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Constant traffic noise affects the behavior and physiology of naïve horses at pasture

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Introduction: Horses are frequently kept on pastures near major roads, exposing them to high levels of traffic noise. In humans, prolonged traffic noise exposure is associated with physiological stress, sleep disruption, and adverse health effects. Despite horses' high auditory sensitivity, comparable data on the behavioral and welfare implications of continuous traffic noise are scarce. This study investigated short-term behavioral and physiological responses of horses naïve to constant motorway noise in their home environment.

Methods: Twenty horses housed in four stable groups across three facilities were exposed to recorded motorway noise for 1–2 weeks. Emitted noise levels ranged from 54 to 71 dB, corresponding to distances of approximately 500 to 10 m from a four-lane motorway, and were played during daytime for up to 11 h/day using portable outdoor loudspeakers. Control periods without motorway noise (average ambient noise level: 38 dB) before and between exposure days served as baseline, intermediate washout, and final control phases. Behavioral parameters were recorded throughout the day using focal and scan samplings. Heart rate was continuously monitored as a physiological indicator of stress.

Results: During noise exposure, horses reduced foraging behavior from a median of 81% at baseline to 41% during the first exposure phase ($p<0.001$), while vigilance increased from nine to 54 instances per day ($p<0.001$). Horses also avoided the vicinity of the noise source ($p<0.001$). Behavioral effects were pronounced at higher noise levels, with clear avoidance responses suggesting aversion as an active coping strategy. Heart rate increased within the first exposure phase, rising from an average of 57.60 bpm to 66.76 bpm ($p<0.001$), suggesting an acute stress response.

Discussion: Although some behavioral habituation was observed over time, spatial avoidance of the noise source persisted, and elevated heart rates indicated continued physiological arousal. Even noise levels of a 500 m distant motorway (≥54 dB) altered behavior and physiology. These findings demonstrate that traffic noise represents a relevant environmental stressor for horses and may compromise welfare when exposure is frequent or prolonged. The study highlights the need to consider noise in equine management and supports mitigation strategies such as providing large pastures with quiet retreat zones or installing noise barriers.

KEYWORDS

equine welfare, horse (*Equus caballus*), noise exposure, pasture use, physiological stress, traffic noise, vigilance

1 Introduction

Roads are a pervasive feature of human-modified landscapes, frequently intersecting both human and animal habitats. In densely populated regions, pastures are often situated close to roads, exposing humans and animals alike to various external stimuli such as air pollution, visual stimuli, and particularly, constant noise. Among these, chronic noise exposure is increasingly recognized as a significant stressor to humans and animals with physiological and behavioral implications (Barber et al., 2010; Arregi et al., 2024). For animals that rely on auditory cues, for instance, for the innate predator recognition in flight animals, traffic noise may ultimately affect their behavior and proximately trigger a stress response (Wright et al., 2007; Kok et al., 2023). In humans, traffic noise is linked to chronic stress responses, even when humans feel accustomed to the noise. Long-term noise exposure contributes to metabolic and cardiovascular diseases (Jarup et al., 2008; Huss et al., 2010; Sørensen et al., 2011). The World Health Organization (WHO) defines environmental noise levels above 53 dB as potentially harmful, associated with higher risks of hypertension and myocardial infarction (World Health Organization, 2018). The German Federal Ministry for the Environment considers physiological effects to occur likely above 65 dB, while chronic exposure above 85 dB causes irreversible hearing loss due to cochlear damage (JAMA, 1990). These thresholds guide human-focused road construction and noise mitigation measures. For example, in Germany, traffic noise must not exceed noise levels of 59 dB at residential buildings (Bundesministerium der Justiz, 2020).

Despite widespread recognition of traffic noise as an ecological stressor, systematic research on its effects on animals remains scarce. Many species possess broader auditory ranges and higher sensitivity than humans, yet livestock regulations are generally based on human thresholds. For example, EU Directive 2008/120/EC sets noise thresholds at 85 dB for pigs in indoor husbandry conditions but disregards outdoor sources such as traffic noise, even when the animals have constant access to outdoor compartments (*Council Directive - 2008/120/EC*, 2009). Conversely, wildlife protection regulations often include specific provisions to minimize disturbance from roads, addressing effects on habitat use, reproduction, and communication—particularly in birds, for which species-specific thresholds have been established (Garniel et al., 2007). It is also well-studied that roads fragment habitats and alter activity rhythms of wildlife (Fahrig and Rytwinski, 2009). Despite this, livestock at pasture remain unprotected from road-related stimuli, although they may experience comparable disturbances, specifically concerning noise.

Horses are specifically vulnerable to environmental noise due to their innate flight response and highly sensitive auditory system (Rørvang et al., 2020). Their mobile, funnel-shaped ears can rotate approximately 180° and amplify sounds by up to 20 dB (Ödberg, 1978). This allows perception from 50 Hz at a distance to 33,500 kHz at close range (Heffner and Heffner, 1983, Heffner and Heffner, 1986). These adaptations enhance environmental awareness but also increase sensitivity to acoustic disturbances. The startle and flight response, an evolutionary survival mechanism, remains largely unchanged in domesticated horses, compared to their wild ancestors (Brubaker and Coss, 2015; Janczarek et al., 2020). When environmental irregularities occur, horses display increased vigilance—raising the head and orienting the ears toward the sound source (Christensen et al., 2005; Leiner and Fendt, 2011). Vigilance has been suggested to be a primary indicator of discomfort (König von Borstel et al., 2010; Noble et al., 2013). Depending on previous experience and the perceived potential of danger, horses may either habituate or become more reactive towards certain stimuli, but their reflexive tendency to flee from sudden, unfamiliar stimuli (e.g., gunshots) remains high (Baragli et al., 2014; Gronqvist et al., 2016; Lindstedt, 2020; Hole et al., 2023).

Horses typically have a cyclical daily rhythm alternating between grazing, locomotion, short periods of dozing while standing, and sleeping while lying down (Mayes and Duncan, 1986; Berger et al., 1999). They typically graze for 60–80% of the day and rest in synchronized bouts lasting about 20 minutes (Maeda et al., 2021). Both standing dozing, and recumbent sleep are essential for recovery and health (Bertone, 2015; Greening and McBride, 2022). Rest usually occurs in quiet, sheltered areas within pastures or stables (Carson and Wood-Gush, 1983). Consequently, appropriate husbandry must provide sufficient space for movement, social contact, and undisturbed resting opportunities (Lesimple et al., 2016). When foraging or resting behavior is disrupted, significant physical and psychological consequences can arise, including digestive disorders (e.g., colic), stress-induced illness, increased aggression, and behavioral abnormalities such as narcolepsy (Chaplin and Gretgrix, 2010; Malmkvist et al., 2012; Greening and McBride, 2022). Individual stress susceptibility varies with breed, age, temperament, and experience (Hausberger et al., 2004; Morgan and Tromborg, 2007). Noise from which horses cannot escape, as by retreating to quiet zones, or heightens vigilance, may therefore induce chronic stress. Reported symptoms of noise-related disturbance include hypersensitivity, irritability, and persistent nervousness (Rochais et al., 2017; Janicka et al., 2022; Wiśniewska et al., 2022). However, it remains unclear at which noise levels these effects emerge, whether horses can adapt, or whether long-term welfare and health are compromised.

