Developmental and Adult Thermal Environments Interactively Shape Calling Song Plasticity in the Decorated Cricket *Gryllodes sigillatus*

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Abstract

Temperature influences insect development and adult behaviour, yet the extent to which thermal conditions experienced during development shape thermally sensitive communication in adulthood remains poorly understood. We investigated the independent and interactive effects of developmental and recording temperature on the calling song of the decorated cricket, *Gryllodes sigillatus*. Crickets were reared continuously from egg stage at either 27 °C or 36 °C and, after reaching adulthood, males were recorded at both temperatures in a full-factorial design. We quantified ten temporal properties of the calling song, including chirp and syllable rates, chirp duration, chirp period, interchirp interval, syllable duration, and the number of syllables per chirp. Recording temperature had pronounced effects on song structure: at 36 °C, males produced faster songs, with higher chirp and syllable rates, shorter chirps, shorter chirp periods, shorter interchirp intervals, shorter penultimate syllables, and fewer syllables per chirp. Developmental temperature produced contrasting effects on several traits. Males reared at 36 °C had lower chirp rates but longer chirps, chirp periods, and interchirp intervals than males reared at 27 °C. Developmental and recording temperatures interacted significantly for last-syllable duration, intersyllable interval, and syllable period, indicating that developmental thermal history modified the adult response to acute heat exposure. Our results demonstrate that developmental and adult thermal environments independently and interactively shape the temporal organisation of cricket acoustic signals. Developmental thermal plasticity may therefore alter the sensitivity of reproductive communication to warming and should be incorporated into assessments of insect responses to increasing thermal variability.

Keywords: developmental thermal stress, cricket calling song, global warming, ambient thermal stress, insect acoustics

1. Introduction

Insects are poikilotherms and thus strongly depend on environmental temperature to maintain their body temperature. With global warming leading to rising temperatures, the implications of such climatic changes are a growing concern. Many insects can adjust their behaviour, physiology, or morphology to tolerate their thermal environment, a process known as thermal plasticity (Rodrigues and Beldade, 2020). Thermal effects have been observed across various traits and processes, including development (Kong et al., 2024), body size (Atkinson, 1994), sex determination (Blackmon et al., 2016), body pigmentation (Sibilia et al., 2018), and behaviour (Abram et al., 2016). Among these, behavioural plasticity is critical to examine as it often serves as the primary immediate response to thermal stress.

Thermal fluctuations can strongly influence behavioural plasticity in insects, thereby shaping how they interact with their environment (Abram et al., 2016). This thermal responsiveness is expressed in a variety of key behaviours during an insect's lifespan, including foraging, locomotion, basking, mating, and communication (Abram et al., 2016). Of these behaviours, communication in insects is essential for processes such as kin recognition, mate attraction, and directing individuals to food sources, which is achieved through physical contact, chemical signalling, vibrations, visual signalling, and acoustic signalling. These different modalities for insect communication can be altered by heat stress. For instance, heat stress can intensify response to vibrational cues (Miler and Czarnoleski, 2021) and increase pheromone secretions (Mueller et al., 2010). Additionally, heat stress can influence temporal patterns of visual and acoustic signalling, such as leading to shorter flash durations in fireflies (Rabha et al., 2021) and faster chirp rates in bush crickets (Cusano et al., 2016). Short-range chemical or physical cues allow mating when individuals are already close together, whereas long-range acoustic signals determine whether pair formation can occur at all. Females rely on specific temporal features of these long-range signals to locate conspecific mates from afar (Gerhardt, 1994), and any thermal disturbance to the signal structure can greatly diminish the reproductive fitness of a male prior to the initiation of physical courtship. Therefore, the thermal sensitivity of long-range signalling is important to examine because it represents one of the primary behavioural constraints on reproductive success.

