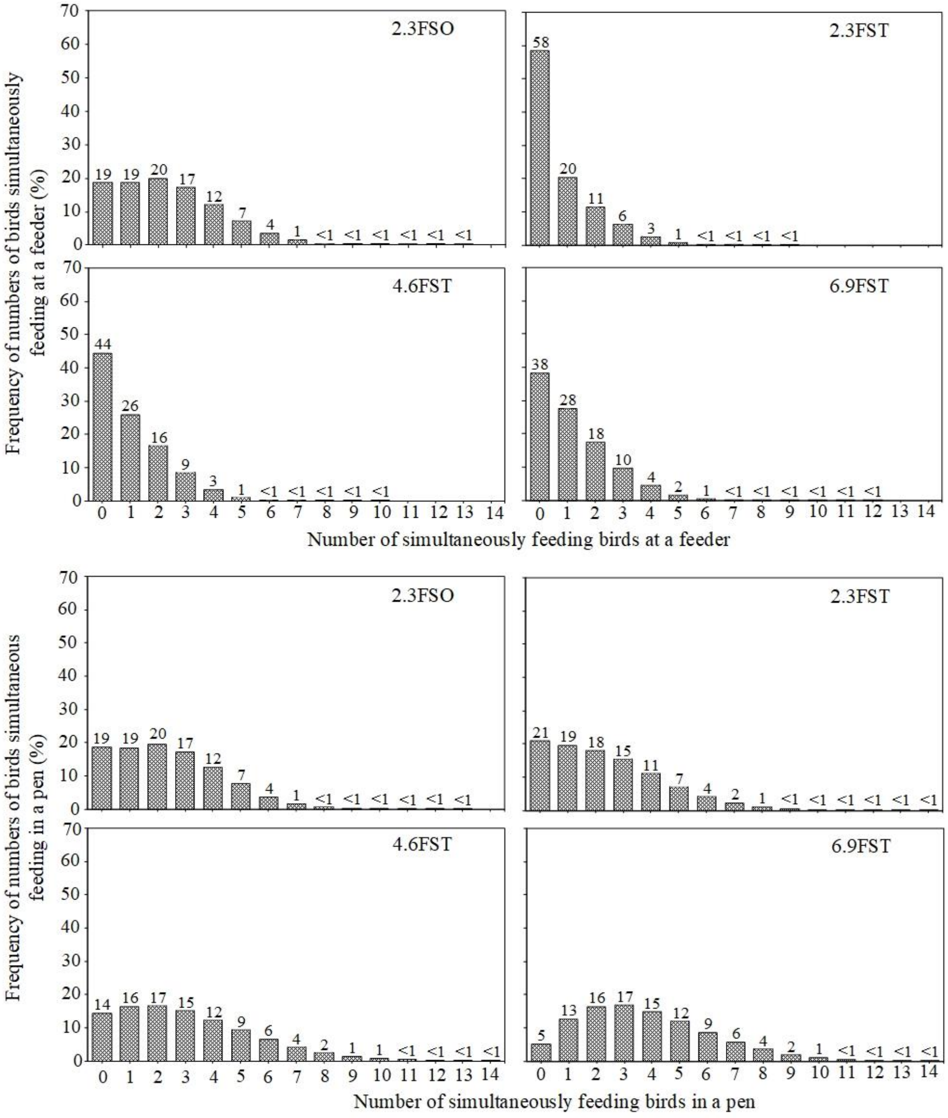

Figure 4.5 Frequency distribution of number of simultaneously feeding birds in week 4

2.3FSO=2.3 cm/bird feeder space with one fully open feeder shared by 45 birds in a pen; 2.3FST=2.3 cm/bird feeder space with three partially blocked feeders shared by 45 birds in a pen; 4.6FST=4.6 cm/bird feeder space with three partially blocked feeders shared by 45 birds in a pen; 6.9FST=6.9 cm/bird feeder space with three fully open feeders shared by 45 birds in a pen. Different numbers atop the bars indicate the frequencies of numbers of birds simultaneously feeding.

4.4 Discussion

In this study, we intended to cover a wide range of feeder spaces that have been recommended previously (Aviagen, 2015; Lemons and Moritz, 2015; USDA Animal and Plant Health Inspection Service, 2013) and examined their effect on feeding behavioral responses of individual broilers. The 2.3FST, 4.6FST, and 6.9FST treatments had three feeders, which can ensure equivalent floor space for birds, while the 2.3 FSO treatment with single feeder was used as a negative control.

4.4.1 Group Sizes

The group size was 45 birds in a pen that is much smaller than that in commercial broiler houses. Birds in larger groups may be more likely to see other birds eating than those in smaller groups, therefore, they may be attracted more frequently to eat, resulting in higher feeder utilization efficiency. Perhaps, fewer feeders are required in commercial farms than in the lab. Meanwhile, birds in larger groups may have fewer chances to recognize individuals clearly and to build a stable dominant-subordinate social hierarchy, hence, they may adopt the low-aggression tolerant social strategies (Estevez et al., 2003). As a result, low feeder allowance in commercial farms may not cause severe bird aggression and frustration and still be acceptable for bird welfare. More research is advisable when the experimental results of the feeder space are applied to commercial farms.

4.4.2 Effects of Feeder Space on Broiler Feeding Behaviors

Broilers had various feeding behavioral responses among the feeder space treatments. Broilers in the three-feeder pens (2.3FST) showed more daily feeding time and number of feeder visits than those in the one-feeder pens (2.3FSO), probably because they were more likely to see other birds eating and were attracted to eat. Collins and Sumpter (2006) also found that multiple birds eating at a feeder trough can induce other birds to arrive at the feeder. Given the same feeder amount, increasing feeder spaces from 2.3 to 6.9 cm/bird did not increase the feeding behaviors measured in the current study. The FUR of the 2.3FST treatment was the highest among the treatments because of higher feeding time with less feeder space. The CVs of feeding behaviors were not significantly different across the feeder spaces, which may be helpful for group uniformity (Diarra and Devi, 2014).

4.4.3 Effects of Bird Age on Broiler Feeding Behaviors

The results of this study show that broiler feeding behaviors did not remain consistent throughout the second half of a production cycle. For weeks 5 to 8, broilers spent less time on feeding and visited feeder less frequently as the bird age increased. Bokkers and Koene (2003) reported that the percentage of time spent on eating for fast-growing broilers decreased from 15% in the first 6 weeks to 10% in the following weeks. Younger birds have lower body weight and may have no problem to walk to feeders (Sørensen et al., 2000). Nevertheless, broilers may be lazy in moving as they grow heavier, resulting in less number of feeder visits and feeding time. In the same study, Bokkers and Koene (2003) demonstrated that for the fast-growing broilers, the percentage of time spent on walking decreased from 11% in week 1 to 1% in week 8. This could be an implication of proper feeder arrangement to ensure easy feeder access by older broilers.

Older broilers (>5 week old) had more variations in feeding time and number of feeder visits in this case. Broilers with different social hierarchy could show individual variability within a group, in which dominant birds may have the priority to access resources while subordinate ones may not access resources at will. Higher individual variability leads to poorer group uniformity (Diarra and Devi, 2014). It is generally accepted that social hierarchy begins to establish at approximately five or six weeks of age in the domestic fowl (Queiroz and Cromberg, 2006). Although a stable social group could reduce aggressiveness among birds, it may also lead to greater individual variations. Properly sizing the group may help to reduce the social effect on individual variations. Estévez et al. (1997) and Li et al. (2020b) found that a group size of more than 50 birds can reduce performance variations of individual broilers.

4.4.4 Feeding Duration per Feeder Visit

The mean, CV, and individual pattern for the feeding duration per feeder visit were similar across all the feeder space treatments and bird ages. Previous research reported that the feeding duration per feeder visit could be affected by various leg conditions (Weeks et al., 2000), growth rate (Howie et al., 2009), and diet type (Li et al., 2020b). In this case, the broilers were fed with the same type of diet among the treatments and can walk to the feeder without leg issues based on observation, therefore, these may be the reasons for the similar performance of the DFV among the treatments. As broilers occupied feeders for mostly less than 60 sec in each feeder visit, other birds did not need to wait for too long before they accessed to feeders, which can avoid broiler feeding frustration (Duncan and Wood-Gush, 1972).

4.4.5 Hourly Feeding Behavioral Responses

Diurnal feeding rhythm can reflect bird welfare status across a day (Savory, 1980). Broilers in Weeks 5 and 6 increased their feeding behaviors after the lights ON and before the lights OFF, which coincides with that in the previous research (Ferket and Gernat, 2006; Thogerson et al., 2009; Widowski et al., 2017). The former peak may be caused by no food during the long-term darkness while the latter peak may be stimulated by the prediction of upcoming darkness (Savory, 1980). Besides the two periods, broilers also ate throughout other hours due to individual differences/preferences. As broilers tended to occupy feeder for more time during these periods, leading to subordinate birds awaiting available feeding space, feeder allowance may be evaluated during these periods to provide sufficient feeder space that can reduce resource competition and bird frustration.

4.4.6 Number of Simultaneously Feeding Birds

Understanding simultaneous feeding behaviors provides insights into feeder allowance evaluation (Sirovnik et al., 2018). Assuming one feeder slot serving one bird in this case, the feeders among the treatments were not fully utilized since for most of the time, number of simultaneously feeding birds was smaller than the number of available feeder slots. Broilers may prefer larger feeder spaces even though they have access to feeders, especially during busy feeding periods (Buijs et al., 2011). The maximum number of simultaneously feeding birds in a 2.3FST treatment pen was larger than that in a 2.3FSO treatment pen (18 vs 13). With the same feeder allowance (2.3 cm/bird), spreading the feeding space seems to accommodate more birds to eat simultaneously. Increasing feeder spaces from 2.3 to 6.9 cm/bird with the same feeder amount in a pen did not proportionally increase the number of birds that ate simultaneously. Proper feeder arrangement/placement may be more important than increasing feeder allowances in terms of accommodating simultaneously feeding birds. The maximum number per feeder in the 2.3FSO treatment (13) was smaller than available feeder slot number, while the numbers in the 2.3FST and 4.6FST treatments (9 and 10) were larger than available slot numbers. Broilers have preference on feeding location (Li et al., 2020a), and multiple birds may share the same feeding slots when they have strong preference in feeding at a preferred location. In sum, to ensure birds to eat at will, not only the feeder allowance should be considered, but also proper arrangement of the feeder allowance.

The goal of this study is to present the bird feeding behavior responses under different feeder space. More research may be needed to conclude an optimal/recommended feeder space because feeding behavior metrics responded differently under the feeder space investigated and to the feeder management. For instance, daily feeding time and feeder visit for broilers of the 2.3FST treatment were similar as those of the 4.6FST and 6.9FST treatments, but higher than those of the 2.3FSO treatment; the feeders of the 2.3FST treatment were used most efficiently among all treatments as reflected by the highest feeder utilization ratio; the coefficient of variations for all feeding behavioral responses were similar among the treatments; and given the same feeder amount, increasing the feeder space could accommodate more birds eating simultaneously. Producers may need to decide the feeder space based on the specific responses they desire.

4.5 Conclusions

Effects of four feeder spaces (i.e., 2.3FSO, 2.3FST, 4.6FST, and 6.9FST) on broiler feeding behaviors were researched from weeks 4 to 8 using an UHF-RFFID system. The results show that broilers had less feeding time and visited feeders less frequently at 2.3FSO and in weeks 7 and 8, while the feeder utilization was the highest (31.1%) with the 2.3FST treatment. Individual broilers presented less behavioral variation at 2.3FSO and in week 5. Broilers stayed at the feeder for less than 60 sec in most of the feeding events and increased their feeding behaviors after the lights ON and before the lights OFF in weeks 5 and 6. For most of the time, less than six broilers chose to eat simultaneously at a feeder. Maximum number of simultaneously feeding birds in a 2.3FST treatment pen was larger than that in a 2.3FSO treatment pen.

4.6 Acknowledgement

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CHAPTER V

RADIO FREQUENCY IDENTIFICATION SYSTEM FOR POULTRY BEHAVIOR MONITORING: EFFECTS OF LIGHTING ON BIRD FEEDING BEHAVIORS

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Li, G., Zhao, Y., Purswell, J.L., Liang, Y., and Lowe, J.W. (2018). Feeding behaviors of broilers at chicken-perceived vs. human-perceived light intensities under two light spectrums. Presented at 2018 ASABE Annual International Meeting, Detroit, Michigan, USA, 2018. American Society of Agricultural and Biological Engineers. doi: 10.13031/aim.201800875.

Abstract: Broilers perceive lighting differently from human due to differences in spectral sensitivity. Better understanding of broiler behavioral responses to their perceived lighting may inform better farm management practices. The objective of this study was to investigate broiler feeding behaviors at chicken- vs. human-perceived light intensities and under broiler specific LED (BLED) vs. conventional LED light spectrums. The treatment combinations of light intensities and light spectrums were randomly assigned to four identical experimental rooms (3.8×1.5 m, L×W), each with 60 tagged broilers. Light intensities at bird level were maintained at either 5 clux (chicken-perceived light intensity) or 5 lux (human-perceived light intensity). Ultra-high frequency radio frequency identification (UHF-RFID) systems were used to register broilers at the feeders. Different feeding behavior responses were summarized for individual broilers. The results showed that the daily time spent at a feeder ($h \cdot bird^{-1} \cdot day^{-1}$) were 2.7±0.1 for 5-clux BLED, 2.6±0.1 for 5-lux BLED, 2.3±0.1 for 5-clux LED, and 2.1±0.0 for 5-lux LED, respectively. The daily times of visit to a feeder ($times \cdot bird^{-1} \cdot day^{-1}$) and duration per visit ($min \cdot visit^{-1}$) were 80±2 and 2.0±0.1 for 5-clux BLED, 88±2 and 1.8±0.1 for 5-lux BLED, 91±3 and 1.5±0.1 for 5-clux LED, and 95±4 and 1.3±0.1 for 5-lux LED, respectively. Numerically, the broilers tended to visit less to feeders but stay longer at feeders under the chicken-perceived light intensity and broiler specific light spectrum. Feeding behaviors (hourly time spent at a feeder and hourly times of visit to a feeder) peaked 2-3 h after initiation of the photoperiod and 2-3 h before the end of the photoperiod. These preliminary observations suggest potential effects of light intensity and spectrum on feeding behaviors of individual broilers, thus providing insights in feeding managements under different light properties.

Keyword: broiler, chicken-perceived light intensity, broiler specific light spectrum, feeding behavior, UHF-RFID system

5.1 Introductions

Lighting is a crucial environmental factor that affects broiler behavior, production performance, and well-being (Lewis and Morris, 1998; Parvin et al., 2014). As for light intensity and spectrum, efforts have been dedicated to investigate their effects on broilers activity (Newberry et al., 1988), body weight (Deep et al., 2010), leg disorders (Prayitno et al., 1997), immune function (Blatchford et al., 2009), mortality (Wabeck and Skoglund, 1974), and muscle mass (Karakaya et al., 2009), etc. Broilers have unique light sensing systems that avail them of higher sensitivity to light at wavelengths of 360-380 nm (ultra violet), 440-480 nm (blue), 550-580 nm (green), and 620-650 nm (red) as compared to humans (Lewis and Morris, 2000). As such, broilers perceive overall 37% higher light intensity than human do under the same light environment (Saunders et al., 2008). While there are guidelines for the light intensity in commercial broiler houses, such as 30-40 lux in the first week of bird age and 5-10 lux hereafter (Aviagen-Ross, 2018; Olanrewaju et al., 2006), they are all based on human-perceived data (Breteuil, 2019). Using human-perceived data as guidelines may result in inconsistent broiler lighting environments and management due to the discrepancy in spectral sensitivities of broiler and human. Modelling of species specific light perception showed clear differences between poultry and human (Saunders et al., 2008); there is, however, extreme lack of experimental information regarding broiler responses under poultry- vs. human-perceived light intensity, especially for popular poultry light sources, for example, Light-emitting diode (LED).

Light-emitting diode lamps have been increasingly adopted for use in commercial broiler farms to reduce energy usage. The most commonly-used LED is essentially a bichromatic source that couples the emission from a blue LED (peak light emission at 450-470 nm) with a yellow phosphor (peak light emission at 580 nm). Recently, some lighting manufacturers have developed broiler specific LED light sources. Compared to conventional LED lamps, the broiler specific LED (BLED) lamp suppressed the light emission at 480-530 nm, 610-620 nm, and 670-700 nm, respectively, while enhanced the emission at 620-630 nm. The manufacturers claimed that this lighting source can improve production efficiency and poultry welfare (ONCE Inc., 2018). To provide un-biased implications on this lighting source, research should be conducted for poultry growers regarding to lighting system purchases.

Previous research showed no differences in broiler production parameters (e.g., body weight, gain, feed intake, and feed conversion) between BLED and conventional LED lamps (Olanrewaju et al., 2016, 2018). However, effects of these two light sources on feeding behaviors of broilers remain unclear. Assessing feeding behaviors of broilers can help to understand not only the bird utilization of feed resources, but also the feeding rhythm of broiler responses to the environmental stimuli (Savory, 1980), thus having critical economic and welfare implications to poultry production and housing system designs (Gonyou, 1994). The objective of this study was to investigate the effect of chicken-perceived vs. human-perceived light intensities on feeding behaviors of individual broilers under BLED and conventional LED light spectrums.

5.2 Materials and Methods

5.2.1 Housing, Animals, and Management

Four identical experimental rooms (Rooms 1-4) were used for the experiment; each room measured 3.81 × 1.47 × 2.06 m (L×W×H) (Figure 5.1). Each room was equipped with two 36-cm-diameter tube feeders and eleven nipple drinkers. Fresh pine shavings were used as bedding material and spread onto the floor at ~4 cm thick before birds were introduced. A dimmable BLED or LED light bulb was installed at the center of the ceiling. Two hundred and forty (240) 28-day-old Ross×Ross 708 broilers were equally allocated to the four experimental rooms (60 birds/room).

The broilers were kept in the rooms for 25 days. Room temperatures were maintained at app. 21 °C throughout the experiment. Standard farm diets were used and provided *ad libitum*. All procedures were approved by the USDA-ARS Institutional Animal Care and Use Committee at Mississippi State.

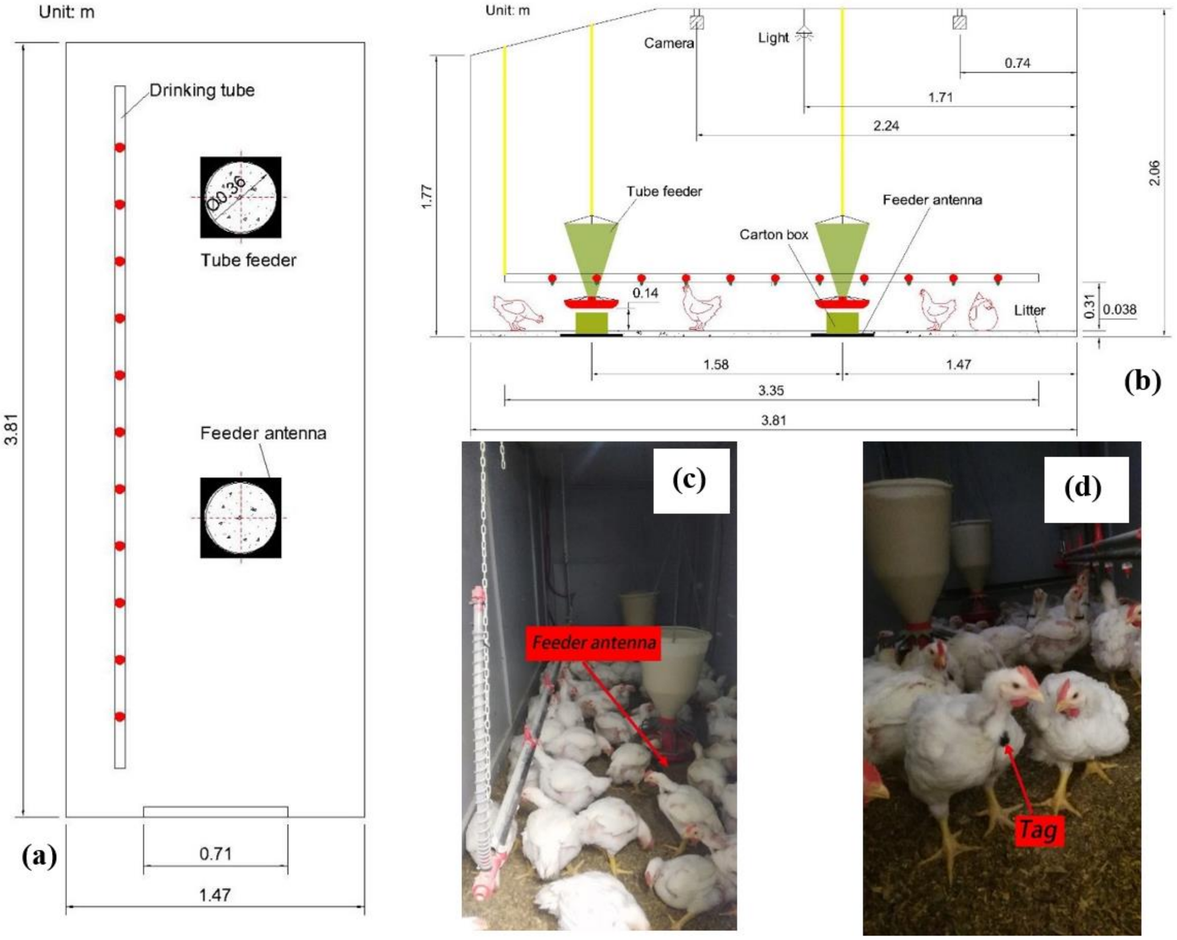

Figure 5.1 Schematic drawings and photos of an experimental room and RFID components

(a) Top view of the experimental room; (b) side view of the experimental room; (c) placement of feeder antenna; and (d) broilers with RFID tags

5.2.2 Ultra-high Frequency Radio Frequency Identification System

Feeding behaviors of individual broilers were recorded by two sets of UHF-RFID systems, each monitoring two experimental rooms. Each system consisted of four antennas, 120 tags, one reader, and one data acquisition (DAQ) system. Two feeder antennas were placed on the litter floor and below the suspending tube feeders in each room (Figure 5.1c). The antennas were protected from accumulation of moisture and manure with plastic wraps. Electromagnetic fields outside the tube feeders were blocked using the steel sheets attached to the corners and edges of the antennas to avoid registering non-feeding broilers. Empty carton boxes were placed in the gaps between the feeders and antennas to prevent access under the feeders. Each bird in all four rooms was fitted with a tag to its neck (Figure 5.1d). Tag ID and the time at feeder were recorded by the antennas and readers and stored in the Python-based DAQ system. Data were saved into a new .csv file every 30 minutes. Based on our previous validation study, the accuracy for recognizing feeding behaviors of broilers through the UHF-RFID systems was above 92% (Li et al., 2019).

5.2.3 Lighting

Two types of dimmable LED light sources were used: a 10 W BLED (MLM-B, ONCE Inc., Plymouth, MN) and a 6 W conventional LED (L6A19/DIM/50K, Overdrive, Roanoke, VA). The normalized spectrums of these two light types at two light intensities are shown in Figure 5.2. The irradiance profile of each light bulb was normalized relative to its maximum irradiance output. Lamp and intensity treatment combinations were randomly assigned to each of four rooms and are shown in Table 5.1. The light schedule was 16L:8D, with the photoperiod beginning and ending at 0500 and 2100, respectively.

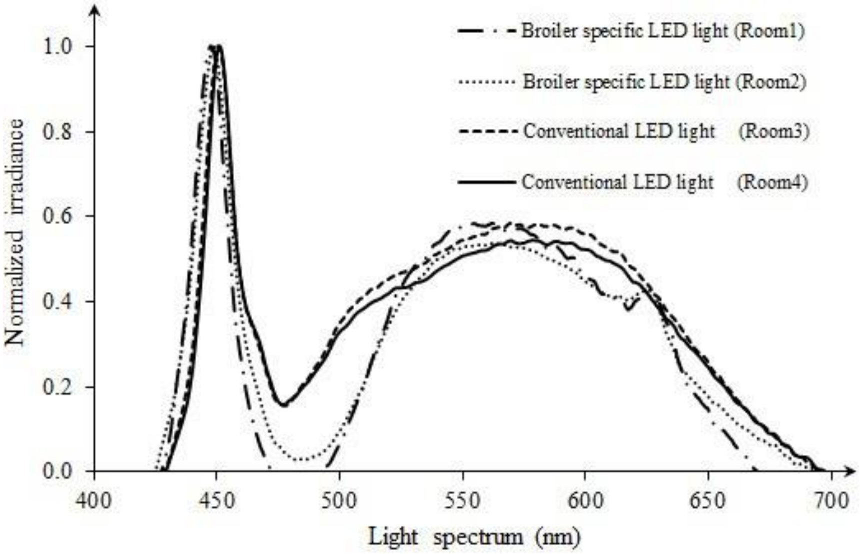

Figure 5.2 Normalized light spectrum at bird level in the four experimental rooms

LED is light-emitting diode.

Table 5.1 Lighting arrangement in rooms 1-4

Room	Light intensity	Light source	Code
Room 1	5 clux (chicken-perceived)	Broiler specific LED	CLUX-BLED
Room 2	5 lux (human-perceived)	Broiler specific LED	LUX-BLED
Room 3	5 clux (chicken-perceived)	Conventional LED	CLUX-LED
Room 4	5 lux (human-perceived)	Conventional LED	LUX-LED

CLUX is chicken-perceived light intensity; LED is light-emitting diode; BLED is broiler specific light-emitting diode.

5.2.4 Feeding Behaviors

The presence of broilers at the feeders was continuously registered by the UHF-RFID systems from 50-54 days of bird age. Data in .csv files were processed with the algorithm in Microsoft Excel using Visual Basic for Applications (VBA). The bird ID, port number, and time stamp in the original data were compared with corresponding given conditions, then birds with certain ID occurring at feeder in certain moment and certain room was detected. In a continuous feeding event, a bird may temporarily withdraw from the feeder for swallowing, which cannot be registered by the UHF-RFID system. To correct the miss-identification of feeding behaviors, the gaps of two consecutive RFID readings that spanned 20 secs or less were filled. Based on previous validations, the 20-sec threshold could cover 95% of the RFID reading gaps induced by the intermittent swallowing behaviors (Li et al., 2019). After filling/ignoring the time gaps, time spent and number of visit for the feeding event were summarized for each bird.

According to our observations and other studies (Kristensen et al., 2007; Malleau et al., 2007), broilers rarely ate during the dark period, therefore, the feeding behaviors of broilers were only analyzed during the photoperiod (0500 to 2100, 16 h). The parameters of feeding behaviors are defined in Table 5.2.

