Too hot or too disturbed? Temperatures more than hikers affect circadian activity of females in northern chamois

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ABSTRACT

Recreational activities often result in a spatial and/or temporal activity shift in wildlife. With the concurrent development of outdoors activities and increase in temperatures due to climate change, mountain species face increasing pressures in terms of managing their activity pattern to limit both risk exposure and thermal discomfort. Using more than 15 years of long-term GPS and activity sensor data, we investigated how female northern chamois (*Rupicapra rupicapra rupicapra*) adjust their summer circadian activity to spatio-temporal variations of both temperatures and hikers' presence. Chamois behaviour was more affected by high temperatures than by hikers' presence. During the hottest days, they shifted their activity peak earlier in the morning (17 minutes earlier), were more active at night (+22%), less active during daytime (-10%), and had longer morning and evening peaks (+60 and +20 minutes, respectively) compared to the coldest days. Global activity was only slightly different during the hottest (+5%) compared to coldest days. Conversely, hikers' disturbance had weak effects on activity levels and on the timing of activity peaks. This is especially true for temporal disturbance (weekdays versus weekends and public holidays), possibly due to the fact that most weekdays in summer fell during school holidays. Only during the hottest conditions, the morning activity peak was shorter (46 minutes) and the evening peak longer (18 minutes) in female living in the most exposed areas compared to females living in the least exposed areas. One possible explanation for the overall low effect of hikers' disturbance may be that behavioural changes buffering animals from high temperatures and hikers' presence (*e.g.*, moving away from trails) allow them to just marginally modify their activity pattern. In the

context of ongoing socio-environmental changes, it is critical to conserve habitats providing thermal refuges against summer heat and preventing them from disturbance to mitigate potential detrimental consequences.

KEYWORDS: behavioural thermoregulation, circadian rhythm, climate warming, ecotourism, human disturbance, mountain ecosystem, nocturnality, recreational activities, *Rupicapra rupicapra rupicapra*

INTRODUCTION

A noticeable development and diversification of outdoor activities has been ongoing in the twenty-first century, especially in Western countries (Wheaton, 2010). While mountain ecosystems have been preserved until recently because of their low accessibility, they now face an increase of unaffiliated activities such as hiking, cross country skiing, trail running, or climbing. Those recreational activities are non-lethal, but humans can be consistently perceived as predators by wildlife (Frid & Dill, 2002), leading to a suite of negative physiological and behavioural responses (Arlettaz et al., 2007; Marchand et al., 2014; Larson, Reed, Merenlender, & Crooks, 2016). The consequences of repeated reactions to disturbance can be detrimental on several fitness-related components (Phillips & Alldredge, 2000; French, González-Suárez, Young, Durham, & Gerber, 2011). This is particularly true in mountain ecosystems, where the diversification of human activities challenges animals all year long, both during the period of energy acquisition from spring to autumn, and of energy loss during winter (Lindstedt & Boyce, 1985). This increased pressure on the animals is accompanied by environmental modifications, including climate change, that are particularly strong in the Alps (Pepin et al., 2015). Accordingly, temperatures are rising rapidly in all seasons, with consequences such as earlier springs and plant cycles, more frequent summer

heatwaves and droughts, and decreased duration of snow cover associated with an augmented risk of frost for plants (*e.g.,* Gobiet et al., 2014). Mountain animals are therefore facing concomitantly two major changes, namely an increased disturbance level and climate change.

To reduce their exposure to human disturbance, animals can adjust their behaviour in terms of movements, habitat use and selection, and time devoted to their different activities (foraging, resting, vigilance and social interactions). When facing a disturbance perceived as a risk, animals can modify their activities (*e.g.,* from foraging to vigilance; Benoist, Garel, Cugnasse, & Blanchard, 2013; Xu, Gong, & Wang, 2021), and move away temporarily or even definitively (Rogala et al., 2011). They can also modify their activity pattern by delaying activities, such as foraging in disturbed places, from high- to low-risk periods (Bonnot et al., 2013). The benefits of such responses have been explained within the "risk allocation hypothesis" framework (Lima & Bednekoff, 1999): the costs of lost opportunities to forage during risky periods could be dampened if animals transfer part of their diurnal activity to night-time when human activities stop for instance (*e.g.,* Marchand et al., 2014; Bonnot et al., 2020). However, activity patterns are regulated, such as the critical foraging/rumination succession in ruminants (Hamel & Côté, 2008). Any forced modification of those patterns can negatively impact the fitness of individuals *via* an increased encounter risk with predators (Lesmerises et al., 2018) or mismatches in interactions with conspecifics (Greives et al., 2015), for instance.

At the same time, animals need to deal with climatic constraints, and behavioural thermoregulation is among the most important mechanisms to avoid thermal stress. Indeed, temperatures influence space use (in arctic ground squirrels *Spermophilus parryii*, Long, Martin, & Barnes, 2005; in Mediterranean mouflon *Ovis gmelini musimon* x *Ovis* sp., Marchand et al., 2015) and activity budget (in Japanese monkeys *Macaca fuscata*, Watanuki & Nakayama, 1993), with animals having to trade off foraging and thermal cover to limit

97 thermoregulatory costs while keeping their energy balance (van Beest & Milner, 2013). In the
98 same way as to avoid human disturbance, animals can shift their activity peaks earlier in the
99 morning and later in the evening, and increase their nocturnal activity during the hottest
100 summer days (Bourgoin et al., 2008; Bourgoin et al., 2011). However, in temperate
101 ecosystems, night can be significantly shorter than day during summer, and riskier when
102 nocturnal predators are present. Thus, the transfer of the diurnal activity to night-time does
103 not necessarily allow to fully compensate for the loss of foraging opportunities during day
104 and may have consequences on mass gain (Garel, Loison, Gaillard, Cugnasse & Maillard,
105 2004) or predation risk (Gehr et al., 2017), for instance. These results highlight the
106 importance of investigating full daily cycles to get a comprehensive picture of how animals
107 may adjust their behaviour in the face of human-induced environmental changes (Marchand
108 et al., 2014; Marchand et al., 2015).

