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Setting the stage to tag "n" track: a guideline for implementing, validating and reporting a radio frequency identification system for monitoring resource visit behavior in poultry

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ABSTRACT Passive radio frequency identification (**RFID**) can advance poultry behavior research by enabling automated, individualized, longitudinal, in situ, and noninvasive monitoring; these features can usefully extend traditional approaches to animal behavior monitoring. Furthermore, since the technology can provide insight into the visiting patterns of tagged animals at functional resources (e.g., feeders), it can be used to investigate individuals' welfare, social position, and decision-making. However, the lack of guidelines that would facilitate implementing an RFID system for such investigations, describing it, and establishing its validity undermines this technology's potential for advancing poultry science. This paper aims to fill this gap by 1) providing a nontechnical overview of how RFID functions; 2) providing an overview of the practical applications of RFID technology in poultry sciences; 3) suggesting a roadmap for implementing an RFID system in poultry behavior research; 4) reviewing how validation studies of RFID systems have been done in farm animal behavior research, with a focus on terminologies and procedures for quantifying reliability and validity; and 5) suggesting a way to report on an RFID system deployed for animal behavior monitoring. This guideline is aimed mainly at animal scientists, RFID component manufacturers, and system integrators who wish to deploy RFID system as an automated tool for monitoring poultry behavior for research purposes. For such a particular application, it can complement indications in classic general standards (e.g., ISO/IEC 18000-63) and provide ideas for setting up, testing, and validating an RFID system and a standard for reporting on its adequacy and technical aspects.

Key words: poultry behavior, automated tracking, RFID installation, validation

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INTRODUCTION

Radio frequency identification (**RFID**) refers to an automatic identification technology and its technical infrastructure. Well-known examples of Auto-ID technologies include the barcode system and smart cards, but unlike these, RFID does not require human intervention, line-of-sight or direct physical contact with the target item to sense, identify, and track it; RFID uses electromagnetic waves to function (Bolic et al., 2010; Finkenzeller, 2010). There are 2 main categories of RFID: active and passive. For some practical reasons (e.g., smaller size, no embedded batteries), passive RFID has mainly found increased applications in animal research. In animal behavior studies, targets for which passive RFIDs have been used as a tracking tool range from large animals, such as cows (Adrion et al., 2020), to tiny insects, such as bees (Streit et al., 2003).

Passive RFID can contribute to advancing poultry behavior studies in various ways. One is the automated and individual-based monitoring of how animals visit resources. For example, each bird can be equipped with a wearable RFID tag that automatically records the timestamp of each visit to the resource of interest with 92.5% accuracy (Li et al., 2019). Another contribution is the possibility of remote, noninvasive, in situ behavioral

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observation. Without being in sight and manipulating the birds or their environment, the behavior scientist can track them with RFID. Also, the wearable RFID device is typically lightweight (e.g., less than a gram) and as small as a grain of rice (Finkenzeller, 2010; Blemel et al., 2019); as a result, it does not interfere with the behavior or physical health of the birds (Buijs et al., 2018; Stadig et al., 2018). In addition, RFID can be deployed on poultry farms (e.g., Gebhardt-Henrich et al., 2014b), allowing the study of bird behavior under commercially relevant conditions. A final contribution of this technology is that it makes continuous monitoring of animals practicable over an extended period. While assessing behavior based on video recordings can be time-consuming, and the human eye can only provide a snapshot (Pluym et al., 2013), RFID technology allows for automated, continuous, and longitudinal recording of resource visit behavior. For example, RFID technology continuously monitored outdoor range visits in poultry over 13 d (Hartcher et al., 2016) or over 53 wk (Kolakshyapati et al., 2020).

However, one can note 2 major bottlenecks that undermine the potential and how RFID technology can advance poultry science. The first is insufficiencies in reports on the validity and technical aspects of the RFID systems deployed in some poultry research studies. The second is inconsistencies in how the validity of deployed RFID systems has been assessed, interpreted, and reported among studies. These inconsistencies, notably about the terminologies and formulas used to address the adequacy and performance indicators of the RFID systems, may lead to confusion. In addition, the insufficiencies and inconsistencies in reporting details about implemented RFIDs' design, performance, and validity make it challenging to compare and replicate RFID systems from different studies. These bottlenecks are consequences of the lack of a guideline for implementing and reporting RFID developed for poultry behavior research.

Exclusive reliance on existing conventional technical documents, such as ISO/IEC 15693, ISO/IEC 18000-63, or GS1 Class1Gen2, to implement RFID technology in poultry behavior monitoring will not be sufficient. Indeed, these documents mainly address communication protocols and parameters for RFID tags and readers at specific operating frequencies (GS1, 2009; ISO/IEC, 2013, 2017), without considering the specific challenges and requirements related to the application of this technology in animal behavior studies. These reference documents do not address, for example, the potential impact of RFID tags on animal well-being, such as tag weight; or interference from the animal body, which is fluid-filled. They also do not consider issues related to unpredictable omnidirectional animal postures, high tag density in confined spaces, or the possibility of animals blocking or obscuring each other's signals. Likewise, these references do not address the potential damage to RFID installations caused by animal activity with beaks, claws or teeth, nor the inherent complexities of the farming environment, including metal structures, 3-dimensional structures, and water. Furthermore, these technical documents are aimed more at RFID technology specialists than at animal behavior scientists, due to their technicality, jargon, and content. A guidance document that complements the existing technical documents is essential for the effective application of RFID technology to poultry behavior monitoring. Such an additional document should address the challenges and requirements of this application, taking into account the specifics of the animals' behavior, welfare, and environment. In this way, it will provide a more comprehensive framework for animal scientists and RFID developers to ensure the effective application of the technology in the study of poultry behavior.

In the present paper, we propose a guideline that includes the important considerations for installing, testing, validating, and reporting on a passive RFID system for monitoring poultry behavior. The paper is structured into 5 main parts. The first intends to provide nonspecialists with an understanding of the passive RFID technology's classes, functioning, and components. The second highlights the potential of this technology to advance the study of poultry behavior. The third describes a process for designing and implementing a passive RFID system for monitoring poultry behavior; this process is organized in phases, each broken down into successive steps to develop, install, test, and deploy the system. The fourth part reviews validation studies on the RFID system for monitoring animal behavior. The last part addresses essential points to report on the technical aspects and validity of a deployed RFID system.

A 4-STEP METHODOLOGY TO REVIEW EXISTING KNOWLEDGE ON RFID SYSTEMS AND DEVELOP A GUIDELINE

This paper intends to provide a broad nonspecialist audience with a comprehensive guideline for installing, testing, validating, and reporting passive RFID systems for monitoring poultry behavior. The literature-reviewing approach adopted to develop the guideline is integrative. The reviewing process was not intended to be critical of existing publications on the topic, nor to provide measurements or in-depth analyses of individual studies; instead, it served to distill important findings and synthesize best practices and valuable information from each of the relevant publications in order to draw relevant conclusions to inform the development of the guideline. The methodology adopted to write this guideline and review paper involved 4 steps: 1) Literature search and filtering; 2) Identification of the relevant RFID systems, 3) Retrieval of relevant reports on the identified RFID systems, 4) Integration and consolidation of extracted information (Figure 1).

Step 1: Literature Search and Filtering. The first step in our methodology was to identify relevant literature on RFID in poultry science. This step allowed us to understand the current state of RFID adoption in the

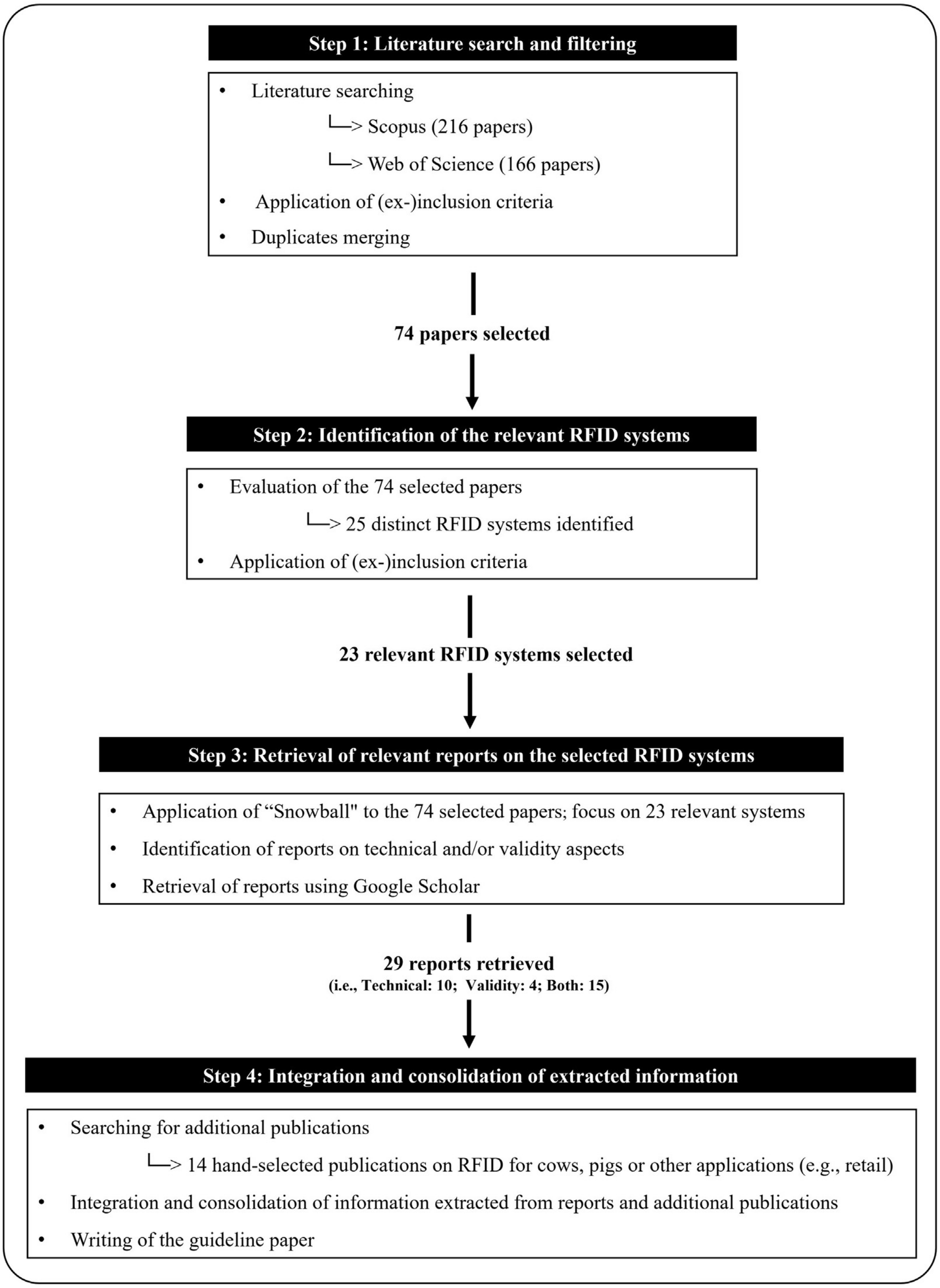

Figure 1. Flowchart of the methodology adopted for the development and writing of a guideline to facilitate the implementation, validation, and reporting of an RFID system deployed for monitoring resource visit behavior in poultry.

field and to identify a set of relevant papers that will provide a foundation and inform the subsequent steps of the methodology.