In this study, we investigated whether continuous motorway noise affects the well-being and stress physiology of horses. In general, we expected initial stress responses, including alterations of the horses' normal behavior. We also expected more pronounced reactions with increasing sound levels and to identify a specific sound level as a critical noise threshold. Our findings aim to inform science-based welfare recommendations and contribute to evidence-based noise mitigation strategies for equine management near roads.

2 Materials and methods

To investigate the influence of constant motorway noise on horses, we deliberately exposed naïve horses to motorway noise in their familiar environment at pasture, while recording their behavior and stress response (heart rate; Figure 1). We selected N = 20 horses kept in four groups (three facilities) on a quiet pasture (37–40 dB only ambient noise) at 2–8 km away from the nearest



FIGURE 1
(A) Setup with two loudspeakers at the pasture and an observation post between the loudspeakers, **(B)** 24 h-surveillance camera, **(C)** view from the focal camera, **(D)** heart rate sensor chest strap with the recording device fixated on the halter. Photographs by Johanna Henke-von der Malsburg.

main road for at least the past two grazing seasons (Table 1). Horses varied in breed (5 Oldenburg warmbloods, 4 Gypsy horses, 2 Alt-Oldenburg warmbloods, 2 Welsh ponys, 2 German riding ponys, 1 Danish sport pony, 1 English thoroughbred, 1 Rhinelander horse, 1 Fjord horse, 1 Hanoverian warmblood), age (3–30 yrs, mean=10.7±9 yrs), and sex (9 mares, 11 geldings), were familiar with occasional traffic noise (e.g., single cars or tractors passing by, walking along a road) but naïve to constant road noise exposure at pasture. We selected the facilities and groups to logistically suit the examination (e.g., distance to major roads and other constant noise sources, easily manageable pasture, constant group composition, relatively constant daily routine over the study period) while maintaining their routine, with, e.g., occasional training or supplemental feeding (Table 1). To minimize disruptions to the respective facility operations and account for the varying circumstances, we adapted data collection to the specific conditions on site (observation sessions, noise exposure procedures), leading to heterogeneous sampling procedures between the facilities (Figure 2). The study was approved by the Regierungspräsidium Giessen (approval number: G 27/2022). All horse owners agreed to the experimental sampling via consent forms.

2.1 Study animals

The three equine facilities were located in Northern and Western Germany. Facility 1 (riding school, Weser-Ems region) comprised school horses (group 1.A, N = 6) and privately owned horses (group 1.B, N = 3) kept on directly adjacent pastures (0.36 and 0.30 ha; Figure 3), ensuring simultaneous exposure to traffic noise for 12 days; one additional donkey in the group of private horses was excluded from analyses. School horses were pastured daily from approximately 0800 to 1200 and housed individually out of earshot in a nearby stable outside this period, whereas private horses remained on pasture for 24 h. Facility 2 (boarding and training stable, Weser-Ems region) included N = 5 horses monitored over 7 days on a 1.3 ha pasture (Figure 3); one horse was partly, and from day 4 onwards continuously, housed in an individual stable with minimal noise exposure. The others were kept at pasture for 24 h. Data for this horse were only included for the periods on pasture. Facility 3 (riding and breeding stable, North Rhine-Westphalia) included N = 6 horses, kept at pasture for 24 h, which were monitored over 13 days. Due to seasonal conditions, three adjacent pasture areas were used sequentially (0.52–0.93 ha; Figure 3; supplementary material). Heart rate was recorded in all horses, with sensor reassignment as necessary (Table 1).

2.2 Procedure

We exposed the horses to motorway noise for a period of one to two weeks during the daily time on pasture (Figure 2). For this purpose, we installed two loudspeakers (Vonyx Splash 300) on one side of the pasture (Figure 1A). Surveillance cameras (ViSiTec) around the pasture recorded the horses' behavior for the entire study period (Figure 1B). We performed direct behavioral observations (15-min *focal sampling* of individual horses alternated with 5-min *scan samplings* of the entire group) in two to three sessions a day, depending on the amount of daylight, and recorded the focal behavior with an additional focus handheld camera (Sony HDR-

TABLE 1 Individual horses and groups studied at the three facilities (1: riding school: groups 1.A and 1.B; 2: boarding stable: group 2.C; 3: riding and breeding stable: group 3.D).

Group individual (current facility)	Breed	Sex (age)	Time at pasture daily absence	Heart rate recording
Group 1.A			4 h pasture in the morning individual stall ca. 12–8 h	
1.A.1 (min. 2 yrs)	Danish sport pony	Gelding (5)		Day 0-11
1.A.2 (min. 2 yrs)	Gypsy horse	Gelding (10)		Day 4-11
1.A.3 (min. 2 yrs)	Gypsy horse	Gelding (10)		–
1.A.4 (min. 2 yrs)	Gypsy horse	Gelding (10)		Day 4-11
1.A.5 (min. 2 yrs)	Welsh pony	Mare (8)		Day 4-11
1.A.6 (min. 2 yrs)	Welsh pony	Gelding (8)		Day 5-11
Group 1.B			24 h pasture	
1.B.1 (4 yrs)	English thoroughbred	Mare (9)	ca. 1 h riding daily	Day 0-2
1.B.2 (18 yrs)	German riding pony	Mare (28)		Day 0-11
1.B.3 (3 yrs)	German riding pony	Gelding (3)	ca. 1 h training every other day	Day 0-11
1.B.4 (4 yrs)	Donkey	Mare (NA)	(excluded from analyses)	–
Group 2.C			24 h pasture	
2.C.1 (3 yrs)	Oldenburg warmblood	Gelding (3)		Day 0-7
2.C.2 (3 yrs)	Oldenburg warmblood	Gelding (3)		Day 0-7
2.C.3 (13 yrs)	Oldenburg warmblood	Gelding (13)	individual stall: ca. 15–8 h	Day 0-6
2.C.4 (12 yrs)	Oldenburg warmblood	Gelding (12)		Day 0-7
2.C.5 (4 yrs)	Oldenburg warmblood	Gelding (22)		Day 0-7
Group 3.D			24 h pasture	
3.D.1 (28 yrs)	Rhinelander horse	Mare (28)	supplementary food next to the pasture	Day 0-13
3.D.2 (3 yrs)	Fjord horse	Mare (3)		Day 0-13
3.D.3 (3 yrs)	Hanoverian warmblood	Mare (3)	supplementary food next to the pasture	Day 0-13
3.D.4 (3 yrs)	Alt-Oldenburg warmblood	Mare (3)		Day 0-13
3.D.5 (3 yrs)	Alt-Oldenburg warmblood	Mare (3)		Day 0-13
3.D.6 (min. 2 yrs)	Gypsy horse	Mare (30)	supplementary food at the barn (ca. 1 h absence)	Day 0-13

While groups 1.B, 2.C, and 3.D were out in the pasture all day (24/7), the horses in group 1.A were kept in individual stalls for use in the riding school in the afternoon and at night.