109 Moreover, ongoing climate change and expansion of human activities in mountain
110 ecosystems are also ultimately connected. An extended summer season or more frequent
111 summer heatwaves in valleys may, for instance, exacerbate human attendance in mountains.
112 Although predicting tourism attendance under scenarios of climate change is probably not
113 straightforward (Beniston, 2003), this context raises questions on animal responses to those
114 interrelated human-induced environmental changes and on their potential cumulative or even
115 multiplicative consequences for populations in terms of both immediate and compensatory
116 responses (Schmeller et al., 2022). One critical challenge is therefore to understand whether
117 the behavioural mechanisms used by animals to buffer against increasing temperatures may
118 also provide an advantage against human attendance or *vice versa*.

119 Here, we relied on the GPS monitoring of 62 females of northern chamois *Rupicapra*
120 *rupicapra rupicapra* to investigate at a fine scale their behavioural responses to temporal and
121 spatial stressors during summer, through the study of their activity pattern. More specifically,

we assessed the day-to-day variation in temperatures and hikers' attendance for each chamois. We also computed an individual-specific index of spatial disturbance, combining data on the density of hiking trails in each chamois summer home range and the attendance of each trail section by hikers. A diversity of activity metrics (*e.g.,* daily activity levels, timing of activity peaks, length of activity peaks) allowed us to investigate the relative contribution of spatio-temporal variations in both temperatures and human disturbance to changes in circadian activity patterns of female chamois in summer. We expected the chamois to adjust their circadian activity pattern by avoiding being active during the hottest hours during the hottest days (**H1**) and during the most disturbed (*i.e.,* weekends and public holidays) versus less disturbed (*i.e.,* weekdays) days (**H2**), with a compensation of activity loss during daytime at night. However, as individuals were exposed to variable levels of disturbance depending on the location of their summer home range, we also expected more marked responses in chamois that were the most exposed to hikers' disturbance (**H3**), as most of them show low tolerance to hikers' presence in this population (Courbin et al., 2022).

MATERIALS AND METHODS

Study Site and Species

The study took place in the National Game and Hunting Reserve of Les Bauges massif (NGHRB), a protected area in the French Alps (45°40' N, 6°13' E; 900 to 2200 m a.s.l.; 5 200 ha). The Bauges massif is made of limestone, with cold (mean annual temperature: 9.6°C, snow cover from November to April above 1 600 m, Duparc et al., 2013) and wet (mean cumulative annual rainfall: 1 600 mm, Duparc et al., 2013) climatic conditions (see Appendix for details about summer temperatures). Fifty-six percent of the area is covered by forests (treeline around 1 500 m a.s.l. in the study site), dominated by beech *Fagus sylvatica* and fir *Abies alba*, 36% by grasslands, and 8% by rocks (Lopez, 2001). This heterogeneous

environment leads to a huge diversity of habitats and landscapes that attracts numerous tourists every year (> 37 000, most of them during summer; 1.1 million and 0.5 million overnight stays in summer and winter respectively in 2014, Cloud Parc des Bauges, 2014). All alpine grasslands are crossed by a network of trails where nearly all hikers are concentrated due to the NGHRB restrictions, exposing chamois to a very localised disturbance (Courbin et al., 2022). Other recreational activities (*e.g.,* paragliding) occur in the study site during summer, but far less frequently than hiking.

Most adult female chamois annually give birth to one young in late May. During summer, they form groups with other females, kids and yearlings, that share and keep the same home range from year to year (Loison, Jullien, & Menaut, 1999). Females play a major role in the demography of the population, particularly through fecundity and survival of young females (Gaillard, Festa-Bianchet, Yoccoz, Loison, & Toigo, 2000). Chamois have no natural predators in the study area during the study period, except golden eagles *Aquila chrysaetos* and red foxes *Vulpes vulpes* that may occasionally predate newborn and injured animals. The presence of very few non-resident wolves *Canis lupus* has been noticed in some years (Loupfrance.fr, 2021). Hunting performed by small groups of three to four hunters occurs in the NGHRB from the beginning of September to the end of February (Courbin et al., 2022), with chamois being the main target species (~100 chamois harvested per year on average, *i.e.,* <12% of the chamois population in the area and ~70% of the total number of ungulates harvested), in addition to Mediterranean mouflon (~20%), roe deer *Capreolus capreolus* (~4%), wild boar *Sus scrofa* (~4%) and red deer *Cervus elaphus* (~2%; see Courbin et al., 2022 for details).

Data Collection

171 We focused on summers from 2004 to 2020, between the 15th June and the 7th September.
172 This period allows to encompass days falling in and out from the French summer break
173 which starts in early July, but excludes the hunting season which ranges from the first
174 weekend of September to the end of February, so that chamois were exclusively exposed to
175 hikers' disturbance during our study period. The study period is critical for female chamois
176 because it follows the birth season and it is characterised by high energy requirements for
177 lactation and storage of fat reserves for winter survival (Clutton-Brock, Albon, & Guinness,
178 1989; Richard, Toïgo, Appolinaire, Loison & Garel 2017), so that any disturbance during this
179 period could be particularly detrimental.

180 We trapped 62 adult female chamois >2 years old during summer in four alpine
181 grasslands near two trails highly used by hikers (Armenaz and Dent des Portes). As
182 deployment/recovery of GPS collars occurred during summer, chamois locations were not
183 necessarily recorded daily during all the study period. Only chamois (n = 62) for which we
184 could reliably estimate the summer home range (95% kernel contour using the *adehabitatHR*
185 package; Worton, 1989; Calenge, 2006) were included in the study, *i.e.,* chamois with GPS
186 locations available during at least 2/3 of the summer period, corresponding to 56 days in
187 total. Animal motion was recorded every 5 minutes by two perpendicular captive-balls in the
188 GPS collars monitoring neck movements (0: no movement, 255: highly mobile) and the
189 proportion of time the animal was head down. We discriminated each chamois as "active"
190 (*i.e.,* feeding, standing, travelling, or doing other activities such as interactions or scratching)
191 or "inactive" (*i.e.,* sleeping, ruminating or resting) for every 5-minutes boot using the
192 discriminant model developed by Bourgoin et al. (2011; see also Darmon et al., 2014). From
193 these animals, we obtained a total of 4 464 complete days of activity records in summer (*n* =
194 131 chamois-year, 1 285 632 5-minutes activity measurements in total). The activity of each
195 chamois was monitored during 18 to 129 days in total, corresponding to 11 to 49 days (*mean*

