Animal 18 (2024) 101192

Contents lists available at ScienceDirect

Animal

The international journal of animal biosciences

Exploring individual responses to welfare issues in growing-finishing pig feeding behaviour

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ARTICLE INFO

Article history:
Received 1 February 2024
Revised 6 May 2024
Accepted 7 May 2024
Available online 17 May 2024

Keywords:
Behavioural deviations
Feeding patterns
Health issues
Heat stress
Precision Livestock Farming

ABSTRACT

The feeding behaviour of individual growing-finishing pigs can be continuously monitored using sensors such as electronic feeding stations (**EFS**s), and this could be further used to monitor pig welfare. To make accurate conclusions about individual pig welfare, however, it is important to know whether deviations in feeding behaviour in response to welfare issues are shown only on average or by each individual pig. Therefore, this study aimed (1) to quantify the individual variation in feeding behaviour changes in response to a range of welfare issues, and (2) to explain this individual variation by quantifying the responses to welfare issues for specific subgroups of pigs. We monitored four rounds of 110 growing-finishing pigs each (3–4 months per round). We collected feeding behaviour data using IVOG® EFSs and identified health issues and heat stress using climate sensors and twice-weekly health observations. For each pig, a generalised additive model was fitted, which modelled feeding behaviour through time and estimated the effect of each welfare issue that the pig had suffered from. The range of these effect estimates was compared between pigs to study the individual variation in responses. Subsequently, pigs were repeatedly grouped using physical and feeding characteristics, and, with meta–subset analysis, it was determined for each group whether a deviation in response to the welfare issue (i.e. their combined effect estimates) was present. We found that the range in effect estimates was very large, approaching normal distributions for most combinations of welfare issues and feeding variables. This indicates that most pigs did not show feeding behaviour deviations during the welfare issue, while those that did could show both increases and reductions. One exception was heat stress, for which almost all pigs showed reductions in their feed intake, feeding duration and feeding frequency. When looking at subgroups of pigs, it was seen that especially for lameness and tail damage pigs with certain physical characteristics or feeding strategies did consistently deviate on some feeding components during welfare issues (e.g. only relatively heavier pigs reduced their feeding frequency during lameness). In conclusion, while detection of individual pigs suffering from heat stress using feeding variables should be feasible, detection of (mild) health issues would be difficult due to pigs responding differently, if at all, to a given health issue. For some pigs with specific physical or behavioural characteristics, nevertheless, detection of some health issues, such as lameness or tail damage, may be possible.

Implications

Growing-finishing pigs may change their feeding behaviour during welfare issues. Detecting these changes with sensors and algorithms could identify welfare-compromised pigs. We observed clear reductions in pigs' feeding activity during heat stress, while during health issues many individual pigs showed no behavioural change or changed in opposing directions. Therefore, the detection of heat stress from feeding behaviour seems feasible, while detecting individual pigs with health issues seems difficult. Since some specific types of pigs did consistently change their feeding behaviour in response to tail wounds or lameness, detecting certain types of health issues in certain types of pigs may be possible.

Introduction

The emergence of modern sensor technology and associated algorithms in livestock farming, commonly referred to as Precision Livestock Farming (**PLF**), has the potential to improve animal welfare through increased availability of real-time information that can support management decision–making (Berckmans, 2014).

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https://doi.org/10.1016/j.animal.2024.101192
1751-7311/

Welfare issues are, in this context, conceptualised as (temporary) events that induce a negative experience in the animal, thus tipping the balance of positive versus negative (or pleasant versus unpleasant) experiences towards the negative (Reimert et al., 2023). PLF can, among other applications, be used to detect welfare issues, such as respiratory disease (Yin et al., 2021) and heat stress (Ji et al., 2017) at barn level and lameness at the individual level (Kang et al., 2021; Fodor et al., 2023). For most welfare issues, sensors cannot currently be applied to directly measure the issue of interest (e.g. tail damage, hernia, rectal prolapse). Instead, sensors are used to monitor animal behaviour, which serves as an indirect alternative. For example, a lame animal (welfare issue) may become more inactive (behavioural change), and this inactivity could be detected using an accelerometer (sensor/PLF application) (O'Leary et al., 2020).

In growing-finishing pigs, radio-frequency identification (**RFID**) systems are of specific interest. When integrated into electronic feeding stations (**EFS**s), they can be used to monitor the feeding behaviour of individual pigs. Pig feeding behaviour can be measured along a range of components, including daily feed intake (kg), daily feeding duration (s), daily feeding frequency and average daily feeding rate (g/s) (hereafter referred to as intake, duration, frequency and rate). In addition, variables can be created reflecting the diurnal and day-to-day patterns in feeding behaviour, including the proportion of intake obtained at night (hereafter referred to as night intake) and the strength of the circadian rhythm (Bus et al., 2023b, 2024). Most of these feeding components are associated with welfare issues, whereby welfare issues induce a deviation from the 'normal', or basal, feeding pattern of a pig (Bus et al., 2021). For example, bacterial or viral infections induced a reduction in intake and duration (Schweer et al., 2016; Helm et al., 2018a, b), heat stress induced the same and additionally led to a higher night intake (Dos Santos et al., 2018; Cross et al., 2020), and osteochondrosis was associated with a reduced frequency (Munsterhjelm et al., 2017). With these deviations in response to welfare issues, detecting individuals suffering from welfare issues by monitoring their feeding patterns seems promising.

Nevertheless, current attempts to detect such deviations from basal feeding patterns and link these to welfare issues have not yet achieved the desired performance. At best, up to 58% of health issues could be detected, and in these studies 55–71% of detected deviations could not be connected to an identified health issue (i.e. were considered false) (Adrion et al., 2018; Maselyne et al., 2018). For tail biting specifically, machine learning methods were applied to detect up to 94% of treated tail wounds on one farm (method: k-nearest neighbours), but application of the system on a different farm achieved detection of at most 50% of treated tail wounds (method: random forests) (Ollagnier et al., 2021). A possible explanation for the limited performance of these algorithms could be related to the large individual variation in the feeding behaviour of pigs (Bus et al., 2021). Deviations from basal feeding patterns in response to welfare issues have been demonstrated at group level, most commonly by comparing diseased pigs to healthy (paired) controls (e.g. Brown-Brandl et al., 2013; Munsterhjelm et al., 2015). However, at basal levels, pigs have individual feeding strategies in at least four dimensions (Bus et al., 2023b; Fernández et al., 2011). A feeding strategy is conceptualised here as a continuum with two extremes along which pigs differ from each other and maintain this difference relatively consistently across time (Bus et al., 2024). The four identified continua range from (1) nibbling to meal eating, i.e. from pigs that eat small meals frequently to those that eat large meals infrequently; (2) fast to slow eaters, i.e. from pigs with a high to a low feeding rate; (3) day to day-night eaters, i.e. from pigs that only eat during the day, or busiest feeding times, to those that obtain a large share of their intake at night; and (4) consistent to inconsistent eaters, i.e. from pigs that eat at similar times from day-to-day to those that eat at irregular times. The existence of feeding strategies complicates comparing diseased pigs to healthy pigs, as it may not only compare the effect of the disease but also the strategy of the individual pig, possibly resulting in an overestimation of the effect of the disease on pig feeding behaviour. In addition, it could be theorised that pigs that apply different feeding strategies may display different responses in their feeding behaviour to the same welfare issues.

If the aim is to detect welfare issues at the level of the individual pig (e.g. detect the individuals that are lame or suffer from tail damage), it is essential to understand whether individual pigs respond to different welfare issues similarly, or whether there is a large variation between pigs. Moreover, if we are aware of certain factors (e.g. age, welfare issue severity, feeding strategy) that contribute to such individual variation, we could use this knowledge to develop individual-specific models that might be better able to detect welfare-relevant deviations from basal feeding patterns. Therefore, our aims with this study were twofold. First, we aimed to explore the individual variation in how pigs deviate from their basal feeding patterns in response to a range of welfare issues, focusing on health issues and heat stress. Second, we aimed to further explain this individual variation in behavioural responses, by comparing pigs with different responses along other characteristics. These characteristics were related to the welfare issue (i.e. issue severity), the environment (i.e. pig batch), and the pigs' physical (i.e. sex, BW, age) and behavioural (i.e. feeding strategies) characteristics.

Material and methods

This observational study was performed on commercially-reared growing-finishing pigs, complying with relevant EU and German guidelines and regulations. As no invasive or harmful procedures were applied, ethical approval for animal experimentation was not required according to Dutch (Article 1 Wet op de Dierproeven, 2021, https://wetten.overheid.nl/BWBR0003081/2021-07-01) and German (Article 7 Tierschutzgesetz, 2022, https://www.gesetze-im-internet.de/tierschg/BJNR012770972.html) legislation. All data processing and analyses were performed in R, version 4.2.3 (R Core Team, 2023). Figures were created using the *ggplot2* package (Wickham, 2016) and tables using the *flextable* package (Gohel and Skintzos, 2023). The significance level was set at $P < 0.05$, and results are reported as mean ± SEM unless stated otherwise.

Animals and housing

This study followed four rounds of tail-docked growing-finishing pigs reared at a Topigs Norsvin (pig breeding company, the Netherlands) farm in Germany. All management procedures and animal caretaking were performed by Topigs Norsvin employees. Each of the four rounds included 110 pigs housed in 10 single-sex pens (11 pigs/pen, total n = 40 pens and n = 440 pigs) spread across five rooms. Pigs were observed from arrival at the farm until different moments of transport to the slaughterhouse. In each round, pigs were transported to slaughter in three sequential groups with the heaviest pigs first, and in rounds 1, 2 and 3 observations continued until the second group of pigs was removed while in round 4 observation ended upon removal of the first group (for practical reasons). Each pen was equipped with fully slatted floors, two drinking nipples providing *ad libitum* water, and intended enrichment in the form of a hanging wooden block, chains with plastic rings, hanging ropes and hanging hosepipes (exact enrichment material differed between rounds, pens and across the growing-finishing phase). Pelleted feed was provided *ad libitum* from one IVOG® EFS (Hokofarm group, the Netherlands) per pen, with the feed composition adjusted to the growth phase by switching feeds (feed 1: Select Delta 2, 16.2% CP, 13.1 MJ/kg metabolisable energy (**ME**); feed 2: Select Delta 4, 15.3% CP, 13.1 MJ/kg ME; feed 3: Select Delta 5, 13.8% CP, 13.0 MJ/kg ME; all produced by Royal Agrifirm Group, the Netherlands; feeds were mixed for 3-4d before the full switch; in round 4, the first and third feeds were accidentally given as meal rather than pellets). In addition, in round 2, a crude fibre source in the form of mixed chopped and pelleted straw was supplied in a separate station, from which pigs could obtain feed by pulling a chain (in rounds 3 and 4, the crude fibre station was present in the pen, but no crude fibre was provided). Rooms were climate-controlled with mechanical ventilation and heating, where temperature was gradually reduced across the growing-finishing phase from approximately 27–22 °C, although temperatures could become higher inside the barn when outdoor temperatures were high. Rooms were lit using natural lighting through windows. More details on each round are provided in Table 1.

Data collection and processing

Individual feeding, welfare and pig characterisation data were collected. Welfare and feeding data were compared to each other to study the effects of different welfare issues on feeding behaviour, and characterisation data were used to study whether individual variation in these effects could be explained by any of these variables.