To this end, we performed a systematic search in Web of Science and Scopus on 19.11.2022; the search query was built as follows: Subject = (RFID OR "radio frequency identification") AND (poultry OR chick* OR bird OR hen OR broiler); search = "All fields." The search resulted in 166 papers in Web of Science and 216 in Scopus. Of these, only selected original papers were derived from research that used RFID for:

- recording activity in poultry;
- measuring behaviors relevant to physiological functioning, production, and health in poultry. Examples of such welfare-relevant behavior are: drinking, feeding, perching, nesting, and ranging;
- investigating the factors influencing the use pattern of resources relevant to welfare in poultry, and
- complementing other technologies for monitoring the behavior of farm birds for research purposes.

On the other hand, we excluded papers derived from research in which RFID was used on poultry carcasses, for slaughter and transport operations, as a mere identification tool for routine animal record keeping, and on wild birds. After filtering, the results were merged; duplicates were removed, and 74 relevant papers were ultimately selected.

Step 2: Identification of the Relevant RFID Systems. The second step in our methodology consisted of cataloging the popular distinct RFID systems installed across various poultry research units worldwide. This step was crucial to ensure the guideline would be based on the most relevant systems from the existing literature.

To this end, we first evaluated the 74 selected papers to identify the different RFID systems they mentioned. It is important to highlight that several of these evaluated 74 papers mentioned the same RFID system. Initially, a total of 25 distinct RFID systems were identified. However, upon further scrutiny, 2 of these systems were disregarded because their validity or technical aspects were addressed by referencing publications about RFID systems deployed in a different environment and for a different purpose. A final count of 23 relevant RFID systems was obtained.

Step 3: Retrieval of Relevant Reports on the Identified RFID Systems. The third step of our methodology was to identify and retrieve relevant reports to evaluate the technical and validity aspects of the 23 RFID systems identified in Step 2. It should be noted that the process of evaluating these reports was a key component of our methodological approach: it provided us with the insight to 1) understand how the authors addressed the main technical and validation aspects of the RFID systems, 2) assess the consistency and clarity of the terminologies and calculation formulas used for the assessment of the performance of the RFID systems deployed, 3) decide which relevant elements should be included in the guideline document, and 4) inform how to structure the document.

Identifying and retrieving relevant reports were done in an atypical way. We used the "snowball" approach, as suggested by Wohlin (2014), which we applied to the 74 papers selected in Step 1; the approach consisted of following the citations and references in those papers along the thread to identify reports of interest related to different RFID systems. Since many of these reports were conference contributions absent in Scopus and Web of Science, we used Google Scholar to retrieve them. To be included in our selection, they had to address either (or both) the technical aspects or validation information of one of the 23 RFID systems selected in Step 2. We considered that the technical aspects of RFID were addressed by a report when it dealt with the system operating parameters, architecture, infrastructure and outcomes of the optimization tests. Similarly, we considered that information on the validation of RFID is provided by a report when it addressed the measurement of performance indicators such as precision, accuracy, reliability, specificity, validity, sensitivity, concordance or agreement, percentage of exact matches, or any other means of validation. In total, 29 reports addressing the technical aspects and validity of the 23 selected RFID systems were identified and retrieved: 4 dealt with validity only, 10 with technical aspects, and 15 with both.

Step 4: Integration and Consolidation of Extracted Information. The fourth step of our methodology was to integrate the variously collected reports on the technical and validation aspects of RFID systems in poultry science and consolidate them with additional relevant resources.

In this step, we analyzed the 29 reports identified in Step 3. From these, we extracted valuable insights to inform our recommendations, thus providing readers with a detailed guideline specifically designed to facilitate RFID adoption in poultry science. For example, tables in our proposed guideline present several ways tags have been fitted to chicken bodies and provide some recommendable examples of how to present technical aspects, such as measures taken to ensure the proper functioning of the deployed system, data management system, and schematics of the adopted RFID architecture.

In addition to the reports on poultry science, we considered 14 publications that addressed RFID systems in other animal species (e.g., pigs and cows) or were developed for other contexts and applications, such as logistics in the retail industry. The additional resources allowed us to consolidate the literature identified on poultry. Indeed, they help us break down and simplify the description of how the RFID system works, develop a comprehensive roadmap for the implementation of the technology, obtain information to develop a roadmap for facilitating RFID implementation in poultry science, and provide a checklist for describing its aspects technical appropriately, and elaborate on how to conduct a validation study on RFID deployed for poultry science. The additional resources were suggested to us by animal scientists with experience in RFID for animal tracking, and RFID specialists; moreover, some of those resources were identified by us; and others originated from the reference lists of the 74 papers selected in Step 1. Here is an example of how these additional resources help consolidate the information extracted from the evaluated reports on RFID deployed in poultry: this guideline paper presents in a table an overview of 17 hand-selected papers on validation studies of RFID systems deployed to monitor animal behavior. These 17 papers, which are not limited to poultry science but also cover RFID in cows and pigs, provide readers with a broader perspective on potentially trackable behaviors, sample sizes, performance indicators, recording durations, and means to consider when planning a validation study of RFID for monitoring animal behavior.

A PROPOSED GUIDELINE FOR THE USE OF RFID SYSTEMS IN POULTRY BEHAVIOR RESEARCH

Understanding the RFID Technology

Classes of Passive RFID. Passive RFID technologies can be classified according to radio frequencies. The most recognizable ones, used for identification and tracking of animals, are low frequency (**LF**; 125−134 kHz), high frequency (**HF**; 13.56 MHz), and ultra-high frequency (**UHF**; 868−868 or 902−928 MHz, depending on the country). Brown-Brandl et al. (2019) mentioned details on the differences between the passive RFID classes that are particularly relevant for livestock production and research.

Overview of How the Passive RFID System Works. An RFID system consists essentially of readers, antennas, tags, and data processing software. The system's functioning is orchestrated by the reader, which relies on the antennas. Depending on the settings, the reader will regularly send power to the antennas. The antennas will convert this power into a radio frequency (**RF**) field around the resource, thereby covering the reading zone. As a tagged item enters this reading zone, it activates and modulates the RF (in the case of LF and HF tags) or backscatters a signal (in the case of a UHF tag) with its unique signature. The antenna will pick up that tag-specific digital signature and retransmit it to the reader. Finally, the reader will decode and pass this signature to the software for further processing (Figure 2). Ultimately, the information in the relevant format (e.g., tag ID, timestamp of resource visit) will be available and stored on the hosting computer (Bolic et al., 2010; Ebrahimi-Asl et al., 2016).

RFID Components and Their Functionalities. Each component of the RFID system has specific characteristics and tasks complementing those of the other components.

- ***Reader.*** Also known as the interrogator or transceiver (van der Togt et al., 2011; Nikitin et al., 2012), the reader is the RFID component through which communications begin and end. It has 4 main tasks. One is to frequently attempt the reading of tags in the area covered by the antenna-generated RF field: it functions as an interrogator. A second task is to supply power through cables to the antennas, thus allowing the passive tags to be inductively powered. A third task is to decode (e.g., analog-to-digital conversion) the tag signal communicated to it via the antennas. Lastly, it transmits the decoded digital information to the host/server or data management system for further processing (Bolic et al., 2010). The reader usually has a built-in computer and a graphical user interface. In addition, it has configurable settings that allow the user to:

  - configure the operating parameters of the network and antennas,
  - define the read range, controllable for each target resource,
  - define the transmit power (i.e., the amount of energy required to activate the tags in the desired read range), and
  - specify how the tags should be interrogated. The specifications include the recording rate (i.e., the frequency at which an RFID reader can scan tags and record data from them). That rate may be slower if a large number of tags are in the reading zone. Other influencing factors of the recording rate include the tags' size, their orientation relative to the antenna's reading direction, the specific RFID protocol being used, and the system's hardware and software capabilities (Li et al., 2017, 2019; Adrion et al., 2020).

  In addition, a reader can centralize data from several antennas (Maselyne et al., 2014). It can be fixed or have an integrated antenna and thus be hand-held (Wadhwa and Lin, 2008; Richards et al., 2011).

- ***Antenna***. The main task of the antenna is to enable communication between the reader and the tags that enter the reading zone. To enable this, the antenna first draws energy from the reader to generate an AC voltage RF field across the defined reading zone around the resources. This field allows passive tags, approaching the resources, to receive power and communicate their ID. Finally, the antenna retransmits the signal communicated by the tags to the reader (Bolic et al., 2010).
- ***Tag.*** Also known as "transponder" (van der Togt et al., 2011), the RFID tag is the component that carries the digital information (e.g., the ID number) of each tagged item. Its main task is to communicate this information to the reader as soon as that tagged item enters the reading zone and establishes communication with the reader. In its most basic form, the RFID tag consists of 2 parts: a tiny built-in antenna to

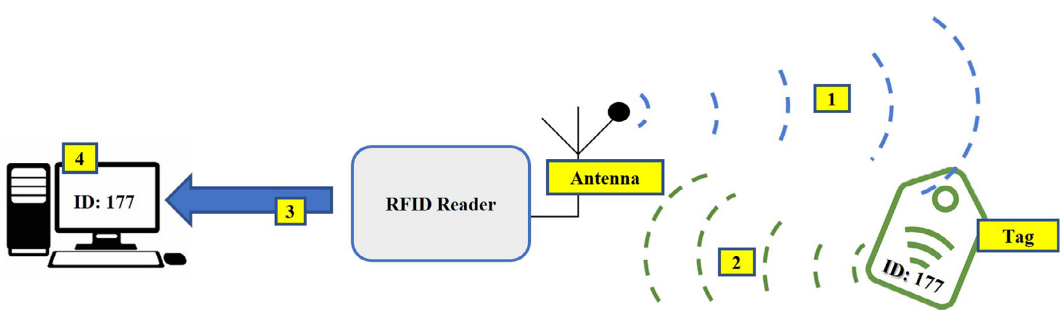

Figure 2. Schematic presentation of the simplified functioning of a passive RFID system (adapted from Wadhwa and Lin, 2008). In 1) a signal from the reader is transmitted by the antenna in an attempt to register the tags; in 2) a signal from the tag is backscattered as it enters the antenna-generated field in order to communicate its ID; 3) shows the interface with a hosting computer, and in 4) the ID that is decoded by the reader and communicated to the host/server or data management system is shown.

transmit and receive signals and an integrated circuit that stores the tag's unique ID (Bolic et al., 2010).

- ***Software.*** RFID software is the generic term for the various intelligent components of the system that manage and process data. Depending on the complexity and applications of the system, RFID software can include application software and middleware.
  - RFID application software is the program that uses the data collected by the RFID system for specific purposes, such as animal identification and behavior monitoring. Its functionality can include processing raw RFID data and providing behavioral estimates (Li et al., 2017; Wang et al., 2019).
  - RFID middleware acts as a bridge between the RFID hardware and the application software. Its primary function is to facilitate communication and data exchange between these 2 elements. It facilitates the management and maintenance of the RFID system as it can be used to configure RFID readers, update RFID tags, and monitor system performance (Bolic et al., 2010). It also improves the readability of RFID tags by means of algorithms that can filter out signal noise and mitigate read loss (Jeffery et al., 2006). The middleware's functionality can also be integrated into the reader, at least partly, thanks to increasingly powerful hardware.

Especially for animal behavior monitoring, a software package that includes these 2 components should be considered because of the complexity of the reader's communication system, data management, and the expected behavioral information.

RFID System Deliverable. When a tag enters the reading zone, it signals its presence to the reader at a predefined rate. At each signaling, the reader generates a row of raw data in a database system until the tag moves away. Based on an adaptation from Alfian et al. (2019), Anu (2014), and Wadhwa and Lin (2008), these data would typically include:

- Tag ID: the unique ID of the RFID tag. It is usually a hexa numerical code;
- Antenna ID: the specific ID of each antenna, which covers the reading zone surrounding a given resource;
- Recorded date-time: Timestamp corresponding to the date and time the reader detected the tag. This timestamp can be in UTC format: [YYYY-MM-DD HH: MM:SS];
- RSSI: defined as received signal strength indicator, representing a measure of the strength of the signal backscattered by the tag once in the reading zone. RSSI is high when the tag is very close to the reader's antennas, thus informative about the quality of the signal; it can be used to filter out false reads.