Table 5.2 The definition of the broilers feeding behaviors

Parameter	Abbreviation	Unit	Definition
Daily time spent at a feeder	DTS	h·bird^{-1}·day^{-1}	Overall time spent at a feeder within a day
Daily percentage of time spent at a feeder	DPTS	%	(DTS/24 h) ×100%
Daily times of visit to a feeder	DTV	times·bird^{-1}·day^{-1}	Number of visit to a feeder within a day
Duration per visit	DV	min·visit^{-1}	Time spent at a feeder within each single visit (DTS/DTV)
Hourly time spent at a feeder	HTS	min·bird^{-1}·hour^{-1}	Time spent at a feeder within each hour in a day
Hourly times of visit to a feeder	HTV	times·bird^{-1}·hour^{-1}	Number of visit to a feeder within each hour in a day

Time spent is the overall time a broiler spends at a feeder within a day (daily time spent, DTS) or within each hour of a day (hourly time spent, HTS). Daily percentage of time spent (DPTS) is the percentage of time a broiler spends at a feeder in a day (24 h). Times of visit are the number of visit a broiler approaches and eats at a feeder with a day (daily times of visit, DTV) or within each hour of a day (hourly times of visit, HTV). Duration per visit (DV) is the time a broiler spends at a feeder during a single visit. All parameters were summarized bird by bird, then calculated as mean ± standard deviation.

5.3 Results and Discussion

5.3.1 Overall Feeding Behaviors of Broilers

Our results show the broilers spent 2.1-2.7 h at the feeders, accounting for 8.8-11.2% of the time in a day (Table 5.3). Alvino et al. (2009) reported higher feeding time budgets of 3.2-3.4 h (13.2-14.1%). The variation in results may be attributable to differences in the photoperiod (16 h in this study vs. 17 h in the study by Alvino et al.), bird age (35-40 days of age vs. 21-35 days of age), light intensity (≤5 lux vs. ≥5 lux), stocking density (10.0 bird·m^{-2} vs 8.8 birds·m^{-2}), bird breed (Ross 708 vs. Cobb 500), etc. Broilers visited the feeders 80-95 times every day on average, with each visit lasting 1.3-2.0 min.

Table 5.3 Feeding behavioral responses under different lighting treatments

Parameter	CLUX-BLED	LUX-BLED	CLUX-LED	LUX-LED
DTS (h·bird^{-1}·day^{-1})	2.7±0.1	2.6±0.1	2.3±0.1	2.1±0.0
DPTS (%)	11.2±0.5	10.9±0.2	9.5±0.5	8.8±0.2
DTV (times·bird^{-1}·day^{-1})	80±2	88±2	91±3	95±4
DV (min·visit^{-1})	2.0±0.1	1.8±0.1	1.5±0.1	1.3±0.1

DTS=daily time spent; DPTS=daily percentage of time spent; DTV=daily times of visit to feeder; DV=duration per visit. CLUX is chicken-perceived light intensity. LUX is human-perceived light intensity. LED is light-emitting diode. BLED is broiler specific light-emitting diode. Values in the table reflect arithmetic means ± standard deviation

5.3.2 Feeding Behaviors of Broilers under Chicken-perceived vs. Human-perceived Light Intensities

Within the same light spectrum/type, DTS under CLUX was 3.1-9.0% higher than that under LUX (Table 5.3). The DTV to feeder under CLUX was 4.2-9.1% lower than that under LUX. The DV under CLUX was 12.3-15.2% higher than that under LUX. The broilers tended to spend more time at the feeders and visit the feeders less in the two rooms at chicken-perceived light intensity of 5 clux, which equals to approximately 70% of the human-perceived light intensity (or 3.5 lux). While DTS and DTV varied among treatments, overall feed intake for the accompanying production experiment was not different (*P*=0.557) for any lamp or intensity combination (Purswell et al., unpublished data). In contrast, broilers spent more time eating under brighter lighting environment when provided with light intensities higher than, i.e., >6 lux, than the tested levels in current study (Newberry et al., 1988; Prayitno et al., 1997). It should be noted that the results of this study were based on one test round and additional replications are needed to validate the findings.

5.3.3 Feeding Behaviors of Broilers under Broiler Specific LED vs. Conventional LED Light Spectrums

At the same light intensity, the DTS at feeder under BLED was 17.5-24.3% higher than that under LED. The DTV to feeder under BLED was 7.4-12.1% lower than that under LED. The DV under BLED was 32.2-35.6% higher than that under LED. The BLED seemed to encourage the broilers spending more time eating with less trips to the feeders compared to the LED. Due to longer occupation at feeder for broilers under BLED, more feeder investment under BLED might be added to avoid resource competition.

5.3.4 Feeding Rhythm of Broilers

Figure 5.3 shows HTS and HTV. In all rooms, HTS peaked in 2-3 h after the light was turned on at 0500, then gradually decreased from 0600 to 0900. HTS was relatively stable between 1000 to 1400, then started to increase and peaked at 1800-1900. HTS gradually decreased thereafter until the photoperiod ended at 2100. A second peak of HTV in a day was observed approximately 2-3 h prior to the end of the photoperiod. The patterns of broiler feeding rhythms among all groups were similar. Our findings are consistent with that of Deep et al. (2012), who reported peak feeding hours shortly after and before dark periods. Fluctuations in diurnal feeding rhythms should be considered for the system design to ensure sufficient feeder space and access during the peak feeding hours.

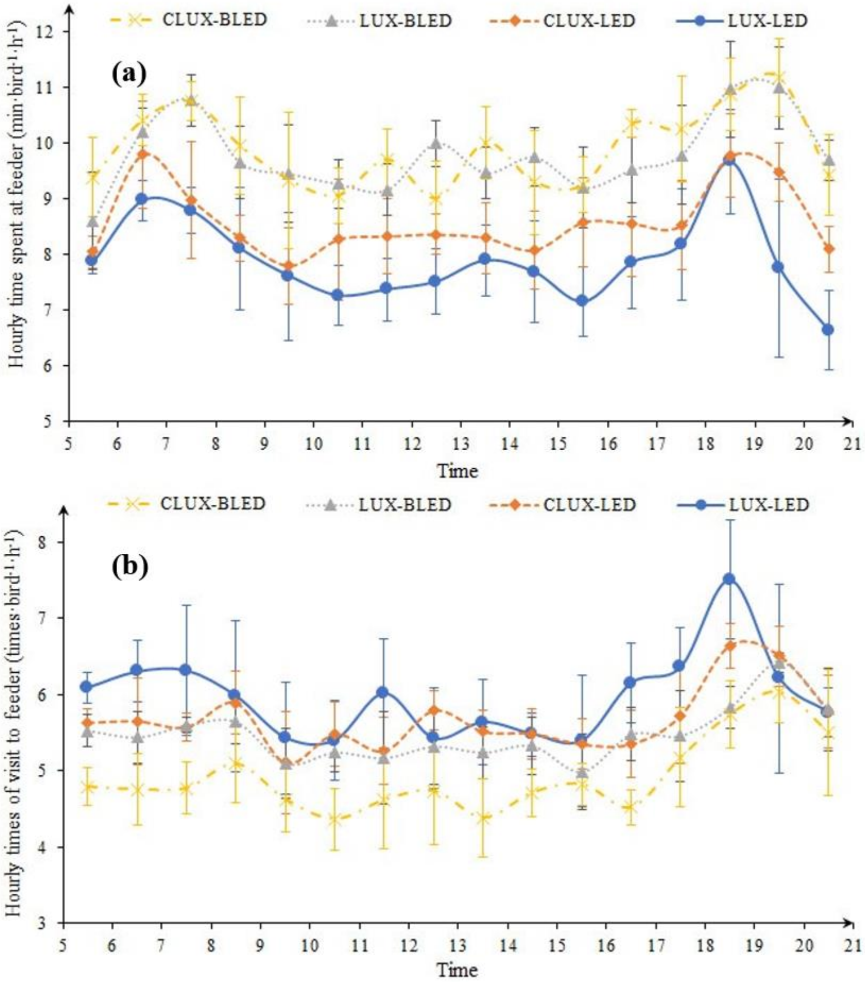

Figure 5.3 Hourly feeding behavior responses under different lighting treatments

(a) Hourly time spent at feeder; and (b) hourly times of feeder visits. The light intensities include 5 lux (human-perceived light intensity) and 5 clux (chicken perceived light intensity). The light spectrums include conventional LED and broiler specific LED (BLED).

5.4 Preliminary Observations

In this study, feeding behaviors of individual broilers under chicken-perceived vs. human-perceived light intensities and under BLED vs. conventional LED light spectrums were investigated. Based on the results in this trial, we observed the following:

- Overall, broilers spent 2.1-2.7 h (or 8.8-11.2% of a day) at the feeders and visited the feeders for 80-95 times within a day.
- Broilers tended to spend more time at the feeders and visit the feeders less at chicken-perceived light intensity of 5 clux than at human-perceived light intensity of 5 lux.
- Broilers stayed longer at the feeders and visit the feeders less under BLED than they did under LED.
- Peak feeding of broilers occurred within 2-3 h before and after the dark period with a 16L:8D light schedule.

5.5 Acknowledgements

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CHAPTER VI

IMAGE PROCESSING TECHNOLOGY: BROILER FEEDING AND DRINKING BEHAVIOR DETECTION

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Li, G., Zhao, Y., Purswell, J. L., Du, Q., Chesser Jr, G. D., and Lowe, J. W. (2020). Analysis of feeding and drinking behaviors of group-reared broilers via image processing. Computers and Electronics in Agriculture, 175: 105596. doi: 10.1016/j.compag.2020.105596.

Abstract: Farm managements and system designs could be improved based on the responses of broiler feeding and drinking behaviors. The objective of this study was to develop and validate image processing algorithms for automatic monitoring of feeding and drinking behaviors of group-reared broilers. Sixty Ross® 708 broilers at 26–28 days of age were kept in a 2.9 m × 1.4 m pen with a tube feeder and five nipple drinkers. Broiler behaviors in the pen were recorded and stored in images. Areas of concern near the feeder and drinkers in the images were segmented for broiler-representing pixels which were quantified to estimate bird number at feeder (BNF) and at drinkers (BND). Two days of data (24000 images) were used for algorithm training and testing. The results show that the algorithms had an accuracy of 89–93% for determining BNF. The mean square error between the predicted BNF and real BNF was 0.3-0.4 bird, indicating a good estimation precision of BNF by the algorithm. The sensitivity, specificity, and accuracy of the algorithms for determining BND were, respectively, 87–90%, 97–98%, and 93–95%. For most of the time on the sampling days, the feeder was simultaneously occupied by 7–13 broilers and each drinker by 0–1 broiler. Broilers showed spatial and temporal preferences in feeding and drinking, with more birds eating and drinking in areas with less disturbances, within a few hours after light ON and before light OFF, and during flock inspection periods. It is concluded that the algorithms had acceptable accuracies in determining BNF and BND, thus being useful components for vision-based behavioral monitoring systems.

Keyword: broiler, behavior, feeding, drinking, image processing

Nomenclature

Acronym

ANOVA	One-way analysis of variance
ARS	Agricultural Research Service
BLS	Bottom left section
BND	Bird number at drinkers
BNF	Bird number at feeder
BRS	Bottom right section
DTSD	Daily time spent at drinkers
DTSF	Daily time spent at feeder
HTSD	Hourly time spent at drinkers
HTSF	Hourly time spent at feeder
LED	Light emitting diode
LSD	Least significant difference
ML	Machine learning
MSE	Mean square error
RFID	Radio frequency identification
TLS	Top left section
TRS	Top right section
SAS	Statistical analysis software
US	United States
USA	United States of America
USDA	United States Department of Agriculture

Variables/Parameters

α	Learning rate
D1-D5	Number of drinker
EndBdPxl	End bird pixels of the *TotBdPxl*
$h_\theta(\boldsymbol{x})$	Bird number at feeder with pixel matrix $\boldsymbol{x}$
I_D	Binary intensity of each pixel at drinkers
$I_D^{'}$	Grayscale intensity of each pixel at drinkers
$I_{BLS}^{'}$	Grayscale intensities of pixels at bottom left section
$I_{BRS}^{'}$	Grayscale intensities of pixels at bottom right section
$I_{TLS}^{'}$	Grayscale intensities of pixels at top left section
$I_{TRS}^{'}$	Grayscale intensities of pixels at top right section
I_{BLS}	Binary intensities of pixels at bottom left section
I_{BRS}	Binary intensities of pixels at bottom right section
I_{TLS}	Binary intensities of pixels at top left section
I_{TRS}	Binary intensities of pixels at top right section
$I(i)$, $I(j)$	i^{th} and j^{th} pixel at an edge
N	Number of negatives
m	Sample size
n	Total pixel length of an edge
P	Nnumber of positives
StrBdPxl	Start bird pixels of the *TotBdPxl*
θ_0 , θ_1	Scalar parameters in the linear equation to be determined
$\theta_0^{'}$, $\theta_1^{'}$	Linear equation parameters in previous iteration
TN	Nmuber of true negatives
TP	Number of true positives
TotBdPxl	Total continuous broiler-representing pixels at an edge
$\boldsymbol{x}$	Normalized broiler-representing pixel matrix
$\boldsymbol{x}^{'}$	Original broiler-representing pixel matrix
$\boldsymbol{y}$	Manually-labeled bird number matrix

6.1 Introduction

Understanding poultry feeding and drinking behaviors helps to evaluate bird utilization of feed and water resources and bird health status, thus providing critical welfare and economic implications for poultry production (Appleby et al., 1992; Kashiha et al., 2013). Research has been conducted to investigate poultry feeding and drinking behaviors as affected by different environmental stimuli (Newberry et al., 1988), management practices (Savory and Mann, 1999), and rearing systems (Tanaka and Hurnik, 1992). Of these investigations, poultry behaviors were often monitored by manual observation onsite or offsite. Manual observation is an accurate and simple way of behavior analysis for a small sample size and limited behavior responses. However, it becomes laborious and time-consuming when the sample size increases and multiple behaviors are required to be monitored simultaneously. Development of automatic methods that can handle large sample sizes and multiple behaviors is, therefore, warranted.

Some automatic monitoring systems have been applied to study poultry behaviors in group settings. For example, weighing systems were used to monitor feeding and drinking of birds (Lott et al., 1992; Puma et al., 2001), and radio frequency identification (RFID) systems were applied to monitor behaviors of group-housed individual birds by registering tagged birds entering electromagnetic fields (Li et al., 2019). Image processing technology is a non-invasive and economical solution for recording and analyzing poultry behaviors. An image-based system commonly consists of image/video acquisition systems and algorithms for animal behavior identifications. Kashiha et al. (2013) applied cameras and image analysis software to analyze bird distribution indices in real time and reported abnormal feeding and drinking behaviors with a 95% accuracy in a broiler house. The same research team investigated hen's preference for environmental factors (e.g., temperature, light, etc.) in a multi-compartment chamber using image processing algorithms (Kashiha et al., 2014). The algorithms they developed achieved >95% accuracy in detecting the compartment occupancy by hens. Leroy et al. (2006) developed a computer vision system to quantify the behaviors of individual hens and the system successfully recognized bird scratching behaviors. Additionally, image processing technology was also used for broiler body weight evaluation (Mortensen et al., 2016), lameness assessment (Aydin, 2017), and flock activity monitoring (Aydin et al., 2010). Although image processing methods have been employed to monitor a few specific behaviors of poultry, there is a paucity of research on their applications in detecting feeding and drinking behaviors of group-housed broilers.

Different machine learning (ML) models have been applied to optimize the performance of image processing. Valletta et al. (2017) used principal component analysis to extract the pheasant egg features (including egg brightness, color, size, and shape) and then used k-means clustering to identify individual pheasant eggs. Michel and El Kaliouby (2003) employed an automatic facial feature tracker to perform face localization and feature extraction. They imported the facial feature displacement to the support vector machine, which generated an average recognition accuracy of 86% in terms of detecting various emotions (e.g., anger, disgust, fear, joy, sorrow, and surprise). Compared with other ML models, the linear regression model with gradient descent is simple and efficient, and it minimizes modeling errors and optimizes modeling parameters by multiple iterations (Goodfellow et al., 2016). Additionally, by using linear regression with gradient descent, we can adjust the training hyperparameters (e.g., learning rate in this case) and observe training loss to judge whether the training process converged to get optimal results. Additionally, with gradient descent, we even can add more features (e.g., edge matrix, corner matrix, etc.) in future research to the linear model to robustize model performance on behavior detection. Despite being widely used for other applications, the model has not been applied to image-based behavioral analysis for broilers. It should also be noted that although there are more cutting-edge techniques (i.e., deep learning) using in precision poultry farming (Gené-Mola et al., 2019; Li et al., 2020). However, we targeted on affordability and applicability for farmers. With that regard, system cost is always among core concern in a real farm application. Compared with machine/deep learning algorithms that require high-end computers for operation, the methods (image processing + linear regression with gradient decent) we proposed can be easily embedded onto some low-cost machines, such as Raspberry Pi (~$55 per unit), for real-time feeding/drinking behavior monitoring, which is acceptable application for farmers.

The objective of this study was to develop image processing algorithms to detect broiler number at feeder (BNF) and at drinkers (BND). The algorithms were improved by a linear regression model using gradient descent. The performances (including sensitivity, specificity, and accuracy) of the algorithms were validated by comparing the results with those of manual observations. With the newly developed algorithms, broiler feeding and drinking behaviors on three consecutive days were analyzed.

6.2 Materials and Methods

6.2.1 Housing, Animals, and Management

The experiment was performed in an environmentally controlled broiler room at USDA Agricultural Research Service Poultry Research Unit at Mississippi State. Sixty 26-day-old Ross® 708 broilers were kept in a pen (2.9 m long and 1.4 m wide) at a stocking density of 677 $cm^2 \cdot bird^{-1}$. Day 26-28 is the transition period from grower diet to finisher diet. Feeding and drinking behaviors could be indicators of the bird adaptation to this critical diet transition period. Therefore, we used behavior data of day 26-28 to develop the model and exemplify the methodology. The pen was equipped with one tube feeder, which had 14 feeder slots, and five nipple drinkers. Pine shavings (~7.5 cm thick) were used as the bedding material. A dimmable LED light bulb was installed at the ceiling. Light intensity at bird level was maintained at 10 lux following typical commercial practices in the US (Olanrewaju et al., 2006). Lighting schedule was 20L:4D (ON at 0100 and OFF at 2100). During the experimental period, the daily mean temperature and relative humidity were maintained at 26.2±1.0 °C and 58±8%, respectively. Birds were provided with a commercial type diet (Dozier III et al., 2007). Feed and water were provided *ad libitum*. The experimental pen is shown in Figure 6.1. The feeding behaviors of broilers in different feeder sections (top right section, TRS; top left section, TLS; bottom right section, BRS; bottom left section, BLS) and drinking behaviors at different drinkers (D1-D5) were processed and analyzed in this study. All procedures in this experiment were approved by the USDA-ARS Institutional Animal Care and Use Committee at Mississippi State.

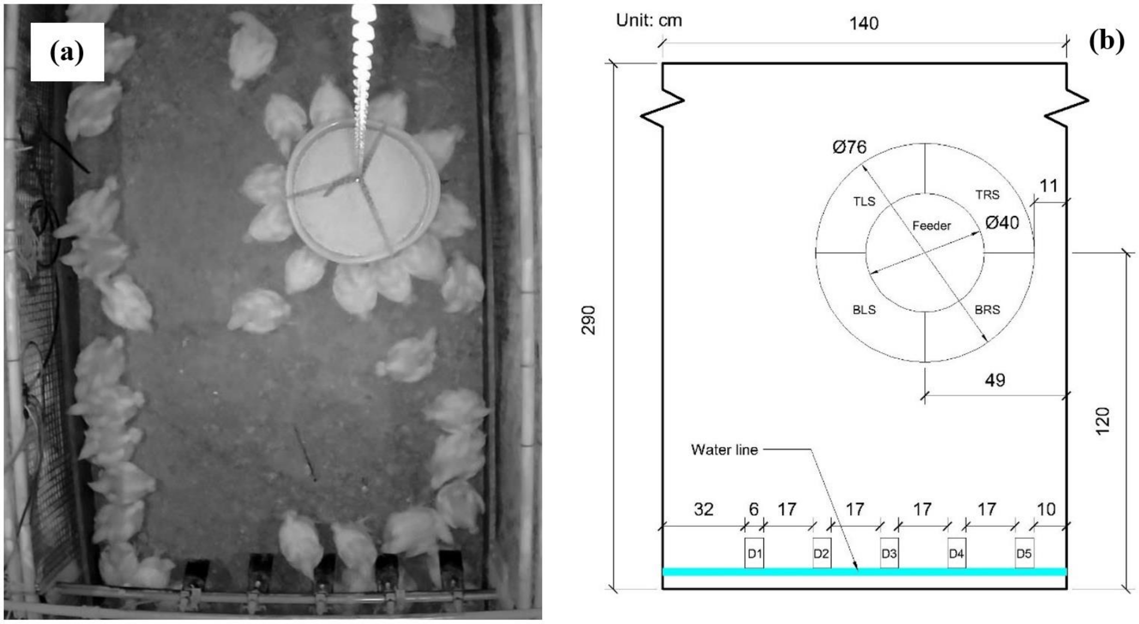


Figure 6.1 Illustrations of experimental settings

(a) A picture of the experimental pen; and (b) a schematic drawing of the experimental pen. TRS = top right section of the feeding area; TLS = top left section of the feeding area; BRS = bottom right section of the feeding area; BLS = bottom left section of the feeding area. D1-D5 are drinker areas from left to right.

6.2.2 Data Collection

A night-vision network camera (NHD-818, Swann Communications U.S.A Inc., Santa Fe Springs, USA) was installed at ~3.6 m above the pen with its lens pointing downward to capture top view of the feeder and drinkers. During the experimental period, broiler behaviors were recorded continuously using a network video recorder (NVR-87400, Swann Communications U.S.A Inc., Santa Fe Springs, USA). The video files were captured with a resolution of 1024×768 pixels at a sampling rate of six frames per second. Videos were stored as AVI files every 30 min in a 3-TB external hard disk. The video files were then converted to images at a rate of one frame per second using Free Video to JPG Converter (ver. 5.0).

6.2.3 Algorithms for Determining Bird Number at Feeder

6.2.3.1 Image Processing for Extracting Pixels around the Feeder

With the image files, the BNF was determined based on broiler-representing pixels in an area around the feeder. The tube feeder used in this experiment was hung to the ceiling and swung when broilers touched it. Movement of the feeder may cause errors if a stationary area around the feeder was selected for image processing. Therefore, a dynamic area around the feeder was determined as described below. A feeder template (168×176 pixels, Figure 6.2a) was used to match the pattern of the feeder in a target image (321×301 pixels, Figure 6.2b) and produce the normalized cross correlation matrix image (488×476 pixels, Figure 6.2c). The brightest point in the matrix image represented the center of the feeder, and the coordinate of this center was marked in the target image (Figure 6.2b). With a given feeder radius of 85 pixels, the feeder in the image was masked in black. Other irrelevant areas were also masked in black so that only an annular area (inner radius: 85 pixels; outer radius: 156 pixels) remained in the image (Figure 6.2d) for further processing. Because the intensity of litter floor in the annular area was not uniform, the annular area was equally divided into four sections (TRS, Figure 6.2e1; TLS, Figure 6.2e2; BRS, Figure 6.2e3; BLS, Figure 6.2e4) where different thresholds were used to segment broiler-representing pixels. The segmentation thresholds (grayscale intensities with values between 0 and 255) for each section were determined based on histogram analysis. Segmentations of broilers from background in the images were done using Equations 6.1-6.4.

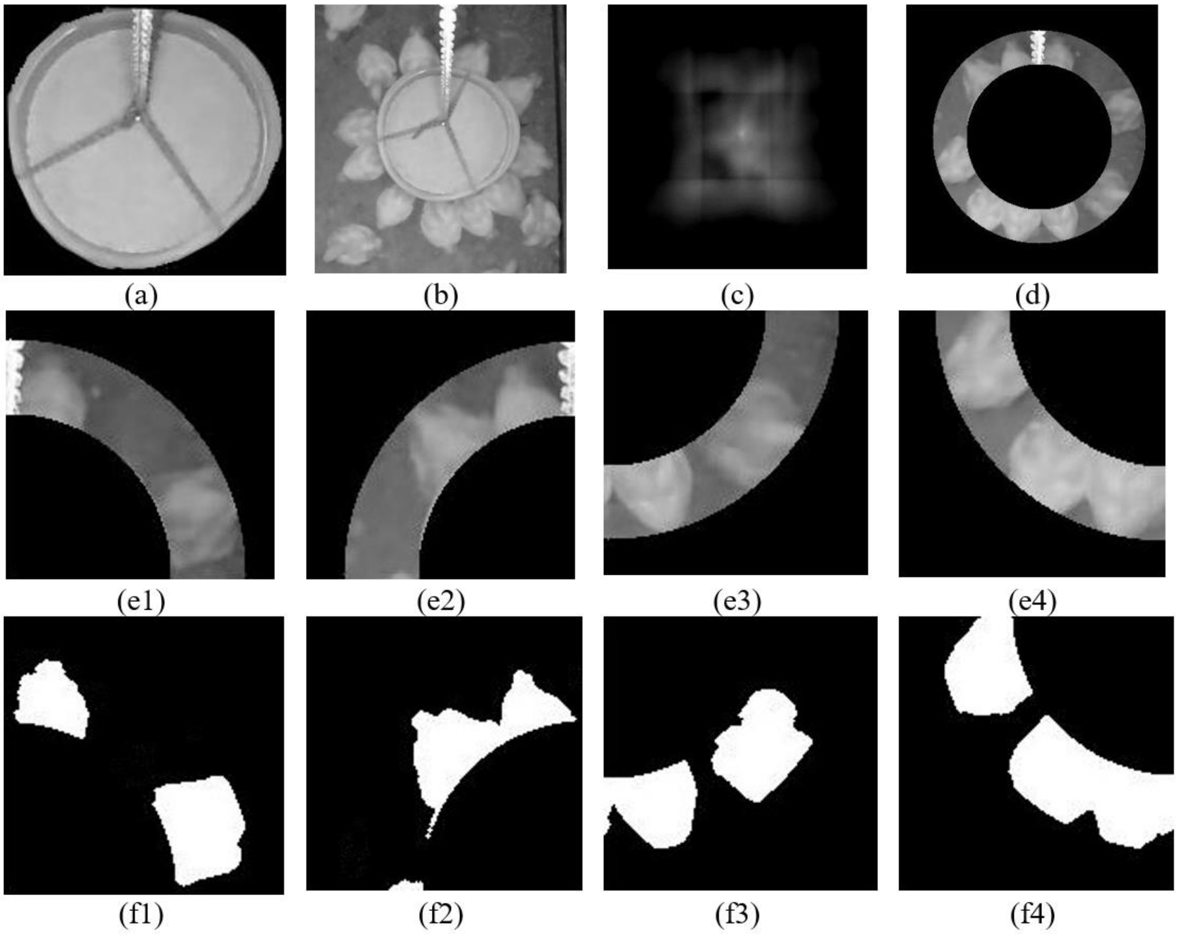


Figure 6.2 Image processing for determining broiler-representing pixels at feeder

(a): Feeder template; (b) target image; (c) normalized cross correlation matrix; (d) image with an annular feeding area; (e1)-(e4): grayscale sectional images of top right section, top left section, bottom right section, and bottom left section, respectively; (f1)-(f4): binary sectional images of top right section, top left section, bottom right section, and bottom left section, respectively.

$$I_{TRS}(x,y) = \begin{cases} 1 & if\ 90 < I'_{TRS}(x,y) < 200 \\ 0 & otherwise \end{cases} \tag{6.1}$$

$$I_{TLS}(x,y) = \begin{cases} 1 & if\ 116 < I'_{TLS}(x,y) < 200 \\ 0 & otherwise \end{cases} \tag{6.2}$$

$$I_{BRS}(x,y) = \begin{cases} 1 & if\ I'_{BRS}(x,y) > 124 \\ 0 & otherwise \end{cases} \tag{6.3}$$

$$I_{BLS}(x,y) = \begin{cases} 1 & if\ I'_{BLS}(x,y) > 130 \\ 0 & otherwise \end{cases} \tag{6.4}$$

where I'_{TRS}, I'_{TLS}, I'_{BRS}, and I'_{BLS} are the grayscale intensities of pixels in 2D coordinates (*x*, *y*) at TRS, TLS, BRS, and BLS, respectively; and I_{TRS}, I_{TLS}, I_{BRS}, and I_{BLS} are the binary intensities of pixels at TRS, TLS, BRS, and BLS, respectively. The grayscale intensity has a range of 0-255, with greater value being brighter. An upper threshold of 200 was used in Equations 6.1 and 6.2 to exclude the hanging chain in the image. The binary intensity value '1' represents a white or broiler pixel, and value '0' represents a black or background/floor pixel. The binary images (Figures 6.2f1-6.2f4) were produced and the total broiler-representing pixels were determined for further analysis. The image processing was conducted using MATLAB (MATLAB R2014b; the MathWorks, Inc., Natick, MA, USA).