Long-range acoustic signalling first evolved in Orthopterans among all animal lineages, arising as a mechanism for sexual communication and predator defence (Song et al., 2020). Across various Orthopteran species, females use specific temporal patterns in these songs to ascertain male characteristics, such as body size, age, nutritional status, and immunocompetence, thereby driving female preference for males with specific traits (Hall & Robinson, 2021). In crickets, these long-range songs (calling songs) are produced by rubbing a scraper on the edge of one forewing against a ribbed file on the lower edge of another forewing, a process called stridulation, thus generating the calling song. Environmental heat stress can alter key temporal components of cricket calling song, including chirp rate, interchirp interval, and buzz duration (Cusano et al., 2016; Martin et al., 2000). Although the effects of ambient temperature on calling song are well studied, the influence of developmental temperature remains comparatively understudied. To date, only a handful of species have been examined, including *Allonemobius fasciatus* (Olvido and Mousseau, 1995), *Gryllus rubens* (Beckers et al., 2019; Beckers, 2020, 2026), *Acanthogryllus asiaticus* (Singh et al., 2020), and *Laupala cerasina* (Grace and Shaw, 2004). Moreover, interactions between developmental and ambient

temperatures have been investigated only in the first three species. Given that climate warming is increasing the likelihood of heat waves overlapping with juvenile development, understanding how rearing temperature shapes calling song, and whether its effects depend on adult thermal conditions, is essential for predicting reproductive responses in other cricket species.

To investigate the effects of developmental temperature (synonymous with rearing temperature) and ambient temperature (synonymous with recording temperature) on the long-distance calling song, we used the decorated cricket, *Gryllodes sigillatus*. Males of this species produce a long-distance calling song usually composed of continuous three-syllable chirps. Like other tropical insects, *Gryllodes sigillatus* inhabits environmental conditions close to its physiological optimum, leaving it with narrow thermal safety margins, defined as the buffer between an organism's optimal temperature and its current habitat temperature (Deutsch et al., 2008). Since thermal performance (the ability of an organism to perform functions over a range of temperatures) declines sharply beyond its optimal temperature, even minor temperature increases can disrupt an organism's functioning, leaving tropical insects exceptionally vulnerable to global warming (Deutsch et al., 2008). Thus, *Gryllodes sigillatus* serves as an ideal model system to study the impacts of heat stress, which individuals can experience during both development and adulthood due to increasingly frequent and prolonged heatwaves. By rearing crickets under standard (27 °C; Rizvi et al., 2025) and heat-stressed (36 °C; Kong et al., 2024) conditions throughout development and recording adult acoustic traits in a full-factorial design at their own development temperature and reciprocal temperature (36 °C or 27 °C), we evaluated the interplay between development plasticity and acute thermal responses. We hypothesise that developmental temperature would interact with recording temperature, significantly altering temporal patterns of calling song, with the potential to aggravate or mitigate the immediate effects of thermal stress on acoustic signalling

2. Methods

2.1 Animal Rearing

To investigate the effects of developmental temperature, ambient temperature, and their interaction on cricket song, two treatment populations were used, one exposed to a higher rearing temperature (36 °C) and another to a lower (control) temperature (27 °C). Animals used in the study originated from a stock of approximately 200 individuals (adults and subadults) sourced from an insect breeder in April 2022 (ReptilienKosmos, Germany). Crickets were maintained in a laboratory room at 27 ± 1 °C on a 12:12 light: dark cycle. They were provided with ad libitum food (Nekton cricket breeding concentrate), water in a glass vial (22 ml) plugged with cotton wool, and egg cartons for shelter. Individuals for this experiment were sourced from the 12th generation of the lab population. Plastic cups filled with moist cotton wool were placed inside the boxes where the populations are maintained to collect eggs for 1 week. Eggs were then counted and placed in separate incubators: one at 27 °C with a 12L:12D photoperiod and the other at 36 °C with a 12L:12D photoperiod to develop the two treatments.