It is common for RFID data on animal presence at a particular resource to contain reading errors (both false and missed readings) or regular discontinuities. Misreading and discontinuity may be due to interference, noise, and other distortions in the signal that the system could not counter, to some system-specific limitations (e.g., a tag sensitive to rapid and omnidirectional movement, or to the presence of other tags), or to settings (e.g., an interval between readings set to more than 1 s; Maselyne et al., 2016b; Li et al., 2017; Adrion et al., 2020).

To counter these misreading problems, a software-based technique called "tag smoothing" is commonly used. This technique involves making the reader's middleware operate with an algorithm that uses a "threshold." The "thresholds" are specific values determined by the RFID middleware, using the slope of a best-fit line based on a sample of observed data and adaptive window sizes, to best approximate the raw readings to reality. The middleware uses this threshold as a sliding-window to adjust the time frames of the raw RFID readings by interpolating missed readings and filtering out false readings. With this built-in data-cleaning technique, an accurate representation of reality is ensured. The width of the window should be large enough to aggregate lost readings belonging to the same read event, and small enough to segregate readings belonging to different read events (Jeffery et al., 2006). Although the enforcement of this RFID data stream cleaning technique can be integrated into the reader middleware and thus applied at the time of tag reading, many authors deploying RFID for animal behavior monitoring filtered their raw data afterward, for example, at the time of data analysis. These authors have generally referred to that "threshold" for gap-filling, reconstruction and correction of RFID dataset as the "bout criterion"—the maximum duration between 2 registrations considered when analyzing RFID data; it represents the threshold for including 2 successive RFID readings in the same resource visit event (Maselyne et al., 2016b; Li et al., 2017; Adrion et al., 2020). The various methods for calculating the "bout criterion" are reviewed in the session "*Validating an RFID System Deployed to Monitor Poultry Behavior.*"

RFID measures "resource visit" but not directly "resource use" unless the technology is combined with a video recording system. This is because RFID can only indicate the presence of a tagged animal in the defined reading zone around a resource; it cannot directly indicate whether the identified animal uses the resource. As Campbell et al. (2017b) noted when tracking pophole use, some hens had jumped onto the pophole without crossing it, yet the RFID system would have identified them as users of the outdoor range unless further filtering had been applied to the data. One must differentiate between "resource visit" and actual "resource use" to understand what RFID can do for animal behavior research.

Estimates of resource visit behavior are one type of behavioral data that can be extracted from raw RFID data. Such extraction is done in several steps: after initial filtering, including the aggregation of successive readings using the defined bout criteria, the corrected raw RFID data can be summarized, on an hourly or daily basis, into numbers of animals using the resource of interest, into estimates of resource visit such as duration, frequency, and detailed time series (Brown-Brandl et al., 2019). Further behavioral data, such as proxies for movement patterns (Gómez et al., 2022), can also be extracted from the raw RFID data.

Applications of RFID in Poultry Sciences

In poultry sciences, passive RFID systems have been used for various purposes. RFID as a tool for recording general activity levels was demonstrated by van der Sluis et al. (2020). These authors recorded activity levels using RFID technology by placing several antennas under the litter. Each of these antennas, covering part of the floor, detected the tag at a specific location in the barn. Then, the spatial travel distance was calculated using an algorithm based on the temporal sequence of tag registrations by adjacent antennas. As such, RFID can support genetic selection in a variety of ways. For example, Kjaer (2017) used it for the initial phenotyping of 2 chicken lines diverging in activity levels; similarly, van der Sluis et al. (2022) used it to examine the relationship between 2 traits of particular interest for genetic selection in broilers: increased early life activity and body weight change. Ellen et al. (2019) described how RFID could be used for selective breeding against feather pecking in laying hens.

Moreover, RFID has been proposed and proven to measure certain functional behaviors at the individual chicken level. Examples of measurements include resting time, order of arrival at the feeding area, and speed between functional locations (Zhang et al., 2016); frequencies and durations of visits around drinking and feeding areas (Li et al., 2019), in nest boxes (Li et al., 2017), on perches (Wang et al., 2019), and in ranging areas (Gebhardt-Henrich et al., 2014b). For all these applications, the system deployment principle is similar: the tag, attached to or implanted into a body part, is detected by an antenna that covers the surroundings of the visited facility with its magnetic field.

RFID has also been tested as a tool for indicating welfare in poultry. Numerous studies used it to examine how subpopulations with opposing outdoor range visit patterns differed on traditional animal welfare indicators. These studies found that chickens that consistently went out earlier, longer or further from the shed differed from their counterparts in terms of health and performance parameters such as body weight, parasite load, laying rate, scores for keel bone, plumage, comb, and beak (Richards et al., 2012; Hartcher et al., 2016; Bari et al., 2020; Sibanda et al., 2020b,c); or in terms of affective state—as revealed by attentional bias, open field, or tonic immobility tests (Hartcher et al., 2016; Campbell et al., 2019); or regarding physiological parameters such as albumen corticosterone levels after a stressful event (Campbell et al., 2020).

Another use of RFID systems is for investigating factors influencing resource visits in individual chickens. For example, previous studies examined how outdoor range visits are influenced by animal-related factors like cecal microbiota composition (Bari et al., 2022) and personality traits such as fearfulness (Hartcher et al., 2016), curiosity (Kolakshyapati et al., 2020), or tendency to visit other components of the aviary (Sibanda et al., 2020d). In addition, by studying the range use, the behavioral and social organizations across individuals were explored using RFID. The technology revealed intra- and interindividual behavior patterns in chickens housed at high commercial stocking densities (Larsen et al., 2017; Campbell et al., 2018b). It also showed that chickens form social associations under commercial farming conditions (Gómez et al., 2022). Further, previous studies focused on the influence of husbandry practices such as enrichment during the rearing phase (Campbell et al., 2018a), indoor or outdoor stocking densities (Gebhardt-Henrich et al., 2014b; Campbell et al., 2017a), or provision of insects as supplementary feed (Ruhnke et al., 2018) on range use. Some other studies focused on factors unrelated to animal or farm management. For instance, Taylor et al. (2017) used RFID technology to investigate the influence of the year's season (winter, summer) and daytime (morning, evening) on outdoor range visits. Apart from the outdoor range visit, the influencing factors on the visit to other poultry facilities were also investigated with RFID. For example, Oliveira et al. (2019b) used the technology to examine the influence of feeder space on feeding behavior in laying hens.

Lastly, RFID has been used as a mere identification support tool for other animal behavior or performance monitoring systems. For example, RFID was used in conjunction with an automated system to record real-time feed intake and body weight in turkeys (Tu et al., 2011). Similarly, it was an added component in a machine vision system to identify multiple nest occupations in laying hens (Zaninelli et al., 2018) and other behaviors such as perching, moving, drinking, and feeding (Nakarmi et al., 2014).

To sum up, RFID has been used to investigate temporal components, motor patterns, underlying physiological mechanisms, and affective states associated with many animal behaviors. It has proven to be valuable for poultry science: it allows an in-depth understanding of various functional behaviors and their influencing factors. This understanding is essential to ensure chicken welfare. It can also help to optimize day-to-day farm management and investment (e.g., resources and labor). In addition, it may prompt, where necessary, updates to resource designs and legislation in poultry farming.

Developing and Implementing an RFID System for Poultry Behavior Monitoring

Developing and implementing an operational RFID system for automated monitoring of poultry behavior will involve 4 main phases (Figure 3). The essential tasks to be carried out in each of these phases are described below.

Defining the Tracking Objectives. The definition of tracking objectives, in the early stages of RFID development, is crucial to ensure the relevance and effectiveness of the technology; it guides the development and deployment of an RFID system to meet the study's specific needs effectively (van der Togt et al., 2011). By establishing clear and relevant objectives, researchers can optimize the system's design, select appropriate parameters, and ensure that the data collected is relevant to the analysis of animal behavior. This crucial phase may also help avoid errors or inaccuracies in the results and saves time and resources by avoiding subsequent adjustments. An example of an objective could be measuring the frequency and duration of animal visits to key resources, such as drinkers, feeders, and perches, to study the impact of a given environmental factor on the animals' resource use behavior and welfare. In this case, the RFID system should be designed to record relevant data, such as animal ID and time stamps of visits to the resources of focus. By defining such specific objectives, researchers can ensure that the RFID system is tailored to their needs and can provide valuable information for studying the animals involved.

Analyzing the Tracking Requirements and Conditions. There are mainly standardized RFID packages on the market, and no "one-size-fits-all" tag, reader or antenna works best in every situation (Reyes and Jaska, 2007). Deploying RFID in an animal facility would entail identifying the tracking conditions and requirements, and adjusting the system accordingly. Failing to perform such an analysis might lead to an ineffective RFID system and a waste of resources (van der Togt et al., 2011). Identifying the tracking conditions and requirements will necessitate 2 complementary efforts: on-site assessment and capitalization on the experience of previous studies.

The on-site assessment is the process by which the physical environment is thoroughly investigated. It aims at identifying factors that may influence the performance of the envisioned RFID system. The process involves an on-site assessment, preferably to be carried out by an RFID system specialist (van der Togt et al., 2011). The main concerns are usually materials containing water, metal, or other dielectric surfaces in the vicinity of the antennas and the tags. RFID systems, especially of UHF and HF frequencies, are susceptible to significant malfunctions caused by these materials. In fact, the proximity of water or metal can reduce the read range of a UHF RFID system by up to a third (Bolic et al., 2010). While water molecules absorb microwaves, thus preventing tags from having sufficient energy to be activated, metals, and dielectric surfaces reflect them in all directions. These reflections can block, distort, multipath, or attenuate the original RF field. As a result, blind or fading areas are created in the reading zone, causing the signal to be insufficient to power up the tag (Bolic et al., 2010; Zhou et al., 2015). Other potential sources of RFID signal disruptions include fluorescent lighting (Ibrahim and Plytage, 2010), materials containing carbon fibers (Veigt et al., 2020), and devices generating competing frequencies (Bolic et al., 2010); such items can be present in livestock environments.

Practical arrangements can be made to counter some of these concerns. For example, Adrion et al. (2020) used plastic to keep UHF RFID antennas away from the concrete wall. This arrangement allowed for an excellent reading performance of their system. In addition, taking advantage of recent developments in the field of RFID can help control these factors. Most recently, special tags and antennas capable of withstanding the influence of metal and water have been proposed (e.g., Ma et al., 2020).

The outcomes of the on-site analysis may consist of a comprehensive list of physical components incompatible with RFID, and a floor plan that locates the components along with the RFID infrastructure and the flow of tagged items. These outcomes may suggest modifying the environment as they highlight physical constraints to installing the RFID equipment (van der Togt et al., 2011). In addition, this analysis allows important purchasing decisions, such as equipment selection and understanding how to install the equipment considering the identified influencing factors and the tracking needs (Reyes and Jaska, 2007).