DAY	−1	0	1	2	3	4	5	6	7	8	9	10	11	12
group 1.A	(in stable)	0 h 0 dB M	0 h 0 dB M	4 h 71 dB M	4 h 65 dB M	4 h 60 dB M	0 h 0 dB M	4 h 71 dB M	6 h 58 dB MA	6 h 56 dB MA	6 h 54 dB MA	4 h 71 dB M	0 h 0 dB M	
group 1.B	start: 1700h	0 h 0 dB MA	0 h 0 dB MAE	11 h 71 dB MAE	11 h 65 dB MAE	11 h 60 dB ME	0 h 0 dB MAE	11 h 71 dB MAE	11 h 58 dB MAE	11 h 56 dB MAE	11 h 54 dB MAE	6 h 71 dB MAE	0 h 0 dB M	
group 2.C	start: 1200h	0 h 0 dB E	0 h 0 dB MAE	11 h 65 dB MAE	11 h 54 dB MAE	0 h 0 dB ME	11 h 65 dB MAE	11 h 58 dB MAE	0 h 0 dB MA					
group 3.D	start: 1400h	0 h 0 dB ME	0 h 0 dB ME	8 h 58 dB ME	8 h 65 dB ME	8 h 71 dB ME	0 h 0 dB ME	0 h 0 dB	0 h 0 dB ME	0 h 0 dB ME	8 h 60 dB ME	8 h 54 dB ME	8 h 56 dB ME	0 h 0 dB ME

FIGURE 2
Procedure of the noise exposure with day −1 as habituation to the experimental setup (excluded from analyses), days 0–1 as pre-exposure baseline control, two succeeding noise exposure phases with an intermediate wash-out day, and a final control day. Given are the hours of daily noise exposure, the respective noise level (color-coded; grey: no noise exposure, only ambient noise of 37–40 dB), and the observation sessions (M: morning session with start after sunrise; A: afternoon session with start 1–1.5 h after the end of the morning session; E: evening session with start so that it was finalized before sunset) per group. Procedures differ between groups due to adaptations to the management within the individual facilities.

CX405; Figure 1C). To record the physiological stress response, the horses wore heart rate girths (Polar® Equine WearLink®) with a recording device fixed to the horse's halter (Polar® RS800 or RS800CX; Figure 1D).

2.2.1 Noise exposure

Before the noise exposure, we recorded the horses' normal behavior and heart rates over two days, which served as habituation to the setup (day −1) as well as baseline for the study (day 0–1). On the following days, we exposed the horses to constant motorway noise (modified sound 'motorway, directly next to the road, fast-moving cars and trucks'[1]) from morning to evening. On the last day and an intermediate wash-out day, we played no motorway noise for control purposes (Figure 2). Each day, we set a different sound level (54 dB to 71 dB) for the noise exposure to simulate varying distances (500 m to 10 m) to a motorway (Table 2). The order of the different sound levels varied between facilities and was pseudo-randomized (Figure 2). The sound level was verified in the proximity area of the pasture (zone 1: 15 m distance from the loudspeakers) using a sound level meter (UNI-T UT353 BT). We also measured noise levels throughout the pasture twice a day, once during noise exposure and once without noise exposure (supplementary material, Supplementary Figure 1, Supplementary Table 1).

The vicinity of the sound source was defined as approximately 30 m around each outer loudspeaker (zone 1 + 2). The specified sound level was ensured in the immediate vicinity of the loudspeakers (approximately 15 m around both loudspeakers, zone 1; Figure 3; supplementary material, Supplementary Table 1). Beyond this close range, the sound level decreased to a greater or lesser extent, depending on the terrain (flat areas at facilities 1 and 2; tree boundaries at facilities 1 and 3). Wind speed and direction were taken into account when adjusting the volume to the desired intensity. The distance from the noise sources, i.e., potential areas of retreat, varied depending on the size of the pasture, with the pasture of group 2.C, at over 1 ha, and the third pasture of group 3.D, at just under 1 ha, being considerably larger than the other pastures (Figure 3).

2.2.2 Behavioral observations

The behavioral observations, with 15-minute *focal animal samplings* alternated with 5-minute group *scan samplings*, took place in two (facility 3) to three sessions (facilities 1 and 2) per day (Figure 2) to obtain a comprehensive picture of the horses' daily routine following a pre-defined ethogram (Table 3). To this end, the observer stood inconspicuously between the two loudspeakers, recording the horses' behavior (Figure 1A). The first session started in the morning after sunrise, as soon as all the horses of a given group were out in the pasture (group 1.A, one individual of group 3.D). The next session took place one to two hours after the end of the first session, around noon. The last session took place in the evening so that it was finished before sunset. Each session began with a 5-minute *scan sampling* of the entire group. This was followed by alternating 15-minute *focal sampling* of one horse and 5-minute *scan sampling* of the entire group. On days with motorway noise exposure, the first session started with two scan samplings – the first without motorway noise, the second after the loudspeakers had been set to the respective sound level. The last session at the end of the day ended with two scan samplings – the first with motorway noise, the second after the loudspeakers had been switched off.

2.2.2.1 Scan sampling

During the 5-minute scan samplings, the current position of all horses in the pasture (zone 1—3) and their behavior were recorded every minute (Table 3). In addition, the noise level was verified, and any audible road noise, wind, and rain were noted to control for potential noise influences.

1 downloaded from https://www.salamisound.de/4788474-autobahn-direkt-an-der.