6.2.3.2 Determining Bird Number at Feeder with Linear Regression Using Gradient Descent

In the pre-processing step, the broiler-representing pixel matrix in the concerned annular area around the feeder, $\boldsymbol{x}$, are normalized by

$$\boldsymbol{x} = (\boldsymbol{x}' - mean)/std \tag{6.5}$$

where $\boldsymbol{x}$ and $\boldsymbol{x}'$ are, respectively, the normalized and original broiler-representing pixel matrix in the concerned area for an image. The '*mean*' and '*std*' are average and standard deviation of broiler-representing pixels for all training images.

The BNF ($h_\theta(\boldsymbol{x})$) is determined using Equation 6.6.

$$\lfloor h_\theta(\boldsymbol{x}) \rfloor = \theta_0 + \theta_1 \boldsymbol{x} \tag{6.6}$$

where θ_0 and θ_1 are scalar parameters to be estimated, and $\lfloor\cdot\rfloor$ is the rounding symbol.

Error function ($J(\theta_0, \theta_1)$) is defined as

$$J(\theta_0, \theta_1) = \frac{1}{2m} \sum_{i=1}^{m} \left(\boldsymbol{y} - h_\theta(\boldsymbol{x})\right)^2 \tag{6.7}$$

where $\boldsymbol{y}$ is the bird number in the concerned annular area around the feeder determined by manual observation, and *m* is the sample size of the training set. The batch gradient descent update rule is

$$\theta_0 = \theta_0' - \alpha \frac{1}{m} \sum_{i=1}^{m} (h_\theta(\boldsymbol{x}) - \boldsymbol{y}) \tag{6.8}$$

$$\theta_1 = \theta_1' - \alpha \frac{1}{m} \sum_{i=1}^{m} (h_\theta(\boldsymbol{x}) - \boldsymbol{y})\boldsymbol{x} \tag{6.9}$$

which are based on the partial derivatives in terms of θ_0 and θ_1, respectively. The θ_0 and θ_1 are the updated parameters within each iteration. The θ_0' and θ_1' are the parameters in previous iteration. The parameters kept updating until the required error achieved. Learning rate is an important hyperparameter for the training. Large learning rate can cause model to converge too quickly and result in suboptimal model, whereas small learning rate can cause slow training process and get stuck at a suboptimal point. Therefore, different learning rates of α= 0.001, 0.003, 0.010, 0.030, 0.100, 0.300, 1.000, and 1.300 were used to determine the optimum in Equations 6.8 and 6.9. The BNF was determined using the well-fitted linear models (Figure 6.3). The processes of regression and determining BNF were conducted in Python 3.5 with a platform of Anaconda 2.0.

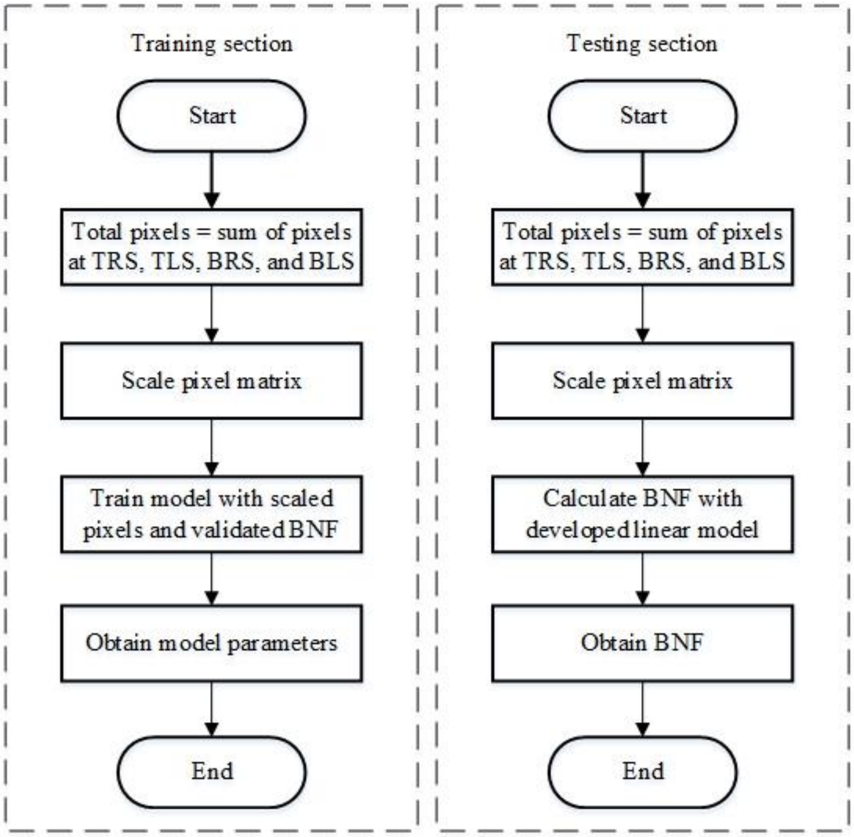
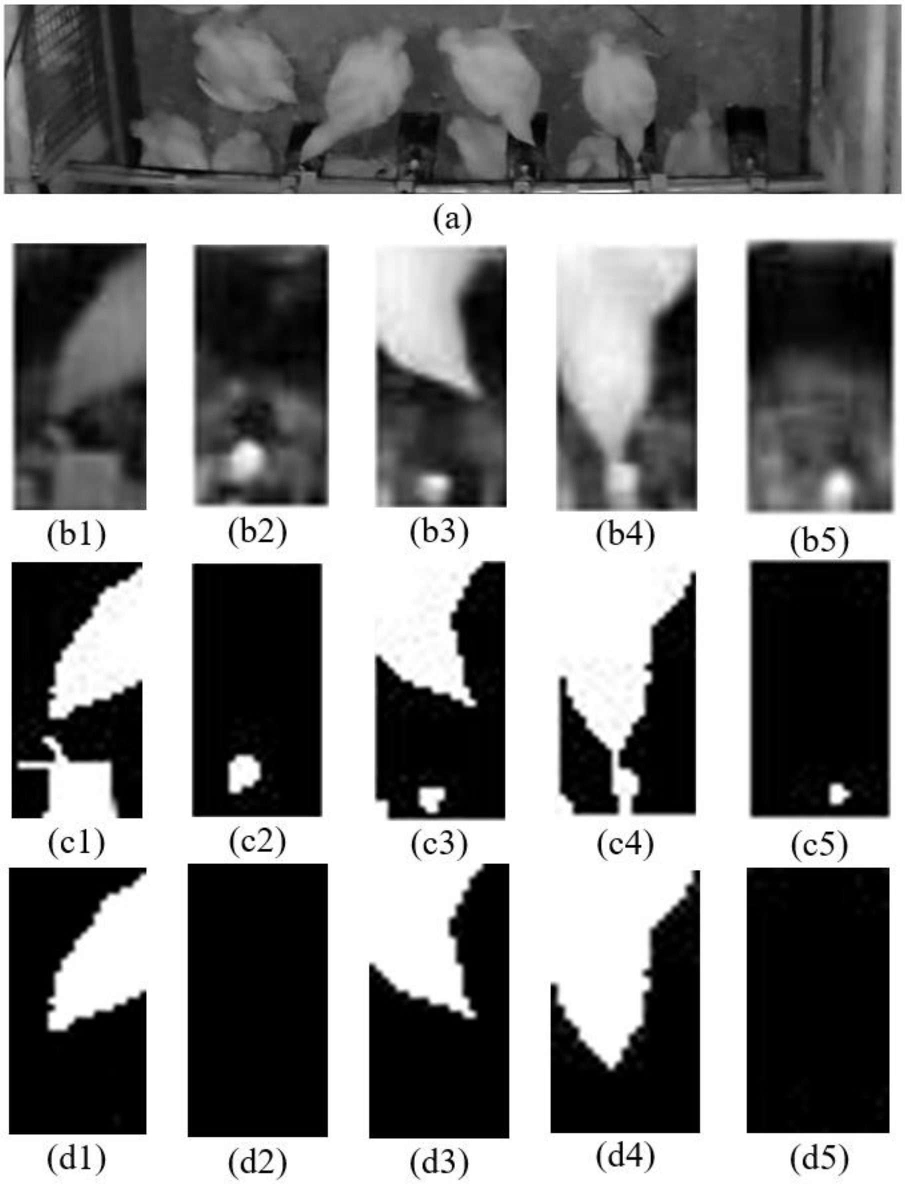


Figure 6.3 Flowchart of the algorithm for counting bird number at feeder

BNF is the bird number at feeder. TRS, TLS, BRS, and BLS are top right section, top left section, bottom right section, and bottom left section of the feeding area.

6.2.4 Algorithms for Determining Bird Number at Drinkers

To improve segmentation results, a black rectangular bracket (120×570 pixels) was installed underneath each nipple drinker (Figure 6.4a). Rectangular sectional images representing the five drinkers (D1 – D5, Figures 6.4b1-6.4b5) were cropped from the target image. The pixels representing drinking broilers in each sectional image were determined using Equation 6.10. The binary sectional images of the five drinkers are shown in Figures 6.4c1-6.4c5. The white pixels representing the drinkers were removed from the binary images (Figures 6.4d1-6.4d5).


(a)

(b1) (b2) (b3) (b4) (b5)

(c1) (c2) (c3) (c4) (c5)

(d1) (d2) (d3) (d4) (d5)

Figure 6.4 Image processing for determining broiler-representing pixels at drinkers

(a): Target image; (b1)-(b5): grayscale sectional images of drinkers 1-5; (c1)-(c5): binary sectional images of drinkers 1-5 after sectional segmentation; (d1)-(d5): binary sectional images of drinkers 1-5 after blocking the white pixels representing drinkers.

$$I_D(x,y) = \begin{cases} 1 & if\ I'_D(x,y) > 80 \\ 0 & otherwise \end{cases} \tag{6.10}$$

where I'_D and I_D are the grayscale and binary intensity of each pixel

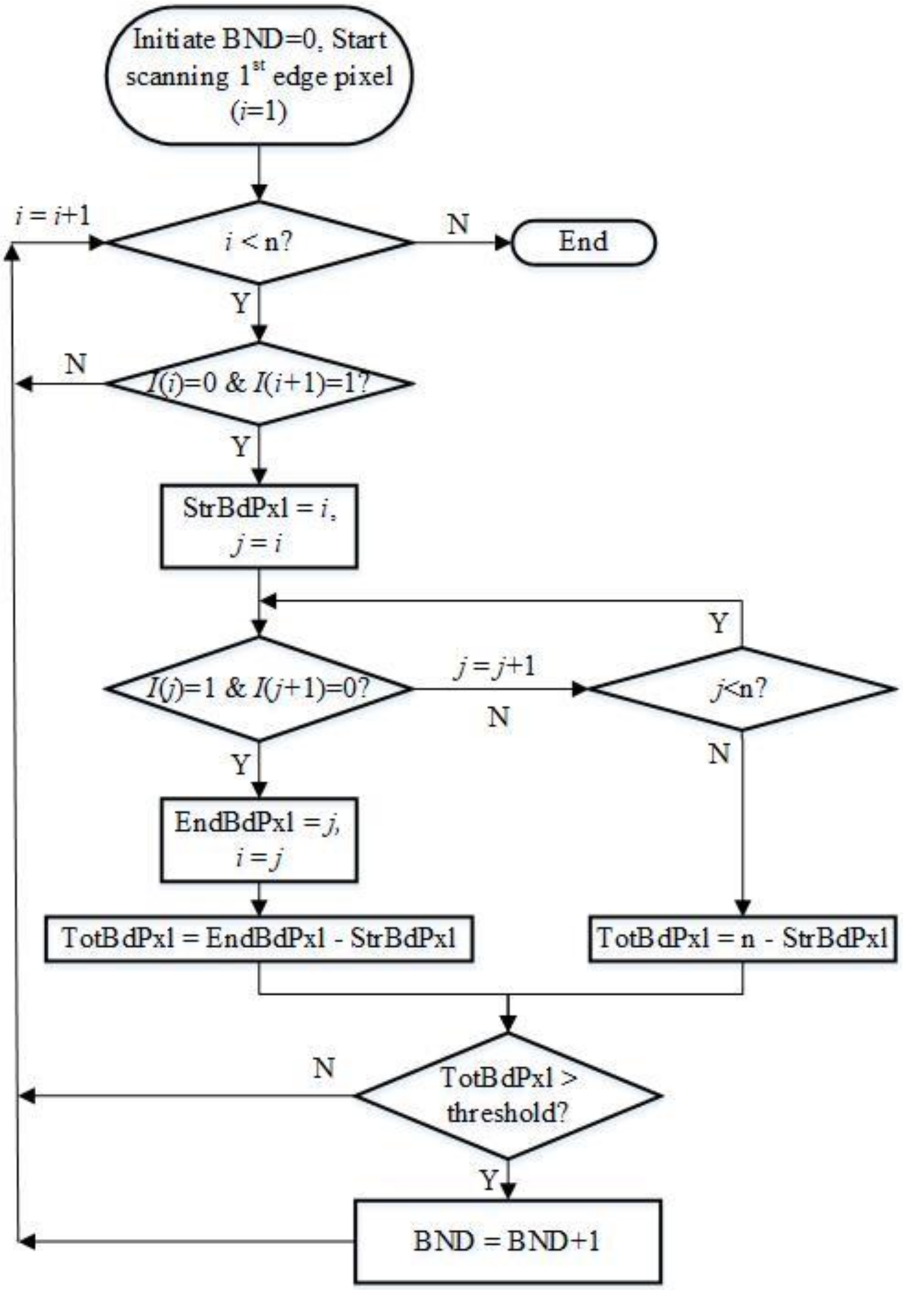


Figure 6.5 Flowchart of the algorithm for counting bird number at a drinker

BND is the bird number at drinker, n is the total pixel length of an edge, $I(i)$ and $I(j)$ are the i^{th} and j^{th} pixel at an edge, and threshold is 6. Y and N mean that the judgement are true and false, respectively. The black pixel ($I(i) = 0$) and white pixel ($I(i) = 1$) represent background and broiler, respectively. TotBdPxl, represents the total continuous broiler-representing pixels at an edge, and StrBdPxl, and EndBdPxl are the start and end bird pixels of the TotBdPxl. The second and third edges repeat the same procedure as that of the first edge and the BND is accumulated throughout these three edges.

Because the concerned area at the drinkers was relatively small, the broiler-representing pixel was not linearly correlated with the BND. Therefore, a different method was used to determine the BND. The outermost pixels of three edges (excluding the edge with a drinker) in the binary images were scanned pixel-by-pixel and edge-by-edge in a clockwise direction. An array containing more than 6 continuous white/broiler-representing pixels was deemed as a broiler at a drinker. In some cases, (non-drinking) broilers walking by the drinkers may appear in the rectangular sectional images. Based on our validation, a threshold of 6 pixels may exclude over 95% of these cases. Figure 6.5 shows a flowchart for determining BND. The analysis was conducted using MATLAB (MATLAB R2014b; the MathWorks, Inc., Natick, MA, USA).

6.2.5 Algorithm Validation

The BNF and BND determined by the image processing and linear model were validated by comparing with the results determined through manual observation. A broiler was identified as "at feeder/drinker" when it was eating/drinking, or when it stood at the feeder/drinker and its head directed to the feeder/drinker. The data on 26 (for training) and 27 (for testing) days of bird age were used to validate the algorithms. Five minutes of every half an hour in the 20 lighting hours were selected and total 12000 frames were obtained for training and testing purposes. The sensitivity, specificity, and accuracy of the algorithms were determined using Equations 11-13 and typically used to determine the correctness of presence, absence, and combined detection by an algorithm (Maselyne et al., 2016; Zhu et al., 2010).

$$Sensitivity[\%] = \frac{TP}{P} \times 100 \tag{6.11}$$

$$Specificity[\%] = \frac{TN}{N} \times 100 \tag{6.12}$$

$$Accuracy[\%] = \frac{(TP + TN)}{(P + N)} \times 100 \tag{6.13}$$

where P is number of positives, i.e., cases when one or more broilers are at feeder/drinkers; N is number of negatives, i.e., cases when no broiler is at feeder/drinkers; TP is number of true positives, i.e., cases when bird number determined by algorithms matches that by manual observation; and TN is number of true negatives, i.e., cases when no broiler is reported by both algorithms and manual observation. Because there were always one or more broilers observed at the feeder (no N), specificity was not calculated for BNF. The mean square error (MSE) was used to evaluate the difference between the predicted value and actual value.

6.2.6 Continuous Behavioral Monitoring Using Algorithms

The BNF and BND were analyzed using the newly developed algorithms on three consecutive days (26-28 days of bird age). To examine the broiler's preference in feeding and drinking locations, BNF at each quadrant section of the feeder and BND at each drinker were also determined. For feeding, a single bird that overlapped in two adjacent quadrant feeding areas was counted only once. The bird was assigned to the quadrant area which contained a larger portion of the body. For drinking, there was no such an overlapped problem because of the drinker apart from each other. Daily time spent at feeder (DTSF, min·bird^{-1}·d^{-1}) and at drinkers (DTSD, min·bird^{-1}·d^{-1}), hourly time spent at feeder (HTSF, min·bird^{-1}·h^{-1}) and at drinkers (HTSD, min·bird^{-1}·h^{-1}), and bird numbers at feeder and at drinkers were calculated.

6.2.7 Statistical Analysis

Daily time spent at different feeder sections and drinkers was compared using one-way analysis of variance (ANOVA) with Least Significant Difference (LSD) post-hoc analysis in Statistical Analysis Software (SAS 9.3, SAS Institute Inc.). All data were analyzed using PROC MIXED statement. An effect was considered significant when P-value was less than 0.05.

6.3 Results

6.3.1 Prediction Errors and Theta Values under Different Iterations and Learning Rates

Prediction errors in different iterations with different learning rates are shown in Figure 6.6. The learning took longer time when using learning rates less than 0.001, while it converged sharply with learning rates more than 0.100. The final prediction errors and theta values are shown in Table 6.1. Theta values of the linear regression model were 9.611 for θ_0 and 2.653 for θ_1, and the final equation was $h_{\theta}(\boldsymbol{x}) = 9.611 + 5.653\boldsymbol{x}$, where $\boldsymbol{x}$ is the normalized broiler-representing pixel matrix in Equation 6.5. Resultant values were rounded to get integer BNF.

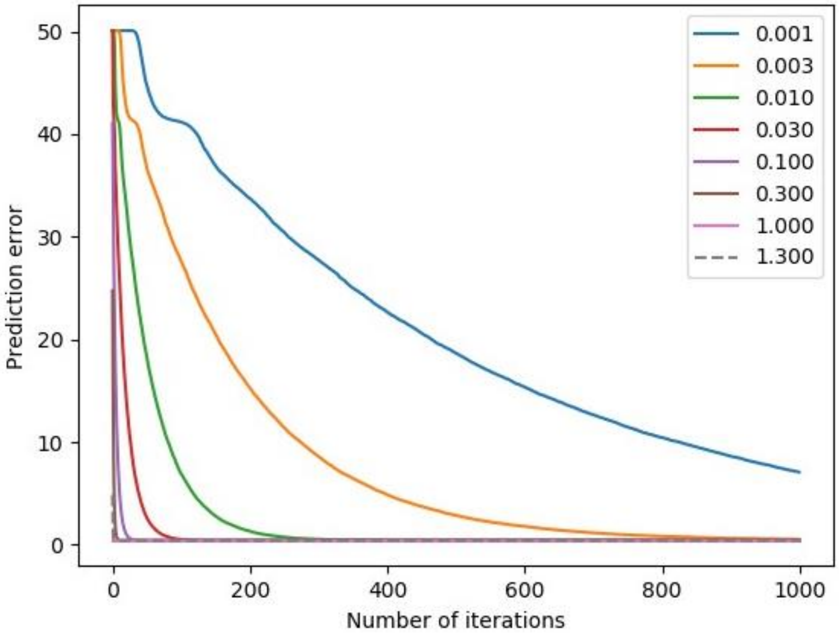


Figure 6.6 Plot of prediction errors in various iterations with different learning rates

Table 6.1 The final prediction errors and theta values based on different learning rates

Learning rate	Final error	Theta value (θ_0, θ_1)
0.001	7.086	(6.077, 1.678)
0.003	0.488	(9.134, 2.522)
0.010	0.366	(9.611, 2.653)
0.030	0.366	(9.611, 2.653)
0.100	0.366	(9.611, 2.653)
0.300	0.366	(9.611, 2.653)
1.300	0.366	(9.611, 2.653)

6.3.2 Performance of Algorithms

Table 6.2 shows that the accuracies of the algorithms for determining BNF were 93% for training and 89% for testing. Mean square errors of the algorithms were 0.3 for training and 0.4 for testing. With average BNF of 10 (Figure 6.7), the error rates were translated to <4% in estimating bird number by the algorithms. The mean sensitivity, specificity, and accuracy for determining BND were 87%, 97%, and 93%, respectively (Table 6.2). The performance of the algorithms varied among drinkers. The sensitivities of D1 and D5 were lower than those of other drinkers. The specificities were high for all drinkers. Overall, D1 had the lowest accuracy than those of other drinkers. Identical sensitivity and accuracy of the algorithms for determining BNF were due to lack of true negatives, which also made specificity calculation impossible.

Table 6.2 Sensitivity, specificity, and accuracy of the algorithms for determining bird number at feeder and drinkers

Evaluation parameter		Bird number at feeder	Bird number at drinker				
			D1	D2	D3	D4	D5
Training	Sensitivity (%)	92.6	83.6	89.1	94.2	94.0	88.6
	Specificity (%)	---	95.6	99.4	99.5	97.6	98.1
	Accuracy (%)	92.6	88.1	95.9	97.9	96.5	96.7
Testing	Sensitivity (%)	89.3	85.5	87.8	89.8	88.0	85.4
	Specificity (%)	--	98.4	95.4	99.2	95.6	99.7
	Accuracy (%)	89.3	89.7	92.2	96.5	93.2	95.4

D1, D2, D3, D4, and D5 represent the five drinkers in the experimental pen.

6.3.3 Bird Numbers at Feeder and Drinkers

Figure 6.7 shows the frequency of number of broilers simultaneously present at the feeder and drinkers on three example days. The most frequent bird number at the feeder was 10, accounting for 18% of the time. About 88% of the time the feeder was used by 7-13 broilers, while 12% of the time by 4-6 and 14-16 broilers. All drinkers were used by 1 bird or none for majority of the time, i.e., 84% for D1, 96% for D2, 97% for D3, 96% for D4, and 98% for D5. Two and more birds simultaneously present at the same drinker accounted for less than 5% of the time. The feeding and drinking behavioral analyses via the developed algorithms were based on three-day data from the same group. Future research with more groups is warranted to validate the findings in this study.

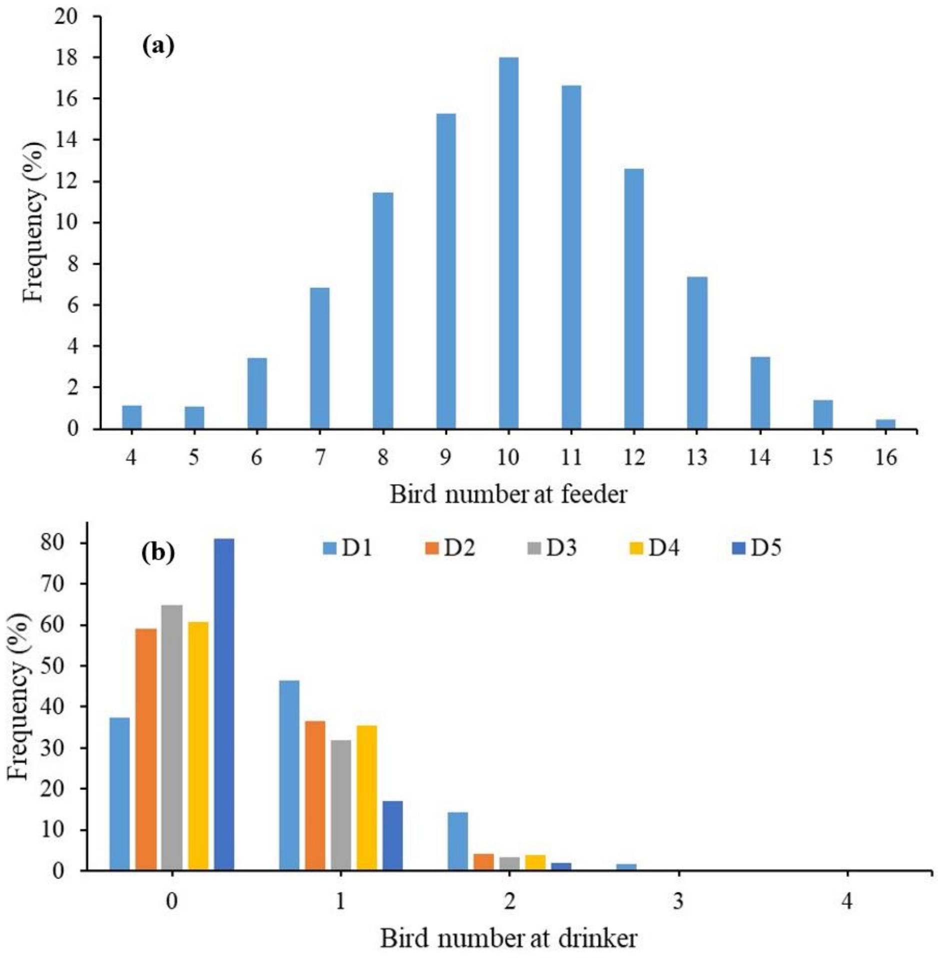


Figure 6.7 Frequency of number of broilers simultaneously present at the resources

(a) The behavior responses at the feeder; and (b) the behavior responses at the drinkers.