Once eggs started hatching, the number of hatchlings was counted daily for a week, and after counting, hatchlings were housed in boxes (16.9 cm × 10.5 cm × 7.4 cm) with some egg carton pieces, a vial of water (13mL) with a cotton plug, and some food (Nekton cricket breeding

concentrate). The hatchlings were then placed under the same environmental conditions in which they had hatched to complete further development. In order to maintain virgin populations, males were segregated from the females as the ovipositor started to become visible in the females. Separation was achieved by administering a 1-minute carbon dioxide (CO2) shock to knock out the crickets, followed by transfer to segregated boxes (16.9 cm × 10.5 cm × 7.4 cm). Once the males had matured into adults by completing their final moult, they were marked by placing a small dot of paint marker on their abdomen. After marking, the males were placed in a measuring cup, and their weights were recorded on a weighing machine (Kern 770).

2.2 Audio Recordings

Adult males were placed in separate boxes with a single piece of egg carton, food and a vial of water (13mL). The individual boxes were transferred to a sound-insulated, dark room with red light, maintained at either 36 °C or 27 °C, depending on the recorded combination (Figure 1). For males whose song recordings were taken at the reciprocal temperatures, they were given at least 1 hour to acclimatize to the environment prior to recording. The boxes were randomly placed across the room, and when an individual started singing, it was brought to the centre of the table. The flap of the focal box was opened, the water vial was removed, and a microphone (Ultrasound Gate 116) was placed on top of the box. At least 1.5 minutes of continuous singing were recorded for each male using the AviSoft Recorder USGH software and stored as 16-bit wav files. Once the recording was complete, the focal male was returned to the incubator. After the daily recording session, all boxes were returned to their respective incubators.