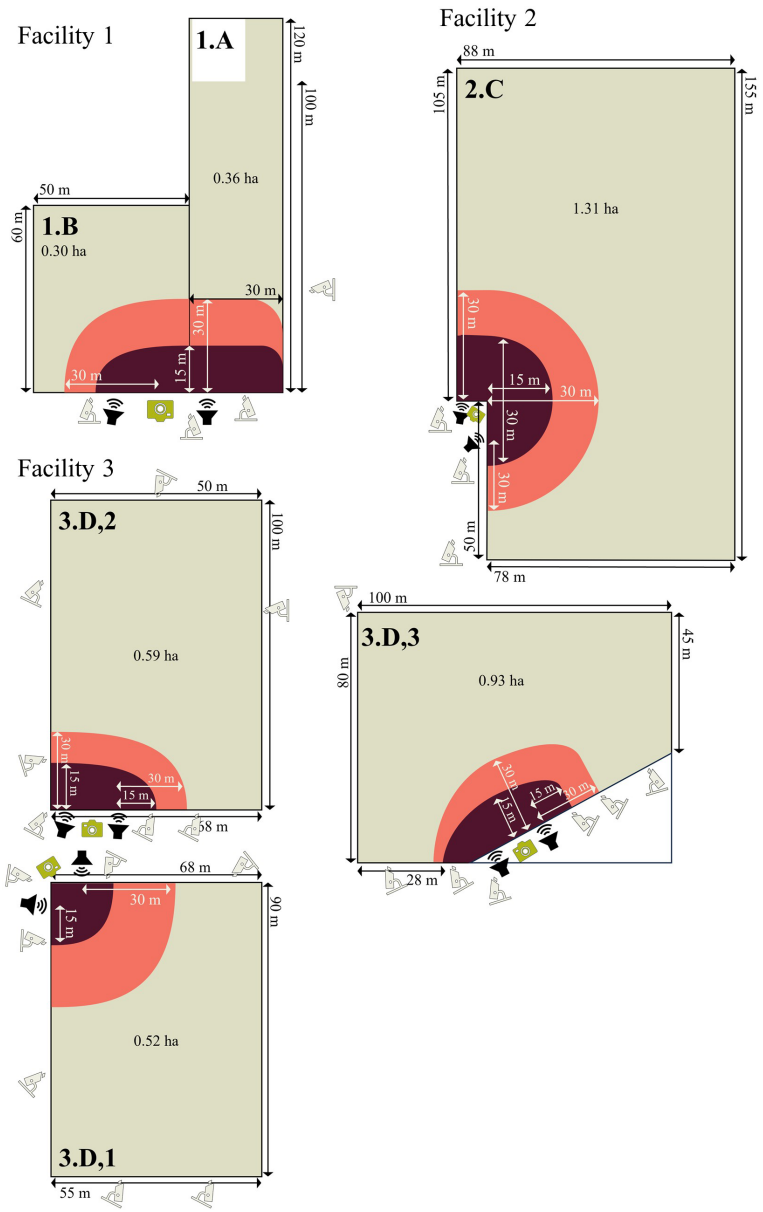


FIGURE 3
Schemes of the pastures at facility 1 (Groups 1.A and 1.B), facility 2 (Group 2.C), and facility 3 (Group 3.D, 3 pastures). Pastures 3.D, 1 and 3.D, 2 were located on the same meadow area, which was divided as shown here. Pasture 3.D, 3 was located opposite 3.D, 2 on the other side of a dirt road. The dimensions given are rounded to the full meter. The colors correspond to the division into different zones in relation to the position of the loudspeakers (🔊): Dark red = zone 1, 15 m radius; orange = zone 2, 30 m radius; beige = zone 3, rest of the pasture. Cameras show the location of the observation point (📷) and the surveillance cameras (📹).

2.2.2.2 Focal Sampling

During the 15-minute focal samplings, the position of the observed horse (focal) and its behavior were recorded. Position changes between zones, as well as ad libitum behaviors related to distraction, stress, and well-being, were also recorded for all other horses (Table 3). The focal horse was filmed (Sony HDR-CX405) for later detailed analysis of body posture and facial expressions, which are prepared for publication elsewhere.

2.2.3 Heart rate

The horses' heart rates were continuously recorded using sensors on girths (Polar® Equine WearLink®) and corresponding data watches as recorders (Polar® RS800 or RS800CX). The recorded pulse values were read out using the manufacturer's Polar ProTrainer 5 software. The fit of the girths and the connectivity of the sensor to the recording device were controlled several times a day. As the horses were able to move freely at all times and

TABLE 2 Daytime noise levels and corresponding distances to a 4-lane motorway with 30, 000 vehicles per day (EIBS GmbH, 2024).

Noise level	Simulated distance
0 dB (only natural noise at 37–40 dB)	No highway
54 dB	500 m
56 dB	400 m
58 dB	300 m
60 dB	200 m
65 dB	100 m
71 dB	10 m

socialized with group members, it was not possible to ensure the girths remained correctly positioned at all times, especially when the horses lay down, sometimes causing the girths to slip caudally and resulting in missing values. Measurements taken while the horse was in the stable, during training, or while being supplementary fed by humans as well as measurements taken around the time of applying and checking the pulse girth (first and last 3 minutes after activation and before deactivation of the sensor, respectively) were manually excluded to evaluate only the heart rate during the time at pasture and free from disturbances unrelated to the experiment.

2.2.4 24 h monitoring

To record resting behavior, spatial distribution on the pasture, and temporary absences throughout the day, surveillance cameras with night vision (ViSiTec) were installed on the pasture to film the groups continuously. If horses were temporarily in the stable (group 1.A, one individual of group 3.D), a camera (Sony HDR-CX405) was also installed there. However, due to technical failure, nighttime recordings were not always available or of sufficient quality to reliably assess resting behavior. Thus, the 24-h monitoring was only used to identify periods of absence of single individuals (e.g., training, additional feeding) but could not reliably present the resting, especially lying behavior, as well as spatial distribution of all individuals as planned.

2.3 Statistical analysis

To evaluate behavioral changes in relation to noise exposure and different sound levels, changes in foraging behavior (mostly grazing while slowly moving forward, also feeding on hay or others), comfort behavior (standing relaxed, lying, rolling, autogrooming), vigilance (alert, spooking, flight), and the location on the pasture (distant area, zone 3; proximity areas, zones 1–2; Figure 3) were assessed (Table 3). Social behavior (e.g., affiliative or agonistic behavior), locomotor behavior (walking, trotting, cantering), and other behavior were generally rare, so a statistical evaluation was not meaningful. To evaluate stress reactions in relation to noise exposure, the recorded heart rates per minute were averaged, excluding clearly erroneous measurements (<24 bpm, >240 bpm).

For statistical evaluation in R (version 4.5.1, R Core Team, 2016), linear mixed models with normal distribution structure (lmer, package lme4; Bates et al., 2014) were calculated for continuous variables (foraging duration, comfort duration, zone factor, heart rate), and generalized mixed models with binomial structure (glmer, family="binomial", package lme4; Bates et al., 2014) were calculated for combined matrices of count data (vigilance). We calculated two models per variable, which either took into account the explicit sound level (0 dB, 54 dB, 56 dB, 58 dB, 60 dB, 65 dB, 71 dB) or the experimental phase (pre-exposure: days before noise exposure; first noise exposure; wash-out days; second noise exposure; post-exposure: after noise exposure) as influencing factors (*fixed factor*). Due to the correlation between the sound level and the experimental phase, it was not possible to perform a calculation in a joint model. As further explanatory variables (*fixed factors*) we used the horse groups (group 1.A, N = 6; group 1.B, N = 3; group 2.C, N = 5; group 3.D, N = 6), the age group of the horse (young: <8 years, N = 7; middle: 8–13 years,

TABLE 3 Behavioral variables recorded, as well as their definition and classification.

Variable	Observation	Definition/Classification
Location	scan sampling focal sampling Ad libitum	Location within the pasture (zone 1—3) in relation to loudspeakers (sound source), see Figure 3
Foraging	scan sampling focal sampling	(Mostly) grazing while slowly moving forward, also: feeding on hay (group 1.B), acorn or gnawing on tree bark (group 3.D)
Comfort behavior	scan sampling focal sampling	Rolling (also *ad libitum*), scratching/autogrooming, lying (also *ad libitum*), etc.
Vigilance/Flight behavior	scan sampling focal sampling Ad libitum	Alert focusing, spooking/startle, fleeing
Social behavior	scan sampling focal sampling Ad libitum	Aggression between group members, affiliative behavior, social grooming, vocalization, etc.
Locomotion	scan sampling focal sampling	Standing, walking, trotting, cantering
Others	scan sampling focal sampling	Drinking, urinating, defecating (also *ad libitum*), contact with humans/other horses outside the pasture (also *ad libitum*)

N = 9; old: >13 years, N = 4), the sex (mare: N = 9; gelding: N = 11), and a zone factor as a relative assessment of the area of the pasture where the horse was kept (see supplementary material for calculation of the zone factor). To consider individual influences due to repeated measurements, the ID of the horses nested in the horse groups was included in the model as *random factors*, as well as individual variances of the explanatory variables within these random factors (*random slopes*). Specifications regarding the structure and calculation of the statistical models are explained in the supplementary material (Supplementary Table 2).