196 ± *SD = 34 ± 10 days, median [Q1; Q3] = 36 [26; 42] days*) during a single summer period
197 for a given chamois (see Appendix).
198
199 *Ethical Note*
200 We trapped chamois using falling nets baited with salt licks. Although captures occurred
201 during the birth and weaning period, females generally avoided drop nets (positioned on flat
202 areas) when juveniles were particularly vulnerable (leading to the use by females of very
203 steep slopes as an anti-predator strategy). During the weaning period, chamois form nursery
204 groups and kids are not always closely associated with their mother, so that temporary
205 separation between them, longer than those resulting from capture/handling, also naturally
206 occurred in this species (Ruckstuhl & Ingold, 1998). The drop nets were triggered manually
207 by an observer located a few hundred meters away from the nets, preventing from non-target
208 captures, and chamois were handled immediately after the capture by several experienced
209 people coordinated by the Office Français de la Biodiversité. As soon as an animal was
210 handled, it was restrained with the eyes covered to reduce stress and legs attached to avoid
211 injuries. An average of three individuals were captured at the same time and this number was
212 adjusted according to the number of handlers to limit the waiting time for each chamois. All
213 efforts were made to minimise the handling time (approximately 10 to 15 minutes per
214 individual) to release animals on site as soon as possible. Juveniles and mothers were
215 released at the same time to prevent them from separation. As part of a long-term Capture-
216 Marking-Recapture monitoring, recaptures were not avoided, although unmarked individuals
217 were targeted when present. Since 2003, 916 individuals have been captured or recaptured,
218 causing 5 deaths (*i.e.,* 0.55% of the individuals handled). When necessary, slaughter was
219 done by shooting a bullet in the head or by destruction of the nervous system by percussion
220 of the cranial cavity (matador), following the ethical and legal ways recommended for large

mammals after important injuries. All captures, handling and sampling were conducted according to the appropriate national laws for animal welfare, following the ethical conditions detailed in the specific accreditations delivered by the Préfecture de Paris (prefectorial decree n°2009–014) in agreement with the French environmental code (Art. R421-15 to 421–31 and R422-92 to 422–94-1).

Females were equipped with GPS collars Lotek 3300S (Lotek Engineering Inc., Carp, Ontario, Canada). The GPS collars weighed < 450 g and were deployed only on individuals > 20 kg judged to be fully healthy so that it never exceeded 2.5% of the body mass of the equipped animal (average weight of females fitted with GPS collar = 30 kg, so 1.5% of individuals body mass on average). To allow for possible seasonal variation in neck circumference, we left a gap of ~ 3 cm between the GPS collar and the animal's neck while making sure that the collar would not rotate. We retrieved the collar using a remote drop-off system triggered manually or automatically (TRRD or TRD drop-offs, respectively; Lotek Engineering Inc., Carp, Ontario, Canada) at the end of the monitoring of the individuals, nearly one year after deployment. From repeated observations of GPS-collared individuals throughout the year as part of long-term Capture-Mark-Recapture monitoring of this population, we have no indication that GPS collars cause changes in behaviour compared to other non-equipped individuals. Similarly, we did not detect any adverse effects linked to the wearing of the collars in terms of injury or reproductive activity.

Estimation of Variables of Interest

We assessed daily characteristics (see below) from 0139 hours UTC of day *d* to 0139 hours UTC of day *d+1*. This allowed us to explore potential compensation processes during the night following the day of interest. We selected the starting hour in accordance with the median value of the beginning of the crepuscular period in the morning during our study

period. We used a micro-climate model that integrates ERA5 hourly weather data produced by the Copernicus Climate Change service at ECMWF (spatial resolution 30 km x 30 km) and a digital elevation model (30 m) for downscaling atmospheric data at the population scale (micro_era5 function in NicheMapR package; Kearney & Porter, 2017; Maclean, Mosedale, & Bennie, 2019; Kearney, Gillingham, Bramer, Duffy, & Maclean, 2020). This allowed us to overcome the issue of incomplete weather data collected in the valley by local weather station and to get standardized temperatures within the population range over the study period. Mean daily temperatures were predicted from this model at 1 m high on flat terrain for a spatial location and elevation (1 950 m a.s.l.) corresponding to the centroid of all chamois GPS locations. We explored the effect of temperatures on female chamois activity through a categorical variable with two levels defined according to the quantiles of the mean daily temperatures distribution. Days with mean temperature ≤ 25% quantile (*i.e.,* 10.8°C) were considered as **cold days** and days with mean temperature > 75% quantile (*i.e.,* 15.5°C) were considered as **hot days**. Cold days experienced by chamois ranged between 3.4°C and 10.8°C (mean ± SD = 8.6 ± 1.6°C, median [Q1; Q3] = 8.9 [7.6; 10.0]°C), while hot days ranged between 15.5°C and 20.9°C (mean ± SD = 17.2 ± 1.2°C, median [Q1; Q3] = 17.1 [16.2; 18.1]°C, see also Appendix).

Temporal disturbance associated with hiking was defined as a categorical variable with two levels. Weekends and public holidays, *i.e.,* vacation days such as National Day, were considered as the most disturbed days, hereafter called **weekends and public holidays**. Days between Monday and Friday, *i.e.,* working days including weekdays during school holidays, were considered as the least disturbed days and hereafter called **weekdays**. To check for the reliability of these two categories in the field, we compared the daily attendance of hikers (number of hikers recorded on the trail) between 0000 hours UTC and 2359 hours UTC and the hour of first arrival for both temporal disturbance levels using an eco-counter