Feeding data

Feeding data were collected using IVOG® EFS throughout the growing-finishing phase. IVOG® EFSs are single-spaced feeding stations equipped with an RFID antenna to identify the (ear tag of the) feeding pig and a load cell to measure the quantity of feed consumed. Upon entering the EFS, the pig's ear tag is registered along with the weight of the feed in the trough and the time stamp. Upon exiting the EFS, the time stamp and weight of the feed in the trough are recorded again. From this, the visit intake (difference between end and start weight, kg), visit duration (difference between end and start time, s), feeding rate (visit intake divided by visit duration, g/s) and interval to the previous visit (difference between the start time of the current and the end time of the previous visit of the same pig, s) were calculated. Feed was always present in the trough, as it was automatically filled from a reservoir on top of the EFS whenever the trough weight went below a fixed threshold; if a pig was feeding during such a filling, its intake was corrected for this. A small fence prevented pigs from entering the EFS simultaneously, but otherwise, the body of the feeding pig was unprotected beyond the neck. A metal bar prevented pigs from lying down in the EFS.

Before use, EFS data were cleaned and aggregated to the meal level as described in Bus et al. (2023a). An overview of the results of the cleaning and aggregation process is provided in Supplementary Material S1. In short, pig rounds 1, 2, 3 and 4, respectively, had in total 4.79, 4.98, 13.36 and 6.21% of visits fully removed, and 6.81, 6.18, 17.59 and 12.61% partially (i.e. only intake and rate) removed. The removal rates were specifically high in round 3 because two EFSs were broken for 13d due to cable gnawing by rats. Aggregation to the meal level was performed using calculated meal criteria of 43, 61, 30 and 50 s in rounds 1, 2, 3 and 4, respectively. The meal-level dataset was subsequently aggregated to the daily level by summing the meal intakes and durations to obtain daily intake (kg) and duration (s), counting the number of meals for the daily frequency, and recalculating the rate by dividing the daily intakes by the daily durations (g/s). Day-level data were directly used for analysis, but in addition, extra day-level parameters describing diurnal features were created using hourly-level intake data, calculated as the sum of the meal intakes within each hour. These diurnal features were (1) night intake and (2) strength of the circadian rhythm. Night intake was calculated as the proportion of intake obtained during the night, defined as 2100–0359 h, compared to the 24 h-intake (i.e. night intake/total intake, a ratio with no unit). The 'night' thresholds were determined based on visualisations of the diurnal patterns per pig round and week, and were chosen as the last hours before and after which the morning intake peak started and the afternoon intake peak ended. The strength of the circadian rhythm was determined using wavelet analysis on the hourly intake data of each pig, as described in Bus et al. (2023b). After data processing and performing wavelet analysis (Morlet base wavelet, continuous wavelet transform, range of periodicities from 8–48 h), the power of the periodicity from 23.5–24.5 h, representing the circadian rhythm, was calculated daily by taking the median of all timepoints on that day (no unit). During visualisations of the wavelet power across time, we noticed that the power dropped severely (to almost zero) if feed intake data on subsequent days were missing. As wavelet analysis results are known to be less reliable near the beginning and end of time series (referred to as the 'edge effect' (Gogolewski, 2020)), we considered these drops in power unreliable and removed all estimated powers during the 2d before bouts of missing data.

Welfare data – general

Data on pig welfare issues were obtained from two sources: on-farm health observations and climate sensors. From these, we isolated two types of welfare issues: health issues and heat stress. In

Table 1
A description of the main characteristics that differed between the four rounds of pigs. Initial and final weights (measured at the farm on arrival and at the final weighing day) are given as the mean ± SEM, and the number of days in the barn reflects the day of arrival until the first (round 4) or second (rounds 1–3) group of pigs were transported to the slaughterhouse. The number (#) of pigs removed early either died (n = 1 in round 4) or were permanently moved to sickbay due to health issues. Medical treatments were only administered at farm level via the drinking water (unless pigs were in sickbay and out of the data collection).

Characteristic	Round 1	Round 2	Round 3	Round 4
No. of pigs	110	109	110	110
Pig breed	Piétrain x (Landrace × Large White)	Landrace × Large White	Landrace × Large White	Tempo x (Landrace × Large White)
Pig sex	Half barrows, half gilts	Barrows	Barrows	Half barrows, half gilts
Months	Dec-Feb	Sep-Dec	May-Sep	Sep-Dec
Days in barn	92	92	100	83
Start weight (kg)	27.5 ± 0.3	24.7 ± 0.4	23.9 ± 0.4	25.9 ± 0.3
Final weighing day	75	76	78	76
Final weight (kg)	107.4 ± 0.8	106.1 ± 0.9	103.4 ± 0.7	108.8 ± 1.0
No. of pigs removed early	7	3	1	7
Medical treatments	–	–	–	2x Pulmodox (2×4d) & 1x Amoxicillin (6d)

addition, possible disturbing events were quantified to be included as corrective factors in the analysis.

Welfare data – health issues

On-farm health observations were performed twice-weekly by a trained observer, using the observation protocol described in Bus et al. (2023c), which contains a list of health issues at pig and pen level to score at discrete scales ranging from binary to 0–5. In round 1, an older version of the protocol was used, in which conjunctivitis and lying bumps were not included. To be able to study the effects of health issues on individual pigs, only pig-level issues were considered because pen-level ones (e.g. coughing, diarrhoea) could not be traced to the individual. Subsequently, the health issues included in the analysis were selected to retain those that were (1) relevant, (2) of sufficient reliability, (3) with sufficient occurrence, and (4) of sufficient additional value. In step (1), tear stains were removed. In step (2), skin disease was removed from round 1, because it was deemed unreliable with later acquired experience, and panting was removed as it was considered unreliable at the individual level (though not at room level, see section 'Heat stress'). In step (3), low body condition score, bursitis, skin disease, hernia, pumping, and shivering had to be removed, because they occurred on fewer than five pigs. In step (4), both types of lying bumps (i.e. front and hind legs) were merged by taking the highest score of the two, because these likely represented similar issues. In addition, from all types of skin lesions (i.e. front, middle and rear), only front and rear lesions were retained, as these may relate to different types of fighting while for middle lesions such an interpretation is difficult (Stukenborg et al., 2012). Finally, all forms of necrosis were removed from the analysis, because for tails and flanks they moderately correlated with damage (i.e. wounds) and for ears necrosis in the absence of damage is hard to interpret (for a review on ear necrosis, see Malik et al., 2021). This process resulted in the inclusion of nine health issues: conjunctivitis, ear base damage, ear tip damage, flank damage, tail damage, skin lesions on the front of the body, skin lesions on the rear of the body, lameness, lying bumps and rectal prolapse. These selection steps led to the removal of three pigs from the analysis, because they had been moved to the sickbay for health issues no longer included in the analysis. In addition, one pig had to be removed because it had been moved to the sickbay prior to the first health observation day, and another pig was removed because it was only scored as lame and hence had no healthy comparison days.

As our analysis method could not handle missing data without removal of the entire observation day, health data had to be interpolated across days on which no health observations were performed. In addition, the health issues were reduced to a binary format, as there were insufficient days with different score levels for individual pigs to allow the analysis of different levels. Therefore, for each health issue we applied a threshold from which the score was considered an issue (i.e. became a one) while all scores below the threshold were denoted as 'healthy' (i.e. became a zero). These thresholds were determined using a combination of literature (e.g. generally 'presence of a wound on the tail' is considered a tail-biting outbreak (Munsterhjelm et al., 2015; Larsen et al., 2018), hence the threshold was placed at the first score that indicated a wound) and distribution of the data, to obtain a sufficiently large sample size but not assign too many sick days to a pig as this could lead to confounding issues in the analysis. The thresholds applied can be found in the results section. These binary data were subsequently interpolated by filling out all days until the next observation day with the most recent score (either 0, 1 or missing, which occurred for example when a tail was too dirty to score tail damage, or when part of the body could not be observed as a pig was too lame to stand). The days before the first observation of the pig round were filled out with the score of the first observation day, and the scores of the last observation day were extrapolated until the end of the pig's time in the barn.

Welfare data – heat stress

Although the rooms were climate-controlled, if the outdoor temperature rose higher than the intended indoor temperature, the indoor temperature could not always be kept below the desired limit, potentially leading to heat stress. To determine days with heat stress, both climate sensors and on-farm observations were used. This combination was used because there is no consensus on which temperature (or temperature humidity index, **THI**) causes heat stress in pigs of different BWs, while panting can reliably reflect heat stress albeit linked to physical activity as well as ambient temperature. The combination of the two, therefore, allowed us to identify days with the risk of heat stress, upon which the animal-based observations could confirm the pigs were likely affected by the heat. Climate data were obtained using a combined temperature and humidity sensor (iDOL114, DOL Sensors, Denmark) installed at approximately 1.8 m height in each room. These recorded the ambient temperature (°C) and relative humidity (%) every 15 min. As climate sensors were only installed from round 2 onwards, heat stress could only be observed during rounds 2, 3 and 4. The data were visualised and put through a cleaning algorithm that removed any temperature measurements lower than 16 °C and any humidity measurements lower than 40% or higher than 90%, as these were judged to be incorrect measurements (i.e. unreasonable outliers) based on visualisations of the data. For temperature, this resulted in the removal of 15 measurements from one sensor (0.05% of the data) in pig round 2, and for humidity this resulted in the removal of 978 measurements from one sensor (3.12% of the data) in pig round 4. After cleaning, for each measurement (i.e. at each 15 min–timepoint), the THI was calculated using Eq. (1) (Kendall and Webster, 2009). For each room, data were aggregated to the daily level by taking the median THI, and subsequently THI was aggregated to the round level (i.e. one level per round per day), again using the median. Panting was scored at the individual level during the on-farm observations, however, it was not deemed reliable enough to identify individuals suffering from heat stress as the performance of panting seemed dependent on the pig's body posture at the moment of observation (i.e. pigs that were lying down panted more than pigs that were sitting, standing or in locomotion, results not shown). Instead, pig-level scores on panting were used to calculate the proportion of pigs panting on each observation day. A day was denoted as a day of heat stress if 1) the aggregated median THI exceeded 79 (i.e. during half of the day THI was higher than this threshold, threshold based on (Kendall and Webster, 2009; Hoofs and Aarnink, 2020)) and 2) the percentage of pigs in the barn panting on the (neighbouring) observation day was $\geq$ 10%.

$$THI = (1.8 \cdot AT + 32) - ((0.55 - 0.0055 \cdot RH) \times (1.8 \cdot AT - 26)) \quad (1)$$

In which: THI = Temperature Humidity Index, AT = Ambient Temperature (°C) & RH = Relative Humidity (%).

Welfare data – corrective factors

For some events, it was either not possible or not of interest to assess its effect on pig feeding behaviour, however, as these events could disturb the feeding behaviour, it was necessary to correct for them. These included (1) feed switches, (2) the removal of pigs from the pen, which may cause social disturbance in the pigs left behind; and (3) an outbreak of respiratory disease in round 4, which was medically treated for three periods. For the first, we noted the type of feed given on each day, taking the new feed from the first day of the switch onwards. For the second, pigs were either removed because they died, were moved to the sickbay, or were in the group of heaviest pigs that were transported to the slaughterhouse first. Each time a pig was removed from a pen, that day and the next 2 days (3d in total) were marked as 'social disturbance' days. This number of days was chosen as dominance ranks upon mixing are generally determined within 24–48 h (Stukenborg et al., 2011), plus an error margin. For the third, the effect of the respiratory disease outbreak on individual pig feeding behaviour could not be determined as our best measure was coughing at pen level, hence it was not possible to reliably identify which pigs were affected by the disease. Nevertheless, lung issues are known to at least affect feeding duration (Brown-Brandl et al., 2016; Kapun et al., 2016; Adrion et al., 2018), and should thus be corrected for. In addition, all pigs were medically treated via the drinking water (for more details, see Table 1), which may have affected their behaviour. Days were denoted as a coughing issue, for the entire farm, if there were more than ninety coughs registered in total (i.e. sum of the coughs in each pen), based on visualisations of the data, and similar to other welfare issues this was interpolated to the next observation day. These rules were applied to all pig rounds, leading to 8d denoted as coughing in round 1, 6d in round 2, 0d in round 3 and 44d in round 4. In addition, the days on which medication was given were denoted as such, separate for both medication types.