6.3.4 Time Spent at Feeder and Drinkers

Table 6.3 summarizes the daily time spent at the feeder and drinkers. Overall, broilers spent 197.9 min·bird^{-1}·d^{-1} at the feeder and 45.8 min·bird^{-1}·d^{-1} at the drinkers. Broilers spent the most time eating at TLS (58.9±2.1 min·bird^{-1}·d^{-1}) and least time at BRS (40.9±2.1 min·bird^{-1}·d^{-1}) (P = 0.002). No significant difference of DTSF was observed between TRS and BLS. Broilers spent more time drinking at D1 and less time at D5 than other drinkers ($P < 0.001$). Time spent in drinking at D2, D3, and D4 did not differ.

Table 6.3 Broiler time spent at the feeder and drinkers

Behaviors		Least square mean	Standard error	*P*-value
Daily time spent at feeder (DTSF, min·bird^{-1}·d^{-1})	TRS	47.0^{BC}	2.1	0.002
	TLS	58.9^{A}		
	BRS	40.9^{C}		
	BLS	51.1^{AB}		
Daily time spent at drinker (DTSD, min·bird^{-1}·d^{-1})	D1	16.1^{A}	0.7	<0.001
	D2	9.1^{B}		
	D3	7.7^{B}		
	D4	8.7^{B}		
	D5	4.2^{C}		

TRS = top right section of the feeding area; TLS = top left section of the feeding area; BRS = bottom right section of the feeding area; BLS = bottom left section of the feeding area. D1-D5 are drinking areas from left to right (see Figure 6.1). ^{A,B,C} Values within a column of the same behavioral category with different superscripts differ significantly at P<0.05 (PROC MIXED, LSD test). Each value is the least square mean of three days of data with 60 birds.

6.3.5 Hourly Time Spent at Feeder and at Drinkers

Figure 6.8 shows hourly time spent at feeder (HTSF) and at drinkers (HTSD) on three consecutive days. Overall, broilers spent 9.9±0.8 min·bird^{-1}·h^{-1} at the feeder and 2.3±0.4 min·bird^{-1}·h^{-1} at the drinkers within each hour throughout a day. During these three days, the HTSF and HTSD typically peaked within 2-3 h after light ON and within 2-3 h before light OFF. Another common peak of HTSF was observed at ~0800 and it lasted longer on day 3. The HTSF and HTSD occasionally peaked at other lighting hours. Based on manual observation, some birds occasionally stayed at the feeder (without eating) during the darkness.

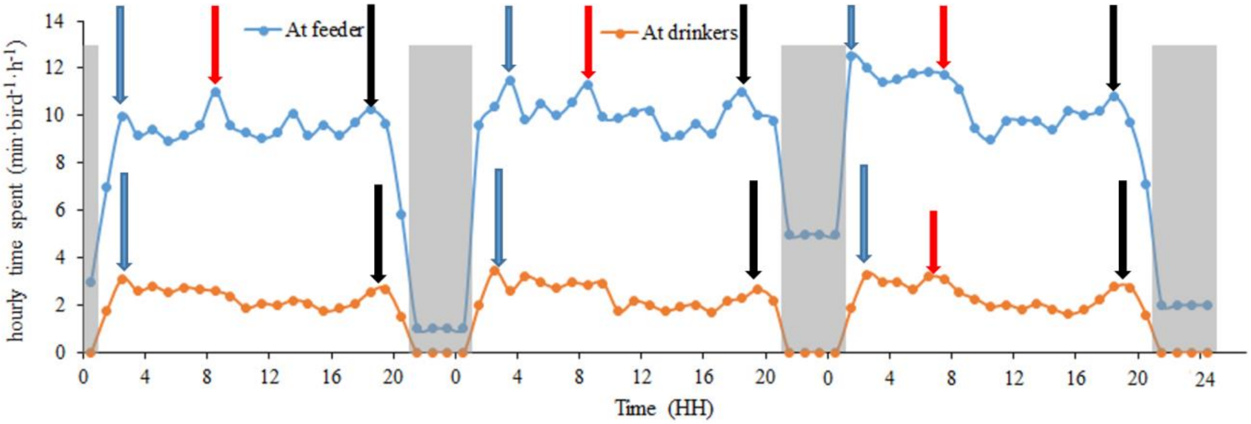


Figure 6.8 Time spent at feeder and drinkers on three consecutive days

Gray shades indicate night periods. Blue, red, and black arrows represent feeding/drinking peaks at 0100-0300, 0800-0900, and 1800-2000, respectively.

6.4 Discussion

In this study, we developed image processing algorithms and examined their accuracies in detecting broilers at feeder and drinkers. The performances (i.e., sensitivity, specificity, and accuracy) of the algorithms were evaluated for the independent training and testing data sets, which are the standard procedure in machine learning to develop generalized algorithms. A well-fitted algorithm should have good performance for both training and testing sets (Goodfellow et al., 2016). In this case, the sensitivity, specificity, and accuracy were more than 89%, and the performance differences of these three parameters between training and testing were mostly less than 5%. That means the algorithms were fitted well from the training set and could be generalized to other data sets.

The overall accuracy of detecting BNF was slightly lower than 90%. For manual observation, a broiler was defined as “at feeder” when it was eating or standing at the feeder with its head directing to the feeder. The image processing algorithms cannot exclude some non-feeding behaviors (e.g., walking by or withdrawing from the feeder) in the concerned area, which compromised the accuracy and sensitivity. These were also the drawbacks of other vision-based behavior monitoring systems (Mehdizadeh et al., 2015). Multiple camera views and advanced algorithms (e.g., deep learning) could probably improve algorithm performance. Accuracy of feeding behavior detection using RFID and sound technology were previously reported at 93% and 89-95%, respectively (Aydin and Berckmans, 2016; Li et al., 2019). The accuracy of the algorithms developed in this study is comparable with those of previous literatures in terms of determining BNF.

The specificities of the algorithms were relatively high for all five drinkers (more than 95%) because the program could not detect any pixel change at edges when no bird was present at drinkers. Specificity can be further improved by excluding the events when birds passed by a drinker and the resultant continuous white pixels at edges were more than 6. The sensitivity and accuracy of the algorithms for determining BND were 87% and 93%. Based on our observation, the algorithms performed well in determining BND when there was no broiler at the drinker. However, it is a challenge to determine two or more drinking birds (Maselyne et al., 2016). When multiple drinking broilers simultaneously present at the same drinker, the broiler standing in front of the drinker was more likely to be detected than those at sides of the drinker. Birds at sides of the drinker only showed their beaks on the binary image and the beak-representing pixels at edges sometimes was less than 6, as a result of which it was treated as noises and filtered out. Because D1 was more frequently used by multiple birds at the same time, the sensitivity and accuracy of D1 were lower than those of other drinkers. Overall, the accuracy of image processing techniques for detecting BND is comparable to that of the RFID-based system developed by Li et al. (2019) (93% for current study vs 95% for RFID study).

The sample size of 60 birds within one pen should be sufficient for the algorithm development. The sample sizes of 4 and 18 were, respectively, used to develop an image processing algorithm to track hens in an environmental preference chamber (Kashiha et al., 2014) and to quantify behaviors of individual hens (Leroy et al., 2006). Bird age could have effects on algorithm performances, for example, broiler-representing pixels of a bird increase as the broiler grows up and feather coverage on the skin and feather color change at different bird ages (Leeson and Walsh, 2004). Algorithm performance may be influenced as well by different environmental conditions (e.g., light intensity, air quality, and litter floor). Therefore, the algorithm needs to be modified in order to extrapolate to other bird ages and environmental conditions.

Sufficient feeder and drinker spaces are essential for broiler welfare (Ferket and Gernat, 2006). Governmental agencies (National Chicken Council, 2005) used a minimum resource allowance of 65 birds·feeder^{-1} and 20 birds·drinker^{-1} and breeder guidelines (Aviagen Ross, 2015) used 45-80 birds·feeder^{-1} and 12 birds·drinker^{-1}. The study used 60 birds·feeder^{-1} and 12 birds·drinker^{-1}, which were lower or equal to the abovementioned recommendations. This may be the reason that the resources had not been fully utilized for most of the time (7-13 birds at the feeder and 0-1 bird at the drinkers). It should be noted that a non-fully-occupied feeder/drinker does not necessarily mean a sufficient resource allowance. Based on our observation (unpublished data), frustration broilers which continuously walked around feeder/drinkers and attempted access to resources were noticed even when feeder/drinkers were not fully occupied. Frustration was defined as an aversive motivational state for birds (Duncan and Wood-Gush, 1972) and caused by deprivation of feed/water (Duncan and Wood-Gush, 1972) or insufficiency of feeding/drinking space (Sirovnik et al., 2018). This indicates that evaluation of resource sufficiency should not only rely on the BNF and BND, but also other behavioral indicators.

Overall, a broiler spent ~3.3 h at the feeder and ~0.8 h at the drinkers per day. The DTSF was lower than that reported by Li et al. (2018) (2.3-2.7 $h \cdot bird^{-1} \cdot d^{-1}$) and the DTSD was also slightly lower than that reported by Deep et al. (2012) (1.0-1.2 $h \cdot bird^{-1} \cdot d^{-1}$). The discrepancy could be caused by the length of photoperiod, light intensity, body weight, and bird age. More experiments are recommended to validate the above hypothesis.

Behavior monitoring at quadrant sections of the feeder and individual drinkers allows to examine the broiler feeding and drinking preference for locations. Broilers spent the most time feeding at TLS and least time at BRS, and most time drinking at D1 and least time at D5. This difference might be caused by available room for feeding and drinking at these locations. Broilers eating at the BRS and drinking at the D5 were more frequently disturbed by other birds due to busy traffic and occupancy of non-eating/drinking birds around these areas. The TRS and BRS both contained some parts close to the pen wall, however, the DTSF was lower in BRS than in TRS. The BRS was closer to drinking line thus being used more frequently by birds. Therefore, bird disturbance seemed to have greater impact than wall disturbance on the feeding choice. The results were similar to those of Buijs et al. (2011) who also reported that broilers expected feeding/drinking areas with less bird disturbance, even though enough space was available to allow multiple birds to eat or drink from the same resource simultaneously. The spatial disturbance by other birds need to be considered for farm managements in terms of broiler welfare.

Hourly behavioral analysis helps to examine temporal feeding and drinking behaviors of broilers throughout a day. Broilers showed feeding and drinking behavior peaks after light ON and before light OFF. These two peaks were also observed in previous research (Li et al., 2018; May and Lott, 1992). The former peak may be caused by no feed/water intake during the darkness, and the latter peak may be stimulated by the bird prediction of darkness (Savory, 1980). Another common feeding peak was observed at ~0800 when caretakers performed flock inspection and refilled the feeder. The simulating effects of caretaker inspection were also found in other investigations (Cain and Wilson, 1972; Suibb and Collier, 1979). The peak at 0800 lasted longer on day 3 (0400-0800) than that in the previous two days. This may result from more human activities (e.g., weighing birds, changing diets, collecting blood samples, etc.) on day 3. In summary, our system can achieve 24-h continuous behavioral monitoring.

6.5 Conclusions

Image processing algorithms were developed and validated to determine bird number at feeder (BNF) and at drinkers (BND) of group-reared broilers. A machine learning model was used to parameterize the equation for determining bird number. The results show that the accuracies were 89-93% for determining BNF by the algorithms and 93-95% for BND (with 87-90% sensitivity and 97-98% specificity). The algorithms were used to continuously analyze behaviors of a group of broilers for three consecutive days. Broiler distribution, time spent, and temporal and spatial behavioral preferences were successfully determined. It is concluded that the newly developed algorithms had acceptable accuracies for broiler behavior analysis, thus are useful components for image-based automatic behavioral monitoring systems.

6.6 Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

6.7 Authorship Contribution Statement

Guoming Li: Conceptualization, Methodology, Data curation, Writing - original draft. Yang Zhao: Supervision, Writing - review & editing, Funding acquisition. Joseph L. Purswell:

Writing - review & editing, Resources. Qian Du: Software. Gray D. Chesser: Resources. John W. Lowe: Resources.

6.8 Acknowledgements

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CHAPTER VII

DEEP LEARNING TECHNOLOGY: BROILER STRETCHING BEHAVIOR DETECTION

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Li, G., Zhao, Y., Porter, Z., and Purswell, J. L. (2020). Automated measurement of broiler stretching behaviors under four stocking densities via faster region-based convolutional neural network. Animal, 15(1): 100059. doi: 10.1016/j.animal.2020.100059.

Abstract: Stretching behavior is one of broiler comfort behaviors that could be used for animal welfare assessment. However, there is currently no methodology for automatic monitoring of stretching behavior under representative production practices. The objectives of this study were to (1) develop a faster region-based convolutional neural network (faster R-CNN) stretching behavior detector for broiler stretching behavior detection; (2) evaluate broiler stretching behaviors under stocking densities (SDs) of 27 (27SD), 29 (29SD), 33 (33SD), and 39 kg·m^{-2} (39SD) and at weeks 4 and 5 of bird age; and (3) examine the temporal and spatial distribution of broiler stretching behaviors. The results show that the precision, recall, specificity, and accuracy were over 86% on broiler stretching detection across all SDs and bird ages using the faster R-CNN stretching behavior detector. Broilers spent 230-533 sec stretching every day and showed more stretching behaviors under the 29SD, 33SD, and 39SD in week 4 and under the 29SD and 33SD in week 5, as compared to other SDs. They performed less stretching in a couple of hours after light ON and before light OFF but preferred to stretch in areas with less traffic and disturbance, i.e., along the fences and away from the inspection aisle. It is concluded that the stretching behavior detector had acceptable performance in detecting broiler stretching, thus being a useful tool for broiler stretching detection. Broiler stretching behavior is affected by stocking density and bird age and shows temporal and spatial variations.

Keyword: poultry, management practice, behavior, welfare, deep learning

7.1 Implications

Automated stretching behavior detection can be developed based on faster region-based convolutional neural network for accurate detection of broiler stretching behaviors. The label method comparison provides important insights into the detector development when processing speed is required for detection purposes. Broiler stretching behaviors under different stocking densities and bird ages could reflect bird comfort status with management strategies, thus having critical welfare and economic implications on broiler production.

7.2 Introduction

Stretching behavior is categorized as a comfort behavior for broilers (Pichova et al., 2016). When a bird stretches, it spreads one wing on one side of its body straight outwards and meanwhile extends its leg on the same side (Rentsch et al., 2019), which may benefit its joint and muscle health (Fraser and Broom, 1990). Schwean-Lardner et al. (2012) reported that lack of stretching could be a sign of compromised bird health. Previous research has investigated poultry stretching behaviors as affected by feed type (Pichova et al., 2016), photoperiod (Bayram and Özkan, 2010), and social hierarchy (Nicol, 1989). The effect of stocking density (SD) on broiler stretching behaviors has not been well studied yet may potentially provide valuable insights into SD management aiming for welfare improvement.

Stocking density can influence broiler productivity, well-being, and health (Sørensen et al., 2000; Dozier 3rd et al., 2005). Animal production associations typically recommend broiler SD in market weight per unit area (i.e., in $kg{\cdot}m^{-2}$) (National Chicken Council, 2017). There have been many studies which describe the effects of SD on poultry behaviors (Andrews et al., 1997; Buijs et al., 2009; Son, 2013). Andrews et al. (1997) investigated broiler behaviors under the SDs of 1.7 and 14 $kg{\cdot}m^{-2}$ and found broilers spent more time walking and sitting and less time dozing and sleeping under the lower SD. Buijs et al. (2009) evaluated the tonic immobility under eight SDs (6, 15, 23, 33, 35, 41, 47, and 56 kg·m^{-2} at 2.6 kg targeting market weight), and broilers showed more fearfulness at higher SDs. Son (2013) compared broiler behaviors within three levels of SDs (30-32 kg·m^{-2}, 36-38 kg·m^{-2}, and 42-44 kg·m^{-2} at 1.7 kg targeting market weight) and reported that the broilers under the highest SD performed more resting and standing and less locomotion. Although research has been conducted to investigate many broiler behaviors at various SDs, little research focused on broiler stretching behaviors.

The typical means by which to investigate poultry behaviors is manual observation which can obtain accurate behavioral information at small scales. However, stretching is a broiler behavior that is performed at a low frequency. For example, Nicol (1987) observed only five bouts of stretching behaviors in an hour for a group of 12 hens, and thus significant effort is required to manually monitor and record sufficient data for comparison. Automated methods may provide a means for efficient monitoring of low frequency behaviors, especially when large bird groups and long-term measurements are needed. Some automated technologies (e.g., image processing, accelerometer, etc.) have been utilized to detect broiler behaviors and provided reliable behavior information for farm management and system design (Decandia et al., 2018; Li et al., 2020b).

Convolutional neural networks have been widely used for object detections (Huang et al., 2017b). With a well-trained model, CNN may detect various objects from the source images or videos captured at different backgrounds and conditions. As a vision- and computer-based technology, application of CNN does not require any sensors to be attached to birds, which makes the CNN desirable for measurements at large laboratory and commercial scales. There are multiple CNN models varying in functions, architectures, and performance. Our previous research investigated three CNN models [i.e., single shot detector, region-based fully convolutional network, and faster region-based CNN (faster R-CNN)] for object detections in poultry; and we found that faster R-CNN had good accuracy and processing speed in processing poultry-related images (Li et al., 2020a). However, the possibility and performance of faster R-CNN for detecting broiler stretching behaviors remain unclear. Although mask R-CNN outperformed faster R-CNN with regards to accuracy due to more pixel information of objects of concern being retained using the Feature Pyramid Network and Regions of Interest Align (Ren et al., 2015), it had a much more massive architecture and resulted in a slower processing speed. Balancing the detection accuracy and processing speed, we decided to test the faster R-CNN in this case because it was an efficient network based on previous research.

The objectives of this study were to (1) develop a faster R-CNN stretching behavior detector to detect broiler stretching behaviors based on image data under four SDs and at two bird ages; (2) measure broiler stretching behaviors under the four SDs (27, 29, 33, and 39 $kg \cdot m^{-2}$, or "27SD", "29SD", "33SD", and "39SD", respectively) and two bird ages (weeks 4 and 5) using the stretching behavior detector; and (3) determine the temporal and spatial distribution of broiler stretching behaviors.

7.3 Materials and Methods

7.3.1 Housing, Animals, and Management

A total of 476 broilers (Ross×Ross 708) were obtained from a commercial hatchery and randomly distributed to eight pens with each adjusted to 3.2 m long and 1.4 m wide, resulting in a 4.4 m^2 pen area. The four SDs (27, 29, 33, and 39 $kg \cdot m^{-2}$), which are recommended by industry allies and welfare groups (Global Animal Partnership, 2017; National Chicken Council, 2017; European Commission, 2018), were randomly assigned to the eight pens for two replications per SD level. Based on 2-kg targeting market weight, bird numbers in each pen were 50 for 27SD, 54 for 29SD, 62 for 33SD, and 72 for 39SD. With the selected SDs, the feeder and drinker allowances in each pen were adjusted to 50-72 bird·feeder^{-1} and 11-12 bird·drinker^{-1} to reflect typical commercial practice. The room temperature, light program, and light intensity in weeks 4 and 5 were, respectively, 24 and 21 °C, 20L:4D and 16L:8D, and 10 and 5 lux (Table 7.1). Birds were provided with a commercial four-phase corn-soy diet (Dozier III et al., 2007), formulated to meet the requirement of National Research Council (1994). Feed and water were supplied *ad libitum*. All procedures in this experiment were approved by the USDA-ARS Institutional Animal Care and Use Committee at the Mississippi State location.

Table 7.1 Room temperature, light program, and light intensity at Weeks 4 and 5 of bird age

Weeks of bird age	Room temperature (℃)	Light program	Light intensity (Lux)
4	24	20L:4D	10
5	21	16L:8D	5

7.3.2 Data Acquisition

Eight night-vision network cameras (NHD-818, Swann Communications U.S.A Inc., Santa Fe Springs, USA) were installed at ~3.6 m above the pens to capture top-view videos. The camera contained an infrared cut filter and can record scenes during darkness. The top view was major concern since it can cover more details of stretching birds with less overlapping than other views. Broiler activity in each pen was continuously recorded and stored in a network video recorder (NVR-87400, Swann Communications U.S.A Inc., Santa Fe Springs, USA). The video files were captured with a resolution of 1280×720 pixels at a sample rate of 6 frames per sec (fps) and converted to images at the same rate using Free Video to JPG Converter (ver. 5.0). Converted images were cropped to 580×680 pixels, which cover only the concerned pen in each image. The initial points for the cropping were manually adjusted at different pixel locations, so that the whole pens of concern can be covered with the same size.

7.3.3 Stretching Behavior Definition

Based on the definitions by previous research (Table 7.2) and our observation (Figure 7.1), a bird extends both wing and leg or only a leg when stretching. As leg stretching is the inevitable process for bird stretching, it was used as the feature to detect stretching birds in this study. A stretching bird in weeks 4 and 5 is represented by 2750 to 3998 pixels in the images, translating to 270-393 cm^2 coverage area with a converting factor of 10.2 $pixel \cdot cm^{-2}$. Theoretically, the experimental pen space (4.4 m^2) is sufficient for 72 birds to stretch simultaneously.

Table 7.2 Stretching behavior definition in previous research

Author (year)	Definition
Nicol (1987)	Stretching both wing and leg.
Bokkers and Koene (2003)	Stretching of wing and/or leg.
Kristensen et al. (2007)	Extending one wing and one leg at the same side of the body.
Pichova et al. (2016)	Stretching one leg often together with the wing of the same side, but also may be stretched alone while sitting or standing.
Rentsch et al. (2019)	The hen spreads a wing on one side of its body straight outwards and at the same time extends the leg on the same side.

The species under this study is Ross×Ross 708 broiler.

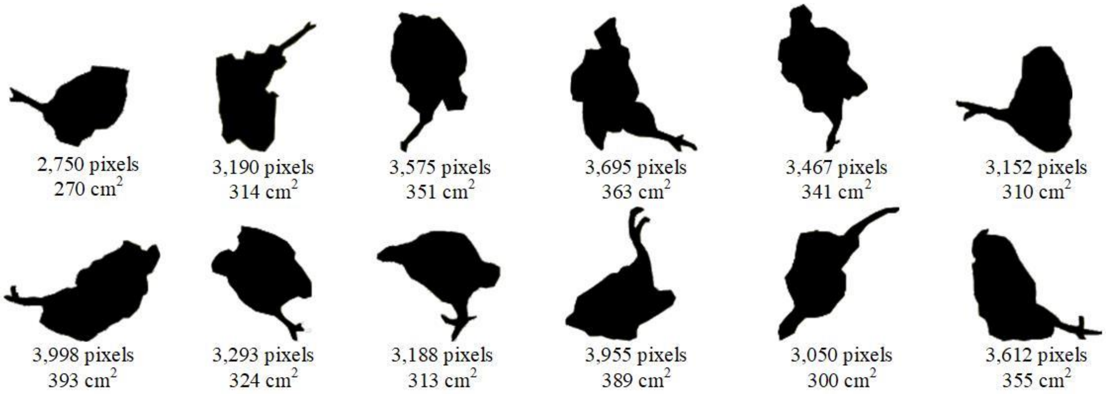

Figure 7.1 Sample binary images of stretching broilers in weeks 4 and 5

The broiler pixel and actual area are provided for each scenario. Actual area is calculated from broiler pixel using a conversion factor of 10.2 pixel·cm^{-2}.

7.3.4 Network Description

The stretching behavior detector was developed based on a region-based network, faster R-CNN with the Resnet101 feature extractor. Unlike its predecessors (R-CNN and fast R-CNN), the faster R-CNN avoids using selective search to find region proposals, which improves the processing speed (Ren et al., 2015).

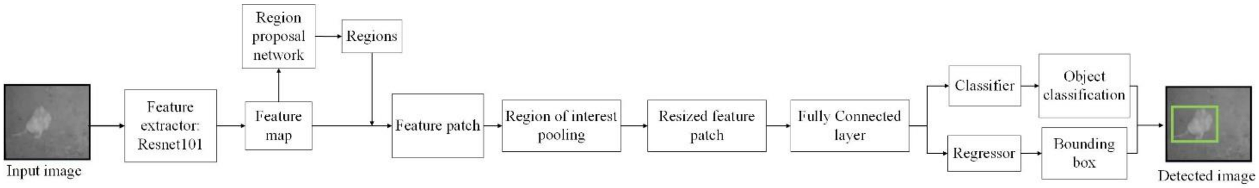

Figure 7.2 The flowchart of the faster R-CNN stretching behavior detector

Faster R-CNN is faster region-based convolutional neural network. The detector labels the stretching bird in a green bounding box.

The network consists of a region proposal network (RPN) generating region proposals and a network using these proposals for classifying objects of concern and creating bounding boxes. The feature extractor is the 101-layer-deep residual network, and the resultant residuals among layers can skip the following layers and be directly transferred to another layer, which can optimize detection performance of the deep network. As shown in Figure 7.2, the input image passes through the Resnet101 feature extractor, and the feature map is generated accordingly, which is then fed into the RPN. Within the RPN, different sizes of anchors with specific scales and aspect ratios are used to output a set of default regions, which are tiled onto the feature map to crop a series of small feature patches. A region of interest (RoI) pooling layer is used to wrap these patches into fixed sizes. Finally, the resized feature patches are input into a set of fully connected layers and predict object scores and bounding boxes. With non-maximum suppression rule, the box with the highest score within the same position is retained for the detected object (enclosed with a green bounding box in Figure 7.2).