(PYRO sensor Eco-Compteur, www.eco-compteur.com; 90 cm above ground) located on Armenaz trail (45°37'18.60" N, 6°13'2.53" E) and present during two consecutive summers (2016 and 2017). Our study period encompassed 189 weekends and public holidays and 440 weekdays. During the same period of the year in 2016 and 2017, hikers were almost two times more on the trails during weekends and public holidays (*mean* ± *SD* = *74* ± *53* hikers, *median* [Q1; Q3] = 73 [39; 106] hikers) than during weekdays (*mean* = 47 ± 34 hikers, median = 40 [25; 73] hikers; Mann-Whitney: *test statistic* = 2 558, *N1* = 41, *N2* = 96, *p-value* = 0.006). Hikers also tended to arrive 60 minutes earlier during weekends and public holidays (mean ± SD = 0744 ± 120 minutes UTC, median [Q1; Q3] = 0700 [0700; 0900] hours UTC) compared to weekdays (mean ± SD = 0813 ± 180 minutes UTC, median [Q1; Q3] = 0800 [0700; 0900] hours UTC), although this difference was not statistically significant (Mann-Whitney: *test statistic* = 1 559, *N1* = 40, *N2* = 91, *p-value* = 0.188; see Appendix). We also conducted a Mann-Whitney test to assess if hikers' attendance was affected by temperatures (see *Results* section). We also ran supplementary analyses considering three contrasted temporal disturbance categories, namely i) weekdays of school period, ii) weekdays of summer break, iii) weekends and public holidays (see Appendix). These supplementary analyses contrasting three levels of exposure to hiker's disturbance (i.e., weekdays of school period, weekdays of summer break, and weekends / public holidays) provided very similar results to the original analysis contrasting two levels of disturbance (i.e., weekdays versus weekends/public holidays; see Appendix).

Potential spatial exposure to hikers' disturbance was evaluated within each female chamois home range using attendance rates of the trails extracted from Strava Global Heatmap (Strava, 2022; www.strava.com, download date: 2022/03/09, data from the two previous years; see also Courbin et al., 2022 for a similar approach on this study site). Strava heatmap provides a value ranging from 0 for no attendance to 255 for the highest attendance

for each pixel (pixel size = 25 m x 25 m) and is a good proxy of relative human attendance (see Appendix; Thorsen et al., 2022; Venter, Gundersen, Scott & Barton, 2023). The lowest and highest values recorded for a trail pixel in our study site were 51 and 255 respectively. We thus defined attendance classes according to the quantiles of the [51; 255] distribution in order to cover trail pixels exclusively: 1 = [51; 119] (between 0% and 33% quantile, low attendance); 2 =]119; 187] (between 33% and 66% quantiles, intermediate attendance); 3 =]187; 255] (between 66% and 100% quantiles, high attendance). We counted the number of trail pixels of each class in a given home range, and multiplied this number by the corresponding class value (*i.e.,* 1, 2 or 3) to give a different weight to each trail pixel according to its attendance level. We then summed these values for a given home range and normalised the total by dividing it by the home range surface to obtain our spatial disturbance index. We used the median spatial disturbance index (*i.e.,* 0.00577) as a threshold to discriminate between **most exposed chamois** and **least exposed chamois**.

As our study period ran over almost three months, day length varied widely and is known to influence chamois activity (Brivio et al., 2016; Fattorini et al., 2019). We accounted for this effect by including day length in our models (for a similar approach, see Semenzato et al., 2021). We evaluated day length as the time elapsed between dawn and dusk using the *crepuscule* function from the *maptools* package (Bivand & Lewin-Koh, 2022; reference angle of the sun below the horizon = 6°, *i.e.,* civil dawn/dusk).

Statistical Analyses: Predicting Activity Patterns and Calculating Activity Metrics

We first modelled the daily activity of chamois as a series of values of either 0 (inactive) or 1 (active) for each 5-minutes boot using a generalised additive mixed model (GAMM) with a binomial distribution of errors (*mgcv* package, Wood, 2011; Wood, Goude, & Shaw 2015; Wood, 2017). We included three fixed effects in the model: 1) *time of the day*, *i.e.,* exact time

every 5 minutes, and 2) *day length*, as well as their interaction (using the *ti* function dedicated to interactions in generalised additive models), as continuous variables with a cyclic cubic regression splines as smoothing basis for terms including *day length* exclusively; 3) a synthesis 8-levels categorical variable representing all possible combinations between temperatures classes, levels of temporal disturbance and of spatial disturbance, in interaction with the *time of the day* (using the *by* argument of the *s* function in the implementation of the GAMM). The levels were ordered, with the reference level corresponding to a chamois living in the least exposed areas during a cold and weekdays (see Appendix). The interaction between *day length* and *time of the day* allowed us to account for the fact that the activity pattern is determined by the timing of sunrise and sunset (Ashby, 1972; Cederlund, 1989), which varies widely according to the date. We defined the unique annual id-year ID of each chamois as a random effect (using the parameter "re" for the *bs* argument in the *s* function in the implementation of the GAMM) to account for inter-individual variations in circadian activity pattern (see Appendix). We set the maximum number of knots for the smoothing functions to 24. We also fitted the null model, which was similar to the model described above but excluded the *temperatures-disturbance* variable, for comparison purposes. All details about model fitting are provided in Appendix.

We used the predictions of the model to investigate the effect of temperatures and hikers' disturbance on several activity metrics derived from this model (described below). We controlled for the effect of *day length* by fixing it to the median of the complete dataset (*i.e.,* 963 minutes) when predicting chamois activity for each level of the *temperatures-disturbance* combination. We derived the *total*, *diurnal*, *nocturnal* and both *morning* and *evening crepuscular activity* as the area under the activity curve (*AUC* function of the *DescTools* package; Signorell, 2023) for each level of the *temperatures-disturbance* variable. We defined daytime as the period elapsed between 120 minutes after dawn and 120 minutes

before dusk, and night-time as the period elapsed between 120 minutes after dusk and 120 minutes before dawn (see Bonnot et al., 2020 for a similar approach). Crepuscular periods corresponded to the remaining periods between daytime and night-time. We assessed the *timing of the morning* and *evening activity peaks* as the time when the highest activity probability occurs in the morning and the evening, respectively. We finally evaluated *morning* and *evening peak duration* as the period elapsed between the first time when the activity probability reached 0.5 and the last time before it went underneath 0.5 for both activity peaks (for a similar approach see Bourgoin et al., 2011). The percentage of variation between two situations was calculated as $100*(value_2 - value_1)/value_1$. We performed all analyses using the R software (R Core Development Team 2022, version R 4.3.0). Data is available from the Zenodo Repository: https://zenodo.org/record/8123239.