3 Results

3.1 Behavior

3.1.1 Foraging behavior

Compared to the baseline (81% foraging behavior; day 0–1), the horses reduced their foraging behavior by about half upon the first noise exposure, to 41% of the observation time (median across all horses; Figure 4). Including the wash-out days without noise exposure, the horses spent significantly less time foraging than before the noise exposure (Supplementary Table 3, model F.PH, full-reduced model comparison phase: $\chi^2(7, N=216)=43.96$, $p<0.001$; Figure 5). With increasing sound level, horses spent less time foraging (Supplementary Table 3, model F.SL, full-reduced model comparison sound level: $\chi^2(7, N=216) = 12.90$, $p<0.001$; $E=-0.01\pm0.002$; Figure 5).

It was also noticeable that the horses in group 1.A (facility 1, 4-hour pasture) were generally more engaged in foraging than the horses in the other groups (Supplementary Table 3, model F.PH, full-reduced model comparison group ID: $\chi^2(8, N=216) = 10.65$, $p=0.014$). Age, sex and location in the pasture did not influence the duration of foraging behavior (Supplementary Table 3, models F.PH and F.SL, all $p>0.05$).

3.1.2 Comfort behavior

Comfort behavior (especially resting: dozing while standing, occasionally with one hind leg resting on the tip of the toe) was observed in all horses that stood in the pasture for 24 hours (groups 1.B, 2.C, 3.D) in regular, mostly synchronized resting phases within the group for about 10–19% of the observation time (median across all horses; Figure 4). The linear models identified no significant effects of the experimental phase (Supplementary Table 3, model C.PH: full-reduced model comparison phase: $\chi^2(7, N=216) = 2.68$, $p=0.613$; Figure 6), the sound level (Supplementary Table 3, model C.SL: full-reduced model comparison sound level: $\chi^2(7, N=216) = 1.47$, $p=0.226$), or any other factor (Supplementary Table 3, models C.PH and C.SL, all $p>0.05$).

3.1.3 Vigilance

Vigilance (alert, startle response, flight response) was recorded for all horses present throughout the entire observation period. Upon the first noise exposure, vigilance significantly increased 6-folds from a maximum of 9 instances per observation period before the noise exposure to a maximum of 54 instances during the first noise exposure (Supplementary Table 3, model V.PH: full-reduced model comparison phase: $\chi^2(7, N=217) = 71.78$, $p<0.001$; $E= 1.63\pm0.21$; Figure 7). They remained more vigilant throughout the entire study period than before the noise exposure, while vigilance reduced from the first to the second noise exposure ($E=0.45\pm0.30$). In addition, horses became increasingly vigilant with increasing sound level (Supplementary Table 3, model V.SL: full-reduced model comparison sound level: $\chi^2(7, N=217) = 14.20$, $p<0.001$; $E=0.01\pm 0.002$; Figure 7). Vigilance did not vary depending on the location within the pasture, group, age or sex (Supplementary Table 3, models V.PH and V.SL, all $p>0.05$).

3.2 Location within the pasture

The general distance from the noise source (zone factor: relative factor of time spent in the different zones) varied depending on the phase of noise exposure (Supplementary Table 3, model Z.PH: full-reduced model comparison phase: $\chi^2(6, N=217)=19.63$, $p<0.001$; Figure 8). As compared to the pre-exposure baseline, the horses kept a significantly greater distance from the noise source during the noise exposures (first phase: $E=2.25\pm0.64$; second phase: $E=1.66\pm0.61$), while reducing this distance on wash-out days ($E=0.42\pm0.74$) and coming closer on the post-exposure day

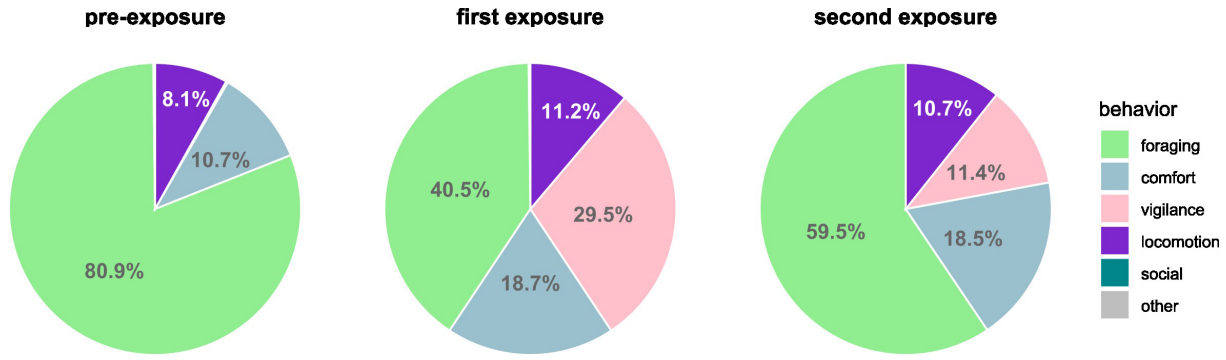


FIGURE 4
Composition of behavioral patterns (median durations) throughout the day. Horses reduced their foraging behavior during the two noise exposure phases compared to the pre-exposure baseline ($p < 0.001$). Vigilance became more frequent ($p < 0.001$).