Capitalizing on previous studies' experience can also help identify some general requirements for implementing an effective RFID system for tracking poultry. Previous studies have reported some difficulties and ways to address them. For example, using orientation-sensitive tags to monitor poultry can be problematic. In the experiment of van der Sluis et al. (2020), where the antennas were embedded under the litter, and the tag attached along the vertical axis of the tarsus, the RFID system worked best when the birds were standing (i.e., tags were perpendicular to the antennas), but when the birds were lying down, the tags were often not detected. Tags oriented perpendicular to the antennas also offered the best performance in Li et al. (2017) and Wang et al. (2019). However, this is not always the case: in Sales et al. (2015), for example, the RFID worked best when tags were parallel to the antennas. Using circularly polarized UHF antennas could help prevent this

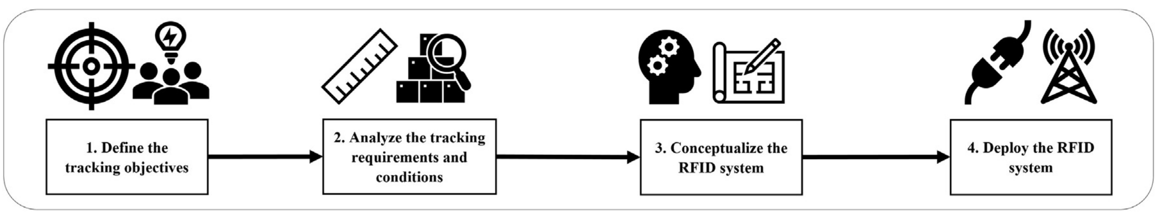

Figure 3. A 4-phase roadmap for developing and implementing an RFID system for poultry behavior monitoring.

problem, as these antennas can pick up the signal emitted by the tags in any direction (Parthiban, 2019). With such measures, the UHF RFID system deployed by Adrion et al. (2018) captured the signal despite the pigs' omnidirectional movements and body postures.

Second, the velocity of tagged animals can be a major limiting factor. For example, in Gebhardt-Henrich et al. (2014a) and Campbell et al. (2017b), where LF RFID systems were deployed to monitor the access to an outdoor range, the detection rate dropped below 10% when the tag speed exceeded 3.0 m/s and became zero above 9.3 m/s, respectively. This limitation could be overcome by using higher frequencies since UHF can detect tagged items moving at high speed, such as 69 m/s (Bolic et al., 2010).

Third, intertag interference or collisions can affect the performance of RFID systems (Sales et al., 2015). Intertag interference can occur in 2 ways. One is observed in tags that are densely colocated in the reading zone. Under these conditions, the backscattered signal from a given tag can overshadow that of the others. This shadowing effect degrades the read rate, which worsens as the intertag distance decreases (Zhou et al., 2015). The second case is observed when several tags attempt to communicate simultaneously with the reader using the same backscatter channel. In this case, the reader may fail to decipher the tag signals; as a consequence, those tags may go undetected within the reading zone (Bolic et al., 2010). Higher frequencies, such as UHF, readily admit an anticollision protocol (e.g., EPC Gen 2 in dense mode) for mass reading. Adrion et al. (2020) implemented such protocols that optimize communication between readers and tags to avoid collisions between and within these components.

Lastly, the long interval between readings, intrinsic to the LF RFID system, makes them unsuitable for continuous readings. Around resources such as feeders, continuous readings are essential to estimate the visit durations (Adrion et al., 2020). Prolonged intervals between readings with low frequencies would lead to nondetection of animal presence for some time, thus underestimating the resource visit behaviors (Sales et al., 2015). Therefore, when continuous identification is required, HF and UHF RFIDs might be more appropriate as they allow multiple readings in less than a second (Brown-Brandl et al., 2019). On the other hand, when just one registration at the resource is needed to estimate the number of resource visits, any RFID class can be used. In many studies, such an application has been made with LF RFID to identify visits to an outdoor range. For a visit to the outdoor range, only entry and exit readings are of interest (e.g., Gebhardt-Henrich et al., 2014b; Campbell et al., 2017b).

In summary, the on-site assessment can help identify potential influencing factors specific to the environment in which the system will be deployed. These factors may include metal-containing materials and water. The assessment can give an insight into the challenges that will be faced when installing RFID. Capitalizing on previous studies' experience may help identify some general requirements of an RFID system for poultry tracking. For example, the deployment of this technology to track individual animals housed in groups would require orientation-insensitive tags capable of reading fast-moving items and unaffected by the proximity of other tags. A well-designed RFID system operating at higher frequencies, such as UHF or HF, can provide most of these capabilities. However, the major limitation of these higher frequencies is their vulnerability to interferences from metal and water (Brown-Brandl et al., 2019). Some ways to address this are mentioned above. The requirements analysis will provide the basis for designing the architecture and selecting the components of the envisaged RFID system.

Conceptualizing the System. This crucial phase in implementing RFID technology involves selecting the system infrastructure and designing its architecture. The equipment used in some prominent animal behavior studies deploying RFID has been supplied by a wide variety of manufacturers and distributors, such as Impinj Inc located in Seattle, Washington (Li et al., 2019; Adrion et al., 2020); Alien Technology based in San Jose, California (Toaff-Rosenstein et al., 2017); Gantner Pigeon Systems GmbH located in Schruns, Austria (Gebhardt-Henrich et al., 2014a); Feig Electronic GmbH based in Weilburg, Germany (Thurner et al., 2010; Maselyne et al., 2014); Guangzhou D-Think Technologies Inc located in Guangzhou, China (Wang et al., 2019); TransTech Systems Inc based in Latham, New York (Li et al., 2017, 2019; Oliveira et al., 2019a); Texas Instruments located in Dallas, Texas (Sales et al., 2015); Freaquent Froschelectronics GmbH based in Graz, Styria, Austria and Dorset ID based in Aalten, Gelderland, The Netherlands (van der Sluis et al., 2020). To make an appropriate choice, one can consider each system component's critical technical aspects (Table 1).

Apart from Adrion et al. (2020), hardly any studies have used commercially available software. Specially designed programs for ethological studies that take into account the specifics of animal behavior are not yet available on the market. As a result, most animal behavior monitoring studies with RFID have used customized or self-programed data collection software. The programing languages or environment mentioned include C# (C Sharp) based on API (Li et al., 2017; Oliveira et al., 2019a), Java (Toaff-Rosenstein et al., 2017), Python (Li et al., 2018; Wang et al., 2019), HT Basic (Sales et al., 2015), and NI Lab-VIEW (Zaninelli et al., 2016). For data management, including processing, programs such as SQL, Excel VBA, or MATLAB were used (Maselyne et al., 2014; Sales et al., 2015; Li et al., 2017, 2018; Oliveira et al., 2019a; Wang et al., 2019). Designing an RFID system for animal behavior research would require transdisciplinary collaboration among the data management program developer, RFID system integrator and animal scientists.

The system architecture defines how the components and subsystems will be networking with each other and where the components will be installed to meet the application needs and tracking conditions. A specialist

Table 1. Relevant key technical characteristics to consider when selecting the main RFID component to develop an RFID system for monitoring poultry behavior.

Components	Important technical aspects	Definition and relevance
Reader	Operating radio frequencies and bandwidth	Operating radio frequencies refer to the specific range of radio frequencies that an RFID system uses for communication between tags and readers. Typically, these are low frequencies (LF), high frequencies (HF), or ultra-high frequencies (UHF). Knowing the operating frequencies is important to ensure compatibility among system components, regarding the intended application, and with (inter-)national regulations (Parthiban, 2019). The bandwidth is the range of frequencies—the difference between the highest and the lowest frequencies—within which the signals will be transmitted. It depends on (inter-)national regulatory directives (Bolic et al., 2010; Parthiban, 2019). For example, the bandwidth of an RFID operating in the European UHF frequencies (865−868 MHz) is 3 MHz, while that deployed in the United States (902−928 MHz) is 26 MHz. The greater the bandwidth, the greater the capacity of transmitting data and switching channels, thus the lower the risk of collision (Bolic et al., 2010).
	Read range max	The hypothetical maximal distance at which a tag can still be powered in an optimal environment. This detail is crucial for choosing a reader that fits the envisaged application and anticipating unwanted reads (Bolic et al., 2010).
	Reader sensitivity	The weakest signal threshold at which a reader can detect a tag (Nikitin et al., 2012). Knowing this beforehand is crucial as it determines the choice of other system components.
	Transmit power max	Represents the maximum power a reader can send out to the antenna. It would be essential to have these details from the manufacturer to anticipate, for example, how to define the read range and compensate for the loss, mainly due to the cables (Bolic et al., 2010; Buffi et al., 2017).
Antenna	Operating radio frequencies	Specific radio frequencies for which the RFID antennas are designed. If not tuned to those frequencies, the antennas cannot retransmit or receive information from the reader or tag. In addition, the antenna frequency must be compatible with the (inter-)national regulations, the application and other system components (Parthiban, 2019).
	Optimal operational conditions	Conditions external to the system, such as ambient temperature and humidity and quality of power supply. Temperature changes, for example, are known to affect the antenna's radiation parameters (Parthiban, 2019).
	Shape and size	The physical appearance of the antenna. Typically, the size correlates positively with the read range, hence critical to the choice of equipment. Physical appearance is notably of practical importance as it determines how to deploy the antenna across the barn and along the locations of interest (Parthiban, 2019). Examples of RFID antenna shapes include free-form cable-like antennas attachable along any support and standard patch antennas (Adrion et al., 2018).
	Antenna gain	Indication of how strong the signal sent or received by the antenna in a given direction would be. As it is correlated with the width and length of the reading area, knowing the gain helps to choose the suitable antenna (Balanis, 2016).
	Mode of operation	Indicates the length and beamwidth of the radiation field generated by the antenna. This characteristic of the antenna is important because it determines the reading range. Typically, the length of the radio field is described as "far-field" or "near-field" (Parthiban, 2019), and the beamwidth is referred to as "narrow," "intermediate," or "wide" or expressed in degrees (Balanis, 2016). A near-field antenna would be appropriate for monitoring the proximity of a given resource (Bolic et al., 2010).
	Directionality	Defines the focusing ability of the antenna's radiation, that is, the direction in which the antenna should transmit and receive the signal (Parthiban, 2019). In standard patch antennas, 2 types of directionalities are common: unidirectional and omnidirectional. While unidirectional antennas concentrate beams and allow reading in one direction (i.e., across a given plan), omnidirectional antennas radiate spherically and thus can be used for reading in any direction (Balanis, 2016). In contrast, cable-like antennas propagate a localized electromagnetic field cylindrically along the cable axis and contour (Buffi et al., 2017). The directionality characteristic is essential for choosing a suitable antenna. For example, a unidirectional antenna would be inadequate for animal tracking, as animals move in every direction; reading failures might occur.
	Polarization options	Polarization applies to the wave pattern generated by the antenna. It defines the geometric structure that characterizes waves' oscillation. In standard patch antennas, 2 polarization options are common: linear and circular. Linearly polarized antennas spread their waves in a single plane, either vertically or horizontally, while circular antennas spread their waves in a circular pattern. There is a further subclassification of circularly polarized antennas depending on whether their waves propagate clockwise or counter-clockwise: right-hand circular polarized and left-hand circular polarized antennas (Parthiban, 2019). These polarization options do not apply to cable-like antennas; in those antennas, the polarization effects can be optimized; for example, by installing them in U-shaped meander ways (Harting, 2015). Polarization is important as it determines how the signal will be affected by structures or objects in its pathway (Parthiban, 2019).