Characterisation data

Characterisation data included the severity of the welfare issue, pig sex, pig BW, pig age, the round in which the pig was reared, and four different types of feeding strategies.

For severity of the welfare issue, it was expected that the effects of welfare issues on pig feeding components would be larger if the welfare issue was more severe. Severity was determined from the health scores before applying the threshold that reduced them to binary data. For each pig, severity was defined as the highest score it had obtained for an issue throughout the growing-finishing phase. This was reduced to a two-level score, labelled as categories 'mild' if the highest score was equal to the thresholds used to obtain binary data, and 'severe' for all scores higher than that.

Pig BW was determined relative to a pig round, to correct for differences in the day on which pigs were weighed between rounds. For each pig, its BW, as measured during the final weighing (Table 1, manual scale, accuracy ± 0.5 kg (Welvaarts Weegsystemen W-2000, The Netherlands)), was classified into categories of relatively lighter, intermediate or heavier using the 33rd and 67th quantiles of the round's BW distribution.

Pig sex was categorised as either a barrow or a gilt, where fewer gilts were included as those were only present in rounds 1 and 4. If castration was incomplete (i.e. one or two testicles were still present on the pig), the pig was removed from the analysis.

Pig age was split into two categories, where pigs primarily suffered from the welfare issue in either the first or in the second half of the growing-finishing phase. If a welfare issue occurred in both halves of the growing-finishing phase, it was assigned to the half with the largest number of affected days if either (1) fewer than 3d in the other half were affected (i.e. representing an interpolation effect) or (2) at least 66% of affected days were in one half. If these conditions were not met, the observation was removed.

Four types of feeding strategies were considered: nibbling/meal eating (based on frequency), fast/slow eating (based on rate), day/day-night eating (based on night intake) and consistent/inconsistent eating (based on strength of the circadian rhythm) (Bus et al., 2024). For each pig, 'basal' daily feeding data were obtained, as described in detail in the Supplementary Methods of Bus et al. (2023b), by removing (1) all days before the first health observations, (2) all days after the first pigs in that round were transported to the slaughterhouse, and (3) all days upon which severe health issues were scored, with a range of 3d before to 3d after the observation. Although feeding strategies should be conceptualised as a continuum of variation between pigs, for the interpretability of the analysis results, it was necessary to create categories for each strategy. As missing data could be differently spread across the growing-finishing phase, confounding effects of age were eliminated by scaling the values of each feeding component for each day (i.e. from each value, the day's mean was deducted and the result was divided by the day's SD, function *scale()* (R Core Team, 2023)). Subsequently, the scaled daily data were used to obtain a median value for each pig, where pigs beneath the 33rd and above the 67th quantile were assigned to the extreme categories and those in between as intermediates (i.e. three categories per feeding strategy).

Data analysis

The data analysis consisted of two sequential analyses, and the procedure is graphically illustrated in Fig. 1. In short, we first determined for each pig and each feeding component how much the pig deviated from its basal behaviour during a range of welfare issues (Step 1, left plot, in Fig. 1). This was done by fitting a spline to the feeding behaviour of each pig, and adding fixed effects of different welfare issues to this spline. The fixed effect estimates represented the deviation from basal feeding behaviour and were visualised using violin plots (for a detailed description, see section 'Quantifying variation in responses to welfare issues). Subsequently, in step 2 (right plot in Fig. 1), these effect estimates were used in a meta–subgroup analysis to identify certain types of pigs for which the deviations may have been smaller or larger. For this, pigs were repeatedly sorted into categories, according to physical, behavioural and environmental characteristics. For each subgroup, it was tested whether their effect estimates (i.e. their deviations from basal feeding behaviour during a certain welfare issue) were larger than zero, which would demonstrate that pigs with that characteristic deviated their feeding behaviour during the welfare issue (for a detailed description, see section 'Explaining variation in response to welfare issues').

Quantifying variation in responses to welfare issues

A spline-based method was used to assess the effect of different welfare issues on pig feeding behaviour. The advantage of a spline-based method over more regular linear mixed models is that it makes no assumptions on the time trends of the data, which for several feeding components are known not to be linear (e.g. Rauw et al., 2006; Boumans et al., 2015). In addition, a spline could be fitted to the data of each pig individually, allowing the assessment of the welfare issues' effects for each pig individually.

Before analysis, the data of each feeding component were scaled by subtracting the mean of the component from each value, and dividing the result by the component's SD (function *scale()* (R Core Team, 2023)). For each pig, a model was fitted for each feeding component, using function *gam()* of the *gamlss* package (Rigby and Stasinopoulos, 2005), a Gaussian family distribution and restricted maximum likelihood (**REML**) estimation. The spline fitted the feeding component as a function of (1) the smoothed effect of the time trend (i.e. day number post arrival in the barn), modelled using a thin plate spline with a maximum of thirty knots; and (2) separate fixed effects for each welfare issue and putative confounding factor (i.e. feed type, coughing, medication use (Pulmodox & antibiotics) and social disturbance due to the removal of pen mates, results on these are not reported). A fixed effect was only included if the pig had suffered from that issue during the growing-finishing phase. Model fit and assumptions were checked visually, using a plot of the model predictions against the original data (model

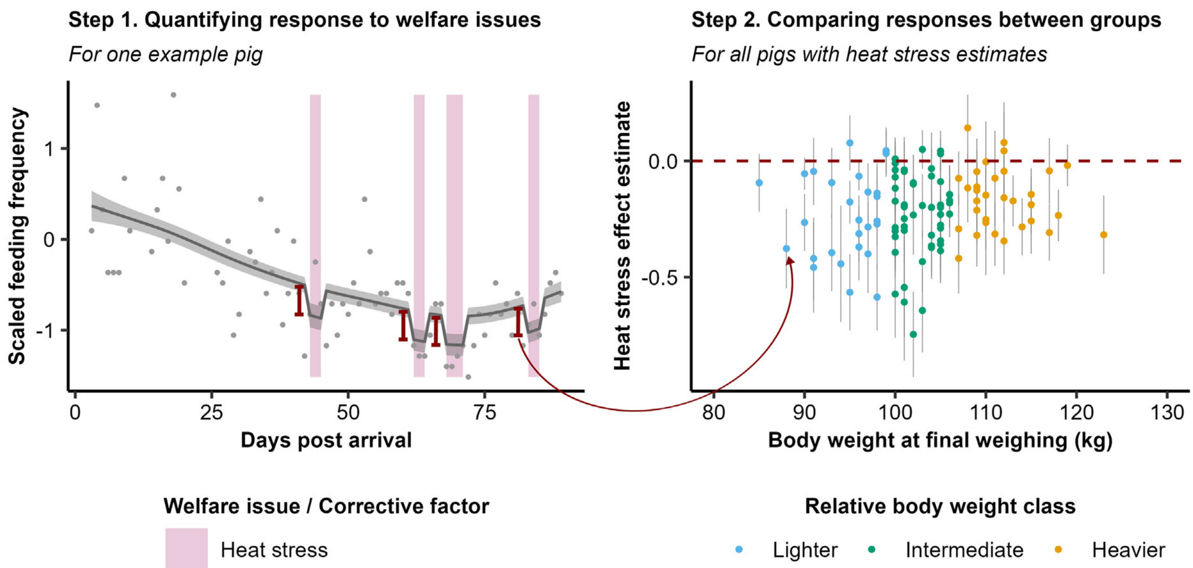

Fig. 1. A graphical example of the analyses performed. The left plot shows the first step, which was performed for each pig individually. For each feeding component, here feeding frequency, we fitted a smooth curve through the scaled time series, to which we added fixed effects for each type of welfare issue (or corrective factor) that the pig had encountered, here only heat stress. The model then estimated the effect of each welfare issue on the smooth time trend of the feeding component (i.e. drops or increases in the curve, one estimate per welfare issue), and for each welfare issue, we extracted this estimate and its error. These estimates were our first result, showing the variation in pigs' responses to welfare issues. Subsequently, in step 2 (right plot), the effect estimates and estimate errors of each pig and welfare issue were used to see if the responses to welfare issues (i.e. the estimates) differed between groups of pigs. Pigs were categorised into subgroups, here pigs of low, intermediate or high relative BW, and for each subgroup it was assessed whether their combined effect estimates significantly differed from zero (the dashed red line), where zero indicated no change in the feeding component during the welfare issue.

fit), a histogram and QQ-plot of the residuals (normality), and a plot of the residuals against the predicted values (heteroscedasticity), however, as this concerned approximately 2 600 sets of plots (one for each pig and feeding component) checks were performed more as an overview than for each model specifically. The maximum number of knots used (30) was deemed to be sufficient as the majority of models obtained their optimal fit with fewer knots than thirty. For seven pigs, a maximum of five knots had to be applied as they were removed from the pen early, and for an additional nine pigs this was necessary for analyses with the strength of the circadian rhythm as the outcome variable. From each fitted spline, we extracted for each welfare issue the estimated effect size (hereafter referred to as the effect estimate) and its error, and whether the effect estimate differed from zero was tested using a *t*-test. Model outcomes were summarised as the percentage of pigs for whom the effect estimates of the welfare issue on the feeding component differed from zero. Violin plots were used to visualise the density distribution of (1) all the effect estimates and (2) only the effect estimates significantly different from zero.

Explaining variation in responses to welfare issues

The variation in the effect estimates was further explored using meta–subset analyses, aiming to study if some of the variation between pigs could be explained by some of the characterisation data. Meta–analysis was used rather than linear models because it allowed the inclusion of not only the effect estimate itself as the outcome parameter but also the uncertainty (i.e. error) of its estimation. The meta–subset analysis tested whether deviations from basal feeding behaviour during a welfare issue could be found in certain subgroups of the data, where the subgroups represented pig characteristics of interest.

Because of sample size limitations, and to reduce the chance of false positive results through performing many tests, only a selection of feeding components and welfare issues were analysed. Selected feeding components were intake, frequency, night intake and strength of the circadian rhythm, and selected welfare issues were flank damage, tail damage, lameness and heat stress, because these represented the main day- and within-day components and diverse, relatively high-occurring issues with different distributions of their effect estimates. A model was fitted for each combination of a welfare issue, feeding component and characterisation variable separately (i.e. a total of 4 welfare issues * 4 feeding components * 9 characterisation variables = 144 analyses, of which only 115 could eventually be performed). Models were fitted using the *rma.mv()* function of the *metafor* package (Viechtbauer, 2010), and included the effect estimate of the welfare issue on the feeding component and the error of this estimate as its outcome parameters, and the different categories of the characterisation variable as explanatory factors. Each model was optimised using REML and also included a random effect of pen. The minimum required sample size for analysis was for each characterisation category set at five pigs; otherwise, the analysis was not performed. Model assumptions were checked using a Shapiro-Wilk test (W > 0.75), histogram and QQ-plot of the model residuals (normality), and a plot of the residuals against the predicted values (heteroscedasticity). If normality assumptions were not met (i.e. for the effect of lameness on the strength of the circadian rhythm – transformation was unsuccessful), the analysis was not performed. Using this model, an accumulated effect estimate was obtained per characterisation category, along with its 95%-confidence interval. Whether the effect estimates of the characterisation categories differed from zero was tested using a z-test.