7.3.5 General Workflow of Detector Training, Validation, and Testing

As the faster R-CNN detector is a region-based network, the processing speed and detection accuracy may be affected by the size of proposed regions (Huang et al., 2017b). Therefore, two label methods (labeling the whole body of stretching bird, ‘labeling body’ vs. labeling the leg of stretching bird, ‘labeling leg’) were compared based on different performance metrics to determine the better label method. Then the stretching behavior detector was developed using the better label method.

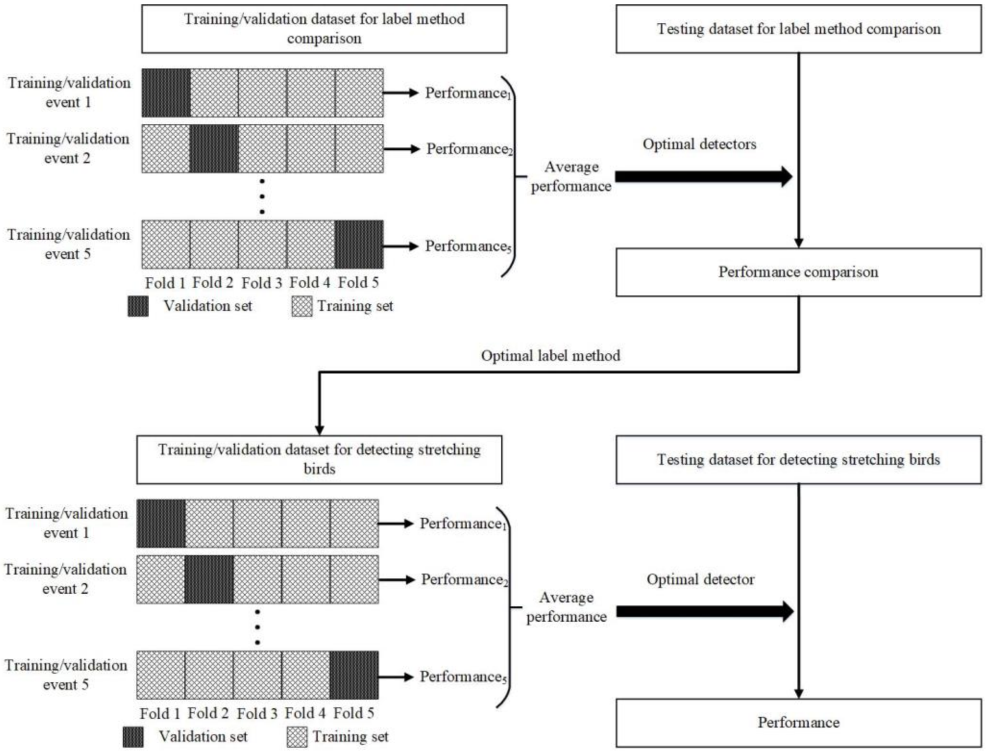

Figure 7.3 Illustration of the training, validation, and testing process

Performance includes precision, recall, specificity, accuracy, and processing speed.

Two sets of dataset were used to train, validate, and test the detector separately, one for two label method comparison and the other for the stretching behavior detector development using the better label method. A five-fold cross validation strategy was used to evaluate the detector (Figure 7.3) (Li et al., 2020a).

7.3.6 Data Labeling and Data Distribution for Training, Validation and Testing

The technician labeled the stretching birds in images and checked the manually labeled images carefully to ensure that every stretching bird can be labeled correctly. The same 1000 images, which were randomly selected from the four SDs and two bird ages, were labeled using both methods. Based on the five-fold cross-validation rule, 800 images were used for training/validation, out of which 640 images were for training and 160 images for validation during each training/validation event. The remaining 200 images were used for testing. A total of 1200 images under each SD and at each bird age were subsequently labeled with the better label method for the stretching behavior detector development, resulting in totally 9600 images for the four SDs and two bird ages. Based on the rule, 7680 images were used for training/validation, out of which 6144 images were for training and 1536 images for validation during each training/validation event. The rest 1920 images were used for testing.

7.3.7 Detector Training

The detector was developed based on a faster R-CNN model (model version: faster_rcnn_resnet101_coco_2018_01_28) in the open source framework of Google TensorFlow Object Detection Application Programming Interface. This model was pre-trained using Common Objects in Context (COCO) dataset (Huang et al., 2017a) and ready for modification into detectors for other objects. The computer system used for detector training, validation, and testing was equipped with a 32 GB RAM, an Intel® Core™ i7-8700K processor, and a NVIDIA GeForce GTX 1080 GPU card. We used the default training configuration provided by Google TensorFlow (Huang et al., 2017a), and configuration details can be found in Table 7.3. The network was trained with 200000 iterations, at which the training loss approximately reached minimal and stayed stable. The trained detector was saved as inference graph, in which the weights and activation function at different nodes were frozen, and output as .pb file for testing.

Table 7.3 Key training configuration for the faster region-based convolutional neural network with Resnet101 feature extractor

Trained configuration parameter		Value
Keep_aspect_ratio_resizer	Min_dimension	600
	Max_dimension	1024
First_stage_feature_stride		16
First_stage_anchor_generator	Scales	[0.25, 0.5, 1.0, 2.0]
	Aspect_ratios	[0.5, 1.0, 2.0]
	Height_stride	16
	Width_stride	16
First_stage_box_predictor_conv_hyperparams	Regularizer	12
	Truncated_normal_initializer: stddev	0.01
First_stage_nms_score_threshold		0.0
First_stage_nms_iou_threshold		0.5
First_stage_max_proposals		300
First_stage_localization_loss_weight		2.0
First_stage_objectness_loss_weight		1.0
Initial_crop_size		14
Maxpool_kernel_size		2
Maxpool_stride		2
Second_stage_box_predictor	Dropout_keep_probability	1.0
	Variance_scaling_initializer	1.0
Second_stage_post_processing	Iou_threshold	0.5
	Max_detections_per_class	100
	Max_total_detections	300
	Score_converter	SOFTMAX
Second_stage_localization_loss_weight		2.0
Second_stage_classification_loss_weight		1.0
Train_config	Batch_size	1
	Initial_learning_rate_at_step 100000	0.0003
	Learning_rate_at_step 100000	0.00003
	Learning_rate_at_step 300000	0.000003
	Momentum_optimizer_value	0.9
	Gradient_clipping_by_norm	10.0

7.3.8 Detector Evaluation and Performance Metrics

The intersection over union (*IoU*) to determine whether the stretching birds and their locations were correctly determined by the stretching behavior detector was calculated via Equation 7.1, with the threshold value greater than 0.5 being true positive (*TP*).

$$IoU = \frac{Area\ of\ ground\ truth\ box\ \cap\ Area\ of\ detected\ box}{Area\ of\ ground\ truth\ box\ \cup\ Area\ of\ detected\ box} \tag{7.1}$$

$$Precision[\%] = \frac{TP}{(TP + FP)} \times 100 \tag{7.2}$$

$$Recall[\%] = \frac{TP}{(TP + FN)} \times 100 \tag{7.3}$$

$$Specificity[\%] = \frac{TN}{(TN + FP)} \times 100 \tag{7.4}$$

$$Accuracy[\%] = \frac{(TP + TN)}{(TP + FP + TN + FN)} \times 100 \tag{7.5}$$

where *TP* is true positive; *FP* is false positive; *FN* is false negative; and *TN* is true negative.

Precision, recall (sensitivity), specificity, and accuracy for detecting each stretching bird in the images were calculated using Equations 7.2-7.5. Precision is the percentage of true stretching cases in all stretching behavior cases detected by a detector. Recall (a.k.a., sensitivity) is the percentage of the true stretching cases detected by a detector in all true stretching cases. Specificity is the percentage of true non-stretching cases detected by a detector in all true non-stretching cases. Accuracy is the percentage of stretching and non-stretching cases correctly detected by a detector in all cases. For all four metrics, a higher value reflects a better performance of the detector (Li et al., 2020a).

Processing speed was examined for the two labeling method comparison in each validation event and testing set. The processing time (ms) reported by Python 3.6 was firstly obtained via processing 160/200 images, and then the processing speed (ms·image^{-1}) was calculated.

7.3.9 Automated Measurement of Stretching Behavior

Broiler stretching behaviors were continuously monitored using the trained faster R-CNN stretching behavior detector under the four SDs and two bird age. The stretching birds were determined only from single images. The first four days of each week were considered as acclimation periods, and thus only data from the last three days of each week were used for the behavioral analysis. The location of the detected bounding box center in an image was determined using the coordinates of its two diagonal corners. When the change of box centers in two consecutive images fell short of a threshold, the enclosed stretching bird was treated as the same one. In this study, the threshold was set to 10 pixels, which can achieve a 98% accuracy for tracking the individual stretching birds. Data were summarized into daily/hourly mean stretching time (DST: $\text{min}\cdot\text{bird}^{-1}\cdot\text{d}^{-1}$; HST: $\text{min}\cdot\text{bird}^{-1}\cdot\text{h}^{-1}$), daily/hourly mean stretching bout (DSB: $\text{bouts}\cdot\text{bird}^{-1}\cdot\text{d}^{-1}$; HSB: $\text{bouts}\cdot\text{bird}^{-1}\cdot\text{h}^{-1}$), and stretching duration per bout (SDB), and hourly maximum number of simultaneously stretching birds. Spatial location of stretching birds was plotted in heat maps. To construct a heat map, a mesh grid was firstly constructed onto each pen map based on the dimension of the pen, in which the gird size was set to 10 pixels. Then a Standard Gaussian Kernel Density Estimation Function was run for the center of each grid area in the map, and the stretching frequency in each grid area was calculated by Equation 7.6. Finally, the density map was visualized using Matplotlib, an open-source visualization tool.

$$P = \sum_{i=1}^{n} \frac{1}{\sqrt{2\pi}} e^{-d_i^2/2} \tag{7.6}$$

where P is the probability in Standard Gaussian Distribution curve; n is the total number of grids in the entire image; and d_i is the pixel-representing distance between the grid center and i^{th} detected stretching bird center.

7.3.10 Statistical Analysis

The effects of SD, bird age, and their interaction on the behavioral responses (DST, DSB, and SDB) were analyzed with ANOVA using PROC MIXED model in Statistical Analysis Software (SAS 9.3, SAS Institute Inc.). Least square mean comparisons of the behavioral responses were conducted using Fisher's least significant difference. The effects were significant when P-value was less than 0.05. The model is defined as

$$Y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijk} \tag{7.7}$$

where Y_{ijk} is the measured behavioral responses during the test; μ is the least square mean of the behavioral responses; α_i is the main effect of SD, i = 27, 29, 33, and 39 kg·m^{-2}; β_j is the main effect of bird age, j = weeks 4 and 5; $(\alpha\beta)_{ij}$ is the interaction effect of SD and bird age; and ε_{ijk} is the random error for the model.

7.4 Results

7.4.1 Performance of the Stretching Behavior Detector with the Two Label Methods

Performance of the faster R-CNN stretching behavior detector with labeling body and labeling leg methods can be found in Table 7.4. With 160 images during each of the five validation events, precision, recall, specificity, and accuracy were mostly over 92.0% for labeling body, while they were over 91.7% for labeling leg. Labelling leg method was 5.3 ms faster for processing one image than labeling body method. With 200 testing images, the evaluation metrics were over 85.7% for labeling method, while they were over 88.3% for labeling leg. The processing speed of labeling leg method was 2.7 ms·image^{-1} lower than that of labeling body method. Overall, the precision, recall, specificity, and accuracy of labeling leg were similar to or slightly better than those of labeling body, while the detector detected the stretching behavior faster with the former labeling method, thus the former being selected as labeling method in this case.

Table 7.4 Performance (mean±sd) of the faster R-CNN behavior detector with labeling body vs. labeling leg

	Performance metric	Labeling body	Labeling leg
Validation	Precision (%)	92.0±2.1	91.7±4.7
	Recall (%)	95.3±3.2	94.1±3.5
	Specificity (%)	99.5±0.1	99.7±0.1
	Accuracy (%)	99.4±0.1	99.6±0.1
	Processing speed (ms·image^{-1})	171.9±8.3	166.6±7.6
Testing	Precision (%)	85.7	88.3
	Recall (%)	87.1	89.8
	Specificity (%)	99.7	99.8
	Accuracy (%)	99.4	99.6
	Processing speed (ms·image^{-1})	169.5	164.8

The validation performance was calculated using 160 images during each of the five validation events, and the testing performance was calculated using 200 images, which was unrelated to training/validation.

7.4.2 Performance of the Stretching Behavior Detector under the Four Stocking Densities and Two Bird Ages

With the labeling-leg method, performance of the faster R-CNN stretching behavior detector under the four stocking densities and two bird ages can be found in Table 7.5. With the 1536 images during each of the five validation events, precision was over 92%, recall was over 94%, specificity was over 99%, and accuracy was over 99% for all SDs and bird ages. The overall precision, recall, specificity and accuracy (%) were 93.2±1.7, 94.5±1.4, 99.7±0.1, and 99.6±0.1, respectively. With the 1920 testing images, precision was over 86%, recall was over 88%, specificity was over 99%, and accuracy was over 99% for all SDs and bird ages. The overall precision, recall, specificity, and accuracy (%) was 88.9, 90.4, 99.7, and 99.5. In sum, the performance of the stretching behavior detector was over 86% for precision and recall, and over 99% for specificity and accuracy. Figure 7.4 shows an example of 1000-sec continuous monitoring of stretching behavior. In addition, the behavior detector successfully tracked individual stretching broilers over time.

Table 7.5 Performance (mean±sd) of the faster R-CNN behavior detector under the four stocking densities and two bird ages.

Performance metric (%)		27SD		29SD		33SD		39SD		Overall
		W4	W5	W4	W5	W4	W5	W4	W5	
Validation	Precision	91.9±1.5	94.3±1.2	95.0±1.3	95.3±0.7	94.1±0.6	93.8±0.6	91.7±0.8	91.6±1.1	93.2±1.7
	Recall	95.8±2.2	94.9±1.7	93.9±0.6	94.6±0.9	93.9±1.4	94.3±1.4	94.2±1.1	94.7±1.5	94.5±1.4
	Specificity	99.7±0.1	99.7±0.1	99.6±0.1	99.7±0.1	99.8±0.1	99.7±0.1	99.7±0.1	99.7±0.1	99.7±0.1
	Accuracy	99.6±0.1	99.6±0.1	99.5±0.1	99.5±0.1	99.7±0.1	99.5±0.1	99.6±0.1	99.6±0.1	99.6±0.1
Testing	Precision	88.3	88.1	90.9	88.8	90.6	86.3	88.2	89.5	88.9
	Recall	89.8	90.8	91.9	92.2	92.0	87.7	88.4	90.2	90.4
	Specificity	99.7	99.7	99.7	99.7	99.8	99.7	99.7	99.7	99.7
	Accuracy	99.4	99.4	99.5	99.4	99.7	99.5	99.5	99.5	99.5

27SD=stocking density of 27 kg·m^{-2}; 29SD=stocking density of 29 kg·m^{-2}; 33SD=stocking density of 33 kg·m^{-2}; 39SD=stocking density of 39 kg·m^{-2}; W4=week 4; and W5=week 5. The validation performance was calculated using 1536 images during each of the five validation events, and the testing performance was calculated using 1920 images, which was unrelated to training/validation.

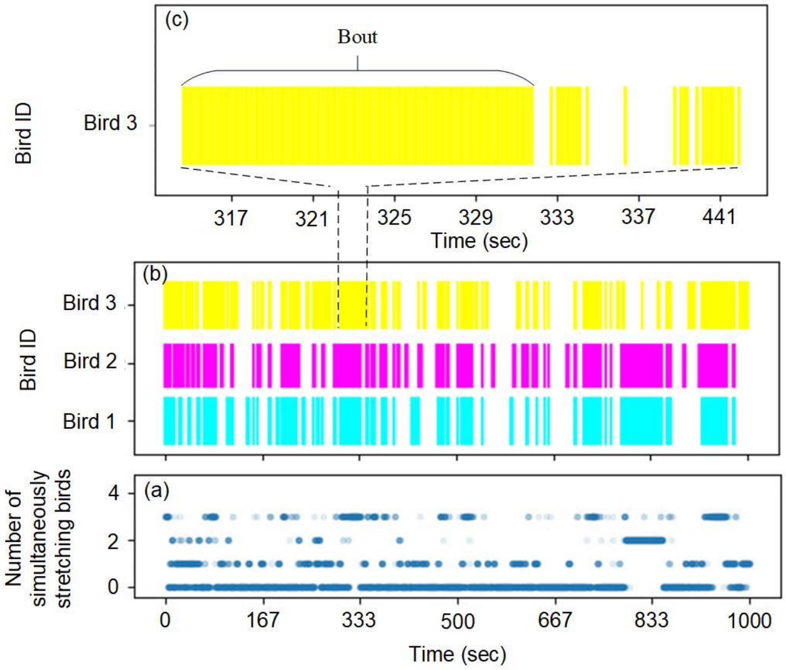

Figure 7.4 Performance for the stretching behavior detector s

(a): Scatter plot of the number of simultaneously stretching birds over 1000 sec. (b) Raster plot of three individual stretching birds over the same 1000 sec. Each vertical raster represents a bird is stretching at that moment. (c) The zoom-in view of a group of vertical raster.

7.4.3 Daily Behavioral Responses under the Four Stocking Densities and Two Ages

Table 7.6 shows daily stretching behaviors of the broilers. A broiler stretched for 230-533 sec per day, 257-640 bouts per day, and 0.84-1.02 sec per bout. Broiler stretching behaviors were affected by SD and age interactively. In general, longer DST and more DSB were found under medium and high SDs (29SD, 33SD, and 39SD) in week 4, and under medium SDs (29SD and 33SD) in week 5. As for the age effect, broilers tended to stretch more often in week 4 than week 5. But the stretching duration was shorter for younger broilers (0.87±0.01 sec·bout^{-1} in week 4 vs. 0.95±0.01 sec·bout^{-1} in week 5).

Table 7.6 The least square mean of stretching behavioral responses under the stocking densities and in ages

Treatment	DST ($sec \cdot bird^{-1} \cdot day^{-1}$)	DSB ($bout \cdot bird^{-1} \cdot day^{-1}$)	SDB ($sec \cdot bout^{-1}$)
Stocking density (SD)			
27SD	371^b	386^b	0.96^a
29SD	511^a	578^a	0.89^b
33SD	496^a	554^a	0.90^b
39SD	335^b	380^b	0.88^b
SEM[1]	13	10	0.01
Age			
Week 4	438	508^a	0.87^b
Week 5	418	441^b	0.95^a
SEM[2]	9	7	0.01
Interaction			
27SD-Week 4	316^d	352^e	0.90^{cd}
29SD-Week 4	533^a	640^a	0.84^e
33SD-Week 4	466^{bc}	537^{bc}	0.88^{cde}
39SD-Week 4	439^{bc}	504^c	0.87^{de}
27SD-Week 5	427^c	420^d	1.02^a
29SD-Week 5	488^{ab}	517^c	0.94^b
33SD-Week 5	526^a	571^b	0.92^{bc}
39SD-Week 5	230^e	257^f	0.89^{cd}
SEM[2]	18	14	0.01
P-value			
SD	<0.01	<0.01	<0.01
Bird age	0.14	<0.01	<0.01
SD × Bird age	<0.01	<0.01	0.02

DST=daily stretching time; DSB=daily stretching bout; SDB=stretching duration per bout; 27SD=stocking density of 27 $kg \cdot m^{-2}$; 29SD=stocking density of 29 $kg \cdot m^{-2}$; 33SD=stocking density of 33 $kg \cdot m^{-2}$; 39SD=stocking density of 39 $kg \cdot m^{-2}$; W4=week 4; and W5=week 5.

[1] Standard error for stocking density effect (*n*=12).

[2] Standard error for age effect (*n*=24).

[3] Standard error for interaction effect (*n*=12).

[a,b,c,d,e] Values within the same column that lack of a common superscript differ significantly ($P \leq 0.05$).

7.4.4 Hourly Behavioral Response

Figure 7.5 shows the hourly stretching time, hourly stretching bout, and maximum number of simultaneously stretching birds under four SDs and two weeks. On average, broilers stretched for 24±10 sec and 25±11 bouts within each hour. The patterns of the hourly stretching time and bout were different between weeks and among SDs (Figure 7.5). The hourly stretching time and bout dropped sharply after gradually peaked at 10:00 in week 4, especially for the low and medium SDs (27SD, 29SD, and 33SD); however, the drops in week 5 seemed to be less steep. Both stretching time and bout were lower for the high SD (39SD) in week 5. Generally, maximal 2-6 broilers were stretching simultaneously, except for the 1:00 of the week 4 when 6-11 broilers stretched simultaneously in the hour immediately after the lights were turned on.

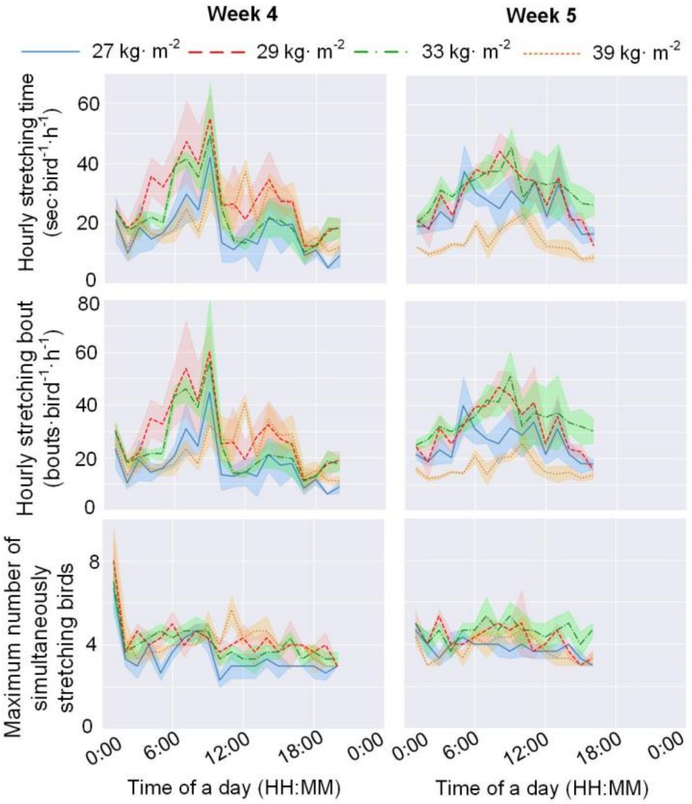

Figure 7.5 Hourly stretching time, hourly stretching bout, and maximum number of simultaneously stretching birds under the stocking densities and in bird ages

In week 4, the lights were turned on at 1:00 and off at 20:00; while in week 5, the lights were turned on at 1:00 and off at 16:00.

7.4.5 Spatial Distribution of Stretching Birds

Figure 7.6 shows the spatial distribution of stretching birds under four SDs and two weeks. In the heat maps, the cool color represents the low frequency of stretching, and the warm color means the high frequency. Across all of the SDs and bird ages, broiler stretched more often along left fences of the pens and near drinking area, but stretched less frequently along the top and right fences of the pens and near eating area.

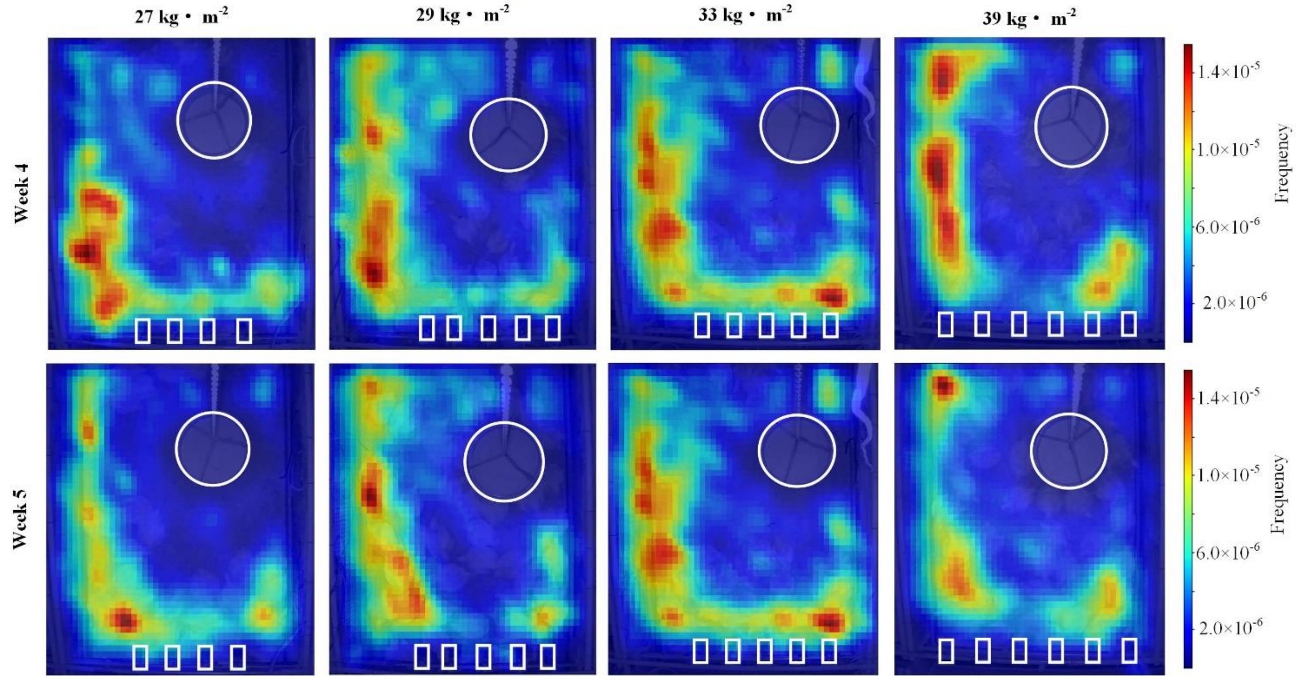

Figure 7.6 Heat maps for the location of stretching birds

The feeder and drinkers in each map are marked as a white circle and white rectangles, respectively.

7.5 Discussion

7.5.1 Stretching Behavior Detector Performance on Broiler Stretching Detection

Proper labeling methods are important to develop an accurate region-based network detector. Compared to the whole-body labeling method, the leg labeling method performed similarly well in stretching behavior detection but required smaller-region proposals, which reduced processing speed of the detector from 0.170 to 0.165 sec image^{-1} (based on testing dataset). Although the 0.05 sec improvement was minor for processing one image, but it could be significant with regards to processing thousands/millions of images. Similar strategies, i.e., reducing labeling area, may be considered when fast processing speed is primary concern of a region-based network (e.g., faster R-CNN, R-FCN, etc.) detector (Huang et al., 2017b).