RESULTS

Model Adjustment

The full generalised additive mixed model (*AIC* = 1 578 865, *explained deviance* = 11.4%, *adjusted R2* = 0.149) was better than the null model including *time of the day* and *day length* effects and excluding the *temperatures-disturbance* variable (*AIC* = 1 591 999, *explained deviance* = 10.7%, *adjusted R2* = 0.140, see Appendix) to predict activity pattern (Fig. 1). All smooth terms (fixed and random effects) were significant (*p-values* < 0.001).

Temperatures

Whatever the level of spatial exposure and temporal disturbance, chamois increased their total activity during hot days compared to cold days, by 5% on average (Fig. 2). This change corresponds to an average increase of 22% in the nocturnal activity and a decrease of 10% in the diurnal activity, from cold to hot days (Fig. 2). In addition, crepuscular activity increased

371 from cold to hot days by more than 31% in the morning and 18% in the evening on average
372 (Fig. 2). Chamois also advanced their morning peak by 17 minutes from cold to hot days, and
373 they only slightly delayed their evening peak by 5 minutes on average (Fig. 3). Morning and
374 evening peaks lasted longer during hot compared to cold days of almost 60 minutes and of 20
375 minutes respectively, on average (Fig. 4). Chamois maintained a certain amount of activity in
376 the middle of the day during cold days (*i.e.,* above 40%), whereas the activity probability at
377 the same hours was much lower and more variable during hot days (Fig. 1).
378
379 *Hikers' Disturbance*
380 All the summer home ranges used by the studied chamois were crossed by at least one hiking
381 trail. Our spatial disturbance index ranged between 0.00317 and 0.02912 (mean ± SD =
382 0.00699 ± 0.00433, median [Q1; Q3] = 0.00577 [0.00458; 0.00774]), with only seven
383 chamois above 0.01000 (see Appendix). In 2016 and 2017, hikers' attendance was
384 significantly higher when temperatures were high (mean ± SD = 45 ± 56 hikers, median [Q1;
385 Q3] = 21 [7; 63] hikers during cold days; mean ± SD = 62 ± 37 hikers, median [Q1; Q3] = 54
386 [31; 84] hikers during hot days; Mann-Whitney: *test statistic* = 333, *N1* = 23, *N2* = 48, *p-*
387 *value* = 0.007).
388 Overall, the effect of temperatures was much more pronounced than the effect of
389 disturbance and very few differences between the general activity patterns were discernible
390 between the different levels of hikers' disturbance for a given temperature (Figs. 1 and 5).
391 Our analyses revealed very similar amounts of total, diurnal, nocturnal and crepuscular
392 activity whatever the level of disturbance (Fig. 2). Similarly, the changes in terms of timing
393 of the activity peaks according to hikers' disturbance was not biologically significant (< 7
394 minutes, Fig. 3). Only the duration of the activity peaks during hot days (also the most
395 disturbed days) was affected by the spatial exposure to hikers' disturbance (Fig. 4) with the

396 morning peak being 46 minutes shorter and the evening peak 20 minutes longer for chamois
397 living in the most exposed areas compared to chamois living in the least exposed areas. On
398 the contrary, temporal disturbance (*i.e.,* weekdays which are the least disturbed days versus
399 weekends and public holidays which are the most disturbed days) had almost no effect on the
400 length of activity peaks (Fig. 4).
401

402 **DISCUSSION**

403 Our objective was to determine and compare the relative contribution of summer
404 temperatures and hikers' disturbance on the activity pattern of females of a mountain
405 ungulate, the northern chamois. During hot days, chamois adjusted their circadian activity by
406 shifting their activity peak earlier in the morning and by increasing its duration. As expected
407 during hot days, they also increased their nocturnal and crepuscular activity while being less
408 active during the hottest hours of daytime. These behavioural adjustments allowed females to
409 maintain a similar level of total daily activity between cold and hot days. On the other hand,
410 and contrary to our expectations, chamois only rarely adjust their activity pattern according to
411 hikers' disturbance (see also Appendix). Only during hot days (also the most disturbed days),
412 we observed a marked decrease in the duration of the morning activity peak and a slight
413 increase in the duration of the evening activity peak for chamois living in the most exposed
414 areas compared to chamois living in the least exposed areas, as well as a tenuous increase in
415 the nocturnal and crepuscular activity at the expense of the diurnal activity. Temporal
416 disturbance (*i.e.,* weekends and public holidays *versus* weekdays) had almost no effect on
417 chamois activity peaks.

418 Though chamois seem to be less sensitive to high temperatures than other alpine
419 ungulate species (see Darmon et al., 2014 for a comparison between chamois and mouflon;
420 see also Semenzato et al. 2021 for Alpine ibex), their faecal glucocorticoid metabolites

concentration increases during drought conditions in summer (Anderwald, Campell Andri, & Palme 2021), as well as the time they spend in thermal refuges during hot days (Malagnino, 2022). This may explain that chamois responded much more strongly to temperatures than to hikers' disturbance. Moreover, in our study site, hikers' attendance was significantly higher when temperatures were high. Hence, the behavioural changes to buffer from high temperatures may also protect chamois from hikers' disturbance, as both factors were related. Animals have to face several stressors (*e.g.,* human disturbance, predation, high temperatures) and they eventually cannot indefinitely adjust their behavioural response as stressors accumulate (Benoist, Garel, Cugnasse, & Blanchard, 2013). During cooler periods, yellow-blotched sawback (*Graptemys flavimaculata*) tend to increase their basking time even when disturbed by humans, presumably because low temperatures force them to favor thermoregulation at the expense of risk avoidance (Selman, Qualls, & Owen, 2013). Moreover, most of the response to human disturbance in our population seems to happen at the spatial level rather than the temporal level (Fig. 4a) and only during the hot days (when hiker's attendance was at its highest level), causing a marked decline in the duration of the morning activity peak in chamois living in the most versus least exposed areas.