Results

Data description

The data are summarised in three tables, which together provide a detailed description of the data used for further analysis. Table 2 provides a description of the ranges of the different feeding components and their missing days, caused by sensor error or removal during the data cleaning process. Table 3 quantifies the health scores directly from the observation days – i.e. before aggregation into a binary format – and also provides the thresholds from which an issue obtained a '1' in the binary format. Table 4 provides a quantification of all pig days denoted as a '1' in the binary format after interpolation of non-observation days. Quantifications are both given in pig days and in the number of bouts per pig, with a bout defined as a sequence of welfare issue days not separated by any days upon which no welfare issue was scored.

Quantifying variation in responses to welfare issues

Table 5 presents the number of pigs for which an effect estimate could be obtained, for each combination of a feeding component and a welfare issue. For some pigs, a specific welfare issue could not be included in the analysis because the issue occurred only during periods in which no feeding data were available. Table 5 also provides the percentage of pigs for which this effect estimate was significantly different from zero. In general, this percentage was low, with the mean ± SEM percentage of pigs at 13 ± 1% and a highest percentage of 77%, for the effect of heat stress on pig feeding duration.

Figure 2 provides the distributions of the effect estimates for each feeding component and welfare issue combination. In general, most distributions approximated normal, centred around an effect estimate of zero. For some welfare issues, the tails of the distribution were longer than for others (e.g. longer for the strength of the circadian rhythm and for skin lesions, both on the front and especially on the rear), implying that for some pigs, there was a large deviation in that feeding component during the welfare issue. The only distribution not crossing zero, i.e. for which all pigs showed either a positive or a negative deviation in the feeding component during the welfare issue, concerned the reduction in duration during periods of heat stress. In addition, there was a clear reduction in intake and frequency in periods of heat stress for almost all affected pigs.

If only the effect estimates that were significantly different from zero were considered (Fig. 3), the distributions changed. Although for several combinations of welfare issues and feeding components, the distributions were still seen to cover both positive and negative effects, for some combinations the significant effect estimates became distinctly or predominantly one-sided. However, most of these one-sided effect estimates were based on very small sample sizes (i.e. 2–4 pigs), except those related to heat stress. For all pigs for which the effect was significantly stronger than zero, intake, duration and frequency were reduced during periods of heat stress, while frequency was reduced during periods of lameness, and frequency and the strength of the circadian rhythm were increased during periods of rectal prolapse. In addition, for almost all pigs with significant estimates, intake, frequency and rate were reduced during periods of ear base damage; rate was reduced and strength of the circadian rhythm increased during ear tip damage; frequency was increased during tail damage; night intake was reduced during periods with skin lesions on the rear part of the body; intake and duration were reduced during lameness; duration was reduced and night intake increased during periods with lying bumps; and rate and night intake were increased and the strength of the circadian rhythm reduced during periods of heat stress.

Explaining variation in responses to welfare issues

Effect estimates (and their errors) of selected combinations of feeding components (i.e. intake, frequency, night intake and circadian rhythms) and welfare issues (i.e. flank damage, tail damage, lameness and heat stress) were compared along different characterisation variables (i.e. welfare issue severity, pig sex, pig BW (relative to its pen mates), pig age, the round in which the pig was reared, and pig feeding strategy in four dimensions (nibbling-meal eating, fast-slow eating, day-day/night eating and consistent-inconsistent eating)). Figs. 4–7 provide the effect estimates for the different subsets.

The effect estimates of flank damage on the different feeding components per characterisation category are shown in Fig. 4. For none of the characterisation categories did feeding components deviate during periods of flank damage (all $P > 0.05$).

The effect estimates of tail damage on the different feeding components per characterisation category are shown in Fig. 5. During periods of tail damage, there was a higher night intake in barrows ($z = 2.26$, $P = 0.02$) and pigs of intermediate BW ($z = 2.18$, $P = 0.03$).

The effect estimates of lameness on the different feeding components per characterisation category are shown in Fig. 6. During periods of lameness, there was a lower intake in barrows ($z = -2.27$, $P = 0.02$), heavier pigs ($z = -2.19$, $P = 0.03$), pigs reared in round 1 ($z = -3.19$, $P < 0.01$), slow eaters ($z = -2.67$, $P < 0.01$), pigs that ate more at night ($z = -2.61$, $P < 0.01$) and pigs that ate inconsistently from day to day ($z = -2.46$, $P = 0.01$). In addition, during periods of lameness there was a lower frequency in barrows ($z = -2.96$, $P < 0.01$), heavier pigs ($z = -3.02$, $P < 0.01$), pigs reared in round 3 ($z = -2.65$, $P < 0.01$), nibblers ($z = -3.35$, $P < 0.01$), pigs with an intermediate feeding rate ($z = -2.48$, $P = 0.01$), pigs that ate more at night ($z = -2.78$, $P < 0.01$) and pigs that were intermediately consistent from day to day ($z = -2.54$, $P = 0.01$). Finally, during periods of lameness, night intake was lower in pigs that normally ate more at night ($z = -2.09$, $P = 0.04$). Sample size was too low to analyse lameness severity (at least one subset < 5 pigs), hence these results are missing.

The effect estimates of heat stress on the different feeding components per characterisation category are shown in Fig. 7. No matter the characterisation category, during periods of heat stress there was always a lower intake and frequency (all $P < 0.05$). Night intake was not changed during heat stress for any of the character-

Table 2
Quantifications of the day-level feeding components analysed in this study. For each feeding component ('Circ. rhythm' = strength of the circadian rhythm, which, along with night intake and frequency, was dimensionless), the proportion of missing days of data per pig and, for each month, the mean, SEM, minimum (Min) and maximum (Max) of the component are shown.

Feeding behaviour	Prop. missing data			Month 1			Month 2			Month 3		
	Mean ± SEM	Min	Max	Mean ± SEM	Min	Max	Mean ± SEM	Min	Max	Mean ± SEM	Min	Max
Intake (kg)	0.12 ± 0.01	0.01	0.64	1.86 ± 0.00	0.00	4.37	2.67 ± 0.01	0.00	5.04	3.17 ± 0.01	0.14	6.43
Duration (s)	0.08 ± 0.00	0.01	0.63	3 867 ± 9	0	11 972	3 673 ± 9	0	10 998	3 249 ± 9	257	8 327
Frequency	0.08 ± 0.00	0.01	0.63	23 ± 0	2	108	18 ± 0	0	68	14 ± 0	1	54
Rate (g/s)	0.12 ± 0.01	0.01	0.64	0.50 ± 0.00	0.11	1.28	0.75 ± 0.00	0.18	1.60	1.02 ± 0.00	0.26	2.03
Night intake	0.12 ± 0.01	0.01	0.64	0.19 ± 0.00	0.00	0.74	0.17 ± 0.00	0.00	0.91	0.16 ± 0.00	0.00	1.00
Circ. rhythm	0.22 ± 0.01	0.03	0.86	0.17 ± 0.00	0.00	1.26	0.16 ± 0.00	0.00	1.09	0.14 ± 0.00	0.00	1.11

Table 3
Quantifications of the health issue scores observed in this study, by pig observation day (i.e. before interpolation). 'All' provides the total number of pig observation days and, for each health issue, the number of observation days with a score higher than 0. 'Pig round', 'Month' and 'Score' provide the same information, but split per round of pigs (there were 26 observation days in rounds 1 and 2, 27 in round 3, and 24 in round 4), month of the growing-finishing phase (month 1: d1-d30, month 2: d31-60, month 3: ≥d61), or score level of the health issue (ranged from 0 to 4, an empty slot means the score did not apply for that health issue), respectively. 'T' provides the threshold value from above which (≥) a health issue was considered 'severe' and was hence included as an issue (i.e. a score '1') in the binary models.

Health issue	All	Pig round				Month			Score					T
		1	2	3	4	1	2	3	0	1	2	3	4	≥
Total obs. days	10 703	2 664	2 670	2 840	2 529	3 569	3 431	3 703	10 703	10 703	10 703	10 703	10 703	
Conjunctivitis	204		50	58	96	89	62	53	7 836	199	5			1
Ear base damage	808	311	68	172	257	445	204	159	9 895	624	140	40	4	2
Ear tip damage	1 385	104	295	724	262	194	396	795	9 319	1 282	82	5	16	2
Flank damage	391	25	88	50	228	193	118	80	10 311	330	61			1
Tail damage	2 360	701	570	686	403	665	738	957	8 260	1 975	271	43	71	2
Skin lesions (front)	6 181	991	1 510	1 844	1 836	2 371	1 954	1 856	4 522	5 943	229	9		2
Skin lesions (rear)	3 450	361	1 114	963	1 012	1 230	1 026	1 194	7 247	3 354	96			2
Lameness	431	65	81	75	210	78	104	249	10 273	339	84	8		2
Lying bumps	3 710		1 101	1 197	1 412	830	1 289	1 591	4 327	2 133	1 412	165		3
Rectal prolapse	70	43	13	0	14	3	22	45	10 634	69	1			1

Table 4
Quantifications of the welfare issues observed in this study, by pig day (i.e. after binary classification of 'severe issues' and interpolation from observation days to all days in the barn). For all welfare issues accumulated (row 'All') and for each welfare issue separate, shown are the number of days on which a severe occurrence was seen ('Days'), the number of unique pigs that suffered from the welfare issue ('Pigs', total n = 440) and the number of unique pens in which these pigs were housed in ('Pen', total n = 40). In addition, the mean, SEM, minimum (Min) and maximum (Max) are given for the number of days upon which a pig had a welfare issue ('Days per pig'), in how many bouts this occurred (i.e. how many occurrences separated by moments of non-issue, 'Bouts per pig'), the length of these bouts (i.e. the number of days within a bout, 'Bout length') and the number of days upon which a pig suffered from at least two welfare issues (i.e. the issue in this row plus any other issue, 'Days co-occurrence').

Welfare issue	Days	Pigs	Pens	Days per pig			Bouts per pig			Bout length			Days co-occurrence		
				Mean ± SEM	Min	Max	Mean ± SEM	Min	Max	Mean ± SEM	Min	Max	Mean ± SEM	Min	Max
All	38 062	394	40	18.0 ± 0.7	0	76							2.2 ± 0.2	0	31
Conjunctivitis	717	101	30	1.6 ± 0.2	0	35	0.4 ± 0.0	0	9	4.0 ± 0.1	1	14	0.4 ± 0.1	0	17
Ear base damage	676	81	23	1.6 ± 0.2	0	35	0.3 ± 0.0	0	5	5.7 ± 0.4	1	28	0.5 ± 0.1	0	21
Ear tip damage	363	54	24	0.8 ± 0.1	0	25	0.2 ± 0.0	0	4	4.7 ± 0.4	1	21	0.3 ± 0.1	0	10
Flank damage	1 409	179	38	3.2 ± 0.3	0	46	0.6 ± 0.0	0	5	5.4 ± 0.3	1	45	0.7 ± 0.1	0	10
Tail damage	1 294	159	39	3.0 ± 0.4	0	76	0.5 ± 0.0	0	4	6.0 ± 0.6	1	73	0.5 ± 0.1	0	31
Skin lesions (front)	1 029	171	35	2.4 ± 0.2	0	18	0.5 ± 0.0	0	4	5.1 ± 0.2	2	17	0.7 ± 0.1	0	8
Skin lesions (rear)	381	79	29	0.9 ± 0.1	0	15	0.2 ± 0.0	0	4	4.2 ± 0.2	1	10	0.5 ± 0.1	0	8
Lameness	290	55	28	0.7 ± 0.1	0	25	0.2 ± 0.0	0	5	3.9 ± 0.4	1	23	0.1 ± 0.0	0	8
Lying bumps	557	42	21	1.3 ± 0.3	0	60	0.2 ± 0.0	0	7	7.0 ± 0.8	1	49	0.3 ± 0.1	0	22
Rectal prolapse	231	23	15	0.5 ± 0.2	0	31	0.1 ± 0.0	0	4	5.4 ± 0.6	1	21	0.1 ± 0.0	0	14
Heat stress	1 942	109	10	4.5 ± 0.4	0	20	1.2 ± 0.1	0	5	3.8 ± 0.1	3	7	0.6 ± 0.1	0	20

Table 5
For each combination of a feeding component ('Circ. rhythm' = strength of the circadian rhythm) and a welfare issue, the number of pigs for which an effect estimate could be calculated (N) and the percentage of pigs for which this effect estimate significantly differed from zero (Sign.) are presented.