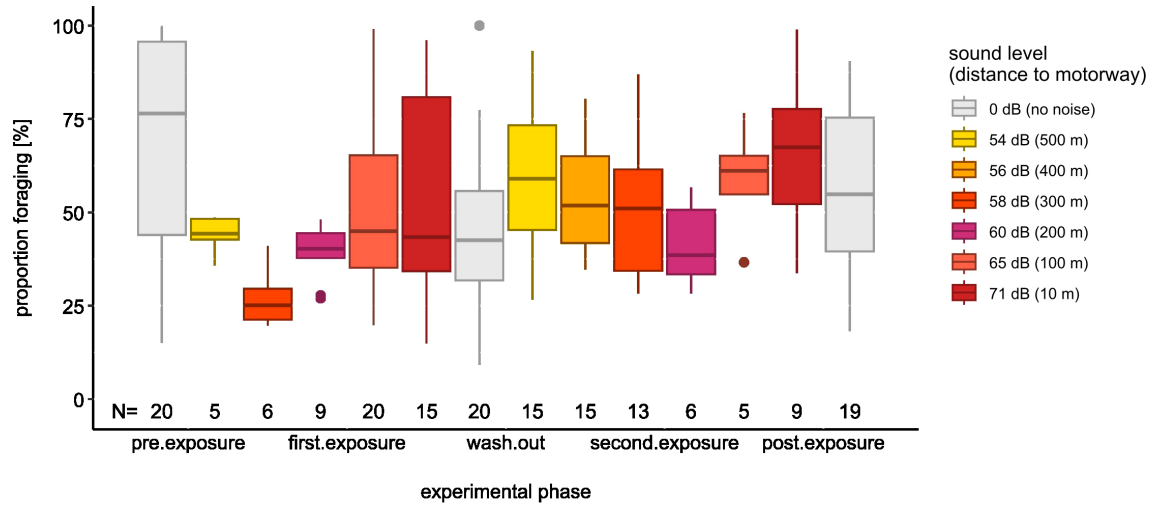


FIGURE 5
Proportional duration spent foraging during the observation period per phase of noise exposure and sound level (0 dB: only natural sounds, no noise exposure). Horses decreased their foraging behavior during noise exposure, specifically at higher sound levels. Sample sizes (N) below each boxplot indicate the number of individuals observed per sound level and phase. The median, 25% and 75% percentiles, minimum and maximum values, and extreme values are displayed.

(*E*=–0.14±0.86). Especially when noise levels were high, the horses tended to stay longer in pasture areas further away (Supplementary Table 3, model Z.SL: full-reduced model comparison sound level: $\chi^2(6, N=217) = 18.97$, $p<0.001$; *E*=0.03±0.01; Figure 8). The location within the pasture did not vary with group, age or sex (Supplementary Table 3, models Z.PH and Z.SL, all $p>0.05$).

3.3 Physiology

The horses studied had a median heart rate of 48.81 bpm (min. = 28.40 bpm, max. = 215.83 bpm; N = 14 horses) before noise exposure. During observation times, heart rates varied with the experimental phases (Supplementary Table 3, model HR.PH: full-reduced model comparison phase: $\chi^2(7, N=35320)=1065.07$, $p<0.001$; Figure 9; N=19 horses). The heart rate increased to a median of 66.76 bpm (*E*=0.54±0.03) during the first and 55.70 bpm (*E*=0.63±0.03) during the second noise exposure. On wash-out days (*E*=–0.00±0.00), noise-free observation times (*E*=–0.02±0.01), and the control day after the noise exposure (*E*=0.02±0.00), heart rate was not significantly different to the pre-exposure baseline. A group effect became significant (Supplementary Table 3, model HR.PH: full-reduced model comparison group ID: $\chi^2(9, N=35320) = 8.08$,

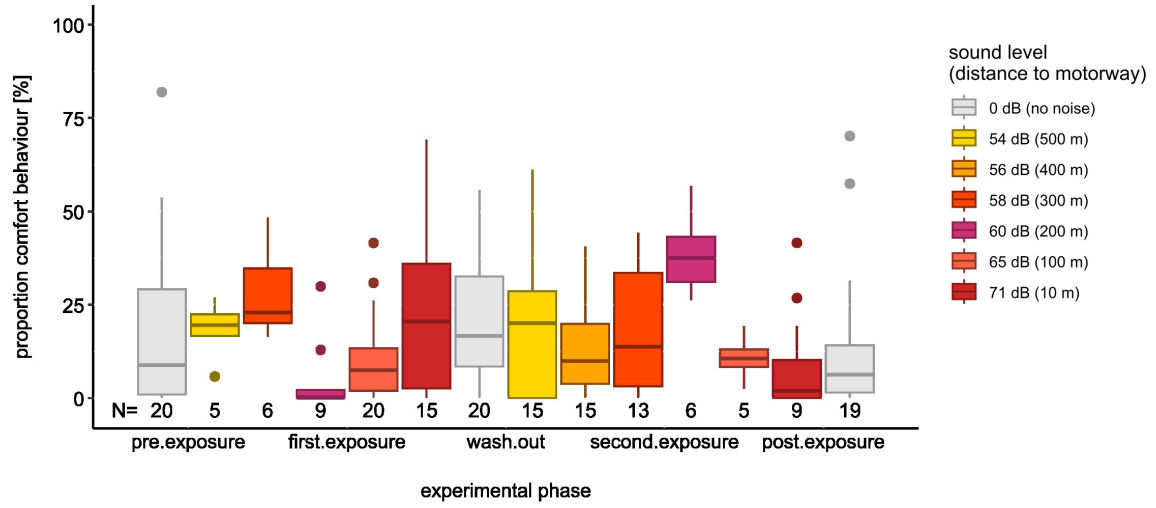


FIGURE 6
Proportional duration of comfort behavior during the observation period per phase of noise exposure and sound level (0 dB: only natural sounds, no noise exposure). Comfort behavior did not systematically vary with either noise exposure phase or sound level. Sample sizes (N) below each boxplot indicate the number of individuals observed per sound level and phase. The median, 25% and 75% percentiles, minimum and maximum values, and extreme values are displayed.

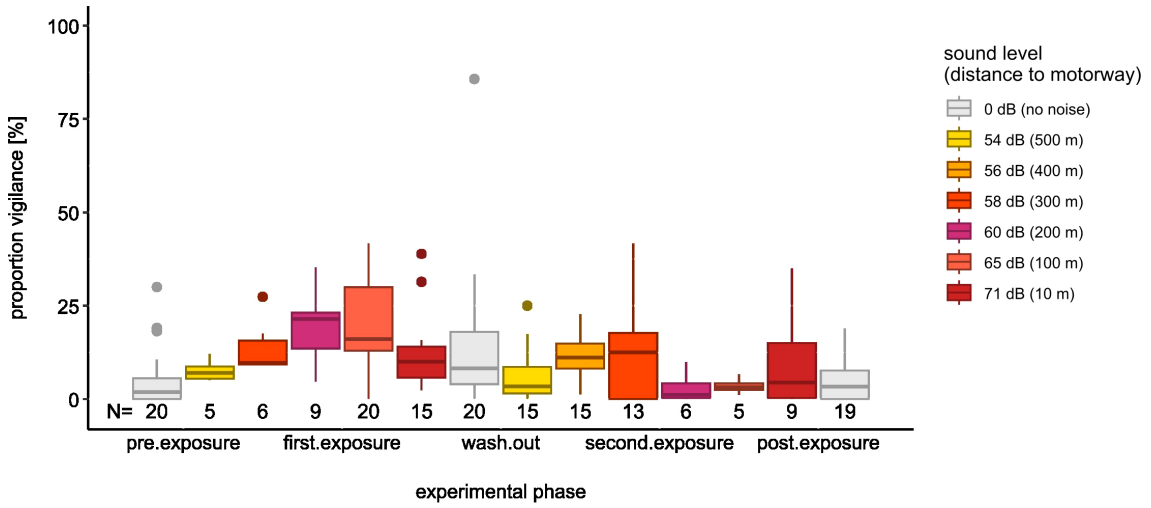


FIGURE 7
Proportional frequency of vigilance (increased alertness and startle response) during the observation period per phase of noise exposure and sound level (0 dB: only natural sounds, no noise exposure). Vigilance increased during noise exposure, specifically at higher sound levels. Sample sizes (N) below each boxplot indicate the number of individuals observed per sound level and phase. The median, 25% and 75% percentiles, minimum and maximum values, and extreme values are displayed.

p=0.044), with group 3.D having the highest (E=0.31±0.41) and group 2.C the lowest heart rates (E=−0.28±0.32). Sound level (Supplementary Table 3, model HR.SL: full-reduced model comparison sound level: $\chi^2(7,N=35320) = 0.00$, p=0.974), the location within the pasture, age, or sex did not influence the heart rate (Supplementary Table 3, models HR.PH and HR.SL, all p>0.05).