Recent studies provided evidence of a non-negligeable nocturnal activity peak in chamois (Carnevali, Lovari, Monaco, & Mori, 2016). Here, we also highlighted that nocturnal activity significantly increased while diurnal activity decreased during hot days, confirming the influence of high temperatures on chamois activity. As in numerous other species, chamois decreased their diurnal activity when exposed to high temperatures and/or human disturbance and attempted to compensate for the activity loss when they are absent (*e.g.,* later in the day or at night, Gaynor, Hojnowski, Carter, & Brashares, 2018). Similarly, the lynx (*Lynx lynx*) displays a spatial answer to disturbance by using less frequently the areas located close to the trails inside its home range during the day than at night (Thorsen et

al., 2022). However, an increase in nocturnal activity could expose individuals to other threats, such as nocturnal predators (Bonnot et al., 2020). This is particularly true in our study site with the progressive return of wolves recorded since 2020. Large herbivores may face the difficult challenge of avoiding being exposed to high temperatures while limiting their exposure to human disturbance, but without shifting completely their activity at night because of predation risk. The shift to more crepuscular activity observed in this study could be an answer to this trade-off.

Interestingly and in contrast with Brivio et al. (2016) and Grignolio et al. (2018) in another chamois population, total activity was slightly higher (+5%) during hot than cold days in our chamois population. Such a finding is not necessarily surprising as other studies have found similar results (in the same population, Malagnino, 2022; in Alpine ibex maintaining a constant activity both during cold and hot days, Semenzato et al., 2021). In addition, this does not necessarily translate into an increase in feeding behaviour, but might be because chamois display diel migrations between refuges and feeding spots (Courbin et al., 2022), particularly if both habitats are distant or heterogeneous. With the increasing temperatures in summer, chamois could be forced to commute more frequently or move further to find shelter from the heat while maintaining the same level of feeding activity, eventually leading to the overall increase observed. Unfortunately, our data provides no clue about the nature of the behaviours displayed (*i.e.,* foraging, moving or social behaviours) and we cannot ascertain if this rise of activity effectively corresponds to spatial displacement. Likewise, the pigmy rabbit (*Brachylagus idahoensis*) selects significantly more ground depressions as refuges during summer to mitigate the adverse effects of high temperatures (Milling, Rachlow, Johnson, Forbey, & Shipley, 2017).

We observed only minor differences between the most and least disturbed chamois, either because chamois respond similarly to human presence regardless of the encounter risk

because hikers are present almost every day even if at different level (especially during summer with summer school break), or because they shift their activity in habitats further away from the main source of disturbance, *i.e.,* the trails (Courbin et al. 2022). In our population, 85% of the individuals move temporarily away from trails every day when hikers are present (Courbin et al., 2022), demonstrating that even the less exposed chamois adjust their behaviour to human disturbance. This low tolerance affects the whole population and not just the most exposed individuals and might explain the weak difference observed between groups. Wolves also display high sensitivity to human disturbance and completely avoid the areas frequented by tourists, even if the level of attendance is as low as 40 visitors per week (Sytsma, Lewis, Gardner, & Prugh, 2022).

Mountain animals face both rising temperatures from ongoing climate warming, and modifications in their exposure to actual and perceived risks from the development of recreational activities and the return of predators in these landscapes. The interaction between those factors could eventually jeopardise their demography if particular attention is not paid in conserving habitats providing both refuge against summer heat and human disturbance (Frid & Dill, 2002; Chirichella, Stephens, Mason, & Apollonio, 2021). Moreover, both constraints can lead either to similar responses (*e.g.,* rest in refuge areas), or to opposite reactions (*e.g.,* reduce activity to avoid thermal stress, increase movement to reach thermal refuges or escape to limit predation risk), which complicates our understanding of their behavioural response. Here we highlight a strong effect of temperatures but low effects of hikers' disturbance on the activity pattern of northern female chamois. Identifying the effect of human disturbance on wildlife remains a difficult task, particularly at the population scale (Tablado & Jenni, 2017), and an integrated approach is needed to consider all forms of response, such as variations in activity level and timing, behavioural budgets and spatial displacements.

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Authors' contributions

Lucie Thel: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Visualization; Writing - original draft; Writing - review & editing. **Mathieu Garel**: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Supervision; Validation; Visualization; Writing - review & editing. **Pascal Marchand**: Conceptualization; Data curation; Methodology; Supervision; Validation; Writing - review & editing. **Gilles Bourgoin**: Conceptualization; Methodology; Supervision; Validation; Writing - review & editing. **Anne Loison**: Conceptualization; Funding acquisition; Methodology; Project administration; Resources; Supervision; Validation; Writing - review & editing.

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Conflict of Interest

The authors declared they have no conflict of interest.

Data availability statement

Data available from the Zenodo Repository: https://zenodo.org/record/8123239.

Figures

Figure 1: predicted circadian activity patterns (activity ranges between 0 for inactivity, to 1 for full-time activity) of 62 female northern chamois in the National Game and Hunting Reserve of Les Bauges massif, in summer (15th June to 7th September, 2004-2020), according to temperatures (blue: cold day; red: hot day) and human disturbance: a) chamois living in the least exposed areas during weekdays; b) chamois living in the least exposed areas during weekends and public holidays; c) chamois living in the most exposed areas during weekdays; d) chamois living in the most exposed areas during weekends and public holidays (see also pictograms directly in the figure). Solid lines represent predicted values from the model, shaded areas around the curves represent 95% confidence intervals. Background shades represent the periods used to calculate the area under the activity curve for morning and evening crepuscules (grey), daytime (yellow) and night-time (blue; see also pictograms directly in the figure). Time of the day represents hours in Coordinated Universal Time (UTC).