Welfare issue	Intake (kg)		Duration (s)		Frequency		Rate (g/s)		Night intake		Circ. rhythm	
	N	Sign.	N	Sign.	N	Sign.	N	Sign.	N	Sign.	N	Sign.
Conjunctivitis	99	10%	99	9%	99	8%	99	4%	99	4%	95	20%
Ear base damage	77	5%	78	17%	78	17%	77	3%	77	3%	75	9%
Ear tip damage	49	12%	49	6%	49	16%	49	12%	49	10%	48	10%
Flank damage	169	5%	173	8%	173	9%	169	10%	169	3%	160	12%
Tail damage	151	10%	150	7%	150	7%	151	14%	151	8%	126	15%
Skin lesions (front)	158	6%	159	17%	159	14%	158	6%	158	6%	155	24%
Skin lesions (rear)	70	6%	69	16%	69	12%	70	9%	70	7%	64	19%
Lameness	50	16%	50	8%	50	20%	50	12%	50	4%	35	14%
Lying bumps	40	8%	40	8%	40	10%	40	10%	40	5%	38	18%
Rectal prolapse	21	0%	22	0%	22	9%	21	19%	21	5%	19	32%
Heat stress	109	61%	109	77%	109	28%	109	27%	109	11%	109	23%

isation categories, and the circadian rhythm was weaker during heat stress only in pigs of intermediate BW (z = −2.51, P = 0.01), nibblers (z = −2.34, P = 0.02), slow eaters (z = −2.39, P = 0.02) and consistent–eating pigs (z = −3.08, P < 0.01). There were no occurrences of heat stress in other rounds than round 3, hence the effects of round, sex (there were only barrows) and age (all pigs had heat stress simultaneously) could not be determined and results on these characterisation variables are missing.

Discussion

This study's aims were twofold. First, we aimed to explore the individual variation in how pigs deviate their feeding behaviour in response to a range of welfare issues, focusing on health issues and heat stress. Second, we aimed to explain this individual variation in deviations by comparing pigs with different characteristics, related to the welfare issue (i.e. issue severity), the environment

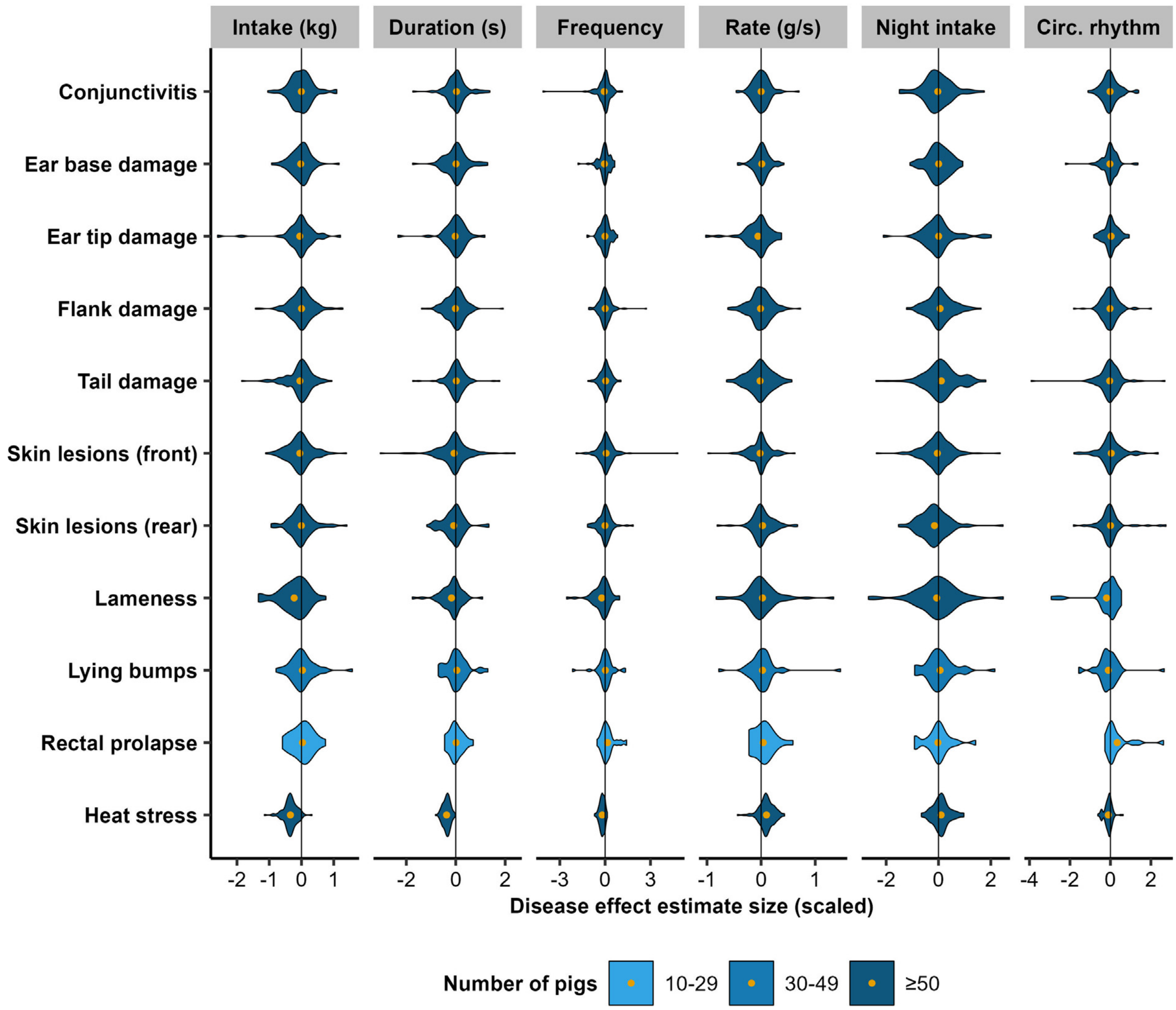

Fig. 2. A violin plot showing the distributions of the effect estimates of different welfare issues on the feeding components of individual growing-finishing pigs. Feeding components ('Circ. rhythm' = strength of the circadian rhythm) were scaled before analysis, hence the scaled effect estimate sizes can be compared between welfare issues and feeding components. The colour of the violin approximates the number of pigs on which its distribution is based. A vertical, black line reflects the 'zero-effect', i.e. no effect of the welfare issue on the feeding component. An orange dot reflects the mean of the effect estimates for each distribution.

(i.e. pig batch), and the pigs' physiology (i.e. sex, BW, age) and feeding strategies.

Individual variation in response to welfare issues

The individual variation in deviations in feeding behaviour during periods of welfare issues was generally very large. For most feeding components and welfare issues, effect estimates of deviations followed a normal distribution around zero, meaning that most pigs did not deviate their feeding patterns during the welfare issue and that the ones that did could show both reductions and increases in the same feeding component. When considering only pigs for which the deviation in feeding behaviour during a welfare issue was significant (i.e. the effect estimate significantly differed from zero), still for most feeding components different pigs showed either increases or reductions during the same welfare issues, indicating a large variation in responses between pigs. These results apparently contradict with literature, in which reduced intake and duration during lameness (Munsterhjelm et al., 2015; Kapun et al., 2016), and reduced intake during tail damage (Munsterhjelm et al., 2015) have been observed at group level. However, when looking at the *average* effect estimates, some of these results actually were reproduced. Although not statistically tested, on average intake and duration did seem reduced during periods of lameness (see the orange dots in Fig. 2), and intake was also reduced during periods of tail damage if only the significant effects were considered (orange dots in Fig. 3). This correspondence at group level suggests that the apparent contradiction between our results and the literature can be explained by individual variation. More specifically, it suggests that even though on average certain responses to welfare issues in pig feeding behaviour are seen, these responses are not consistent across individual pigs. Indeed, for most combinations of feeding components and health issues, neither individual nor average effects were seen, implying that pigs did not deviate from their normal feeding behaviour during periods of compromised health. It could be that pigs have been bred to continue eating as long as they can, and therefore that feeding behaviour is unlikely to deviate during mild health issues. However, to our knowledge, there is currently no data on the individual responses of pigs to health issues for other types of behaviours, so it cannot currently be established that this large individual variation is specific to feeding behaviour, or even to growing-finishing pigs. For the damage scores specifically, it could also be theorised that the multifactorial nature of damaging