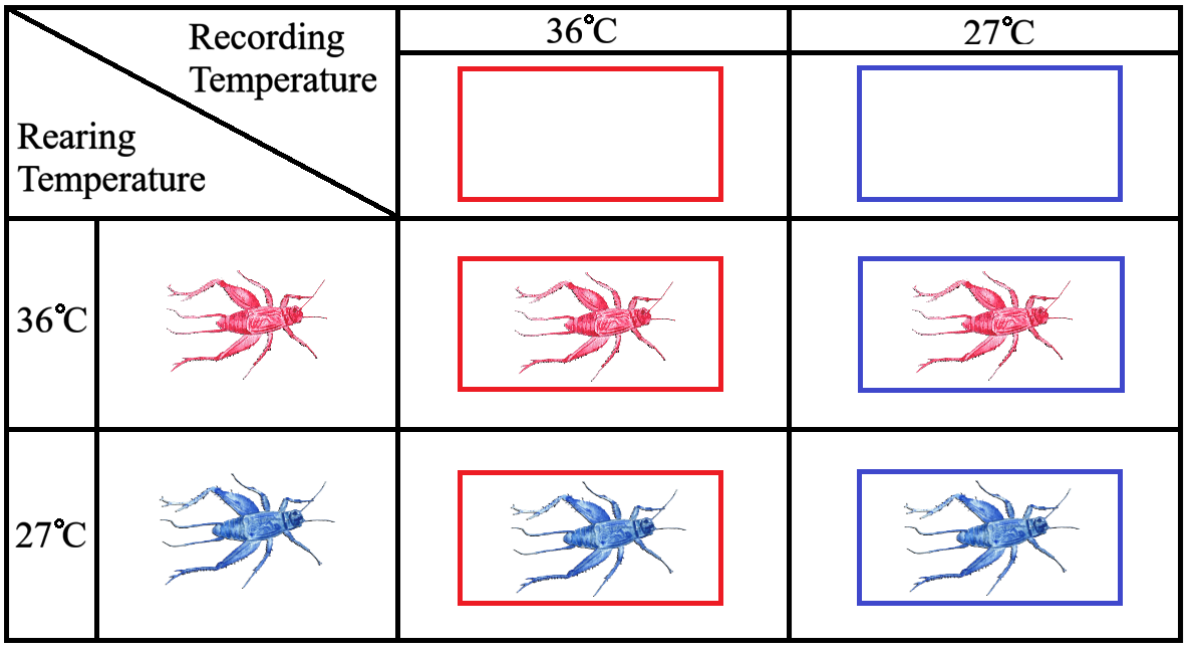

Figure 1: *Audio Recording Design*

2.3 Data Cleaning and Extraction

Audio cleaning was performed prior to analysis using RavenPro 1.6 (Cornell Laboratory of Ornithology, Ithaca, NY), where only sections of recordings with minimal background noise were selected. Data extraction was performed using R version 4.5.2. The Rthoptera (Rivas et al., 2025) and tuneR (Ligges et al., 2023) packages were used to extract ten temporal factors of the cricket song: chirp duration (onset to offset of a single chirp), chirp period (onset of one chirp to the onset of the next), inter-chirp interval (offset of one chirp to the onset of the next), chirp rate per 0.5 seconds, syllable rate per 0.5 seconds, the number of syllables per chirp, penultimate syllable duration, last syllable duration, syllable period (onset of the penultimate syllable to the onset of the last syllable), and the intersyllable interval (offset of the penultimate syllable to the onset of the final syllable). These factors were extracted from all the treatment groups. For the syllable analysis, we calculated a rolling mean ($k = 200$) from the absolute amplitude normalized to the peak amplitude (scaled 0 to 1). A relative amplitude threshold of 0.1 (10% of peak amplitude) was applied to define signal onset and offset boundaries, while a gap greater than 0.04 seconds was used to separate chirps. Since the mean number of syllables per chirp ranged between 2 and 3 across all recordings, syllable properties were restricted to the final two syllables of each chirp to ensure structural homology. Data manipulation and automated extraction pipelines were deployed using the dplyr (Wickham et al., 2023) and zoo (Zeileis and Grothendieck, 2005) packages.