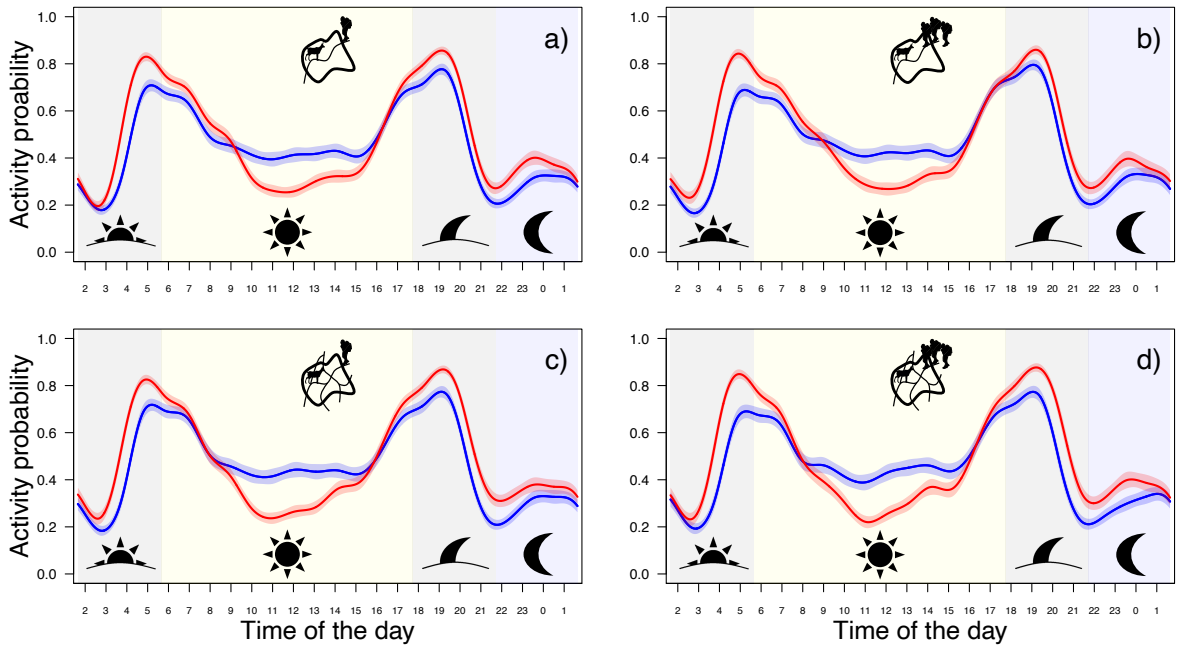

Figure 2: Area Under Curve (AUC, unitless) normalised by the duration of each period for each situation of interest, namely a combination of different levels of temperatures (blue: cold day; red: hot day), spatial (dot: low exposure; triangle: high exposure) and temporal (empty symbol: weekdays; filled symbol: weekends and public holidays; see also pictograms directly in the figure) disturbance: a) total (1 440 minutes), b) diurnal (724.8 minutes), c) nocturnal (235.2 minutes), d) morning crepuscular (240 minutes) and e) evening crepuscular (240 minutes) activity (see also pictograms directly in the figure). AUC are calculated from predicted circadian activity patterns of northern chamois of the National Game and Hunting Reserve of Les Bauges massif, in summer (15th June to 7th September, 2004-2020). We defined "diurnal" as the period elapsed between 120 minutes after dawn and 120 minutes before dusk, "nocturnal" as the period elapsed between 120 minutess after dusk and 120 minutes before dawn, and "crepuscule" as the remaining periods in the morning and in the evening (see text for details).

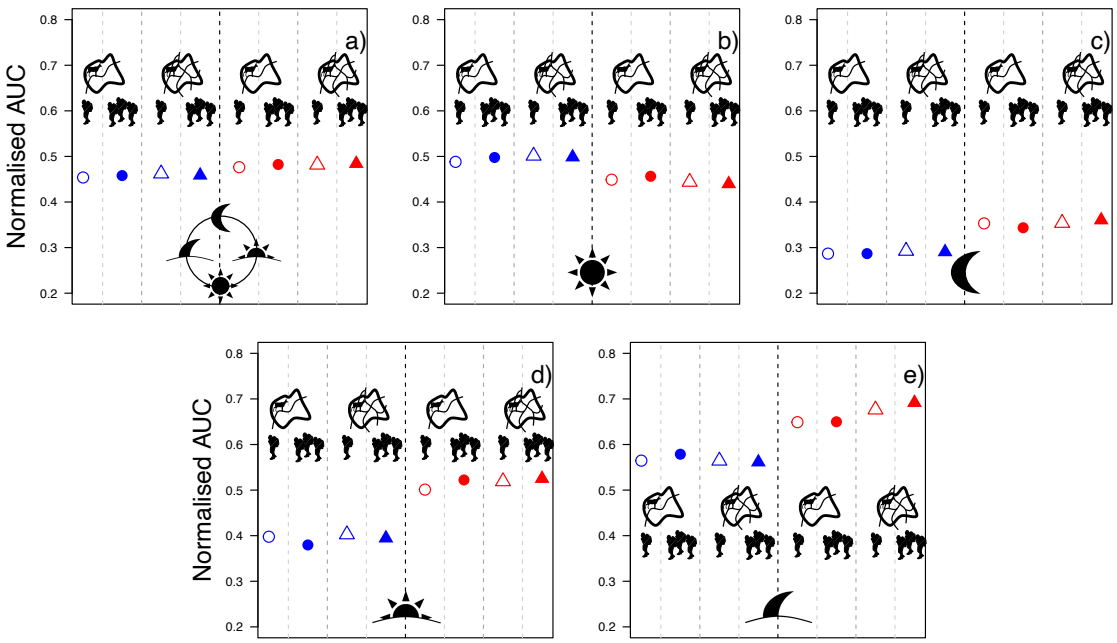

Figure 3: Timing of the Activity Peak (TAP, time of the day when the activity peaks happen, *i.e.,* the time when the highest probability of activity occurs) for each situation of interest, namely a combination of different levels of temperatures (blue: cold day; red: hot day), spatial (dot: low exposure; triangle: high exposure) and temporal (empty symbol: weekdays; filled symbol: weekends and public holidays; see also pictograms directly in the figure) disturbance: a) morning peak and b) evening peak. TAP are calculated from predicted circadian activity patterns of northern chamois of National Game and Hunting Reserve of Les Bauges massif, in summer (15th June to 7th September, 2004-2020). Note the change of interval on the y axis between figures, although the scale stays the same.