(*continued*)

Table 1 (*Continued*)

Components	Important technical aspects	Definition and relevance
Tag	Size	Is about the physical dimensions of the tag. The size is important because it correlates with the reading range. Typically, the larger the tag, the longer the reading range (Bolic et al., 2010).
	Weight	Passive RFID tags are generally small and lightweight, often weighing only a few grams or less (Blemel et al., 2019). Using a lightweight tag is crucial for animal tracking as it allows for attaching the tag easily to the animal's body, avoiding harm to the animal's well-being while providing the necessary data on resource visits. Lightweight tags are, for example, convenient for monitoring the activity of broiler chicks throughout the fattening period (van der Sluis et al., 2020).
	Ways of fitting the tag to the animal's body	The tag is fitted to birds in various ways: attached to the ankle (Wang et al., 2019; van der Sluis et al., 2020; Gómez et al., 2022), wing (Tu et al., 2011), neck (Li et al., 2017, 2019a), back (Daigle et al., 2012); or implanted into the feet (Zaninelli et al., 2016), wing, neck or abdominal cavity (Toth et al., 2013). It is important to consider this before purchasing the tag, as how it is fitted to the animal can significantly influence the tracking performance (Zaninelli et al., 2016).
	Operating radio frequencies	Operating radio frequencies are the frequencies (in hertz; Hz) at which a passive RFID tag will operate. Usually, these are LF, HF or UHF. It is important to know the operating frequencies to ensure compatibility with other system components, intended application, and (inter-)national regulations (Bolic et al., 2010).
	Tag range max	Hypothetical maximal range or distance at which a tag can be read in the ideal direction and environment. This detail is crucial for choosing the tag that fits the envisaged application or for anticipating unwanted reads (Bolic et al., 2010; Nikitin et al., 2012).
	Tag sensitivity	Indicates the minimum backscatter signal strength the tag would emit to be identified by a reader (Nikitin et al., 2012). Knowing this detail is important to set the reader's transmit power and reading distance.
	Orientation	Orientation refers to the physical positioning of an antenna, that is, the direction in which it is pointing in order to pick up signals. Here, it applies to the small antenna inside the tag (tag-integrated antenna is not described in the paper). All indications above about antennas also apply here. Some tags can be orientation insensitive, others not. Orientation-insensitive tags pick up the signal in any orientation, making them very suitable for tracking animal behavior, as animal postures and movements can be in any direction.
	Ideal operating conditions	The conditions to be met for the tag to function adequately. These conditions include particularities of the deployment environment such as ambient temperature and humidity ranges, dust levels, frequency of exposure to UV light, presence of metal, water or other tags, and the amount of power supplied by the antenna. Knowing these conditions is necessary to set up a system that meets the user's needs (Parthiban, 2019).
RFID cables	Length and attenuation factor	The length indicates how far the energy sent out by the reader has to travel through the cables to reach the antenna. The attenuation factor is an appreciation of the energy lost per unit of cable measurement; it helps to rate the insulation (Buffi et al., 2017). In particular, the series to which UHF coaxial cables belong, that is, 195, 240, or 400, indicates their insulation ratings. By knowing these 2 characteristics, Adrion et al. (2018, 2020) anticipated how much of the transmit power would be lost to the cables and how much antenna input would ultimately remain.

should carry out the system conceptualization; this guides the deployment of the infrastructure.

Deploying an RFID System. This phase involves 2 steps: installing the equipment and setting up the system.

The installation of an RFID system consists of mounting the equipment, for example, the antenna, reader, and auxiliaries, onto structures across the animal house as planned during the system conceptualization phase. While installing the components, practical arrangements and modifications to the physical environment can be made in order to counteract some potential sources of influence on the performance of the RFID system. Such measures are described in the literature. For example, plastic panels or empty carton boxes have been used to prevent the RFID system from registering animals out of the resources' functional areas (Maselyne et al., 2016a; Li et al., 2019). Likewise, changes can be made to the standard resource dimensions and format to reduce unwanted registrations (Thurner et al., 2009). In addition, a blocking structure can be introduced to prevent animals using the resource from positioning themselves at points where the electromagnetic signal is weakest within the RFID reading zone (Wang et al., 2019). Plastic pipes (e.g., PVC) can be used to protect antennas from dirt, water, or chewing by animals (Adrion et al., 2018), or to distance the antennas from a wall containing metal (Adrion et al., 2020). Also, advantages can be taken from steel's shielding effect to constrain the antenna's magnetic field, thus restricting the reading range to the functional areas of the resource (Li et al., 2019). Most of the remaining adjustments will be in the component settings if appropriate practical arrangements and environmental changes are made during installation.

Setting up the RFID system entails identifying the ideal operational parameters of each component, fine-tuning and operating the system, under reserve of validation with animals, as intended. It is a meticulous process as it includes a lot of trial and error, testing, and comparing combinations of different settings on the reader and antennas. The optimal setting gives the best result from the tests and comparisons. Best results are obtained when the read rate is 100%; the read rate being the fraction of the number of times a tag is read over the number of seconds during which the readings are performed (Ramakrishnan and Deavours, 2006) or over the number of requests sent to the tag (Bolic et al., 2010). Some authors, however, are more flexible; for example, in Wang et al. (2019), 3 reads out of 5 were sufficient.

The range map—a map of the read rate across the area of interest—is the ultimate metric for comparing the various combinations of parameters under test. As presented in Wang et al. (2019), this map is used to assess how detections vary across the area of interest. Sales et al. (2015) used a paper reference of over thirty grid nodes spaced 6 cm apart to map the range. First, the reference grid was placed in the desired reading zone, and the tags, attached to plastic support at a distance of 1 or 2 cm from the ground, were oriented perpendicular to the antennas. Then, the tags in such a position were tested from one node to another. At last, the read rates observed at each node were used to map the range. Range mapping can be used to optimize system performance, as it helps to identify possible dead spots in the zone of interest, destructive interference from the surrounding environment and limits of the applied settings.

Parameters that can be adjusted to achieve a desirable reading zone include “transmit power.” This is the amount of power the reader transmits to the antennas, and it correlates with the reading distance. Therefore, changing the transmit power allows the system’s configurator to define the read range of an RFID system around a given resource (Bolic et al., 2010). The optimal transmit power can be identified by testing several transmit powers starting from 0, as the set point, with increments of 0.5 units (Ramakrishnan and Deavours, 2006; Li et al., 2017). An aid to deciding on the best transmit power can be the “power mapper,” an instrument that measures the RF power at various points of the reading zone. This instrument can be informative about the quality and pattern of the RF signal across the reading zone (Xie et al., 2020). Besides the transmit power, the system configurators have control over other parameters, such as digital modulation and bit error rate, to achieve the desired operating range and best results (Bolic et al., 2010). Setting these latter operational parameters might require an RFID specialist’s assistance and the use of technical documents, such as ISO/IEC 15693 and ISO/IEC 18000-63.

Validating an RFID System Deployed to Monitor Poultry Behavior

The system validation involves testing it with animals to examine its deliverables and report on its fitness-for-purpose: it establishes the reliability and suitability of the RFID system for behavioral monitoring. In other words, the validation study aims to establish the extent to which RFID technology can be accepted as an alternative to the traditional approaches of animal behavior monitoring, such as direct visual observation. Therefore, it would provide valuable evidence and support for adopting the technology.

Before fully adopting the RFID system, the validation study will always be important because each system is unique (Gebhardt-Henrich et al., 2014a). In fact, the read range is highly dependent on the environment and the system components, and there are no standard setting parameters that work for every application. The validation study will be the ultimate step to fine-tune the system setup. For example, in Li et al. (2017) and Adrion et al. (2020), the validation study enabled setting relevant operating standards as it required these researchers to identify technical anomalies and biases in the system outputs, unanticipated system limitations, and critical system elements or operational procedures using animals in the RFID deployment environment.

Approaches of Validating RFID. Various approaches have been used to validate RFID systems for monitoring animal behavior. These approaches may require a comparison of RFID system outputs with external or internal references.

The external reference is often called the "gold standard" or “benchmark.” It should indicate reliably and consistently how the animals use the resource. In behavioral sciences, the most common reference is the human vision which, for practical convenience, involves digital video recordings instead of live observations (reviewed in Table 2). Another external reference may be other automated devices or systems, used in conjunction with the cameras or not, which may indicate how animals use a given resource. For example, in addition to the camera recordings as a reference, Maselyne et al. (2016a) benchmarked their RFID system outputs against water flow meter data for pig drinking behavior; Adrion et al. (2020) used noseband pressure sensor data; van der Sluis et al. (2020) used ultra-wide band system measurements.

Internal reference applies when only information from the same system is used to assess its validity; for example, using the number of entries against the number of exits from the outdoor range (Gebhardt-Henrich et al., 2014a) or using the registrations obtained from a tag attached to 1 leg against those from a tag attached to the second leg of the same chicken (Sibanda et al., 2020a). This approach would be ineffective when 1 or both tags fail to operate. In this respect, the internal 2-tag validation approach might not be as convenient as video validation. Nevertheless, it has the merit of enabling comparison of performance between tags. Moreover, this 2-tag approach can add value to a video-based validation, as shown in Maselyne et al. (2016a).

Indicators of Reliability. The reliability of an instrument is a major indicator of its adequacy. It indicates how repeatable and consistent the measurements

Table 2. Overview of some aspects in selected validation studies of RFID systems deployed for animal behavior monitoring.

Validation study reports	Species	Behavior(s) of interest	Approaches	Duration of registrations and sample size for study or analyses	Bout criteria	Variable (s) used	Indicators used: authors' terminology and formulas
Thurner et al. (2008)	Laying hen	Nesting	RFID outputs vs. Camera recordings (external reference)	374 visits were extracted from the video recordings, and data were collected over 74 d. 699 hens, divided into 2 flocks, were used.	30 s	▫ Timestamps of nest visits ▫ Number of nest visits	▫ "Identification reliability" = (number of visits suggested by RFID × 100)/number of visits indicated by the cameras ▫ "Accuracy" (also referred to as "time discrepancies" and "time differences") = difference (in seconds) in timestamps between videos and RFID
Zaninelli et al. (2016)	Laying hen	Nesting	RFID outputs vs. Camera recordings (external reference)	1,120 nest visits extracted from the videos were analyzed. 20 individuals, equally divided into 2 groups, were involved.	-	Timestamps of nest visits	▫ "Identification speed" = difference (in seconds) timestamps videos vs. RFID. It represents the time it takes to identify individual hens entering the nest.
Thurner et al. (2009)	Laying hen	Outdoor ranging	RFID outputs vs. Camera recordings (external reference)	16 d of video recording, at least 8 h/d; 181 individuals involved. Depending on the pophole width, 582, 606 and 3113 passages were used for the analyses.	-	Number of passages through the popholes	▫ "Identification reliability" = (number of passages suggested by RFID × 100)/ number of passages indicated by the cameras
Thurner et al. (2010)	Laying hen	Outdoor ranging	RFID outputs vs. Camera recordings (external reference)	12,195 passages through the pophole were extracted from a 5-day recording period on 225 hens and a 4-day recording period on 328 hens.	-	Number of passages through the popholes	▫ "Identification reliability" = (number of passages suggested by RFID × 100)/ number of passages indicated by the cameras
Gebhardt-Henrich et al. (2014a)	Laying hen	Outdoor ranging	Number of detected entries vs. Number of detected exits (internal reference)	Data were collected over 12 d. 100−900 focal individuals were tagged, representing 5% of the size of various flocks. 12 commercial flocks were involved.	-	Number of hens passing through barn and veranda popholes	▫ "Probability of registration" calculated using binary variables: "1" if all hens exiting the barn or veranda return effectively, and "0" otherwise.
Li et al. (2017)	Laying hen	Feeding and nesting	RFID outputs vs. Camera recordings (external reference); 2 tags on one of the animals: 1 on the neck for monitoring feeding behavior and 1 on the left leg for nesting behavior	38 one-hour and 78 half-hour episodes of video observations were sampled for feeding and nesting, respectively. Episodes were extracted from a 3-day recording period, and only lighted hours were considered: from 5:00 am to 6:00 pm. A total of 60 individuals were monitored.	30 s for each of the 2 behaviors	Number of animals visiting the resources simultaneously	▫ "Accuracy" = (number of hens detected at the resource according to RFID × 100)/number on videos ▫ Correlation between the number of hens at the videos vs. RFID
Wang et al. (2019)	Laying hen	Perching	RFID outputs vs. Camera recordings (external reference); a load cell module was used to enhance the overall performance of the monitoring system; 2 tags per bird, 1 attached to each leg	Recordings were over 7 d. 15 individuals, evenly distributed across 3 pens, were involved.	15 s or 3 s, depending on the considered variables	▫ Number of visits ▫ Duration of visits	▫ "Sensitivity" = TP × /P ▫ "Specificity" = TN × /N ▫ "Precision" = TP × /(TP + N-TN) ▫ "Accuracy" =(TP + TN)/(P + N)