4 Discussion

Exposing pastured horses to reproduced motorway noise produced a consistent pattern: (1) rapid habituation to the experimental equipment (installation/habituation on day −1; baseline behavior observed on Days 0–1), (2) an immediate species-typical startle reaction on first noise presentation (Day 1–2) that subsided within ~5–15 min and usually declined by the second exposure day, and (3) pronounced changes in normal behavior and stress parameters during and after noise exposure, including reduced foraging, increased vigilance, persistent spatial avoidance of the noise source, and elevated heart rates. Although behavioral indicators (foraging, vigilance) showed partial habituation over the study period, horses continued to avoid the noisy areas, and elevated heart rates were detectable to some extent even in the absence of the noise source during wash-out periods. This suggests that disturbances persist throughout a period of 10 days rather than that full habituation to traffic noise occurs.

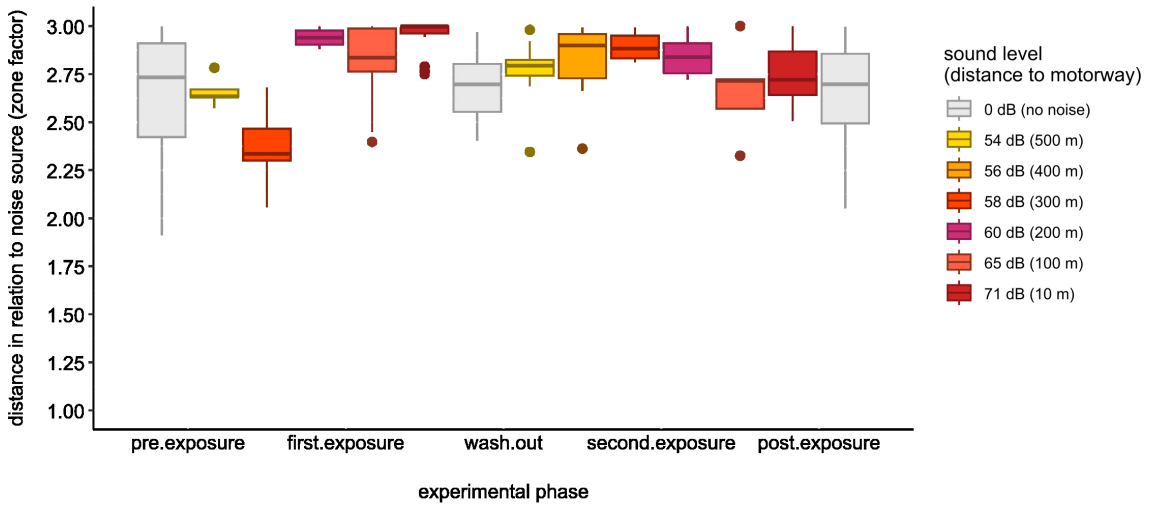


FIGURE 8
Location at pasture (zone factor based on the duration spent in zones relative to the noise source, with 1 spent in close vicinity and 3 spent in distance) during the observation period for each phase of noise exposure and sound level (0 dB: only natural sounds, no noise exposure). Horses avoided the proximity to the noise source, specifically at higher sound levels. Sample sizes (N) below each boxplot indicate the number of individuals observed per sound level and phase. The median, 25% and 75% percentiles, minimum and maximum values, and extreme values are displayed.

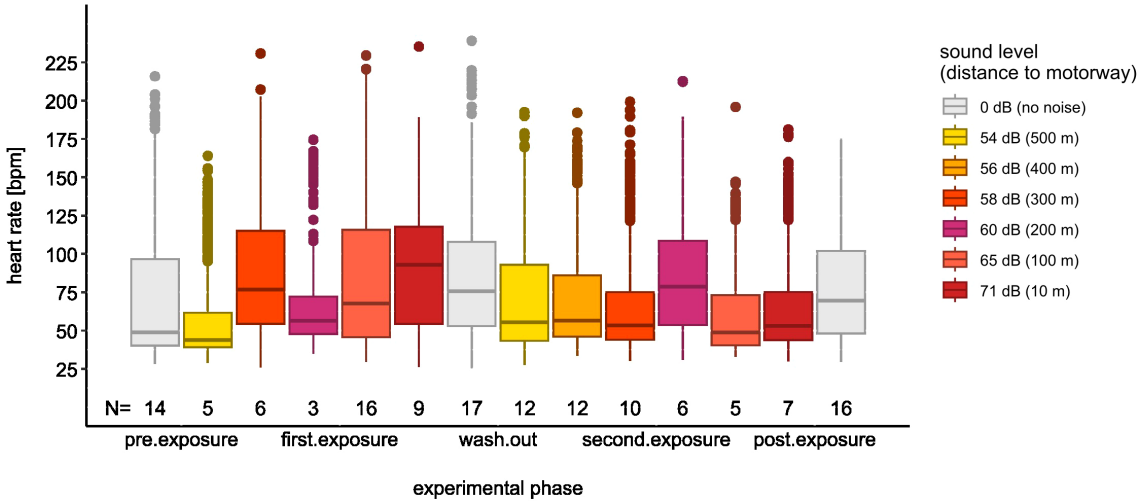


FIGURE 9
Average heart rate per minute during the observation period for each phase of noise exposure and sound level (0 dB: only natural sounds, no noise exposure). Heart rates increased during noise exposure, irrespective of the sound level. Sample sizes (N) below each boxplot indicate the number of individuals sampled. The median, 25% and 75% percentiles, minimum and maximum values, and extreme values are displayed.

4.1 Behavioral changes and physiological effects upon noise exposure

During traffic noise exposure, horses increased vigilance and reduced foraging, indicating disruption of normal behavioral rhythms. The concurrent increase in heart rate further confirms physiological arousal consistent with the activation of the sympathetic nervous system and the onset of a stress response (von Borell et al., 2007). Reduced feeding and increased vigilance, therefore, likely reflect a shift from energy intake to environmental monitoring, a typical short-term trade-off under perceived threat (Khater et al., 2016). Chronic activation of this system can lead to maladaptive outcomes, including gastrointestinal dysfunction, metabolic disorders, and stereotypic behavior (Wagner, 2010; Henshall et al., 2022). Such negative effects on health may become visible upon long-term exposure to traffic noise but were not further assessed or noticed during the short-term exposure within the current study.