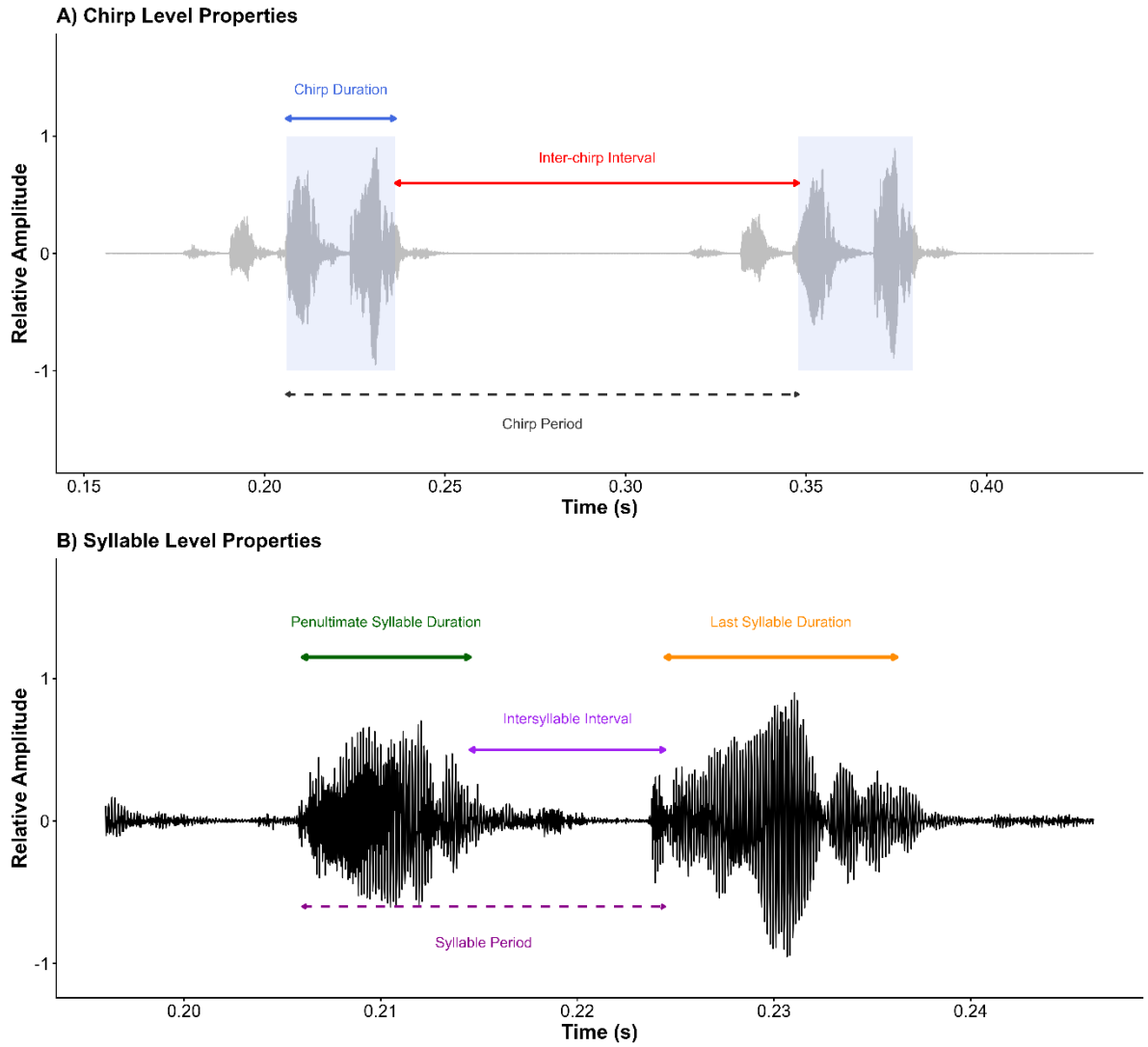

***Figure 2**: Temporal patterns of Gryllodes sigillatus calling song*

2.4 Statistical Analyses

All statistical analyses were performed in R version 4.5.2 (R Core Team 2026) with packages loaded via pacman (Rinker and Kurkiewicz 2017). The analyses were based on song recordings obtained from a total of 100 individuals across all experimental treatments. For each temporal property of the cricket calling song, we used either frequentist linear models or a Bayesian generalised linear model via brms (Bürkner, 2017), depending on the nature of the data. Specifically, a Bayesian framework with a robust Student-t error distribution and weakly informative priors was used for the interchirp interval analysis to handle its specific data structure, while standard linear models were used for all other song properties. For all models, male rearing temperature, recording temperature, and their two-way interaction were included as fixed effects, with male body weight included as a covariate. All linear models were assessed using the DHARMa (Hartig, 2024) package to generate residual diagnostics and verify the assumptions of normality, homoscedasticity, and the absence of outliers. Post hoc comparisons of estimated marginal means and interaction effects were performed using the emmeans (Lenth and Piaskowski, 2025) package with Tukey's HSD adjustment for multiple comparisons. All data visualisations were conducted using ggplot2 (Wickham, 2016), patchwork (Pederson,

2025), with the tidybayes (Kay, 2024) and modelr (Wickham, 2023) packages used to extract and plot the posterior distributions from the Bayesian model.

3. Results

3.1. Thermal Effects on Pace of Signalling

Recording temperature of 36 °C consistently accelerated song speed, causing a significant increase in chirp rate by 42.25% (Estimate = 1.659, t_{95} = 15.27, $p < 0.001$, Figure 3a) and syllable rate by 20.48% (Estimate = 2.323, t_{95} = 4.16, $p < 0.001$, Figure 3b). On the other hand, developmental temperature of 36 °C led to a decrease in the chirp rate by 8.73% (Estimate = -0.343, t_{95} = -3.02, $p < 0.01$, Figure 3a) irrespective of the recording temperature. However, syllable rate was not affected by the developmental temperature (Estimate = -0.674, t_{95} = -1.15, $p = 0.251$). Additionally, the interaction between developmental and recording temperatures had no significant effect on either chirp rate or syllable rate (S1).