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Table 2 (*Continued*)

Validation study reports	Species	Behavior(s) of interest	Approaches	Duration of registrations and sample size for study or analyses	Bout criteria	Variable (s) used	Indicators used: authors' terminology and formulas
Sibanda et al. (2020a)	Laying hen	Feeding, nesting, movement	Recordings from right leg tag vs. Recordings from left leg tag (internal reference)	Data collected over 30 d, 18 hens involved	-	▫ Number of visits ▫ Duration of resource visits	▫ Coefficient of determination (r^2) for the number of visits suggested by right leg tag vs. left leg tag on each laying hen; linear regression was used ▫ Coefficient of determination (r^2) for the duration of visits suggested by right leg tag vs. left leg tag on each laying hen; linear regression was used
Sales et al. (2015)	Laying hen	Preference and transition across functional locations	RFID outputs vs. Camera recordings (external reference)	256 h of recordings were collected over 24 h. 40 individuals were involved: 32 (divided into groups of 4) were monitored as a group, and 8 monitored individually.	-	▫ Timestamps of entries ▫ Duration of visits ▫ Number Frequency of visits	▫ "Delayed detection times" (i.e., lag timestamps of entries) video vs. RFID ▫ "Detection success rates" based on entries = (number of entries suggested by RFID × 100)/number of actual entries indicated by the cameras) ▫ "Detection success rates" based on duration = (duration of visits according to RFID × 100)/ duration of visits indicated RFID by videos) ▫ Statistical comparisons of total visit duration, number of entries and average single visit duration between data from cameras and RFID
van der Sluis et al. (2020)	Broiler	Activity	RFID outputs vs. Recordings from cameras and ultra-wideband (UWB) tracking system (2 external references)	4 videos, each 7 min long, were selected at different time points over 34 d of recording; videos were converted into frames per second, and the bird's location was annotated. A total of 1,629 frames were analyzed. 40 broilers were involved.	-	▫ Locations visited ▫ Distances walked (in meters)	▫ "Percentage of exact matches" or "percentage of (dis)agreement" of identified location = registrations of locations according to RFID × 100/registrations of locations according to videos ▫ Correlation between walk distances calculated from RFID outputs vs. Video recordings ▫ Correlation between walk distances calculated from RFID data vs. UWB data
Li et al. (2019)	Broiler	Feeding and drinking	RFID outputs vs. Camera recordings (external reference); a tag attached to the neck used to monitor both behaviors	55 two-minute video recordings were obtained over 7 d. The videos were sampled every 2 h, and only the lighted hours of the day were considered. The videos were converted into frames on a 1-s basis: a total of 13200 frames were analyzed. A total of 120 tagged individuals equally distributed in 2 experimental rooms were used.	20 s for each of the 2 behaviors	▫ Instantaneous number of birds at each of the resources ▫ Duration of visits	▫ For the instantaneous number of birds, "Accuracy" = (number of seconds for which the number of birds observed in each frame matches the number suggested by the RFID × 100)/ number of seconds in a 2-min video, i.e., 120 s) ▫ For time spent at resources, "Accuracy" = (total number of birds at resources as suggested by RFID × 100)/ total number of birds at resources as indicated by the frames

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Table 2 (*Continued*)

Validation study reports	Species	Behavior(s) of interest	Approaches	Duration of registrations and sample size for study or analyses	Bout criteria	Variable (s) used	Indicators used: authors' terminology and formulas
Adrion et al. (2018)	Pig	Feeding	RFID outputs vs. Camera recordings (external reference)	13 d of observations, 10 h of recording per day, and 25 individuals involved	20 or 30 s, depending on the type of antenna	▫ Duration of visits ▫ Number of feeding events (meals)	▫ "Sensitivity" = TP/P ▫ "Specificity" = TN/N ▫ "Precision" = TP/(TP + FP) ▫ "Accuracy"=(TP + TN)/(P + N) ▫ Correlation of total daily duration visit based on data from RFID vs. Cameras ▫ Correlation of total daily number of meals based on data from RFID vs. Cameras
Maselyne et al. (2014)	Pig	Feeding	RFID outputs vs. Camera recordings (external reference); 2 ear tags used	11.5 h of video recording were analyzed. A total of 20 focal pigs were considered.	9 s	▫ Duration of resource visits ▫ Number of resource visits	▫ Correlation of visit durations based on data from RFID vs. Cameras ▫ "Sensitivity" = TP/P ▫ "Specificity" = TN/N ▫ "Accuracy" = (TP + TN)/(P + N) ▫ "Precision" = TP/(TP + N-TN) ▫ "Percentage of correct RFID registrations" on a 10-s basis ▫ "Percentage of correctly identified visits" ▫ "Agreement between video and RFID" on a 20-s basis
Maselyne et al. (2016b)	Pig	Feeding	RFID outputs vs. Camera recordings (external reference); 2 ear tags used	Two experiments: One with 20 pigs and 11.5 h of video recording obtained 1 d; the other with 6 pigs with 14 h of video recording obtained over 3 d.	20 s when 1 tag was considered, 10 s for 2 tags	▫ Duration of resource visits ▫ Number of visits ▫ Inter-visit duration	▫ "Sensitivity" = TP/P ▫ "Specificity" = TN/N ▫ "Accuracy" = (TP + TN)/(P + N) ▫ "Precision" = TP/(TP + FP) ▫ Correlation of visit durations based on data from RFID vs. cameras
Maselyne et al. (2016a)	Pig	Drinking	RFID outputs vs. Recordings from cameras and Water flow meters (2 external references); 2 ear tags used	393 visits were extracted from the camera recordings. The videos were collected over 2 d, with 12 h of observation per day. In total, 53 tagged animals were involved.	20 s	▫ Duration visits ▫ Average duration ▫ Intervisit duration ▫ Number of visits	▫ "Sensitivity" = TP/(TP + FN) ▫ "Specificity" = TN/(FP + TN) ▫ "Precision" = TP/(TP + FP) ▫ "Accuracy" = (TP + TN) / (TP + FN + FP + TN) ▫ Correlation RFID vs. Video recordings ▫ Correlation RFID vs. Water flow meter recordings ▫ Comparison test (paired *t* test) of recordings from RFID vs. Videos ▫ Comparison test (paired *t* test) of recordings from RFID vs. Water flow meters
Toaff-Rosenstein et al. (2017)	Cow	Grooming	RFID outputs vs. Camera recordings (external reference); 2 ear tags used	6 h of continuous video recording per group were obtained, and 2 groups of 8 cows each were used. The recordings were made over 2 d.	16 s	Duration of visits	▫ Regression of visit duration based on data from RFID vs. Videos ▫ "Sensitivity" = TP/P ▫ "Specificity" = TN/N

(*continued on next page*)

Table 2 (*Continued*)

Validation study reports	Species	Behavior(s) of interest	Approaches	Duration of registrations and sample size for study or analyses	Bout criteria	Variable (s) used	Indicators used: authors' terminology and formulas
Adrion et al. (2020)	Cow	Feeding	RFID outputs vs. Camera and Noseband pressure sensor recordings (2 external references).	48 h of video recordings from a 3-day observation period were analyzed. 10 cows were involved in the validation study	120 or 180 s, depending on the type of tag.	Duration of visits	□ "Sensitivity" = TP/P □ "Specificity" = TN/N □ "Precision" = TP/(TP + FP) □ "Accuracy" = (TP + TN)/(P + N) □ "Mean of the differences" in visit durations based on data from RFID vs. Cameras □ "Mean of the differences" in visit durations based on data from RFID vs. Noseband pressure sensor □ Correlation of hourly time spent at resource based on data from RFID vs. Videos □ Correlation of hourly time spent at resource based on data from RFID vs. Noseband pressure sensor

taken from the instrument are (Bateson and Martin, 2021). The body of literature on RFID in animal behavior research shows that reliability has been assessed using the following indicators: precision, sensitivity, correlation coefficient, and the difference in measurements between the reference and the RFID.

Precision refers to the degree to which measurements provided by an instrument are free of random error (Bateson and Martin, 2021). For example, in the context of RFID deployment, a 50% precision would indicate that about half of the registrations that RFID suggests are not real; these are false positives (**FP**, Figure 4), identified as such after comparisons with video registrations (Adrion et al., 2018). Low precision is observed when the antennas or the reader settings are not carefully tuned to ensure that the read range adequately covers the functional area of the resource of interest. As a result, the read range exceeds the functional area of the resource of interest, and FP (i.e., unwanted registrations) become significant (Brown-Brandl et al., 2019). Such a definition of precision was adopted by Adrion et al. (2020) and Maselyne et al. (2016a). The calculation formula used by these authors is: Precision = TP/(TP + FP), where TP are true positives and FP are false positives. Figure 4 illustrates each of the terms in the formula. For the calculations, these authors used the number of seconds each visit sequence lasted or the number of visits. The precision calculated in this way is also called the "positive predictive value" (Adrion et al., 2020). The minimum accuracy recommended by Brown-Brandl et al. (2019) before adopting RFID in livestock tracking is 70%.

The sensitivity of an instrument indicates how many instances or figures measured by it are true (i.e., actual occurrences); sensitivity is the proportion of instances correctly identified by the instrument being evaluated relative to the total number of actual occurrences indicated by an external reference (Caguci, 2003). A quite common way of calculating sensitivity is to divide the correctly identified instances of the instrument by the "true" instances, which are marked as "gold standard" or "reference": Sensitivity = TP/P; where TP are true positives and P are positives. For example, if there are 10 actual occurrences of a chicken passing through a pophole, as confirmed by video recordings, while only 7 of these are detected by the RFID system, the sensitivity of the RFID system would be 70% (7/10). In such a case, the 10 actual occurrences are referred to as "positives"; the 7 successfully detected occurrences by the RFID are termed "true positives"; and the 3 missing instances are regarded as "false negatives." According to that commonly used formula, the higher the fraction, the more sensitive RFID is. Sensitivity was defined and calculated in this way by Adrion et al. (2020), Maselyne et al. (2014), and Toaff-Rosenstein et al. (2017). However, other authors have used this formula but named it in different ways: percentage of "exact matches" or "(dis)agreement" (van der Sluis et al., 2020) and "identification reliability" (Thurner et al., 2010). It is important to note that, like sensitivity, these metrics do not

	Positives (P)						Negatives (N)					
Videos	✓	✓	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗
RFID	✓	✓	✓	✗	✗	✗	✗	✗	✗	✓	✓	✓
	Correct readings **(True Positives; TP)**			Reading failures **(False Negatives; FN)**			Correct readings **(True Negatives; TN)**			False readings **(False Positives; FP)**		

Figure 4. An illustration of the terms included in the formulas for quantifying the adequacy of RFID systems deployed for monitoring animal behavior. Positives (P) are seconds of visit events according to the videos. The negatives (N) are seconds of nonvisit events, according to the videos. True positives (TP) are seconds of visit events indicated by the RFID and which agree with the video recordings. True negatives (TN) are seconds of nonvisit events suggested by the RFID and confirmed by the video recordings. False negatives (FN) are seconds of visit indicated by the videos, but the RFID suggests otherwise. False positives (FP) are seconds of nonvisit events indicated by the videos, but the RFID suggests otherwise. Whereas TP and TN are correct readings, FN and FP are misreadings compromising the validity of the RFID system.

consider "false positives" and focus solely on correctly identified actual occurrences—"true positives." For example, in Van der Sluis et al. (2020), the "percentage exact matches" represented the proportion of correct location records made by the RFID system compared to video observations. Accordingly, the authors calculated that percentage without taking into account FP locations of tracked birds; "false positives" being the mismatches resulting from intermittent tag registrations between the antennas. "Sensitivity" would be calculated in the same way. Low sensitivity will generally be observed for an RFID whose recordings do not occur continuously but with an irregular interval between recordings; irregular reading is quite common in RFIDs deployed for animal tracking (Adrion et al., 2018). Nevertheless, Brown-Brandl et al. (2019) recommend a minimum sensitivity of 80% before fully adopting an RFID system for monitoring the behaviors of livestock, including poultry.