The faster R-CNN stretching behavior detector had similar performance across the four SDs and two ages. Our previous experiment reported that a well-trained faster R-CNN detector was not profoundly affected by the number and size of detected objects (Li et al., 2020c), which helps to explain the stretching behavior detector having similar performance on detecting different numbers and sizes of stretching birds under the four SDs and two ages. The previous experiment also reported that the detector was affected by the light intensities (>1 lux) neither, which may be the reason for the similar performance between the two light intensities among the two ages (10 lux for week 4 and 5 lux for week 5). Overall, the detector performance was comparable to that of Li et al. (2020a), in which the sensitivity (a.k.a., recall), specificity, and accuracy was over 87% for detecting broiler drinking behavior. Therefore, the faster R-CNN behavior detector should be an appropriate tool to detect stretching behaviors in all SDs and weeks.

7.5.2 Daily Stretching Behavioral Responses under the Four Stocking Densities and Two Ages

The interaction effects of SD and age were observed for all stretching behavioral responses, which means that the stretching behavioral responses of broilers under different SDs performed differently at different ages. Son (2013) reported that the pecking, resting, locomotion, and standing behaviors of broilers under the three ranges of SDs (i.e., 30-32, 36-38, and 42-44 kg·m^{-}

^{2}) were different from weeks 2 to 5 of bird age. Due to little previous research related to the interaction effects of SD and bird age on broiler stretching behaviors, the mechanism of the interaction is not fully understood.

The SDs tested in this study were selected based on recommendations by industry trade associations and animal welfare groups. It was found that broilers tended to stretch more under medium SDs (29 and 33 kg·m^{-2}). Broilers are social animal, they may not be socially attracted for stretching under a lower SD (27 kg·m^{-2} in this case) (Febrer et al., 2006). Under a higher SD (39 kg·m^{-2} in this case), broilers may be disturbed more frequently by other birds, thus reducing stretching behaviors (Buijs et al., 2011). Birds under the lower SDs (27 kg·m^{-2}) could enjoy longer stretching per bout probably because of less bird disturbance. Balancing the social attraction and social disturbance, the SDs of 29-33 kg·m^{-2} may be suitable for bird comfort behavior expression.

The bird age influenced stretching behavioral responses differently. Bayram and Özkan (2010) reported that older broilers reduced their stretching and attributed the decrease to less space when the broilers grew up, which can help to explain that the DST were numerically decreased from the weeks 4 to 5. As broilers got older, they also became less active (Andrews et al., 1997). That may be the reason that the broilers stretched for less bouts but for longer time per bout in week 5. It should be noted that light program and light intensity were 20L:4D and 10 lux in week 4 but 16L:8D and 5 lux in week 5. Bayram and Özkan (2010) found that the lighting conditions had effects on broiler stretching behaviors. As the effect of bird age could be confounded by light program and light intensity, more experiments are recommended to verify the age effect.

7.5.3 Hourly Stretching Behavioral Responses

Broiler hourly stretching behaviors varied in time and at different SDs and bird ages. The lowest frequency of stretching behavior appeared in a couple of hours after light ON and before light OFF. Based on previous validation (Li et al., 2020b), broilers in these two periods tent to spend time in feeding, drinking, and looking for resting area (before dark) therefore reducing stretching time. Human activity could also disturb poultry behavior expression (Appleby, 1986). Human activity (e.g., collecting feed and pen weight, changing diet type, collecting blood samples, changing lighting conditions, etc.) happed more frequently in week 4 than in week 5, which could be the reason for the steep decrease of broiler stretching behavior at 9:00-10:00 in week 4. As broilers got older, they may require larger space to stretch while free space became smaller. Some subordinate birds may wait for space to stretch until dominant broilers finished stretching (Shimmura et al., 2008), which may be the reason for the even distribution of number of simultaneously stretching birds in week 5. Because peak hours of broiler stretching may reflect maximal need of space, evaluation of space allowance should focus on these periods.

7.5.4 Distribution of Stretching Broilers

In general, broilers performed more stretching behaviors in areas with less traffic, e.g., along the fences, away from feeders and inspection aisles. Li et al. (2020b) reported that most traffic in pens occurred around the feeders and drinkers. Broilers avoid stretching along the outermost fences of the pens, which served as entry points for human traffic. Therefore, human disturbance appeared frequently around those areas where birds avoided stretching. Interestingly, broilers preferred to stretch around drinking area, which was also the heavy traffic area. The drinking line was placed away from the inspection aisle. Human disturbance seemed to have greater impact than bird disturbance on spatial stretching choices. It should be noted that our experimental pens are considerably different from commercial broiler houses. More research is recommended to consolidate such findings in commercial farms.

7.6 Conclusions

A faster R-CNN stretching behavior detector was developed to detect broiler stretching behaviors. With the stretching behavior detector, stretching behaviors were continuously monitored and analyzed under the SDs of 27 (27SD), 29 (29SD), 33 (33SD), and 39 kg·m^{-2} (39SD) and in weeks 4 and 5 of bird age. As compared to whole-body labeling method, the detector developed based on leg labeling method had similar precision, recall, specificity, and accuracy on stretching detection, but had 3% faster processing speed. The behavior detector had over 86% performance across all SDs and bird ages. Broiler stretching behaviors were affected by the SD, bird age, time of a day, and location of the pens. Specially, broiler stretched more often under the SD of 29, 33, and 39 kg·m-2 in week 4 and SD of 29 and 33 kg·m^{-2} in week 5. They spent more time stretching around 10:00, and 6-11 broilers stretched simultaneously after the light was turned on in week 4. Broilers preferred to stretch along left fence of the pens with less bird disturbance and around the drinking areas with less human disturbance.

7.7 Declaration of Interest

The authors confirm that there are no known conflictions of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

7.8 Ethics Approval

All procedures were approved by the USDA-ARS Institutional Animal Care and Use Committee at Mississippi State.

7.9 Data and Model Availability Statement

None of the data and models were deposited in an official repository.

7.10 Author Contributions

Guoming Li: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Visualization, Supervision, Project administration. Yang Zhao: Writing - Review & Editing, Funding acquisition. Zach Porter: Methodology, Validation, Investigation. Joseph L. Purswell: Writing - Review & Editing, Funding acquisition.

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CHAPTER VIII

DEEP LEARNING TECHNOLOGY: BROILER RESTRICTED FEEDING BEHAVIOR DETECTION

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Li, G., Hui, X., Chen, Z., Chesser, G. D. Jr, and Zhao, Y. (2020). Development and evaluation of a method to detect broilers continuously walking around feeder as an indication of restricted feeding behaviors. Computers and Electronics in Agriculture, 181: 105982. doi: 10.1016/j.compag.2020.105982.

Abstract: Broilers attempting to, but being restricted to, access feed due to competition and/or lack of feeding space may continuously walk around feeder for extended periods of time, which is an indication of restricted feeding behavior. The objectives of this study were to 1) verify the walking duration of the restricted feeding birds and birds without restricted feeding; 2) develop and evaluate computer vision algorithms with machine/deep learning models to track broilers continuously walking around feeder; and 3) analyze different behavior responses related to restricted feeding under four stocking densities, or "SD", such as frequency of number of birds simultaneously eating when birds continuously walking around feeder, daily number of continuously walking around feeder, and spatial distributions of birds continuously walking around feeder and corresponding eating birds. The algorithms included a faster region-based convolutional neural network object detector, a bird tracker, and a support vector machine behavior classifier. The results show that the restricted feeding birds continuously walked around feeder for >2 sect, which took up 64.8-76.4% of the observation cases. The object detector had over 92% precision, recall, and F1 score for detecting feeder, eating birds, and birds around feeder. The lowest error rate of tracking individual birds around feeder was 3.2% with appropriate parameter tuning. The behavior classifier achieved over 92% performance for classifying walking birds. Then the threshold (>2 sec) of walking duration was set to differentiate birds continuously walking around feeder. The cases of 8-10 birds eating simultaneously were most likely to trigger events of birds continuously walking around feeder. Lowering SDs reduced the daily number of continuously walking around feeder ($P<0.01$). The birds were more likely to walk around the feeding area where birds preferred to eat. In summary, the developed algorithms can automatically analyze restricted feeding behaviors of broilers and assist in precision poultry management.

Keyword: poultry, restricted feeding behavior, deep learning, computer vision, tracking

8.1 Introduction

In modern intensive broiler production, access of birds to feeding resources such as amount of food and feeding space is sometimes restricted due to blockage by other birds in a high stocking density, leading to stress and frustration of birds (De Jong et al., 2002; Carbonaro et al., 1992). These are signs of poor bird welfare and should be reduced for welfare-oriented broiler production. Birds restricted to feeding resources may perform displacement behaviors (e.g., ground pecking, sitting, wing flapping, preening, etc.) or aggressive behaviors (e.g., pecking other birds, climbing up eating birds, competing feeding space, etc.)(Duncan and Wood-Gush, 1971, 1972). They also continuously walked around feeder for extended periods of time and attempted access to the resource (Li et al., 2020c). Therefore, the birds continuously walking around feeder were used to indicate restricted feeding birds around feeder and major concern in this study. Forkman et al. (2000) demonstrated that birds spent more time walking with thwarting access to food and water. Birds restricted to feeding resources could suffer from hunger and frustration (De Jong et al., 2005), therefore, they may continuously walk to explore available resources and displace their frustration (Forkman et al., 2000). But the walking duration of these restricted feeding birds remains to be verified.

Appropriate evaluation tools are important for animal behavior analysis, as they serve to reduce labor and time and aid in collecting sufficient data for some rarely-performed behaviors. Currently, there are a wide range of precision agriculture tools being applied in animal farming. Automatically detecting the restricted feeding birds that continuously walk around feeder could be intricate. As a result, the tools should be strategically selected and evaluated. Firstly, the behaviors of interest were expected to extract with minimal human/equipment interference. Computer vision is a non-invasive technology, thus being selected to capture bird behaviors at/around feeder (Leroy et al., 2006). Secondly, feeder, birds at feeder, and birds around feeder are of primary interest due to reflections of restricted feeding behaviors. As faster region-based convolutional neural network (faster R-CNN), a deep learning technique, has been successfully used to detected poultry behaviors (Li et al., 2020a), it should have potential to detect the objects of concern in this study. Modern CNNs detect objects along with bounding boxes. The centroid coordinates of the bounding boxes can be used to track individual objects between adjacent frames (Rosebrock, 2018). The tracking algorithm may assist continuously tracking individual birds around feeder which involved the restricted feeding birds. Once individual birds are continuously tracked, the geometric features (e.g., changes of moving distances between adjacent frames, angle changes between adjacent frames, etc.) of those birds can be fed into a classifier to classify bird behaviors (Hong et al., 2015). Among different classifiers, support vector machine (SVM) is a popular machine learning algorithm and was used to accurately classify heathy and sick broilers based on extracted posture features (Zhuang et al., 2018), therefore, it may help to classify bird behaviors (e.g., walking, sitting, etc.) of concern. Per observation, the restricted feeding birds continuously walked around feeder for a relatively long period while the birds without restricted feeding walked in a short term. Therefore, the birds continuously walking around feeder may be differentiated with a verified walking duration. The above-mentioned are valuable components to detect and track the restricted feeding birds but need to be developed in this study.

Some management practices have been introduced to reduce poultry restricted feeding behaviors, such as increasing frequency of food provision for broiler breeders (De Jong et al., 2005), loosening constraints of eating for broiler breeders in a restricted feeding schedule (De Jong et al., 2002), increasing feeder space for laying hens (Sirovnik et al., 2018), and so forth. Additionally, reducing stocking density (SD) could be another alternative. Based on our previous study (Li et al., 2020b), reducing SDs is beneficial for broilers expressing behaviors, such as feeding, drinking, and stretching, and these are positive indicators of improved bird welfare. Therefore, this management strategy may potentially diminish the restricted feeding behaviors as well but remains to be determined.

Different behavior responses could help to interpret restricted feeding behaviors. Number of birds eating simultaneously at one feeder reflects situations of crowdedness at the feeder (Oliveira et al., 2019). Understanding how many of these birds can trigger a restricted feeding event may provide insights into feeder design. Performance of daily number of continuously walking around feeder under treatments could reflect which treatments are better for reducing the restricted feeding behaviors. Our previous research also showed broilers having preference to eat in different feeding sections of one feeder (Li et al., 2020c). Broilers attempting to eat may be more likely to be restricted near the feeding area where birds prefer to eat. However, the spatial relationship between the birds continuously walking around feeder and eating birds remains to be explored. These are important responses for evaluating restricted feeding behaviors but have not been investigated under different SDs.

The objectives of this study were to 1) verify the walking duration of the restricted feeding birds and birds without restricted feeding; 2) develop and evaluate computer vision algorithms with machine/deep learning models to track the birds continuously walking around feeder; and 3) analyze the abovementioned behavior responses of broilers under four SDs (27, 29, 33, and 39 $kg \cdot m^{-2}$, or “27SD”, “29SD”, “33SD”, and “39SD”, respectively), which are recommended by industry allies and welfare groups (European Commission, 2018; National Chicken Council, 2017; Global Animal Partnership, 2017).

8.2 Materials and Methods

8.2.1 Housing, Animals, and Management

The experiment was conducted in USDA-ARS poultry research unit at Mississippi State. A total of 476 broilers (Ross×Ross 708, male) were obtained from a commercial hatchery and randomly distributed to eight pens with each measuring 3.2 m long and 1.4 m wide (4.4 m^2 pen area). The behaviors were measured when broilers were in 4 weeks of age, which was also the transition period from grower diet to finisher diet. The eight pens were randomly assigned with one of the four SDs (27, 29, 33, and 39 $kg\cdot m^{-2}$). Each pen was equipped with one tube feeder. The tube feeder was 40 cm in diameter with 14 10.4-cm-wide feeder slots. Based on the 2-kg targeted market weight, bird number in each pen was set to 50 for 27SD, 54 for 29SD, 62 for 33SD, and 72 for 39SD. The ambient temperature set point, lighting program, and light intensity level in week 4 were 24 °C, 20L:4D, and 10 lux, respectively. Birds were provided with a commercial four-phase corn-soy diet (Dozier III et al., 2007) formulated to meet the recommendations by National Research Council (1994). Feed and water were supplied ad libitum. All procedures in this experiment were approved by the USDA-ARS Institutional Animal Care and Use Committee at Mississippi State.

8.2.2 Data Acquisition

Eight night-vision network cameras (NHD-818, Swann Communications U.S.A Inc., Santa Fe Springs, USA) were installed at ~3.6 m above the eight pens to capture top-view videos. Broiler activity in each pen was continuously recorded and stored in a network video recorder (NVR-87400, Swann Communications U.S.A Inc., Santa Fe Springs, USA). Video files were captured with a resolution of 1280×720 pixels at a sampling rate of 6 frames per sec (fps) and converted to images at the same rate using Free Video to JPG Converter (ver. 5.0). To reduce overlapping areas between adjoining pens, the converted images were cropped and resized to 580×680 pixels. Finally, each image contained only one pen of concern and one feeder. Feeding areas in images were fully observed within each video frame without blind spots.

8.2.3 Behavior Definition

The detecting area within each pen was determined as a circle area with the center being the feeder center and radius being ~50 cm. The radius included the radius (20 cm) of the feeder and the length (30 cm) of one and a half birds. The annular area (inner radius: 20 cm; outer radius: 50 cm) was the zone where restricted feeding birds mainly appeared based on observation. Eating birds and birds continuously walking around feeder were examined to study the restricted feeding behavior. Eating birds (yellow solid objects in Figure 8.1) were the birds with their heads being in feeder slots. Restricted feeding birds (gray solid and dash-line objects in Figure 8.1) were the birds continuously walking around feeder for over a period and attempting access to feeding space. Walking birds without restricted feeding (green solid and dash-line objects in Figure 8.1) were the birds walking near feeding areas without targeting on eating. Other birds around feeder (blue solid objects in Figure 8.1) included, but were not limited to, the birds sitting, stretching, and preening around feeder.

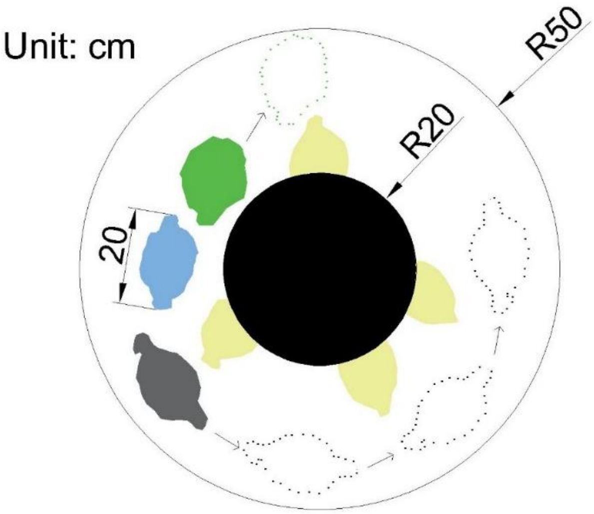

Figure 8.1 Schematic drawing of birds within a detecting area

Black solid object is feeder; gray solid object is a restricted feeding bird that continuously walks around feeder in the current image; gray dash-line objects are the same restricted feeding birds in following images; green solid object is a walking bird without restricted feeding; green dash-line object is the same walking bird in a following image; blue solid objects are non-restricted feeding birds (e.g., resting birds) around feeder; and yellow solid objects are eating birds.

8.2.4 Verification of Walking Duration

As mentioned above, the walking duration were different between restricted feeding birds and other birds without restricted feeding. To verify it, we watched 4637 small video episodes from the four SDs. Each video lasted for 1-2 min. Duration of different walking events were recorded. Walking duration was set to 0.5-5 sec (with 0.5-sec intervals) and >5 sec, and percentage of recorded walking duration in each range was calculated. Then the percentage was cumulated if the duration of a walking event was less than a set point.

8.2.5 Overview of Algorithms

The overall algorithms for automated behavior recognition mainly consisted of three parts that were an object detector, a bird tracker, and a behavior classifier (Figure 8.2).

The object detector was constructed with faster R-CNN, a two-stage and region-based CNN (Ren et al., 2015). In Figure 8.2, an input image was fed into the CNN detector, and the three classes that were feeder, eating birds, and birds around feeder were detected accordingly. The pixel coordinates $(x_{min}, y_{min}, x_{max}, y_{max})$ of each bounding box were extracted and stored for further analysis. As birds walking around feeder were major concern to determine restricted feeding behaviors, the feeder was one of the classes of interest to be detected for facilitating the analysis. The detector cannot differentiate walking birds from other birds (e.g., sitting birds, stretching birds, etc.) due to similar gestures and features between them. Therefore, the two were combined into one class, birds around feeder. Walking birds are determined later.

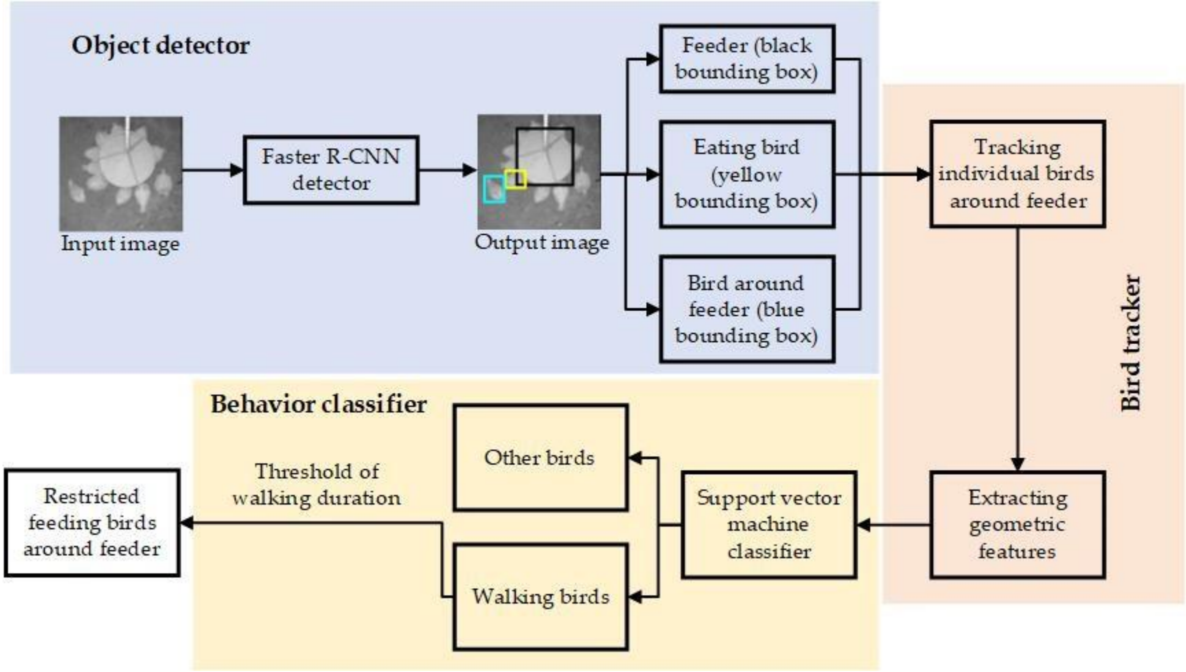

Figure 8.2 Schematic drawing of the overall algorithms for automated broiler behavior recognition

Faster R-CNN is faster region-based convolutional neural network.

Based on the coordinate information, the bird tracker was used to track individual birds around feeder. The algorithm continuously compared difference of centroid coordinate of birds in current frame and in previous frame (Figure 8.3). The number of birds located within the annular area in one frame could be up to 20, considering the annular area being ~6594 cm^2 and area of one bird being ~330 cm^2 from top view. Therefore, the number of 40 (Line 9 in Figure 8.3) should cover all birds around feeder between two adjacent frames. If the present bird had the smallest distance change (*MinValue* in Line 17 of Figure 8.3) of center coordinates compared to the bird in the previous frame and the distance change was less than a threshold (*thre* in Line 19 of Figure 8.3), the present bird was assigned with the same ID number as that in the previous frame (Line 20 in Figure 8.3). Otherwise, the present bird was assigned with a new ID number (Line 23 in Figure 8.3). The threshold of distance changes is verified later and presented in result section.

```
Data: pixel coordinate $(X_{min}, Y_{min}, X_{max}, Y_{max})$ and frame number
Result: ID number for each bird in each frame
Initialization;
$X_{center} = (X_{min} + X_{max})/2$;                  /* Calculate center coordinate */
$Y_{center} = (Y_{min} + Y_{max})/2$;
Insert 40 empty rows on the head;                      /* Avoid ‘index out of range’ */
Set $arr, brr$ as arrays $(40 \times 1)$;                 /* Build temporary arrays */
Set index of the last row as $N$;
Set $x, ID[41]$ as 1;
for $i = 41$ to $N$ do                                   /* Loop over the $N$ samples */
    for $j = 1$ to 40 do                       /* Loop over the previous 40 samples */
        if $frame(i)$-$frame(i - j)$= 1 then      /* Judge frame number difference */
            $arr(j) = \sqrt{(X_{center}(i) - X_{center}(i - j))^2 + (Y_{center}(i) - Y_{center}(i - j))^2}$;
        else
            $arr(j) = 10000$;                     /* Assign extremely large number */
        end
        $brr(j) = ID(i - j)$;          /* Store ID number of previous 40 samples */
    end
    $MinValue = \mathbf{Min}(arr)$;                                 /* Obtain minimum */
    $MinIndex = \mathbf{Where}(arr = MinValue)$;              /* Obtain minimum index */
    if $MinValue > 0$ & $MinValue < thre$ then       /* Judge range of minimum */
        $ID(i) = brr(MinIndex)$;    /* Assign ID of minimum to current bird */
    else
        $x = x + 1$;
        $ID(i) = x$;                              /* Assign new ID to current bird */
    end
    for $j = 1$ to 40 do                               /* Reformat temporary arrays */
        $arr(j)$;
        $brr(j) = 0$;
    end
end
```

Figure 8.3 Pseudocode for the procedure of tracking individual birds around feeder

Contents in the symbols of “/*…*/” are comments/explanations on codes and not implemented during process. $(x_{min}, y_{min}, x_{max}, y_{max})$ are upper left and lower right coordinates of each bounding box. (x_{center}, y_{center}) are centroid coordinates of each bird. *arr* and *brr* are temporary arrays to store processed data. *i* is index for looping over *N* samples. *j* is index for looping over previous 40 samples. *MinValue* is minimum value in array of arr. *MinIndex* is index of minimum in array of *arr*. *Thre* is threshold of minimum of bird moving distances. *x* is temporary variable to update ID.

After tracking, the birds were sorted with the same ID number being assigned together in time series. The geometric features were extracted from the sorted birds. The difference of frame number reflected whether the birds were adjacent (Equation 8.1). A feeder coordinate system was built based on a translation movement from the imagery coordinate system (Equations 8.2-8.3). The angle change and distance change in the feeder coordinate system reflected bird activity change around feeder (Equations 8.4-8.5). The absolute angle change and absolute distance change reflected overall bird activity in an entire image (Equations 8.6-8.7). The extracted features may help to classify bird behaviors around feeder.

$$DFN = |Number(i) - Number(i-1)| \tag{8.1}$$

$$x' = x - x^f \tag{8.2}$$

$$y' = y - y^f \tag{8.3}$$

$$ACRF = \left|\tan^{-1}\left(\frac{y_i'}{x_i'}\right) - \tan^{-1}\left(\frac{y_{i-1}'}{x_{i-1}'}\right)\right| \tag{8.4}$$

$$DCRF = \left|\sqrt{(x_i')^2 + (y_i')^2} - \sqrt{(x_{i-1}')^2 + (y_{i-1}')^2}\right| \tag{8.5}$$

$$AAC = \left|\tan^{-1}\left(\frac{y_i}{x_i}\right) - \tan^{-1}\left(\frac{y_{i-1}}{x_{i-1}}\right)\right| \tag{8.6}$$

$$ADC = \left|\sqrt{(x_i)^2 + (y_i)^2} - \sqrt{(x_{i-1})^2 + (y_{i-1})^2}\right| \tag{8.7}$$

where *DFN* is difference of frame number; Number is frame number; *ACRF* is angle change relative to feeder; *DCRF* is distance change relative to feeder; *AAC* is absolute angle change; *ADC* is absolute distance change; x, y are center coordinates of each bird in the imagery coordinate system, in which the origin is on the top left of images; x^f, y^f are center coordinates of feeder in the imagery coordinate system; x', y' are center coordinates of each bird in the feeder coordinate system, in which the origin is the center of feeder; i indicates present frame; and $i-1$ indicates previous frame.