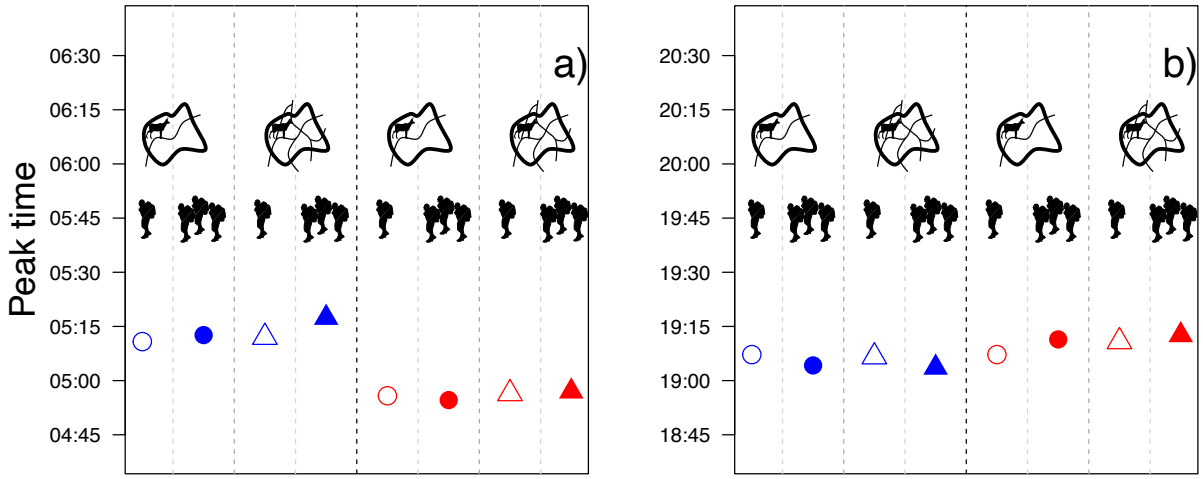

Figure 4: Peak Duration (PD, in minutes) for each situation of interest, namely a combination of different levels of temperatures (blue: cold day; red: hot day), spatial (dot: low exposure; triangle: high exposure) and temporal (empty symbol: weekdays; filled symbol: weekends and public holidays; see also pictograms directly in the figure) disturbance: a) morning and b) evening peak. PD are calculated from predicted circadian activity patterns of northern chamois of National Game and Hunting Reserve of Les Bauges massif, in summer (15th June to 7th September, 2004-2020).

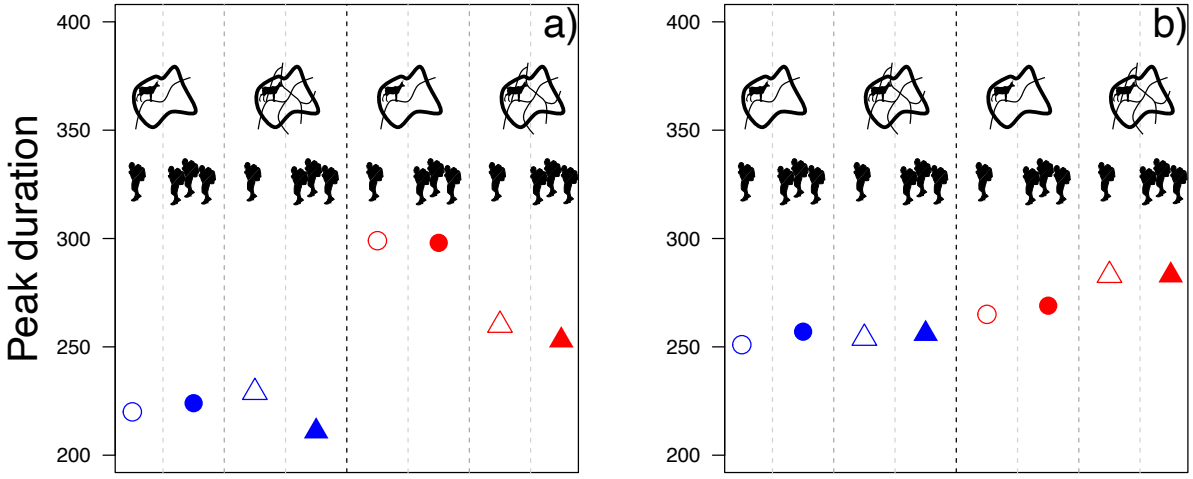
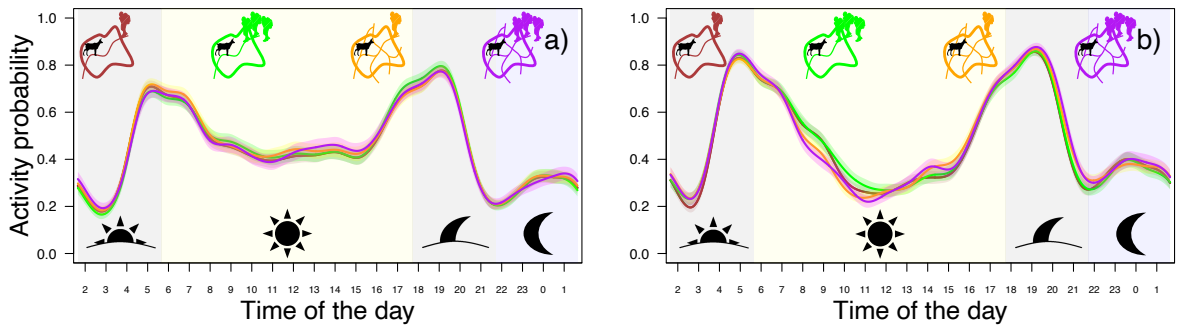
Figure 5: predicted circadian activity patterns (activity ranges between 0 for inactivity, to 1 for full-time activity) of female northern chamois in the National Game and Hunting Reserve of Les Bauges massif, in summer (15th June to 7th September, 2004-2020), according to temperatures and human disturbance: a) cold day and b) hot day. In both panels, brown represents chamois living in the least exposed areas during weekdays; green represents chamois living in the least exposed areas during weekends and public holidays; orange represents chamois living in the most exposed areas during weekdays; purple represents chamois living in the most exposed areas during weekends and public holidays (see also pictograms directly in the figure). Solid lines represent predicted values from the model, shaded areas around the curves represent 95% confidence intervals. Background shades represent the periods used to calculate the area under the curve for morning and evening crepuscules (grey), daytime (yellow) and night-time (blue; see also pictograms directly in the figure). Time of the day represents hours in Coordinated Universal Time (UTC).