The correlation between the instances recorded by the behavior-measuring instrument and the reference (or gold standard) can also be an indicator of reliability (Martin and Bateson, 2007). It is quite common in reports of RFID validation for animal behavior monitoring (Table 2). The correlation between RFID and camera outputs expresses statistically the extent to which the 2 behavioral monitoring means agree. For example, with a correlation coefficient of $r = 0.7$, the coefficient of determination is $r^2 = 0.49$, meaning that the video recordings would statistically explain about 50% of the variance in the RFID data. In the body of literature on RFID in poultry behavior research, correlation as an indicator of reliability was calculated using variables such as the duration of resource visits, the number of visits (Sibanda et al., 2020a), or the number of animals in the read range (Li et al., 2017). Martin and Bateson (2007) recommended a minimum correlation coefficient of 0.7 to attest to the reliability of an animal behavior monitoring instrument.

Last, the difference in measurements between the reference and RFID was used as an indicator of adequacy. This approach, estimating variability using the mean or standard deviation, implies that the closer the measurement of the 2 recording means, the more adequate the instrument is (Salkind, 2010). The formula is as follows: difference = video recordings − RFID recordings (reviewed in Table 2). However, the terminology used to refer to this formula varies among authors: "delayed RFID detection time" (Sales et al., 2015), "identification speed" (Zaninelli et al., 2016), "average differences" (Adrion et al., 2020), "accuracy," "time differences," and "time discrepancies" (Thurner et al., 2008). These inconsistencies may lead to confusion.

Indicators of Validity. Validity is a second major indicator of the adequacy of a newly developed instrument. It expresses the extent to which the instrument measures what it is supposed to measure (Bateson and Martin, 2021). Based on the literature, 2 indicators are commonly used to quantify the validity of the RFID systems deployed to monitor animal behavior: accuracy and specificity. The classic formulas used are "Accuracy" = (TP + TN)/(P + N) and "Specificity" = TN/(FP + TN), with the camera recordings as reference (Table 2).

However, using these formulas to quantify the validity of RFID deployed for monitoring indoor resource visit behaviors in group-housed chickens can be misleading. The main reason for this is that specificity and accuracy tend to be high and may therefore lead to overestimating the system's performance. Overestimations occur because, in the formulas, the numerators comprise "true negatives" (i.e., when the animal does not visit the resource), which are usually high. Chickens spend most of the day away from indoor resources; they usually use them only briefly and only at certain times of the day. For example, cage-free and colony-caged laying hens spend around 6.2 and 4.4% of their daily time budget in the nest boxes, respectively (Oliveira et al., 2019a; Sibanda et al., 2020d). Broilers spend only about 3% of their day at the drinker and 13% at the feeder (Li et al., 2020). In addition to their tendency to inflate the performance indicators, true negatives are inefficient to record. Recording video only during the time windows when the animals mostly visit resources would be more practical and cost-effective than recording the lengthy periods of nonvisit.

Some authors introduced alternatives to the classic formula for calculating accuracy. For example, Li et al. (2019) used the instantaneous number of animals. The authors obtained this using frames extracted on a 1-s second basis from 2-min video samples. Accuracy was then calculated as the percentage of birds detected by the RFID system relative to the number of hens observed in the video images. Li et al. (2017) also used a similar approach.

Overall, we recommend that whenever an author evaluates and reports on the validity of RFID for monitoring poultry behavior, care should be taken to use the most common terminologies and calculation methodologies possible and, above all, to describe these. As for the interpretation of validity indicators, there is no black-and-white threshold above or below which the acceptability of the RFID system would be unequivocal. However, suggestions in the literature are provided in the present study.

Methods for Calculating the Bout Criterion. Bout criterion is the maximum inter-registration duration considered during RFID data processing; it is the threshold for the inclusion of 2 consecutive RFID registrations in the same resource visit event (Maselyne et al., 2016b; Li et al., 2017; Adrion et al., 2018; Wang et al., 2019). For example, if a 10-s bout criterion is used, and the interval between 2 successive RFID registrations is shorter than 10 s, then the 2 registrations will belong to the same resource visit event. But, if that interval was larger than 10 s, these 2 registrations would belong to different visit events.

The methods for calculating the bout criterion vary according to the authors. Brown-Brandl and Eigenberg (2015) introduced a method consisting of 3 steps. In the first step, the authors plotted the average number of daily visits, and the total and average duration of daily visits for all animals studied against different bout values, potential optimal minimum intervals between visits. These examined potential bout values, for which the rationale for selection was not mentioned, were: 1, 2, 3, 5, 10, 15, 22.5, 30 and 60 s. Of these graphs of visit estimates, those that changed as uniformly as possible with a single inflection point were selected. For example, the plot of the number of meals per day was selected over others because it showed a steady decrease at the beginning, followed by a plateau. Next, the authors investigated the rate of change of this selected resource visit estimate. This investigation required the plotting of the first and second derivatives of estimates. Last, the authors identified the point where the first derivative is at its minimum and the second is equal to zero. The corresponding bout value was thus considered optimal. The reason behind this procedure is that, at that point, the rate of change of the resource visit estimates was also minimal. Following this method, Adrion et al. (2018) identified 20 or 30 s, depending on the type of antennas, as the optimal bout criteria applicable to their RFID data to determine the daily number of visits to the feed trough in pigs.

Maselyne et al. (2016b) introduced a second method based on the mean deviation between data obtained from RFID technology and video recordings in a study on pig feeding behavior. This method was subsequently adopted by Wang et al. (2019), who referred to it as the "average error rate" to investigate the perching behavior of laying hens monitored with RFID. The approach involves 3 steps. First, different potential bout values were considered: 0, 1, 2, 3, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, and 60 s in Maselyne et al. (2016b); and 1, 3, 5, 10, 15, 20, 25, 30 s in Wang et al. (2019). The rationale for choosing these specific potential bout values was not specified in both papers. Second, the measurements suggested by the RFID system for each animal involved were adjusted using the different bout values. In parallel, the corresponding "true" measurements were extracted from the video recordings. Third, from both types of measurements, the average error rates were calculated as follows: average error rate = AVERAGE[(bout-corrected measurements − video-based measurements) × 100/ video-based measurements)]; the absolute value was used. An illustrative example of this third step is as follows: if, after using a given bout value, the average bout-corrected number of visits according to the RFID is 401 while that indicated by the video recording is 443, then the average error rate will be: $\left|(401 - 443) \times 100/443\right| = 9.48\%$. Finally, the bout value resulting in the lowest average error rate was adopted. Maselyne et al. (2016b) thus identified 20 s as an appropriate bout criterion applicable to their RFID registrations about feeding behavior in pigs tagged at 1 ear. Similarly, Wang et al. (2019) identified 15 s as suitable for their RFID data on the number of perch visits in laying hens.

A third method Li et al. (2017) proposed involves plotting the differences in duration between adjacent RFID recordings from a number of tags to obtain a histogram. These duration differences were then considered as potential bout values. The time difference for which 95% of the RFID recordings match those of the videos was then considered as the optimal bout criterion. Using this method, the authors identified 30 s as the optimal bout criterion for reconstructing out of their RFID data the visits to drinkers and feeders in broilers.

The last method is a 2-step method introduced by Adrion et al. (2020). In the first step, the authors considered different potential bout values. Then, they selected the bout value that gave the maximum average accuracy, the minimum FP and the minimum false negatives. Using this method, the authors identified 120 or 180 s, depending on the type of tags, as the optimal bout criteria applicable to their RFID data to reconstruct the duration of the cow visits to the feed trough.

To sum up, various methods of calculating the bout criterion have been developed, and all of them have merits. However, even if the use of the bout criterion allows to compensate for the missing data to a certain extent, it does not apply to false readings. Therefore, precautions are essential when designing and implementing the system since they help minimize false readings and missing data.

Data Requirements for RFID Validation in Poultry. Despite the importance of a validation study before the full adoption of RFID technology for monitoring animal behavior, very little is known about the amount of data needed to conduct such a study; there is no golden rule in this respect. Here, we attempt to address this gap.

Based on 17 hand-selected papers on RFID validation in animal science (Table 2), the determination of the number of use events ("positives") and nonuse events ("negatives"), major outcome variables used as references, can be seen as a good starting point for assessing the amount of data required for a validation study. Although we did not find, in the context of RFID, any established reference mentioning the use of sensitivity and specificity to estimate the number of sequences corresponding to these outcome variables to be extracted from videos, we believe, following Bujang and Adnan (2016), Akoglu (2022), and Bujang (2023), this approach is relevant if complemented by other assumptions and statistical considerations, such as the prevalence of the targeted behavior and the desired level of statistical power. Then, several other factors can be taken into account to approximate the amount of data needed to validate RFID for poultry behavioral monitoring.

Conventional sample size estimation formulas (e.g., Akoglu, 2022) can be used to approximate the total number of use events ("positives") and nonuse events ("negatives") from video recordings to be included in the analyses. These formulas can be supplied with desired sensitivity and specificity values.

With a desired sensitivity, the approximation will be as follows:

$$Nr\_seq = \frac{(Z_{\alpha/2})^2 \times \mathit{Sensitivity} \times (1 - \mathit{Sensitivity})}{E^2}$$

where sensitivity, estimated from previous or pilot studies and desired by researchers, is the proportion of true positives (**TP**) among the positives (**P**): it measures the ability of RFID to identify use events correctly. The term $\mathit{Sensitivity} \times (1 - \mathit{Sensitivity})$ represents the variance of the sensitivity. $Z_{\alpha/2}$ is the Z-score associated with the probability $\alpha/2$, and E is the tolerable margin of error for the sample estimate.

Similarly, with a desired specificity considered, the approximation will be as follows:

$$Nr\_seq = \frac{(Z_{\alpha/2})^2 \times \mathit{Specificity} \times (1 - \mathit{Specificity})}{E^2}$$

where specificity, estimated from previous or pilot studies and desired by researchers, is the proportion of true negatives (**TN**) among negatives (**N**); it measures the ability of the RFID to identify nonuse events correctly. In this formula, the term $\mathit{Specificity} \times (1 - \mathit{Specificity})$ represents the variance of specificity; $Z_{\alpha/2}$ is the Z-score associated with the probability $\alpha/2$; E is the tolerable margin of error for the sample estimate.

Applying the 2 formulas results in 2 different sample sizes. In order to determine the relevant one, the larger of the 2 sample sizes can be selected, as this approach ensures that the sample is large enough to achieve the desired sensitivity and specificity. Regarding RFID for monitoring animal behavior, sensitivity, and specificity should be considered important adequacy indicators (Brown-Brandl et al., 2019).