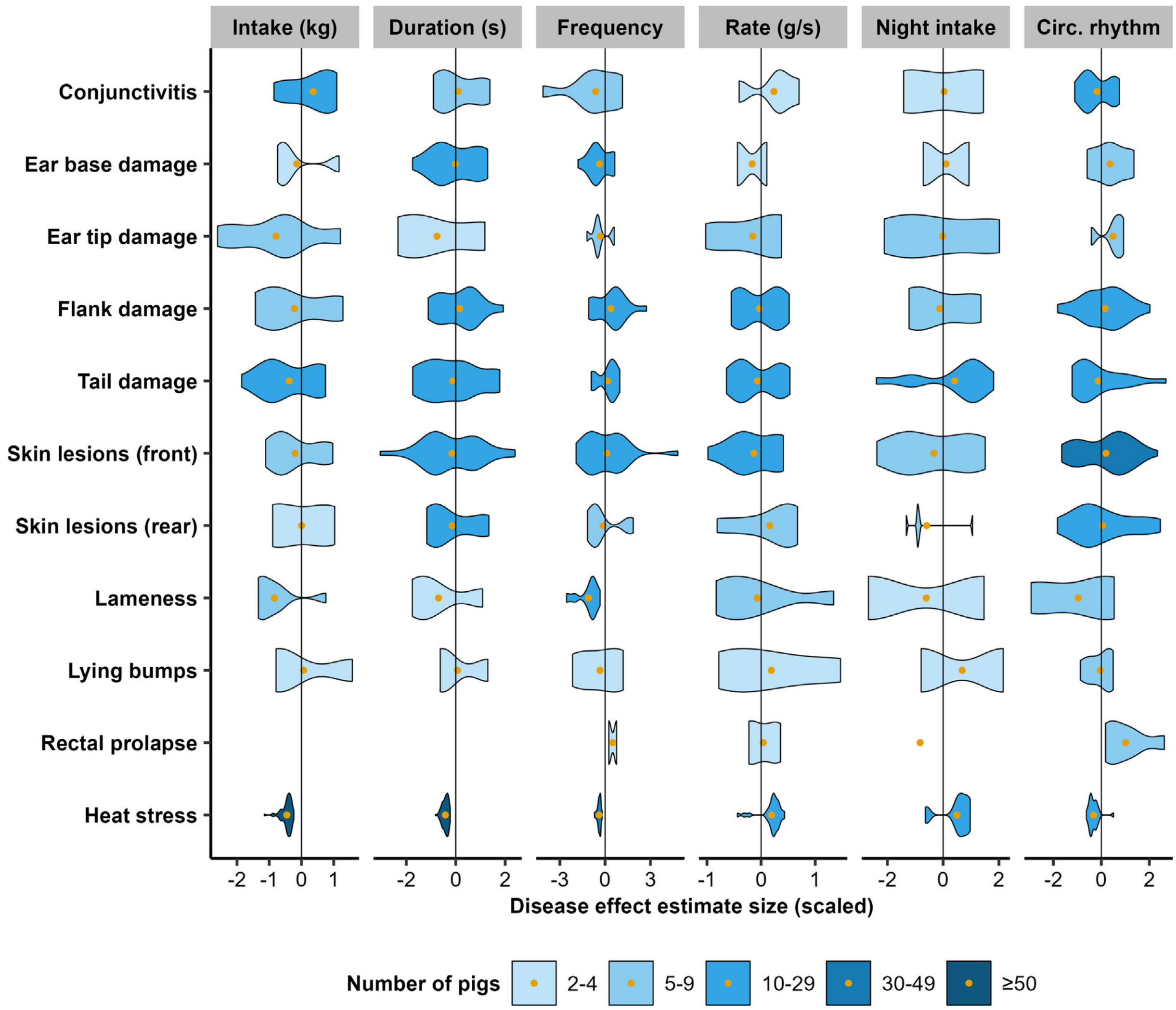

Fig. 3. A violin plot showing the distributions of the effect estimates of different welfare issues on the feeding components of individual growing-finishing pigs, including only those effect estimates that were significantly different from zero. Feeding components ('Circ. rhythm' = strength of the circadian rhythm) were scaled before analysis, hence the scaled effect estimates can be compared between welfare issues and feeding components. The colour of the violin approximates the number of pigs on which its distribution is based. A vertical, black line reflects the 'zero-effect', i.e. no effect of the welfare issue on the feeding component. An orange dot reflects the mean of the effect estimates for each distribution.

behaviour (e.g. tail biting, Henry et al., 2021) might induce different behavioural responses in victims of different forms of biting, hence leading to a large variation in feeding pattern deviations.

Heat stress formed a clear exception to this lack of consistent responses. During heat stress, intake, duration and frequency were reduced in almost all pigs. In addition, most pigs showed either no response or an increase in rate and night intake, and did not change or reduced the strength of their circadian rhythm. These results correspond well with literature on the effects of constant heat (i.e. throughout day and night) on pig feeding behaviour (e.g. Nienaber et al., 1987; Kerr et al., 2005; Dos Santos et al., 2018) and are more extreme than results reported in situations when heat stress only occurred during the day (e.g. Feddes et al., 1989; Lopez et al., 1991; Quiniou et al., 2000), despite these studies using widely different thresholds for what was considered heat stress. Compared to the inconsistency in deviations during health issues, it was nevertheless surprising that deviations during heat stress were consistently shown by all pigs, and this may suggest different mechanisms underlying deviations during heat stress versus health issues. Previous studies reported reductions in feed intake for both health issues and heat stress (Bus et al., 2021), but the types of health issues mainly associated with intake drops were clinical diseases presenting with fever, such as pneumonia (Brown-Brandl et al., 2013) and viral (Schweer et al., 2016) or bacterial (Helm et al., 2018a, b) infections. For such diseases, intake drops are an adaptive part of the sickness response, used to fight the infection (Johnson, 2002). Similarly, for heat stress, intake drops prevent increasing pigs' body temperature further due to additional heat production from digestion (West, 2003). Possibly, for other health issues, such advantages of reduced feed intake may be absent, making it beneficial to sustain feeding for as long as possible. Therefore, pigs may have rapidly adapted their feeding activity to heat stress, but not to the types of health issues studied here.

For some specific health issues, nevertheless, one-sided deviations (i.e. only increases or decreases) occurred if only significant effect estimates were considered. This suggests that there are certain welfare issues that induce specific feeding pattern deviations, but these are not shown by all or even the majority of pigs (significant deviations were generally detected in 5–20% of the pigs (Table 5)). For example, during periods of lameness, pigs clearly either did not change their frequency or reduced it. A reduction

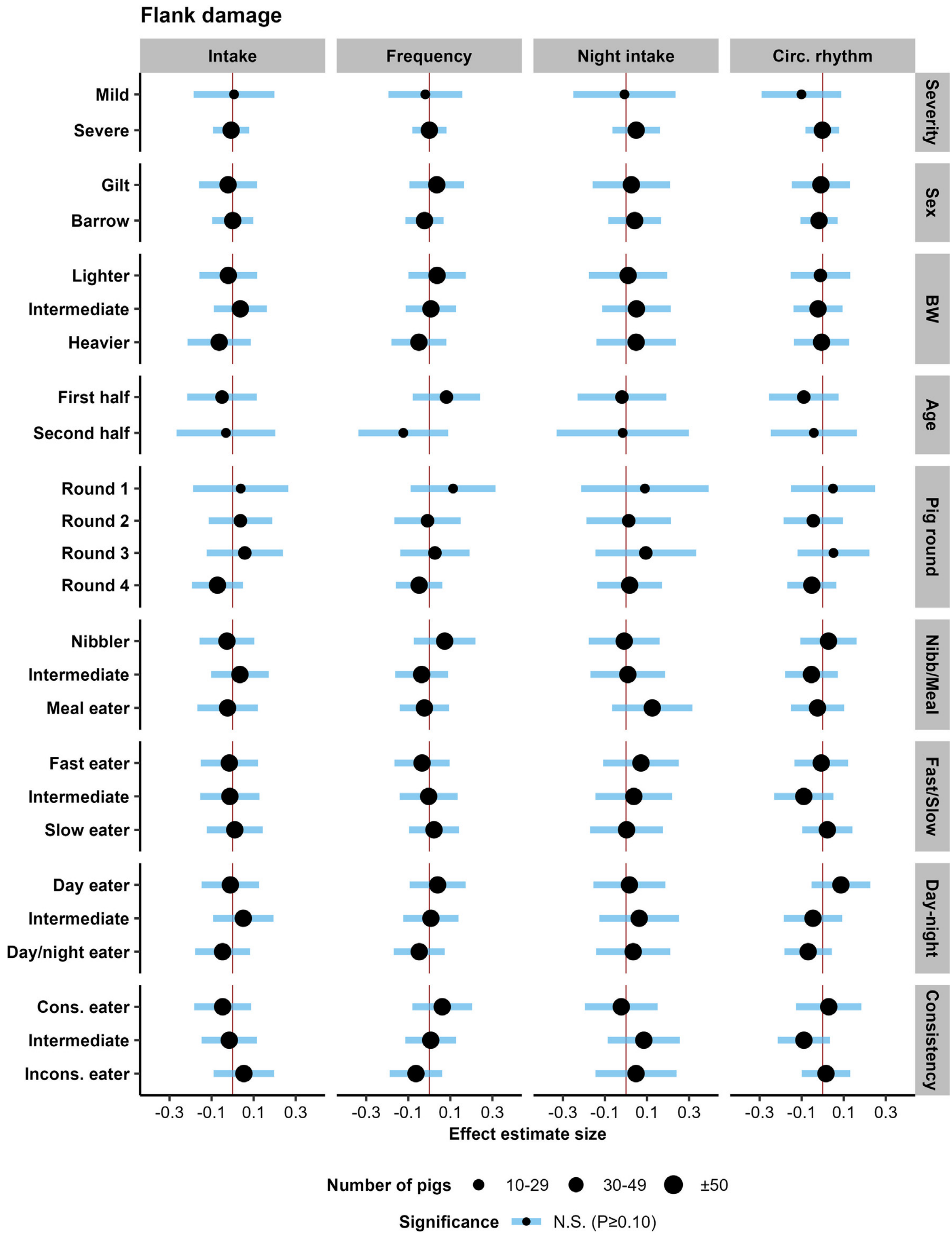

Fig. 4. The effect estimates (black dots) and their 95% confidence intervals (coloured lines) of flank damage on different feeding components (intake, frequency, night intake, and the strength of the circadian rhythm), split into different characterisation categories using meta–subset analysis. Characterisation variables included the severity of the welfare issue, the sex, relative BW and age of the pig, the round in which the pig was reared, and the pig's feeding strategies (in four dimensions: nibbling/meal eating, fast/slow eating, day/day-night eating and consistent/inconsistent (cons./incons.) eating), each split into two to four categories. All feeding components were scaled before analysis, hence the effect estimate sizes are comparable between feeding components, welfare issues and subsets. A dark red line represents the zero-effect, where there was no association between the welfare issue and the feeding component for that subset. The type of shape used for the effect estimate size and the colour of its confidence interval reflect whether the estimates of the subset significantly differed from zero. The size of the shape approximates the number of pigs included in the analysis for each category.

in frequency during lameness would be expected, as painful walking is likely to cause a pig to visit the feeder less frequently, but apparently it does not get to that level for all lame pigs. Similarly, reduced frequency and strength of the circadian rhythm was seen during periods of rectal prolapse – albeit on a small sample size due to it being uncommon (n = 2–6, Table 5) – which possibly indi-