The last part of the overall algorithm (Figure 8.2) was the behavior classifier, which was consisted of SVM. The SVM classifier is to use hypothesized space of a linear function in a high dimensional feature space and suited for nonlinear classification of complex but small-medium sized datasets (Géron, 2019). Using the extracted geometric features, the classifier classified two classes that were walking birds and other birds (e.g., sitting birds, stretching birds, etc.). The restricted feeding birds were further differentiated if birds walked around feeder for over a duration.

8.2.6 Data Labeling

A total of 14126 images from the four SDs in week 4 of bird age were labeled for the object detector development. Three classes including feeder, eating birds, and birds around feeder were labeled accordingly. The heads of eating birds were in feeder slots. Birds around feeder included those performing sitting, walking, fleeing, running, and other behaviors, except for eating. The range of birds around the feeder is shown in Figure 8.1.

The trained CNN detector detected the three classes of interest and the detection results were saved for another labeling with regards to tracking. A total of 401 episodes, each containing 180-1080 continuous frames stratified evenly from the four SDs, were processed by the detector and only the detected class of birds around feeder was selected for the labeling of tracking. The same birds that continuously appeared between adjacent frames were manually marked with unique ID numbers (1,2,…). Totally, 56329 labeled data points from the four SDs were used for the bird tracker development.

After tracking, the birds with the same IDs were sorted and arranged together in a sequence for labeling of the behavior classifier development. Among the 56329 tracked data points, only 16000 data points were labelled for developing the SVM classifier. The labelled dataset contained 2000 walking birds and 2000 other birds for each SD. The similar distributions of the two classes made the classifier learn features without bias.

8.2.7 Algorithm Development

The faster R-CNN object detector was trained with 9040 images, validated with 2260 images, and tested with 2826 hold-out images. The trained detector was validated with validation images during the training and observed whether it was under-fitted or over-fitted. Training configurations, such as learning rates, image resizers, and number of region proposals, were fine-tuned during each training to determine the optimal ones. We used the pre-trained model (model version: faster_rcnn_resnet101_coco_2018_01_28) from Google TensorFlow and followed the guidelines of TensorFlow Object Detection Application Programming Interface (Huang et al., 2017). Training losses and validation losses were reported simultaneously by a visualization tool, TensorBorad, which facilitated the hyperparameter tuning.

The bird tracker was validated based on the threshold of moving distances of birds between adjacent frames. The validated moving distances between adjacent frames ranged from 20 to 150 pixels with 5-pixel intervals, corresponding to 4.9-36.7 cm based on a conversion factor of 4.09 pixel/cm. The whole 56329 labeled data points were used to determine an optimal threshold for tracking birds.

The geometric features of individual tracked birds as mentioned in Section 8.2.5 along with the data label as mentioned in Section 8.2.6 were used to train the behavior classifier using a training strategy of five-fold cross validation. Among the 16000 labeled data points, 9600 data points were for training, 3200 were for validation, and 3200 were for testing. Hyperparameters, such as learning rate and type of kernel, were fine-tuned to determine the optimal behavior classifier.

8.2.8 Evaluating Algorithms

Precision, recall, and F1-score were calculated (Equations 8.8-8.10) for evaluating the performance of the object detector and behavior classifier.

$$Precision = \frac{True\ positive}{True\ positive + False\ positive} \tag{8.8}$$

$$Recall = \frac{True\ positive}{True\ positive + False\ negative} \tag{8.9}$$

$$\text{F1 score} = 2 \times \frac{Precision \times Recall}{Precision + Recall} \tag{8.10}$$

Correctly locating detected objects was critical since it may determine the correctness of the geometric feature extraction. Therefore, root mean square error (RMSE, mm) between detected center coordinates of objects via the object detector and true center coordinates of objects was also calculated in Equation 8.11.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\{(\hat{x}_i - x_i)^2 + (\hat{y}_i - y_i)^2\}}{N}} \tag{8.11}$$

where $\hat{x}_i$ and $\hat{y}_i$ are the i^{th} predicted center coordinates; x_i and y_i are the i^{th} manually-labelled center coordinates; and N is the total number of objects for each class in images.

As the IDs of tracked birds were the major concern, erroneous cases of switching IDs were summed and calculated in Equations 8.12-8.13. The error rate was calculated for each threshold of moving distances as mentioned in Section 8.2.7.

$$error = \begin{cases} 1, & if\ M_p \neq M_t \\ 0, & if\ M_p = M_t \end{cases} \tag{8.12}$$

$$error\ rate = \frac{\sum_{i=1}^{N} erro_i}{TN} \tag{8.13}$$

where M_p is moment of switching IDs predicted by the algorithm; M_t is moment of switching IDs in the true labels; *N* is total number of tested samples; $erro_i$ is error value (1 or 0) for the i^{th} tested sample; and *TN* is total number of true cases of switching IDs.

8.2.9 Measured Behavior Responses and Behavior Analysis

As for behavior analysis, we used three days of data in week 4 of bird age and the data were from eight pens and four SDs. With the developed algorithms, eating birds and birds continuously walking around feeder were detected and tracked as mentioned above.

Number of birds eating simultaneously was computed when there was at least one bird continuously walking around feeder. Then, the frequency of different number was analyzed for each of the four SDs.

Daily number of continuously walking around feeder ($\text{bouts}\cdot\text{bird}^{-1}\cdot\text{day}^{-1}$) was formed by summing all walking events related to restricted feeding in a day for each SD. The statistical analysis of the daily number was conducted in the Statistical Analysis Software (SAS 9.3, SAS Institute Inc., Cary, NC., USA). PROC MIXED statement and Least Square Difference post-hoc analysis was implemented to compare the mean difference of the daily number among treatments. Significant difference was considered when $P<0.05$.

Locations of birds continuously walking around feeder and corresponding eating birds were summarized into heat maps based on the extracted center coordinates. To construct a heat map, a pen-size mesh grid with cell size of 4 pixels (~1 cm) was created. Then a Standard Gaussian

Kernel Density Estimation Function was run on each center of grids, and the frequency in each grid representing probability of presence of birds performing above-mentioned behaviors was calculated by the Standard Gaussian Distribution.

8.3 Results

8.3.1 Cumulative Percentage of Walking Events

Figure 8.4 shows cumulative percentage of walking events corresponding to different walking duration.

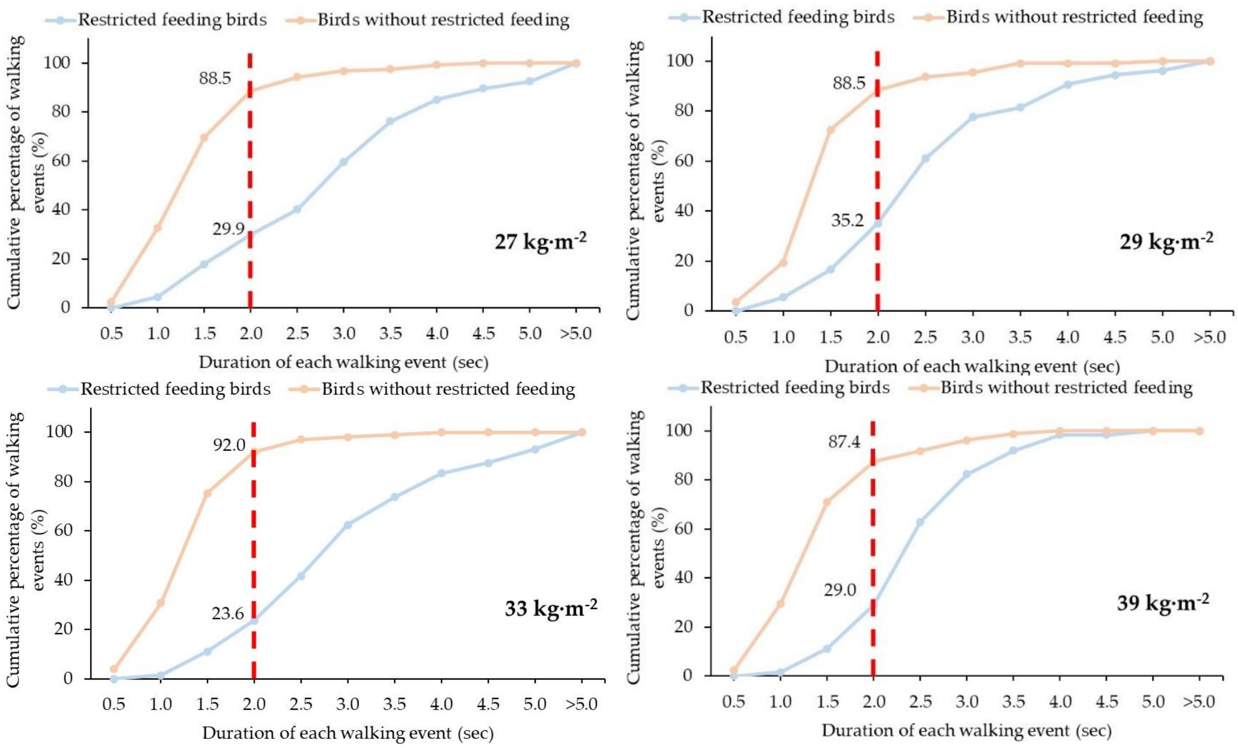

Figure 8.4 Cumulative percentage of walking events corresponding to different walking durations

Despite the overall tendency being slightly different among the SDs, the cumulative percentage increased as we leveled up the duration of bird walking. For over 87% of the observation cases, broilers without restricted feeding walked for less than 2 sec. In contrast, the restricted feeding birds generally walked for over 2 sec, which took up 64.8-76.4% of the cases. Therefore, if a bird continuously walked around feeder for over 2 sec, it was indicated as a restricted feeding bird in this case.

8.3.2 Performance of the Object Detector

Table 8.1 shows the performance of the object detector for detecting the feeder, eating birds, and birds around feeder. The faster R-CNN detector detected and located feeders in four SDs well, with precision, recall, and F1 score being 100% and RMSEs being 3.1-4.2 mm. The small errors are good for building the precise feeder coordinate systems and extracting geometric features of birds around feeder. Eating birds were also well detected based on the high precision, recall, and F1 score (≥98%) across all SDs, while the performance of locating eating birds were slightly compromised with the RMSE being over 19 mm. As for detecting birds around feeder, the detector had high precision and F1 score (>95%) but slightly lower precision (92.5-94.5%).

Table 8.1 Performance of the object detector for detecting the three classes under the four stocking densities

Evaluation metrics	27SD			29SD			33SD			39SD		
	Feeder	EB	BAF	Feeder	EB	BAF	Feeder	EB	BAF	Feeder	EB	BAF
Pre (%)	100	99	93	100	98	93	100	98	95	100	99	94
Rec (%)	100	99	99	100	99	98	100	99	96	100	99	97
F1 (%)	100	99	96	100	99	95	100	99	95	100	99	96
RMSE (mm)	4	29	8	4	18	8	4	25	12	3	27	10

27SD, 29SD, 33SD, and 39SD are the stocking densities of 27, 29, 33, and 39 kg·m^{-2}. EB is eating bird, BAF is bird around feeder, Pre is precision, Rec is recall, and F1 is F1 score.

8.3.3 Error Rates of Switching IDs via the Bird Tracker

Figure 8.5 shows the error rates of switching IDs via the tracking algorithm. The rate had a similar trend under the four SDs. It decreased sharply with the increasing thresholds of moving distances (5-10 cm) of birds between adjacent frames and then increased in a flat slope when the threshold increased from 15 to 40 cm. As the threshold of 12.5 cm (~50 pixels) corresponded to the lowest error rate 3.2%, it was used to tracked individual birds around feeder.

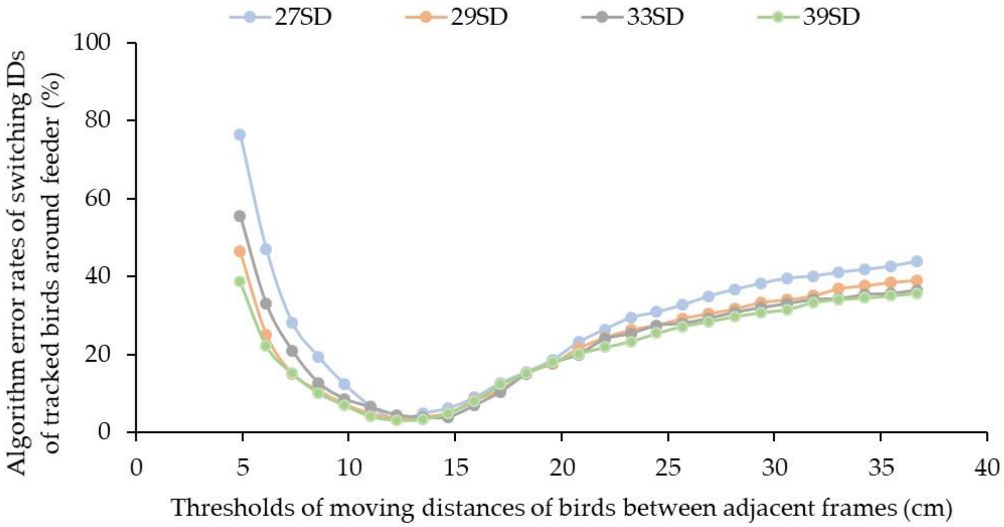

Figure 8.5 Algorithm error rates of switching IDs of tracked birds around feeder corresponding to different thresholds of moving distances of birds between adjacent frames

27SD, 29SD, 33SD, and 39SD are the stocking densities of 27, 29, 33, and 39 kg·m^{-2}.

8.3.4 Performance of the Behavior Classifier

Table 8.2 shows the performance of the behavior classifier. Overall, the classifier accurately classified the two classes with precision, recall, and F1 score being greater than 92%. The precision of the SVM classifier under 27SD was averagely 2-4% higher than that under other SDs, while no obvious difference of recall was observed among the SDs. The performance of classifying walking birds was averagely 0.3-2.7% lower than classifying other birds. The birds were judged to continuously walk around feeder by the algorithms, indicating restricted feeding, if they walked around feeder for over 2 sec.

Table 8.2 Performance of the behavior classifier for classifying walking birds and other birds

Evaluation metrics	27SD		29SD		33SD		39SD	
	Walking	Others	Walking	Others	Walking	Others	Walking	Others
Precision (%)	94.6	97.5	93.8	93.7	93.1	94.1	92.7	92.6
Recall (%)	95.1	97.6	96.7	97.4	95.5	96.9	97.1	98.4
F1 score (%)	94.9	97.5	95.3	95.5	94.3	95.5	94.9	95.4

27SD, 29SD, 33SD, and 39SD are the stocking densities of 27, 29, 33, and 39 kg·m^{-2}. 'Others' indicates other types of behaviors, such as sitting and stretching, excluding walking.

8.3.5 Frequency of Number of Birds Eating Simultaneously

Figure 8.6 shows the frequency of number of birds eating simultaneously when at least one bird continuously walking around feeder.

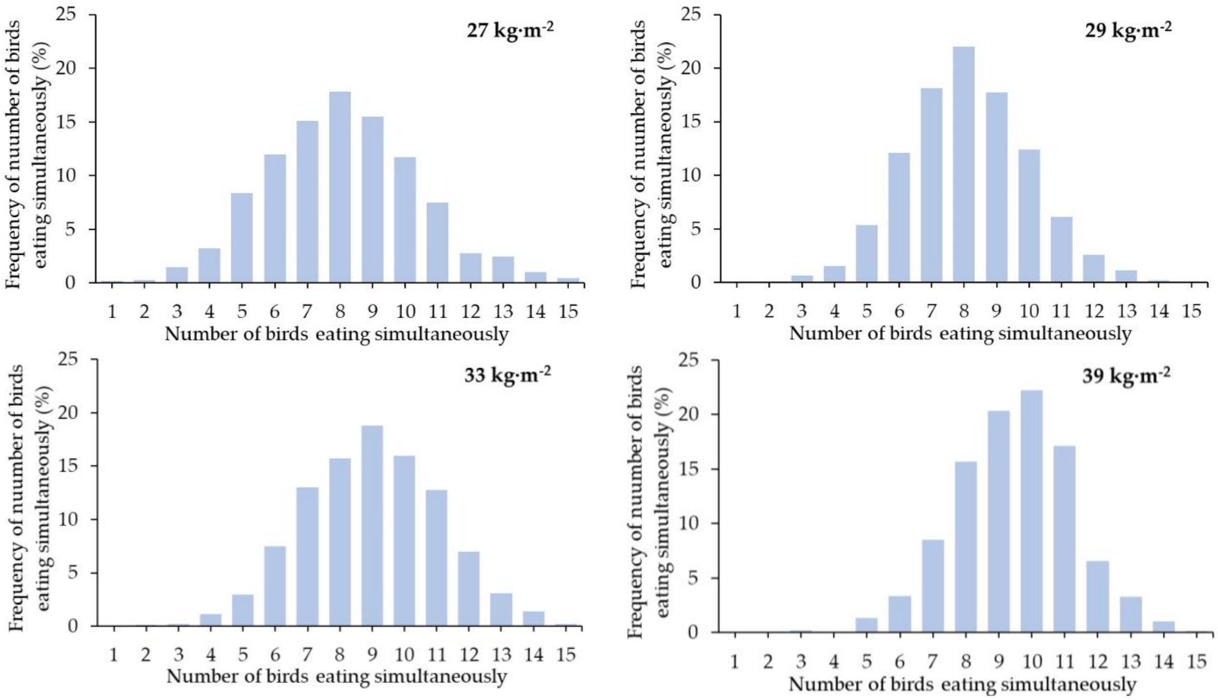

Figure 8.6 Frequency of number of birds eating simultaneously when at least one bird continuously walking around feeder

The overall frequency distribution among the SDs was in a shape of standard normal distribution. The highest frequency and the corresponding number were, respectively, 17.8% and 8 for 27SD, 22.0% and 8 for 29SD, 18.8% and 9 for 33SD, and 22.1% and 10 for 39SD. Interestingly, a lower bird number of <4 can trigger the restricted feeding event, and over 13 birds eating simultaneously were less likely to trigger the birds continuously walking around feeder.

8.3.6 Effect of Stocking Density on the Restricted Feeding Behavior

Figure 8.7 shows the daily number of continuously walking around feeder under the four SDs. A broiler continuously walked around feeder for 12-15 bouts in a day, and it walked more frequently under higher SD (i.e., 39SD) (*P*<0.01), indicating more restricted feeding behaviors with increasing SD.

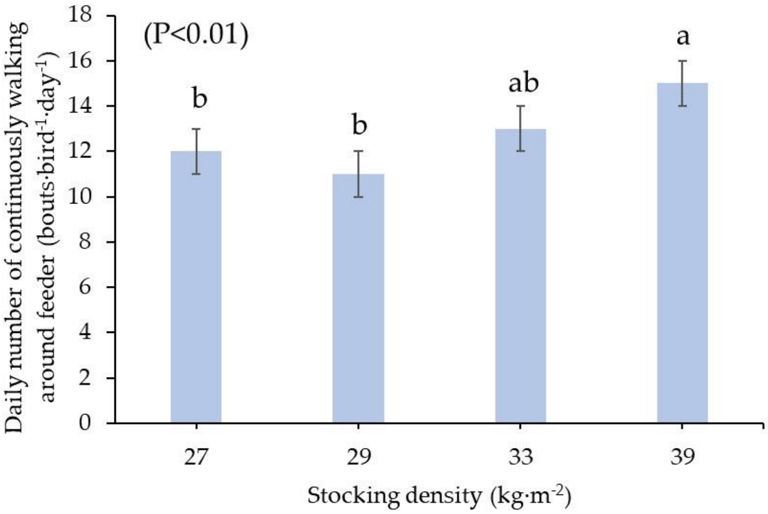

Figure 8.7 Daily number of continuously walking around feeder under the four stocking densities

8.3.7 Spatial Distribution of the Birds Continuously Walking around Feeder and Corresponding Eating Birds

Figure 8.8 shows heat maps of locations of the birds continuously walking around feeder and corresponding eating birds. The top parts of the heat maps were closed to human inspection aisles. Except for under 27SD, the restricted feeding birds under other SDs were more likely to walk around left sections of feeding area. The spatial distribution of eating birds was not the same among the SDs. Interestingly, the birds continuously walked around feeding areas where birds preferred to eat, indicating that a crowded feeding space was more likely to trigger restricted feeding behaviors of birds.

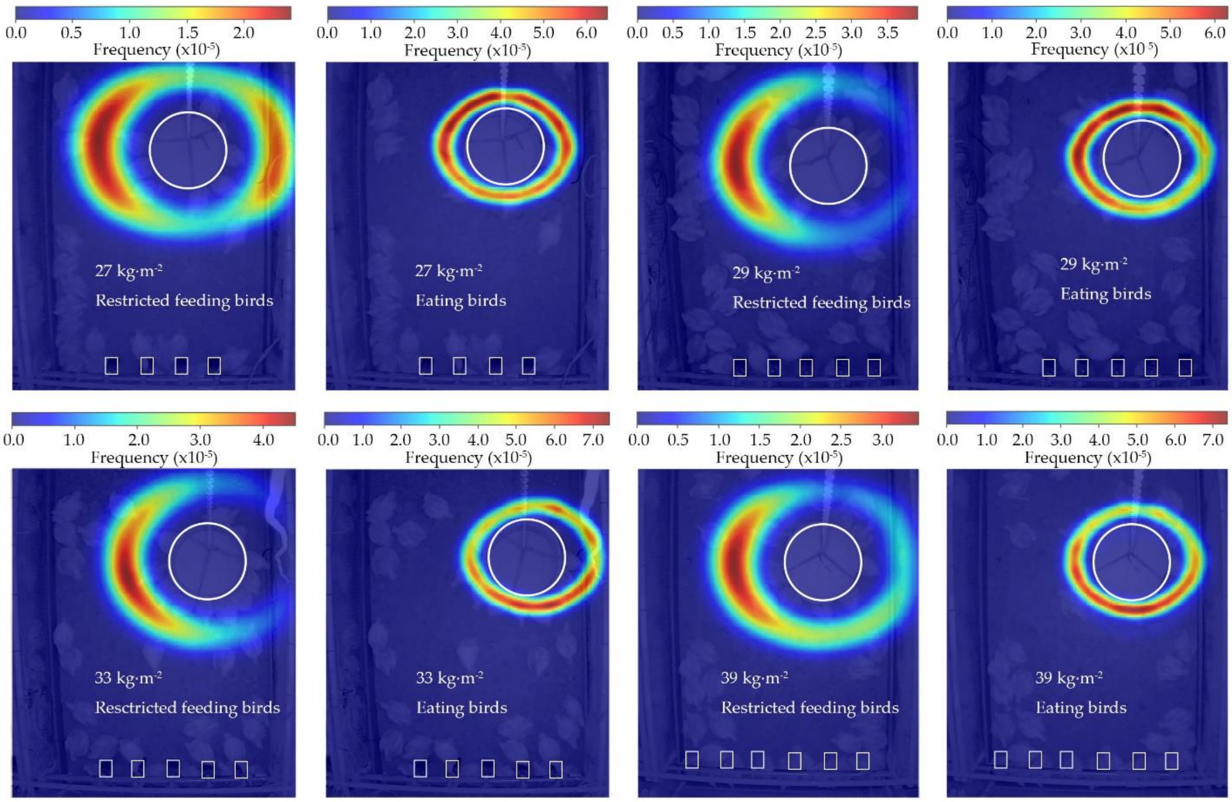

Figure 8.8 Heat maps of locations of the birds continuously walking around feeder and eating birds

White circles indicate feeders and while rectangles indicate drinkers.

8.4 Discussion

8.4.1 Walking Duration of Restricted Feeding Birds around Feeder

Broilers in current production systems are fast-growing and may be lazy in moving as they grow heavier. Bokkers and Koene (2003) reported that fast-growing broilers in week 4 spent less than 4% of time walking. Based on our observation, broilers without restricted feeding generally walked for a short term (<2 sec) and rested for a while near the feeder. Perhaps, these activities were luxury behaviors and performed casually (Duncan, 1992). In contrast, feeding is of primary importance for birds to survive (Duncan, 1998). Birds could urgently walk around feeder and search the available feeding spaces until the primary need was satisfied. That is why the threshold of continuously walking around feeder for over 2 sec is reasonable for indicating the restricted feeding birds.

By using the threshold of over 2 sec in the algorithms, we also ruled out some short-term restricted feeding event (23.6-35.2%). This could be treated as mild restricted feeding (Duncan, 1998), since birds could find resources in a short term and their needs were satisfied quickly. Longer duration of walking around feeder may reflect higher degree of restricted feeding, which helped us to interpret the treatment effect.

8.4.2 Performance of the Object Detector

Labeling classes of concern connected with other objects may facilitate object detection. Yang et al. (2018) labelled the detected head of eating pigs connected with parts of a feeder trough and trained a faster R-CNN-based detector. They achieved 99.6% precision and 86.9% recall for detecting pig feeding behaviors. Similarly, the labelled eating birds were connected with the feeder in this case, which may be the reason for high precision, recall, and F1 score of detecting eating birds. The features of the feeder were obvious and simple, such as fixed location, stable shape, and constant color, which also resulted in high performance on detecting feeder. Birds around feeder could overlap together, for instance, sitting birds could be overlapped by walking birds. These may lead to false recognitions of birds around feeder and decrease the precision (Jiang et al., 2020; Li et al., 2020a). The listed factors should be considered when a deep learning detector is developed.

A higher RMSE indicates a poorer performance of a detector with regards to locating objects of concern. Eating birds sometimes pushed the feeder, which could lead to changes of their body shapes and locations. Although not testing the same parameter, Jiang et al. (2020) also reported that a changing object shape could lead to misidentifications. Therefore, the RMSEs of locating eating birds were higher than those of feeder and birds around feeder, which had relatively stable shapes. It should be pointed out that the overall 18.8-29.3 mm RMSEs for locating eating birds were still small compared to the length of one bird (200 mm) and size of a pen (3200 mm long and 1400 mm wide). Therefore, the detector had no problem on locating birds in a pen.

8.4.3 Threshold of Tracking Birds

The threshold for tracking birds should be carefully adjusted. When smaller thresholds of moving distances were set, the tracker may not continuously track some walking birds, resulting in more frequent ID changes and larger error rates. When larger thresholds were set, the tracker may treat adjoining birds with close distances as ones, leading to fewer ID changes and larger error rates as well. To trade off, the threshold of 12.5 cm were selected, corresponding to a walking speed of 0.75 m/s. Bokkers and Koene (2004) reported a maximal walking speed of broilers to be 0.7 m/s, and Hocking (1994) also demonstrated broiler walking speeds ranging from 0.26-0.75 m/s. Although the threshold of bird moving distances was fitted to the range as reported previously, it cannot cover some fleeing birds marked with the orange bounding box in Figure 8.9 and running birds marked with the green bounding box in Figure 8.9, which were moving too fast between adjacent frames. These fast-moving birds did not affect our final analysis, since we mainly focused on the frustrated birds walking around feeder and eating birds, which moved in a relatively low speed and should be accurately captured by the tracker.