Behavioral data indicate a partial habituation, as the horses gradually returned to their near-normal foraging and reduced vigilance (Figure 4). However, they consistently preferred quieter pasture zones during noise exposure throughout the study. This spatial avoidance of the noise source suggests that, while horses may behaviorally adapt, the underlying perception of noise as an aversive stimulus remains. Such behavior is in line with findings in wildlife that shift habitat use under noise exposure (Brown et al., 2012; Shannon et al., 2016; Buxton et al., 2020). Because horses in managed pastures cannot fully escape the stimulus, this active coping mechanism may be limited, potentially leading to sustained stress, even if at a comparably low level. The heart rate of adult horses is 28–40 bpm at rest (Younes et al., 2016). In our study, we consistently recorded higher mean heart rates, reflecting the short resting periods of only about 11–16%, as well as a general high arousal at times of noise exposure. Elevated blood pressure and heart rates in response to noise exposure are observed in humans, too (Lusk et al., 2004; Kraus et al., 2013). Therefore, comparable to humans living near busy roads, behavioral habituation may mask continued physiological strain, which may still lead to substantial, negative health consequences in humans (Palatini and Julius, 2004; Custodis et al., 2010; Arana et al., 2014; Recio et al., 2016; Tobollik et al., 2019) and potentially in animals, too (Arregi et al., 2024). Thus, avoidance behavior may serve as an active coping strategy supporting partial resilience but cannot lead to full recovery from noise-induced stress.

4.2 Critical noise levels

The study identified behavioral and physiological alterations already at the lowest tested sound level of 54 dB, equivalent to the noise level of a motorway at 500 m distance. This is within the range known to trigger psychological stress (30–65 dB), as well as physiological responses (55–65 dB) in humans (BMUKN, 2017; World Health Organization, 2018), and to impair habitat suitability in several bird species (47–55 dB) (Garniel et al., 2007). Given horses' broader auditory range and higher noise sensitivity compared to humans (Heffner and Heffner, 1983), their sensitive response highlights the need to consider species-specific thresholds. While we could not establish precise critical noise thresholds, our findings still indicate that constant traffic noise of noise levels below established thresholds (usually 65 dB) has the potential to compromise equine welfare.

4.3 Study limitations

Despite providing an overview of the impact of sudden, monotonous exposure to motorway noise on horses on pastures, methodological and contextual limitations must be acknowledged. First, heart rate served as the sole physiological indicator of stress in this study, not differentiating between positive eustress, negative distress, or varying locomotion. Although elevated heart rate is a

valid proxy for acute stress responses in horses (von Borell et al., 2007; König von Borstel et al., 2017), the use of long-term field measurements introduced technical constraints. The Polar® equine system, although widely validated, proved unreliable during extended outdoor use. Sensor disconnections, movement artefacts, and signal duplication led to data losses and potentially occasional overestimation of heart rates. At one site, only five of nine horses could be reliably equipped with sensors, and data completeness varied between phases. Even though the heart rate data in this facility could only be partially included in the analysis, complete data for the entire observation periods were available for the remaining eleven horses. Despite these challenges, the consistently higher heart rates during noise exposure, particularly during the initial exposure days, support a physiological response to the stimulus. However, equipment-dependent measurement noise may have obscured smaller differences between experimental phases or noise levels.

Second, the experimental setup employed loudspeakers to broadcast motorway noise at defined sound levels within the horses' normal pasture environment. While this approach ensured control over noise intensity and duration, it did not fully replicate the acoustic complexity or spatial distribution of the noise associated with a real motorway, or associated distractions (e.g., visual stimuli, vibrations). Sound attenuation was stronger than expected, and noise levels declined steeply with distance from the speakers. Consequently, horses in more distant areas experienced substantially lower sound intensities than would occur in a pasture directly adjacent to a real motorway. The behavioral and physiological effects observed here may therefore underestimate the responses to real motorway noise. Moreover, the exposure varied between facilities and was limited to daytime hours (4–11 h daily) to comply with local noise regulations, as well as animal welfare concerns. This allowed the animals to recover overnight, reducing cumulative exposure and likely moderating the stress response, which we could not further control for. Horses exposed to continuous 24-hour noise would not benefit from such recovery periods. Thus, the current results cannot be directly extrapolated to chronic or permanent motorway exposure but rather represent a minimum nuisance level that already affected the horses. Further, the limited duration of exposure and observation period precludes conclusions about nighttime rest. Horses require regular periods of recumbent sleep to maintain physiological and psychological health (Greening and McBride, 2022), yet they typically lie down only under conditions perceived as safe (Bertone, 2015). Continuous nocturnal noise could therefore disrupt essential resting behavior without being observable during daytime. Future investigations should include 24-hour behavioral monitoring, preferably with automated video or accelerometer systems, to determine whether chronic noise exposure interferes with resting patterns or leads to sleep deprivation-related problems such as pseudo narcolepsy.

Third, the study was limited to a small number of naïve horses that had no known prior experience with continuous traffic noise. Consequently, the findings primarily reflect the responses of noise-naïve individuals. Horses habituated to traffic environments may exhibit less pronounced behavioral responses but could still experience long-term physiological or auditory effects. Moreover, the sample did not represent the full variation in age, breed, or management systems found in domestic horse populations. With future studies including larger, more heterogeneous samples and encompassing both noise-experienced and unexperienced horses, we can assess a broader picture of individual differences in sensitivity and coping capacity. To determine a critical threshold of noise tolerance in horses, future experiments need to systematically expose horses to defined noise levels over extended periods using randomized and repeated designs. This would allow the determination of the noise intensity at which behavioral or physiological indicators deviate from baseline, leading to concrete advice for noise barriers. In addition, combining behavioral observations with hearing assessments could clarify whether chronic motorway noise leads to sensory impairment similar to that reported in humans and other mammals (Arana et al., 2014; Tobollik et al., 2019; Pollarolo et al., 2022).

5 Conclusion

Motorway noise significantly influenced horses' behavioral and physiological responses at pasture. We observed partial behavioral habituation over time, as horses gradually returned to their pre-exposure foraging behavior. In contrast, persistently elevated heart rates along with persistent avoidance of areas close to the noise source indicate a sustained physiological stress response and active coping strategy, suggesting potential long-term welfare risks. It is also noteworthy that even the lowest noise level (54 dB, equivalent to about 500 m distance from a four-lane motorway), which is below standard noise thresholds (65 dB), elicited measurable changes in heart rate and behavior. As the observed horses mainly used more distant areas within the pasture, large pastures with quieter retreat areas may help cope with constant noise exposure and mitigate long-term health effects. To ensure horse welfare, management practices should be revised with this regard, and potentially also adopted for other livestock, given the similarity of sensory perception.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The animal studies were approved by Regierungspräsidium Giessen, approval number: G 27/2022. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent was obtained from the owners for the participation of their animals in this study.

Author contributions

JH-M: Writing – original draft, Writing – review & editing, Conceptualization, Data curation, Formal analysis, Investigation,

Methodology, Project administration, Resources, Visualization. UKB: Writing – original draft, Writing – review & editing, Conceptualization, Project administration, Supervision.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fetho.2026.1802957/full#supplementary-material

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