The Nr_seq calculated and selected in this way includes events and nonuse events, but these need to be proportional to each other to reflect how a given behavior is naturally expressed in the animal population. The ratio of the use events to nonuse events can be determined in advance by observing a sample of videos. Finally, this ratio will be applied to the considered Nr_seq in order to distinguish the number of use and nonuse events that should be randomly extracted from the videos and focused on for the analyses. By randomly extracting from the video recording sequences according to the considered ratio, one can ensure that the sample is representative of the animal population to be monitored with the RFID.

To illustrate, let us assume that we would like to validate an RFID monitoring system deployed to record chickens as they pass through a pophole to access an outdoor range. Let us also assume that the desired sensitivity is 80%; the desired specificity is 95%; and the assumed ratio of passages to nonpassages is 6:4. Finally, let us assume a 95% confidence level and a 5% margin of error are desired. The Z-score corresponding to the confidence level would be 1.96. Using the sample size estimation formulae, we can calculate the required sample sizes as follows:

$$\text{With the desired sensitivity value} : Nr\_seq = \Big(1.96\,\hat{}\,2 \times 0.80 \times (1 - 0.80)\Big)/0.05\,\hat{}\,2; \quad Nr\_seq \approx 246$$

$$\text{With the desired specificity value} : Nr\_seq = (1.96\,\hat{}\,2 \times 0.95 \times (1 - 0.95)\Big)/0.05\,\hat{}\,2; \quad Nr\_seq \approx 73$$

Of the 2 obtained Nr_seq's, the one calculated with sensitivity is the higher; it will be retained for further steps of the approximation. For the sample to be representative of the behavior that would be observed in the total population of birds studied, it would be appropriate to include approximately 60% of use events and 40% of nonuse events in the video sequences to be extracted for analysis—the assumed ratio of passages to nonpassages was 6:4. Thus, in this case, where 246 (i.e., the Nr_seq calculated using sensitivity) is retained, the required number of passages (i.e., use events or positives; P) to be extracted from the videos will be: P ≈ 148 (i.e., 246 × 0.60); and that of the required number of nonpassages (i.e., nonuse events or negatives; N) will be N ≈ 98 (i.e., 246 × 0.40).

To sum up, we would need for analysis a sample size of approximately 246 sequences (i.e., passages: 148; nonpassages: 98) to extract from the video recordings in order to achieve an 80% sensitivity and 95% specificity while maintaining the 6:4 ratio of use to nonuse events. It is important to note that this illustrated approach cannot be generalized to all poultry behaviors; for simplicity, we chose the pophole usage because it is likely to be one of the least complex behaviors to monitor in poultry: monitoring it with RFID requires just entry/exit registrations as opposed to other more complex behaviors (e.g., feeding, drinking), whose monitoring would involve duration calculations or determination of bout criteria (Brown-Brandl et al., 2019).

Once the number of use events (P) and nonuse events (N) required are known, consideration can be given to the number of animals, pens, and facilities to focus on, the recording durations, and the sampling method necessary for the validation study. In order to obtain a representative data sample, several factors need to be taken into account. These factors include environmental variability, intra- and interbehavioral variability, intra- and interanimal variability, time of day, age, genetics, type of animal, and practicability of the validation study.

Environmental variability is an important factor to consider when deciding on the type and amount of data required to validate an RFID system in poultry behavior science. Environmental factors, such as position, accessibility, design, and other specifics of a given housing facility, and microclimatic conditions within the barn, can lead to variations in the use of resources by the birds. For example, chickens prefer less exposed nests located at the end of the row or in corners (Clausen and Riber, 2012), and perch as high as possible (Brendler and Schrader, 2016). In addition, a poultry barn may contain different pens or compartments, each with distinct characteristics, requiring data collection in each of these to capture behavioral variation fully. Therefore, it is essential to consider environmental variability when designing validation studies for poultry RFID systems.

Intrabehavioral variability is another important factor to consider when estimating the amount of data required to validate an RFID system in poultry behavior science. This variability may be reflected in differences in the frequency with which the behavior is performed at different times of the day or under different environmental conditions. For example, dustbathing behavior is more intense at the warmest or brightest times of the day. In addition, this behavior has several distinct aspects, such as scratching, crouching on the substrate, lateral laying and rubbing, and usually ends after about 20 min—if undisturbed—with body parts' straightening and shaking to remove the dust (Olsson and Keeling, 2005). It is, therefore, essential to consider these variations when recording videos and extracting relevant sequences to obtain a representative sample of the behavior expression. Also, it would be inappropriate to validate the use of RFID based on only one part of the behavior sequences or aspects. Therefore, researchers must be informed of and include all aspects of behavior when recording videos and selecting sequences for analysis.

Interbehavioral variability is another crucial factor to consider when estimating the amount of data needed to validate an RFID system for monitoring poultry behaviors. This is because the various types of behavior differ considerably from each other. For example, under typical climate conditions, a white-strain laying hen in an enriched colony housing may spend, on average, 310 min at the feeder but only 56 min in the nest to meet its daily needs (Li et al., 2017). Therefore, the amount of data, the recording duration, the number of video footages, and animals required in the RFID validation study are behavior-specific. Moreover, it will be important to consider the age, genetic line, or type of animal involved.

Furthermore, animals may differ considerably from each other in the display or pattern of a specific behavior. For example, some birds may show consistent behavioral patterns across days, while others do not (Rufener et al., 2018; Gómez et al., 2022) . This suggests that it would be inappropriate to validate the use of RFID based on the behavior of a single bird, as the behavior of an individual bird may not be representative and generalizable. Therefore, including as many individuals as possible in the study sample is essential to capture these variabilities.

A final important aspect to consider is the practicality of the validation approach to be used. Indeed, researchers need to strive for a balance between the representativeness of the data to be collected and the feasibility of its management, which includes, for instance, the time and resources needed to evaluate the videos. Although the use of videos to validate animal behavior is a very useful and recommendable approach, it can also present difficulties: identifying different animals on a video can be challenging for human observers. Some methods, such as plumage coloration or distinctive markings on the back of the birds, can help to differentiate them (Wang et al., 2019; van der Sluis et al., 2020). Nevertheless, it is conceivable that difficulties in differentiating individuals may arise when the sample size is large; the difficulty would be more pronounced in the case of a shared resource to be visited simultaneously by many animals. Therefore, determining an approach that minimizes constraints and allows for efficient collection, storage, and analysis of video and RFID recordings is crucial.

In summary, there is no golden rule for determining the amount of data needed to validate RFID systems for monitoring poultry behavior. However, considering several factors intrinsic to the environment, animals, and behaviors of interest, as well as the material resources available, researchers can assess the amount of data on which validations can be based. For such an assessment, the number of use events (i.e., positives; P) and nonuse events (i.e., negatives; N) to be extracted from the videos, considering previous studies, can be a reasonable starting point. A statistical approach to approximating these numbers was explained and illustrated with a hypothetical case of RFID deployed to monitor the pophole use behavior in chickens.

Reporting on Technical Aspects and Validity of a Deployed RFID System

A detailed report describing the technical aspects and presenting the results of a validation study of a deployed

Table 3. A checklist and examples of how to present the relevant technical aspects.

Relevant technical aspects	How to present them	Checkboxes
Indicate the motive for the RFID deployment	Indicate the tracking objectives, including estimates of behaviors to be computed, that motivate the deployment of the RFID system.	☐
Describe tracking conditions and requirements	Describe the particularities of the behaviors of interest and characteristics of the deployment environment, with a particular focus on how these behavioral and environmental specifics can be potential sources of influence on the RFID system's performance.	☐
Specify the measures taken to ensure the proper functioning of the deployed system	Describe and justify the optimization measures, be they environment-related or regarding the technical settings of the system components, or considering the behavioral specificities of the animal species, which are implemented to ensure the proper functioning of RFID. The way in which Li et al. (2019) presented these system optimization measures can serve as an example.	☐
Specify the technical characteristics of each of the main components of RFID	Specify each main RFID component's technical characteristics and why these characteristics have been used as criteria for selecting the components. If the components are commercially available, referencing them with at least the commercial name of the model and the name of the manufacturer would be sufficient. Sales et al. (2015) provide a good example. If these components are not commercially available (cases of customized or self-built components), giving information about each main RFID component's manufacturer and technical aspects will be necessary.	☐
Present a system architecture diagram	Provide a conceptual diagram that shows schematically how the components and the subsystem interwork. This structural diagram is meant to give an idea of the system's behavior and data flow. For example, Zhang et al. (2016), Li et al. (2017), and Sibanda et al. (2020a) present such conceptual diagrams for RFID deployed for animal behavior tracking.	☐
Present the data management system	Indicate the system for acquiring data, the procedure for processing them, and how the resource visit is estimated to answer the research questions. If the data management system is commercially available, the name of the program and the firm providing it should be specified. If it is custom-made, then specifying at least the programing environment and language and the database management tools will be crucial. Li et al. (2017) can inspire how to present the data management system.	☐
Describe measures taken to control potential influencing factors of system performance	Describe practical arrangements and modifications made to the physical environment to counteract the potential sources of influence on the performance of the RFID system. Examples of such descriptions are presented in Maselyne et al. (2016a) and Li et al. (2019).	☐
Describe testing and fine-tuning processes	Describe the trial-and-error made with various combinations of configuration and operating settings of system components to achieve the best possible performance.	☐
Indicate the placement of the antennas	Describe the antennas' placement, including where their location and how they are physically mounted and protected in the deployment environment. This description also includes the configuration, for example, polarization. In the literature, antenna placement is described and presented in images by Maselyne et al. (2016a) and Adrion et al. (2020). Their ways of describing the antennas' placement can be recommended.	☐
Indicate the operating parameters of the system finally adopted	Indicate the configuration and operating settings adopted finally. Such indications may include the adopted transmit or output power and mode of communication between tags and readers (Adrion et al., 2020).	☐
Characterize the reading range	Schematically present the tags' detectability across the reading area. For example, one could be inspired by Wang et al. (2019) and Adrion et al. (2020).	☐

RFID system for observing animal behavior is essential to ensure the reproducibility of research involving this technology and the reliability of the data collected. The report should first address the technical aspects, such as the infrastructure, architecture, optimization tests, and their results, and the operating parameters adopted. It is also appropriate to mention technical anomalies, identified biases, unforeseen limitations of the system, and critical elements of the deployment environment. Next, the report should present the results of the system validation, examining the deliverables and determining its fitness-for-purpose. Details of external references used, such as video recordings or other forms of behavioral measurement, and performance indicators, such as reliability, accuracy, validity, sensitivity, or agreement, should be included. To facilitate the writing of such a report, we propose a checklist and examples of presenting the relevant technical aspects (Table 3), and a review of validity and reliability indicators (Table 2).

CONCLUSIONS

This guideline paper explains, for a nontechnical audience, how RFID works and its potential to improve the study of poultry behavior. It provides a 4-phase roadmap to facilitate the development and implementation of an RFID system for monitoring poultry behavior. It also summarizes validation approaches in the literature and highlights relevant aspects to be reported on the technical aspects and validity of a deployed RFID system. The guideline is intended for animal behavior scientists, RFID system integrators and equipment manufacturers. It provides a reference for effectively deploying an RFID system in poultry behavior research. By following this guideline, researchers will be able to exploit RFID technology better to advance the study of poultry behavior, thereby improving our understanding of these animals and ultimately contributing to animal welfare and sustainable production.

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DISCLOSURES

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

SUPPLEMENTARY MATERIALS

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.psj.2023.102799.

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