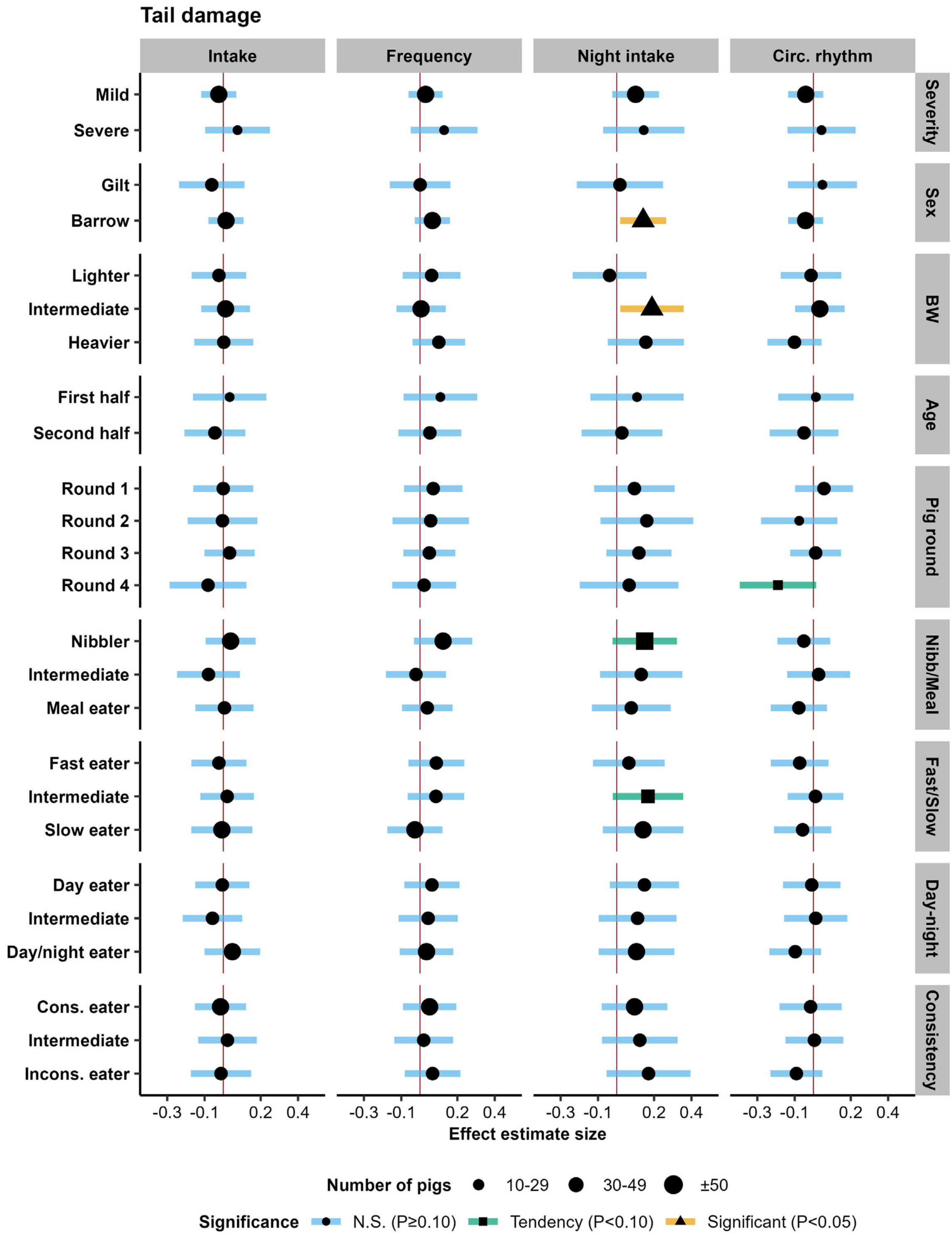

Fig. 5. The effect estimates (black dots, squares and triangles) and their 95% confidence intervals (coloured lines) of tail damage on different feeding components (intake, frequency, night intake, and the strength of the circadian rhythm), split into different characterisation categories using meta–subset analysis. Characterisation variables included the severity of the welfare issue, the sex, relative BW and age of the pig, the round in which the pig was reared, and the pig's feeding strategies (in four dimensions: nibbling/meal eating, fast/slow eating, day/day-night eating and consistent/inconsistent (cons./incons.) eating), each split in two to four categories. All feeding components were scaled before analysis, hence the effect estimate sizes are comparable between feeding components, welfare issues and subsets. A dark red line represents the zero-effect, where there was no association between the welfare issue and the feeding component for that subset. The type of shape used for the effect estimate size and the colour of its confidence interval reflect whether the estimates of the subset significantly differed from zero. The size of the shape approximates the number of pigs included in the analysis for each category.

cates discomfort or an avoidance of standing in the EFS as this would expose the prolapse to manipulation by pen mates. Similar but less evident results were seen for ear tip damage, ear base damage, tail damage, skin lesions and lying bumps. It could be that only the least resilient or most pain-sensitive pigs show deviations in feeding behaviour in response to health issues (Putz et al., 2019; Nguyen-Ba et al., 2020; Van der Zande et al., 2022), that these pigs really were more severely affected but this was not recorded in our

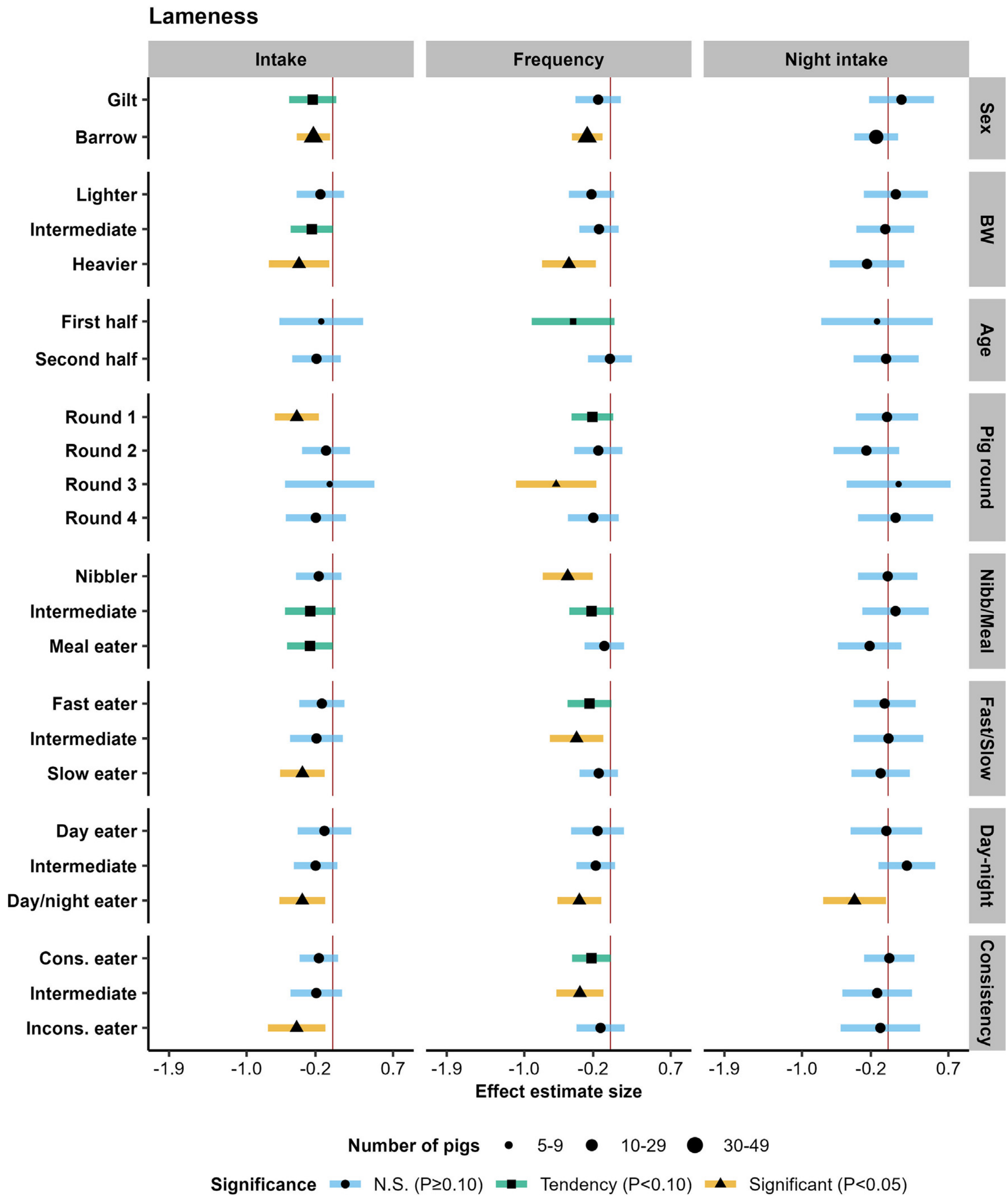

Fig. 6. The effect estimates (black dots, squares and triangles) and their 95% confidence intervals (coloured lines) of lameness on different feeding components (intake, frequency and night intake (strength of the circadian rhythm is not included because its analysis did not meet normality assumptions)), split into different characterisation categories using meta–subset analysis. Characterisation variables included the sex and relative BW of the pig, the round in which it was raised, and the four feeding strategies (in four dimensions: nibbling/meal eating, fast/slow eating, day/day-night eating and consistent/inconsistent (cons./incons.) eating), each split into three categories. Severity of lameness could not be included as there were too few pigs with high lameness scores in the dataset. All feeding components were scaled before analysis, hence the effect estimate sizes are comparable between feeding components, welfare issues and subsets. A dark red line represents the zero-effect, where there was no association between the welfare issue and the feeding component for that subset. The type of shape used for the effect estimate size and the colour of its confidence interval reflect whether the estimates of the subset significantly differed from zero. The size of the shape approximates the number of pigs included in the analysis for each category.

observations (e.g. internal infections), or that only pigs with certain characteristics deviate during welfare issues.

Characterising pigs with different responses to welfare issues

Whether the large variation in responses to welfare issues can be explained by certain pig and environmental characteristics seems to depend on the welfare issue and feeding component considered. We found that no deviations in feeding behaviour during periods of flank damage were present for any of the identified subgroups of pigs, while, as logically follows from (almost) all pigs showing these effects, reductions in intake and frequency during heat stress were seen no matter the subgroup of pigs. During lameness or tail damage, there were subgroups of pigs with specific

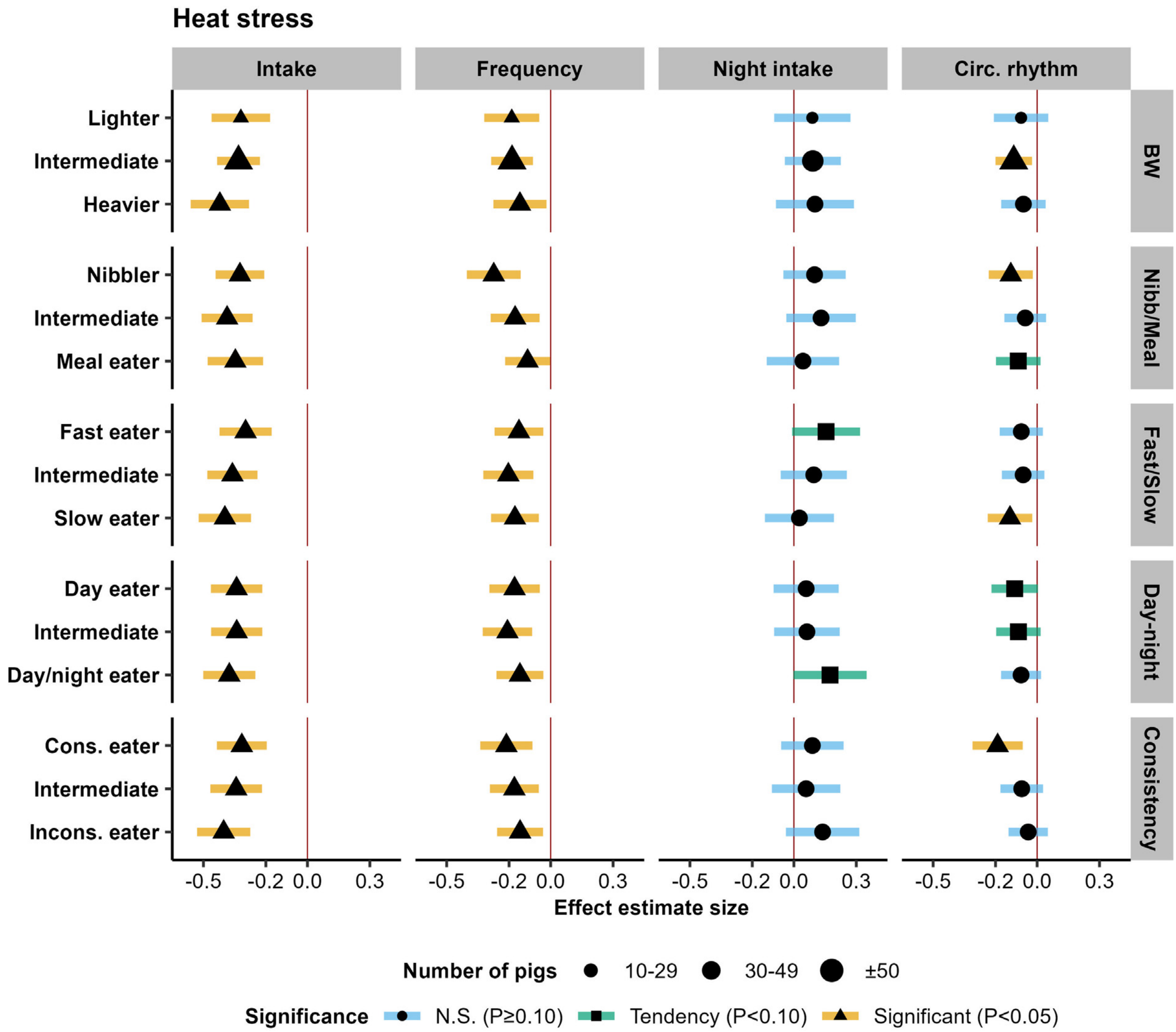

Fig. 7. The effect estimates (black dots, squares and triangles) and their 95% confidence intervals (coloured lines) of lameness on different feeding components (intake, frequency, night intake, and the strength of the circadian rhythm), split into different characterisation categories using meta–subset analysis. Characterisation variables included only the relative BW of the pig and pig feeding strategies (in four dimensions: nibbling/meal eating, fast/slow eating, day/day-night eating and consistent/inconsistent (cons./incons.) eating, each split into three categories), as the other characterisation variables contained too few pigs per category for analysis. All feeding components were scaled before analysis, hence the effect estimate sizes are comparable between feeding components, welfare issues and subsets. A dark red line represents the zero-effect, where there was no association between the welfare issue and the feeding component for that subset. The type of shape used for the effect estimate size and the colour of its confidence interval reflect whether the estimates of the subset significantly differed from zero. The size of the shape approximates the number of pigs included in the analysis for each category.