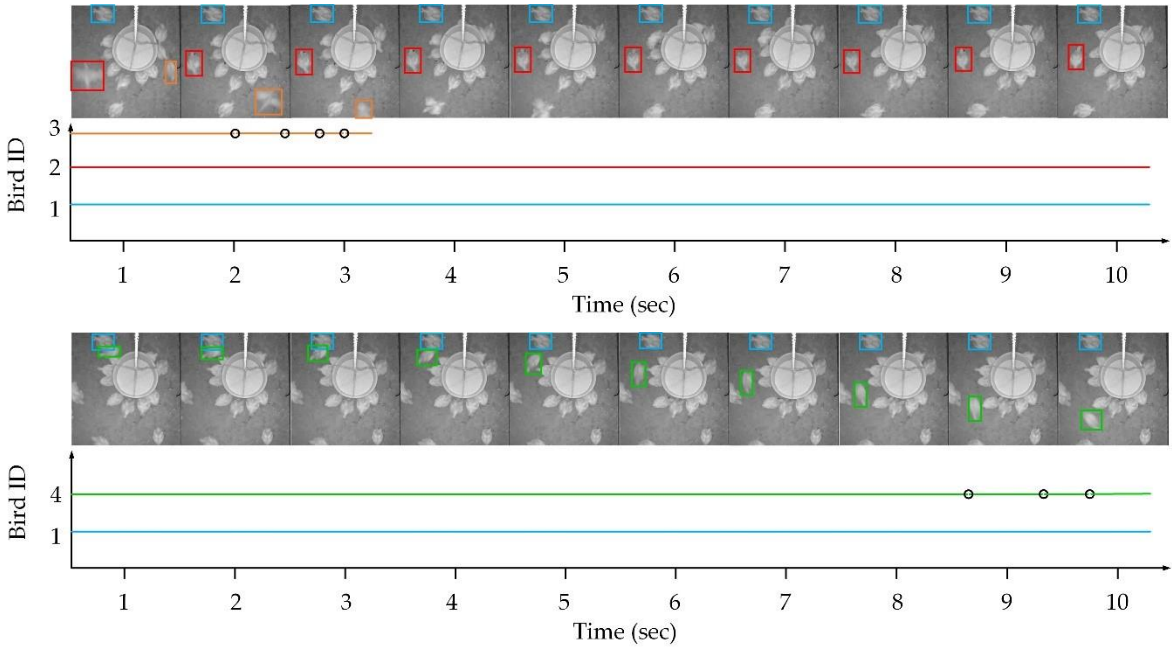

Figure 8.9 Erroneous tracking examples

Bird IDs are real IDs rather than the assigned IDs by the tracking algorithm. Black circles indicate the moments when the algorithm failed to continuously track the same birds and assigned new IDs. The image size is 380×390 pixels and convenient for presentation rather than the real testing image size (580×680 pixels).

8.4.4 Behavior Classification

Various factors could influence the behavior classification results. Broilers in a lower density may have less body contact with others and consequently were less likely to be misclassified (Li et al., 2020a), which resulted in higher precision of the classification under 27SD. The ‘others’ class was a combined class including sitting, stretching, preening, etc. Perhaps, the performance of classifying a combined class is higher than classifying a single class. That’s why performance of classifying the class of walking was slightly lower than that of classifying the class of others. It should be noted that the dataset for developing the classifier contained the data points from the sections of object detection and bird tracking. Although this could provide us with a better understanding of how the classifier performed across the entire algorithms, the performance of the classifier was inevitably compromised by the errors transferred from previous steps. If these errors were excluded, the classifier could achieve over 98% performance on classifying the two classes.

8.4.5 Frequency of Number of Birds Eating Simultaneously

Broilers are social animals and may adapt different behavior strategies under different environment (Estévez et al., 1997). Perhaps, under lower SDs, broilers may prefer more feeding space due to fewer birds in unit area, as a result of which a lower number of birds at feeder could trigger the restricted feeding behavior; under higher SDs, broilers may be more social tolerant since more birds need resources, and thus a higher bird number at feeder resulted in the restricted feeding behavior. Accordingly, the number corresponding to the highest frequency increased as SDs increased. In our case, a low eating bird number of <4 could trigger the restricted feeding event, which may be caused by mis-classification of restricted feeding birds and birds without restricted feeding. In Figure 8.5, there were still 8.0-12.6% of the cases that included the walking events irrelevant to restricted feeding being retained with the threshold of over 2 sec. Interestingly, a higher than 13 birds eating simultaneously at feeder triggered very few cases of the restricted feeding, which was contrary to our expectation that more birds at feeder could trigger more restricted feeding events. The feeder only had 14 feeder slots. Considering one feeder slot serving one eating bird, when the restricted feeding birds realized that there were more than 13 birds eating simultaneously, they may stop walking around feeder because of nearly no available feeder slot. In sum, as 8-10 birds eating simultaneously were more likely to trigger the restricted feeding behavior, the 14-feeder-slot tube feeder could be inefficient with regards to improving bird welfare.

8.4.6 Stocking Density Effect

Our results consolidated the solutions that lowering SD may help to alleviate broiler restricted feeding. Similar results were also observed in our previous test and unpublished data (Li et al., 2020b) that reducing the dense living space could be beneficial for bird performing behaviors, such as feeding, drinking, and stretching, which is a good sign of improved animal welfare.

Different industry trade associations and animal welfare groups have recommended different standards of SDs for welfare-oriented broiler production. Global Animal Partnership (2017) advocated that for birds placed from July 1st, 2020 onwards, stocking density must not exceed 29 $kg \cdot m^{-2}$. European Commission (2018) reported a general rule of stocking density to be less than 33 $kg \cdot m^{-2}$. National Chicken Council (2017) suggested that maximum stocking density is 32 $kg \cdot m^{-2}$ for broilers less than 2 kg in week 4. Our results show that higher SD could increase restricted feeding behaviors of broilers. This provides scientific justifications on the recommendations of SDs.

To study the SD effect, we set different numbers of birds in a pen and controlled other variables, such as pen area and number of feeders. The similar experimental settings were used to study SD effect on broiler feeding and drinking behaviors (Li et al., 2020b). However, the factor of feeder allowance could not be ignored. The feeder allowance is defined as cm/bird (Lemons and Moritz, 2015) and was 2.5 cm/bird for 27SD, 2.3 cm/bird for 29SD, 2.0 cm/bird for 33SD, and 1.7 cm/bird for 39SD. Further research is recommended to verify the SD effect and feeder allowance effect.

8.4.7 Spatial Distribution of the Birds

In general, the restricted feeding broilers were more likely to walk around areas with less traffic, e.g., the left sections of the feeding space. Although it was not the same behavior, Li et al. (2020c) also reported that broilers preferred to eat in the feeder sections with less traffic. In contrast, the top section involved more human activity, and right and bottom sections involved more bird movements. These were less preferable areas for the frustrated birds to be there. An extra hot spot was observed on the right section of the feeding space under 27SD. Perhaps, the area was not so crowded in the lowest SD that the restricted feeding birds were still willing to walk around there. Besides traffic, distribution of eating birds also can affect the restricted feeding birds. The phenomenon of more restricted feeding birds distributing at hot spots of eating birds lied in the fact that the restricted feeding birds may be attracted by eating birds. Collins and Sumpter (2006) also found that multiple birds eating at a feeder trough can induce other birds to arrive at the feeder. Traffic and bird attraction are factors to be considered for placing feeders in poultry houses.

The eating birds distributed irregularly at feeder, which was conflicted with the previous study that birds preferred to eat at the top left section of the feeder with less bird traffic (Li et al., 2020c). The eating birds were selected only when there was at least one bird continuously walking around feeder, therefore, they may not be representative to describe the whole scenario of the spatial distribution.

8.4.8 Limitations

In this study, we developed comprehensive algorithms containing an object detector, a bird tracker, and a behavior classifier. Advanced machine learning models, such as faster R-CNN and SVM, were embedded into the algorithms and achieved decent performance for automated analysis of broiler continuously walking around feeder. Our algorithms inevitably had limitations in different aspects. Firstly, current offline settings of the algorithm were right fitted for analysis of the restricted feeding behavior but may be far from real-time behavior monitoring. For example, in the bird tracker, we sorted birds with the same assigned IDs in a time series for further analysis. A completed data set needed to be stored and built to make this happen, which could be hard to achieve in a real-time processing. Secondly, multiple thresholds needed to be tuned carefully to make the algorithm generalizable to other situations. To track individual birds, we validated the threshold of moving distances of birds between adjacent frames; to differentiate the restricted feeding birds walking around feeder, we validated the threshold of duration of each walking event. These parameters could be affected by different bird ages, SDs, and feeders in other environments. In the future, to make the algorithms more generalized, the thresholds can be set to learnable variables during training.

8.5 Conclusions

We verified the walking duration of restricted feeding birds and developed comprehensive algorithms to track the birds. The algorithms included a faster R-CNN-based object detector, a bird tracker, and a SVM-based behavior classifier. We then used the developed algorithms to automatically analyze different behavior responses related to restricted feeding behaviors of broilers under four SDs. The results show that the restricted feeding birds continuously walked around feeder for over 2 sec, taking up 64.8-76.4% of the observation cases. The algorithms successfully detected, tracked, and classified walking birds in the feeding areas with precision, recall, and F1 score being greater than 92%. The walking duration of over 2 sec was then used to differentiate the restricted feeding birds via the algorithms. The cases of 8-10 birds eating simultaneously were the most likely to trigger the restricted feeding events. Lowering SDs reduced the daily number of restricted feeding events. More restricted feeding birds distributed around the areas where birds preferred to eat.

8.6 Author Contributions

Conceptualization, G.L.; methodology, G.L.; software, G.L.; validation, G.L. and X.H.; formal analysis, G.L.; investigation, G.L.; resources, G.L.; data curation, G.L.; writing—original draft preparation, G.L.; writing—review and editing, Y.Z., Z.C., and G.C.; visualization, G.L.; supervision, Y.Z. and G.C.; project administration, Y.Z.; funding acquisition, Y.Z. All authors have read and agreed to the published version of the manuscript.

8.7 Author Contributions

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8.8 Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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CHAPTER IX

SUMMARY

The dissertation systematically evaluated different precision tools for monitoring different types of broiler behaviors. Detailed methodology, results, and discussions can be found in Chapters II to VIII. In this final chapter of the dissertation, we summarized the major results and conclusions.

Radio frequency identification systems achieved high performance (over 90% accuracy) for detecting broiler feeding and drinking behaviors, after they were customized and modified, such as tag sensitivity test, power adjustment, radio wave shielding, and assessment of interference by add-ons. The systems accurately and continuously tracked individual broilers at feeders and drinkers. Image processing algorithms including sectional thresholding, linear regression with gradient decent, and edge detection precisely detected birds at feeder and at drinkers, and the detection performance was 89-95% for accuracy, 87-90% for sensitivity, 97-98% for specificity, and 0.3-0.4 for mean square error. The algorithm measured broiler feeding behaviors in different feeder sections and drinking behavior at different drinkers. After adjusting label method and hyperparameter tuning, the faster region-based convolutional neural network (faster R-CNN) had over 86% precision, recall, specificity, and accuracy for detecting broiler stretching behaviors. The stretching behavior detector continuously tracked individual stretching broilers. In comprehensive algorithms, the faster R-CNN showed over 92% precision, recall, and F1 score for detecting feeder, eating birds, and birds around feeder; the bird trackers had 3.2% error rate to track individual birds around feeder; and the support vector machine (SVM) behavior classifier achieved over 92% performance for classifying walking birds. Then if birds continuously walked around feeder for over 2 sec, they were identified as restricted feeding birds. In sum, the above-mentioned precision tools can meet different purposes of behavior study.

During a day, broilers at weeks 4 to 8 spent 62.7-197.9 min at feeders; visited feeders for 48-95 times; stayed for 0.4-2.0 min in each feeder visit; spent 23.6-45.8 min at drinkers; visited drinkers for 42-54 times; stayed for 0.5-0.7 min in each drinker visit; spent 230-533 sec stretching; stretched for 257-640 bouts; stretched for 0.84-1.02 sec in each stretching bout; and continuously walked around feeder (for over 2 sec) for 12-15 bouts. The coefficient of variations of feeding and drinking behaviors of individual broilers were 23.9-65.1%. Feeders and drinkers were utilized by broilers for 23.9-65.1% of the time. Most broilers chose to eat or drink after lights ON and before lights OFF. Broilers preferred to perform behaviors (e.g., stretching) in the areas with less bird or human disturbance, and they were more likely to be restricted to eat around the feeding area where other birds preferred to eat. In sum, broilers are dynamic and time-varying organisms and their behavior responses are different in various surroundings. Farm managers may need to consider those to better bird welfare when they manipulate birds or resources in broiler houses.

Management practices can be improved based on broiler behaviors. Lowering stocking densities (SDs) was beneficial for birds expressing behaviors, such as feeding, drinking, and stretching, and helpful to reduce restricted feeding behaviors of broilers. Using antibiotics-free diets reduced overall time spent at feeder/drinkers for broilers. Adopting lower feeder space did not compromise broiler feeding time but improved the efficiency of feeder utilization. Given the same feeder space, increasing the amount of feeders can accommodate more birds to eat simultaneously. Using chicken-perceived light intensity and broiler specific light spectrum can increase broiler feeding behaviors numerically. Farmers may adjust their management practices based on these results to improve broiler welfare.

APPENDIX A

CURRICULUM VITAE

A.1 Education

Ph.D. Agricultural Engineering, Mississippi State University, USA 2021
- Dissertation: Developing and applying precision animal farming tools for poultry behavior monitoring
- Advisor: Dr. Yang Zhao and Dr. Daniel Chesser

M.S. Agricultural Bioenvironmental and Energy Engineering, China Agricultural University, China 2017
- Thesis: Chamber design and algorithm development for testing hen lighting preference
- Advisor: Dr. Baoming Li and Dr. Zhengxiang Shi

B.S. Agricultural Structure Environment and Energy Engineering, China Agricultural University, China 2015
- Thesis: Housing design and environmental evaluation for the Chinese Aviary system of laying hens
- Advisor: Dr. Baoming Li

A.2 Research Experience

2017.08 – 2021.05	*Research Assistant*. Department of Agricultural and Biological Engineering, Mississippi State University, USA
2015.08 – 2017.06	*Research Assistant.* College of Water Resource and Civil Engineering, China Agricultural University, China

A.3 Research Interest

- ➢ Precision animal farming
- ➢ Animal housing and environment
- ➢ Animal behavior
- ➢ Poultry robot

A.4 Major Awards and Honors

- ➢ AOC Student Paper Competition Award (2020)
- ➢ AOC Graduate Scholarly Achievement Award (2020)
- ➢ Outstanding Graduate Student Paper and Presentation Award in the 2019 International Symposium on Animal Environment and Welfare (2019)
- ➢ Student Presentation Award in the 2018 ASABE AIM (2018)
- ➢ Outstanding Graduate Student in Beijing (2017)
- ➢ National Scholarship in China (2016)
- ➢ Graduate School First Prize Scholarship in China Agricultural University (2016)
- ➢ Outstanding Graduate Student Award in Beijing (2015)
- ➢ Meritorious Winner in American Mathematical Modeling Contest (2015)
- ➢ National Scholarship in China (2014)

- Outstanding Award in Agricultural and Biological Engineering Design Competition (2014)
- Second Prize Award in BIM Architectural Design Competition (2014)
- National Scholarship in China (2013)
- Second Prize Award in Chinese College Students Physics Competition (2012)

A.5 Reviewer Experience

- Review for Biosystems Engineering (2021.02)
- Review for Computers and Electronics in Agriculture (2021.02)
- Review for Computers and Electronics in Agriculture (2020.12)
- Review for Computers and Electronics in Agriculture (2020.11)
- Review for Computers and Electronics in Agriculture (2020.11)
- Review for Biosystems Engineering (2020.08)
- Review for Transactions of the ASABE (2020.08)
- Review of International Journal of Agricultural and Biological Engineering (2020.07)
- Review of Transactions of the ASABE (2020.06)
- Review of International Journal of Agricultural and Biological Engineering (2020.03)
- Review of Biosystems Engineering (2020.01)
- Review of Computers and Electronics in Agriculture (2019.07)
- Review of Computers and Electronics in Agriculture (2019.04)
- Review of Computers and Electronics in Agriculture (2019.04)
- Review of Computers and Electronics in Agriculture (2019.01)
- Review of Computers and Electronics in Agriculture (2018.11)
- Review of Computers and Electronics in Agriculture (2017.10)

A.6 Professional Activities

- Evaluation of cow udder and teat scores through digital image process method, Starkville, Mississippi, USA (2018.01)
- Housing design and construction for hen floor egg project, Starkville, Mississippi, USA (2018.01)
- Housing design and construction for broiler evaluated perching platform, Starkville, Mississippi, USA (2017.11)
- Diagnosis of the ventilation system in a case-free hen housing system for Cal-Maine Food, Bremen, Kentucky, USA (2017.10)
- Housing design and construction for hen light preference test, Beijing, China (2016.05)
- Design of a family hen farming system, Beijing, China (2015.05)
- Design of an innovative swine manure removal system, Beijing, China (2014.07)

A.7 Oral Presentation and Invited Talk

- Li G. 2020. Reducing floor eggs in cage-free hen housing systems using ground robots. In: 2020 ASABE Annual International Meeting, Virtual meeting, USA.
- Li G. 2020. Convolutional neural network for analyzing broiler stretching behaviors. In: 2020 ASABE Annual International Meeting, Virtual meeting, USA.

- Li G. 2019. Quantification of animal behavior. In: 2019 International Symposium on Animal Environment and Welfare, Chongqing, China.
- Li G. 2019. Evaluation of convolutional neural networks for detecting floor eggs of cage-free hen housing systems. In: 2019 International Symposium on Animal Environment and Welfare, Chongqing, China.
- Li G. 2019. Image processing for analyzing broiler feeding and drinking behaviors. In: 2019 ASABE Annual International Meeting, Boston, Massachusetts, USA.
- Li G. 2019. Effects of stocking density and antibiotic-free diet on feeding and drinking behaviors of broilers. In: International Poultry Scientific Forum, Atlanta, Georgia, USA.
- Li G. 2019. Image processing for poultry behavior detection. In: 2019 MSU-CAU exchanging seminar, Starkville, Mississippi, USA.
- Li G. 2018. Radio-frequency identification (RFID) system for monitoring specific behaviors of group housed broilers. In: 10th International Livestock Environment Symposium (ILES X), Omaha, Nebraska, USA.
- Li G. 2018. Radio frequency identification system for poultry behavior monitoring. In: ABE 4473 class, Starkville, Mississippi, USA.
- Li G. 2018. Feeding Behaviors of Broilers at Chicken-perceived vs. Human-perceived Light Intensities under Two Light Spectrums. In: 2018 ASABE Annual International Meeting, Detroit, Michigan, USA.

A.8 Publications

A.8.1 Peer-reviewed Articles

1. **Li, G.**, Hui, X., Lei, T., and Liu, T. (2020). Comprehensive analysis of faster region-based convolution neural networks on poultry feeding behavior detection. International Journal of Agricultural and Biological Engineering (under review).
2. **Li, G.**, Huang, Y., Chen, Z., Chesser, D., Purswell, J.L., Linhoss, J., and Zhao, Y. (2021). Practices and applications of convolutional neural network-based computer vision systems in animal farming: A review. Sensors 21, 1492.
3. **Li, G.**, Hui, X., Chen, Z., Chesser Jr, G.D., and Zhao, Y. (2021). Development and evaluation of a method to detect broilers continuously walking around feeder as an indication of restricted feeding behaviors. Computers and Electronics in Agriculture 181, 105982.
4. **Li, G.**, Hui, X., Lin, F., and Zhao, Y. (2020). Developing and evaluating poultry preening behavior detectors via mask region-based convolutional neural network. Animals 10, 1762.
5. **Li, G.**, Ji, B., Li, B., Shi, Z., Zhao, Y., Dou, Y., and Brocato, J. (2020). Assessment of layer pullet drinking behaviors under selectable light colors using convolutional neural network. Computers and Electronics in Agriculture 172, 105333.
6. **Li, G.**, Xu, Y., Zhao, Y., Du, Q., and Huang, Y. (2020). Evaluating convolutional neural networks for cage-free floor egg detection. Sensors 20, 332.
7. **Li, G.**, Zhao, Y., Porter, Z., and Purswell, L.J. (2020). Automated measurement of broiler stretching behaviors under four stocking densities via faster region-based convolutional neural network. animal 15, 100059.

8. **Li, G.**, Zhao, Y., Purswell, J.L., Chesser Jr, G.D., Lowe, J.W., and Wu, T.-L. (2020). Effects of antibiotic-free diet and stocking density on male broilers reared to 35 days of age. Part 2: feeding and drinking behaviours of broilers. Journal of Applied Poultry Research 29, 391-401.
9. **Li, G.**, Zhao, Y., Purswell, J.L., Du, Q., Chesser Jr, G.D., and Lowe, J.W. (2020). Analysis of feeding and drinking behaviors of group-reared broilers via image processing. Computers and Electronics in Agriculture 175, 105596.
10. **Li, G.**, Zhao, Y., Purswell, L.J., and Magee, C. (2020). Effects of feeder space on broiler feeding behaviors Poultry Science 100, 101016.
11. Li, X., Ye, Z., **Li, G.**, Shen, P., Zhao, S., Zhang, J., Zhu, S., Shen, Z., Gao, W., and Yang, Y. (2020). The effects of intelligent carbon fiber heater on pig behavior, production performance, and energy consumption Transaction of ASABE 64, 259-272.
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21. Bi, S., Zhou, Q., **Li, G.**, Zhang, J., Du, E., and Shen, R. (2014). Effect of the concentration of ethanol solutions and processing time on *Fusarium oxys porum* and *Phytophthora ca psici* in biological soil disinfection using ethanol. Northern Horticulture (13), 172-176.

A.8.2 Conference Proceedings/Abstracts

1. **Li, G.**, Hui, X.H., Zhao, Y., Zhai, W.Z., Purswell, J.L., Porter, Z., Poudel, S.P., Jia, L., and Zhang, B.Z. (2020). Reducing floor eggs in cage-free hen housing systems using

ground robots. In the proceedings of ASABE Annual International Meeting. (Abstract only)

2. **Li, G.**, Zhao, Y., Porter, Z., and Purswell, J.L. (2020). Convolutional neural network for analyzing broiler stretching behaviors. In the proceedings of ASABE Annual International Meeting. (Abstract only)
3. **Li, G.**, Xu, Y., Zhao, Y., and Du, Q. (2019). Evaluating convolutional neural networks for cage-free floor egg detection. In the proceedings of International Symposium on Animal Environment and Welfare.
4. **Li, G.**, Zhao, Y., Chesser, D., Lowe, J.W., and Purswell, J.L. (2019). Image processing for analyzing broiler feeding and drinking behaviors. In the proceedings of 2019 ASABE Annual International Meeting.
5. **Li, G.**, Zhao, Y., Purswell, J., Chesser, D., and Lowe, J.W. (2019). Effects of stocking density and antibiotic-free diet on feeding and drinking behaviors of broilers. In the proceedings of International Poultry Scientific Forum. (Abstract only)
6. Yang, X., Huo, X., **Li, G.**, Purswell, J.L., Tabler, G.T., Chesser Jr, G.D., and Zhao, Y. (2019). Application of elevated perching platform and robotic vehicle in broiler production In the proceedings of ASABE Annual International Meeting.
7. **Li, G.**, Zhao, Y., Hailey, R., Zhang, N., Liang, Y., and Purswell, J.L. (2018). Radio-frequency identification (RFID) system for monitoring specific behaviors of group housed broilers. In the proceedings of 10th International Livestock Environment Symposium (ILES X).
8. **Li, G.**, Zhao, Y., Purswell, J.L., Liang, Y., and Lowe, J.W. (2018). Feeding behaviors of broilers at chicken-perceived vs. human-perceived light intensities under two light spectrums. In the proceedings of 2018 ASABE Annual International Meeting.
9. Cao, Z., Shi, Z., and **Li, G.** (2017). Evaluation of the thermal insulation for dairy barns in cold regions via infrared thermography. In the proceedings of International Symposium on Animal Environment and Welfare.

A.8.3 Projects Participated

- Environmental management strategies for improving health and well-being in poultry production, *USDA Cooperative Agreement*, $200,000/yr, PI: Zhao et al., 2019-2024.
- Robots for reducing and collecting floor eggs in cage-free hen housing systems, *Egg Industry Center*, $85,605, PI: Zhao et al., 2018-2020.
- Development and evaluation of elevated perching platforms to improve animal welfare, animal health, aerial environment, and productivity for broiler chickens, *Mississippi Agricultural and Forestry Experiments Station*, $50,000, PI: Zhao et al., 2018-2019.
- Enhancing sustainability and production efficiency through improved management and housing design in commercial broilers, *USDA Cooperative Agreement*, $500,000, PI: Pote et al., 2017-2019.
- Objective evaluation of broiler welfare and behavior as affected by growth rate and stocking density, *US Poultry & Egg Association*, $123,937, PI: Zhao et al., 2019-2021.
- Animal housing and equipment, *China Agricultural Research System*, $457,836.6, PI: Li B. et al., 2016-2020.
- Animal housing and equipment, *China Agricultural Research System*, $98,991.7/yr, PI: Li B. et al., 2008-2015.

A.8.4 Undergraduate Assistants Co-supervised

- Rhet Hailey. Role of Li: co-work with RFID system development. 2017.08-2018.08.
- Matt Rowland. Role of Li: co-work with RFID system setup in the broiler house. 2017.12-2018.12.
- Taylor Bushart. Role of Li: co-work with RFID system setup in the broiler house. 2018.02-2018.12.
- Anna Kaitlyn Hinton. Role of Li: co-work with RFID system setup in the broiler house. 2018.02-2018.12.
- Dallas McKinnon. Role of Li: co-work with RFID system setup in the broiler house. 2018.02-2018.12.
- Brady Cagle. Role of Li: co-work with RFID system setup in the broiler house. 2018.02-2018.12.
- Suraj Neupane. Role of Li: co-work with RFID system setup in the broiler house. 2018.06-2019.06.
- Zach Porter. Role of Li: co-work with hen floor egg project. 2019.03-2020.03.
- Tate Howard. Role of Li: co-work with hen floor egg project. 2019.08-2020.06.