characteristics that showed consistent deviations in feeding patterns. Additionally, heat stress weakened the circadian rhythm in only some subgroups of pigs. These subgroups of pigs seemed to be mostly related to either physical characteristics of the pigs, the round pigs were reared in and pig feeding strategies. As the effects of pig round were only seen for those rounds with low numbers of lame pigs, these likely reflect chance effects and will hence not be further discussed.

Regarding pig physical characteristics, it was seen that only heavier pigs and barrows reduced their intake and frequency during lameness, while during tail damage only barrows increased their night intake. For lameness, this could be explained by relatively heavier pigs, which include barrows compared to gilts, possibly being more affected by lameness as they would have to carry more weight when walking on their lame leg(s). Therefore, heavier pigs may be more prone to avoid walking, hence adapting their feeding patterns more severely. An increase in night intake during tail damage may reflect an avoidance of the feeder when other pigs are active, as during feeding in the EFS the tail was exposed to pen mate manipulation. Why this specifically occurs in barrows and pigs of intermediate BW is difficult to interpret and may represent a chance result. From data visualisations, we saw no clear indication that barrows, gilts, heavier, lighter or intermediate–weight pigs were more or less exposed to different types of tail damage outbreaks, such as with more or fewer pigs affected or shorter- or longer-lasting wounds (results not shown). It is known that sex differences in tail damage exist, but whether gilts, barrows or boars are more affected differs between studies (Schrøder-Petersen and Simonsen, 2001; Zonderland et al., 2010; Hunter et al., 2011). For relative BW, it could be that intermediate pigs had more physical ability to adapt by eating more at night, similar to their higher ability to increase their feeding rate during heavy feeder competition (Georgsson and Svendsen, 2002). For example, smaller pigs may have been forced to eat more throughout the day due to a smaller stomach capacity, while larger pigs may have wanted to defend their presumably higher position in the dominance hierarchy by feeding during peak hours. These relationships warrant further study.

Deviations in feeding behaviour during periods of lameness or heat stress were also present in subgroups of pigs with certain feeding strategies. We propose three possible explanations for why pigs may deviate their feeding behaviour dependent on their feeding strategies. Firstly, their feeding strategies may be a prerequisite for behavioural adaptation. For example, night intake or day-to-day consistency can only be reduced if the pig normally eats at night or behaves consistently from day to day. Secondly, some responses seem dependent on physical relationships. For example, only pigs that normally visited the EFS frequently (i.e. nibblers) were seen to reduce their frequency during lameness, implying they avoided walking as much as they normally did. Nibblers were likely more physically able to do so than meal eaters, because they had the available stomach capacity to increase their meal intake without compromising daily intake. Similarly, it could be that only slow eaters reduced their intake because they had to stand in the EFS longer to obtain the same daily intake as faster eaters, and they may have been unable (or unwilling) to do so when lame. These explanations could also hold for the weakening of the circadian rhythm during heat stress in nibblers and slow eaters, where nibblers and slow eaters may have adapted their frequency and intake more than meal eaters and fast eaters. Finally, there may have been an effect of social facilitation, where pigs that normally behaved more independently from the group (e.g. by eating more at night or more inconsistently) were when lame more dependent on the feeding activity of other pigs to obtain sufficient motivation to get up and feed. For example, it could be that pigs that normally were inconsistent eaters reduced intake because they skipped the meals that they would normally have without pen mates feeding, and that pigs normally eating at night refrained from doing so as no other pigs were eating at that time. The latter is supported by these pigs not only reducing their night intake but also their total intake and frequency, indicating that they skipped meals. There is currently limited evidence for an effect of social facilitation on the feeding behaviour of pigs (reviewed by Bus et al., 2021), but whether social facilitation is more important during periods of welfare issues has, to our knowledge, not been explicitly studied. A simpler explanation could also be that lame pigs mostly went to feed when disturbed by pen mates (e.g. being bitten or pushed may have caused them to stand up) and these disturbances would have most frequently occurred when the pen mates were active and feeding as well.

Interestingly, we found no influence of pig age nor of the severity of flank or tail damage on whether pigs displayed deviations in feeding behaviour during the period of damage (this could not be tested for lameness due to small sample sizes). We had, however, hypothesised that older pigs would be more physically able to adapt their feeding behaviour (e.g. gastrointestinal capacity is larger), and thus more likely to deviate, and that pigs with more severe flank or tail damage would show a larger deviation from their basal feeding behaviour. Although it could be that behavioural adaptation to flank or tail damage is not affected by either age or the severity of the wound, as in all cases being bitten on a wounded tail is painful, it could also be that we had insufficiently large contrast in age and the severity of flank or tail damage to detect differences. For age, for example, pigs were often seen to suffer from the same health issues at both younger and older ages, possibly masking different effects. Regarding the severity of tail damage, however, a lack of contrast seems unlikely, as the highest scores before 'full loss of the tail' were reached for several pigs. It should be noted that severity levels were not compared for any other health issues than flank and tail damage, hence it cannot be excluded that a more consistent change in feeding behaviour would be observed for other health issues of high severity.

Implications for using deviations to detect welfare issues

Our study was performed in the context of developing an algorithm that could detect deviations from basal feeding behaviour and relate these to welfare issues of individual pigs (e.g. detecting bouts of health issues). Our results suggest that this may be very difficult, if not impossible, for most types of welfare issues, as individual pigs do not appear to show clear deviations from their basal feeding behaviour during welfare issues. A clear exception to this is heat stress, to which pigs showed a clear, almost unanimous response in at least intake and duration, and which should hence be detectable using both EFSs and less costly systems like RFID antennas at the feeder (e.g. Maselyne et al., 2018; De Bruijn et al., 2023) or camera vision algorithms that detect presence of pigs in the feeder (e.g. Alameer et al., 2020; Zhuang et al., 2022). It could be questioned, however, how valuable this detection is beyond direct tracking of the temperature in the barn, which would be less computationally demanding.

Although for most health issues, it does not appear possible to detect them in individual pigs, there are some interesting pathways warranting further attention. For example, some types of pigs did deviate their feeding behaviour during lameness or tail damage. It may, therefore, be possible to develop an algorithm that uses specific feeding components to detect specific health issues, at least in some of the pigs. Lameness, for example, seems to be most clearly related to deviations in feeding behaviour in pigs more physically challenged during lameness (i.e. heavier pigs), more able to adapt (i.e. nibblers) or less dependent on pen mate behaviour prior to the lameness (i.e. day-night eaters), suggesting that lameness may be detectable in a proportion of pigs. Similarly, tail damage seemed to increase pigs' night intake but only in barrows and pigs of intermediate BW. Studying further why these groups of pigs are more affected may elicit subgroups of pigs for which algorithmic detection of welfare issues through feeding behaviour is possible.

Study limitations and suggestions for future research

Both the feeding and the health data were subjected to many processing choices before analysis, including, among others, the cleaning of the EFS data (which removed feeding visits and days), meal and day aggregation choices, choice of health score thresholds, interpolation of health data to non-observation days, and choice of corrective factors in the analysis (e.g. medication use, pig removal, feed type). If possible, these choices were based on theory, but when necessary they were based on sample size requirements and the balance of days denoted as with and without welfare issues for each pig. Theoretically, all of these could have had an impact on the analysis' ability to detect deviations from basal feeding behaviour during days of welfare issues. Nevertheless, for most of these choices, in the exploration phase of this study, data were analysed after applying a range of different processing choices, and the distributions of the effect estimates (i.e. Fig. 2) were never observed to change. Therefore, we believe that this large variation between pigs is a true observation, and not an artefact of our data processing decisions.

The data in this study were obtained from four consecutive rounds of pigs raised in the same barn, in which a relatively conventional management system for growing-finishing pigs was applied. Extrapolation of the results to other farms, and especially other types of management systems, should be performed with caution. In addition, all feeding data were obtained using IVOG® EFSs with *ad libitum* feeding, while the way in which feed is provided heavily influences pig feeding patterns (Nielsen et al., 1996; Botermans et al., 2000; Botermans and Svendsen, 2000). Therefore, extrapolation to other feeder systems may be limited.

Finally, this study has solely focused on pig feeding behaviour; it would be interesting to see to what extent this large individual variation in response to welfare issues extrapolates to other types of behaviours, such as activity. Moreover, considering that welfare monitoring algorithms are also being developed in other types of farm animals (e.g. dairy cows (Zhou et al., 2022), veal calves (Belaid et al., 2020), laying hens (Welch et al., 2023) and gestating sows (Durand et al., 2023)), whether large individual variation in response to welfare issues also limits the validity of welfare issue detection in other farm animals warrants research attention.

Conclusion

We conclude that the individual variation in how pigs change their feeding behaviour in response to a range of health issues is very large, ranging from individuals with no deviation at all to individuals with either reductions or increases, in all feeding components. For some health issues, especially lameness, clear and consistent deviations could, nevertheless, be observed in pigs with common characteristics related to their physique (e.g. sex and BW) and feeding strategies. Moreover, very consistent changes in feeding patterns were seen during heat stress, where almost all pigs displayed a reduced intake, duration and frequency. These results suggest that while for heat stress it should be easy to detect its occurrence, for most (mild) health issues it may be difficult or even impossible to use deviations from basal feeding behaviour to detect their occurrence in individual pigs – at least with the feeding features and health issues considered here. There may, however, be opportunities to detect specific welfare issues, such as lameness or tail damage, in specific types of pigs.

Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.1016/j.animal.2024.101192.

Ethics approval

Not applicable.

Data and model availability statement

None of the data nor the model were deposited in an official repository, but both are available upon request.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) did not use any AI and AI-assisted technologies.

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Declaration of interest

None.

Acknowledgements

We would like to thank Topigs Norsvin, specifically Egbert Knol, Stefanie Nuphaus and Severin Rueskamp, for the pigs, infrastructure and their help in the research. In addition, we would like to thank Heinz Volmer for taking care of the pigs, and the colleagues and students who helped with the on-farm data collection.

Financial support statement

This work was part of the ClearFarm project, supported by the European Union's Horizon 2020 research and innovation programme [grant agreement No. 862919]; and was further supported by the innovation programme Next Level Animal Sciences of Wageningen University and Research.

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