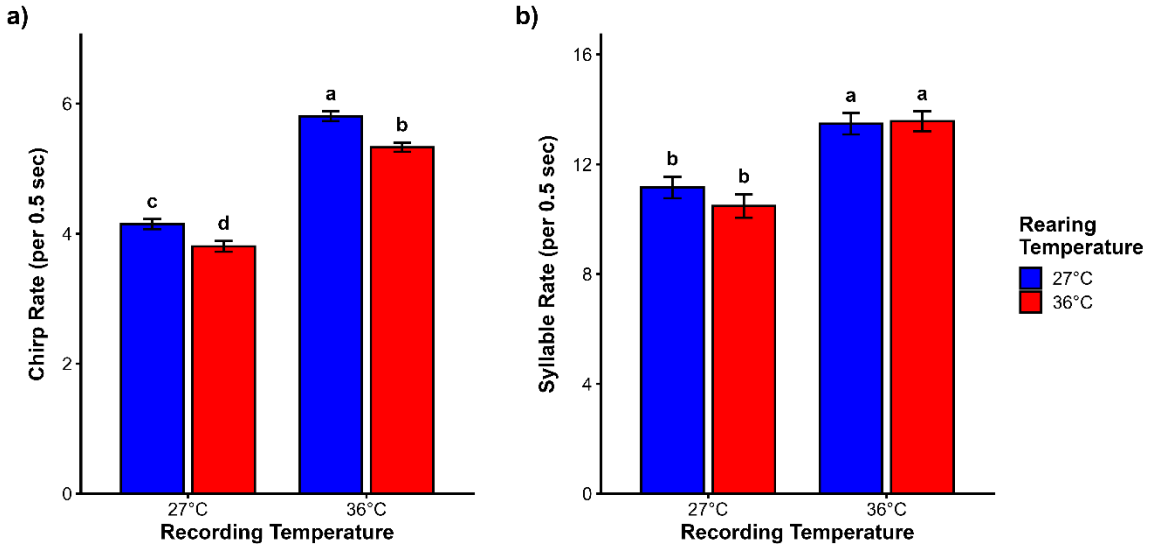

Figure 3: *Effects of rearing and recording temperature on the pace of calling song. Males recorded at 36 °C had a faster chirp rate (a) and syllable rate (b) than those recorded at 27 °C, while males reared at 36 °C had a slower chirp rate (a) than those reared at 27 °C. Vertical bars indicate standard error (± SE) for both plots.*

3.2. Thermal Effects on Temporal Patterns of Calling Song

Recording temperature significantly influenced five examined temporal patterns of the calling song. Males recorded at 36 °C exhibited a reduction in chirp duration by 32.50% (Estimate = -0.013, t_{95} = -8.01, $p < 0.001$, Figure 4a), chirp period by 29.55% (Estimate = -0.039, t_{95} = -14.30, $p < 0.001$ Figure 4b), interchirp interval by 33.33% (Estimate = -0.03, 95% CI: [-0.03, -0.02], Figure 4c), penultimate syllable duration by 25.00% (Estimate = -0.002, t_{95} = -3.90, $p < 0.001$, Figure 4d), and number of syllables per chirp by 13.20% (Estimate = -0.373, t_{95} = -3.63, $p < 0.001$, Figure 4e) as compared to males recorded at 27 °C. Conversely, a developmental temperature of 36 °C led to an increase in chirp duration by 10.00% (Estimate = 0.004, t_{95} = 2.48, $p < 0.05$, Figure 4a), chirp period by 8.33% (Estimate = 0.011, t_{95} = 3.94,

$p < 0.001$, Figure 4b), and interchirp interval by 11.11% (Estimate = 0.01, 95% CI: [0.00, 0.01], Figure 4c). However, developmental temperature had no significant effects on the penultimate syllable duration (Estimate = 0.0004, $t_{95} = 1.02$, $p = 0.308$) or the number of syllables in a chirp (Estimate = 0.058, $t_{95} = 0.54$, $p = 0.59$). Moreover, the interaction between developmental and recording temperatures had no significant effect on any of the above-mentioned traits (S2, S3).

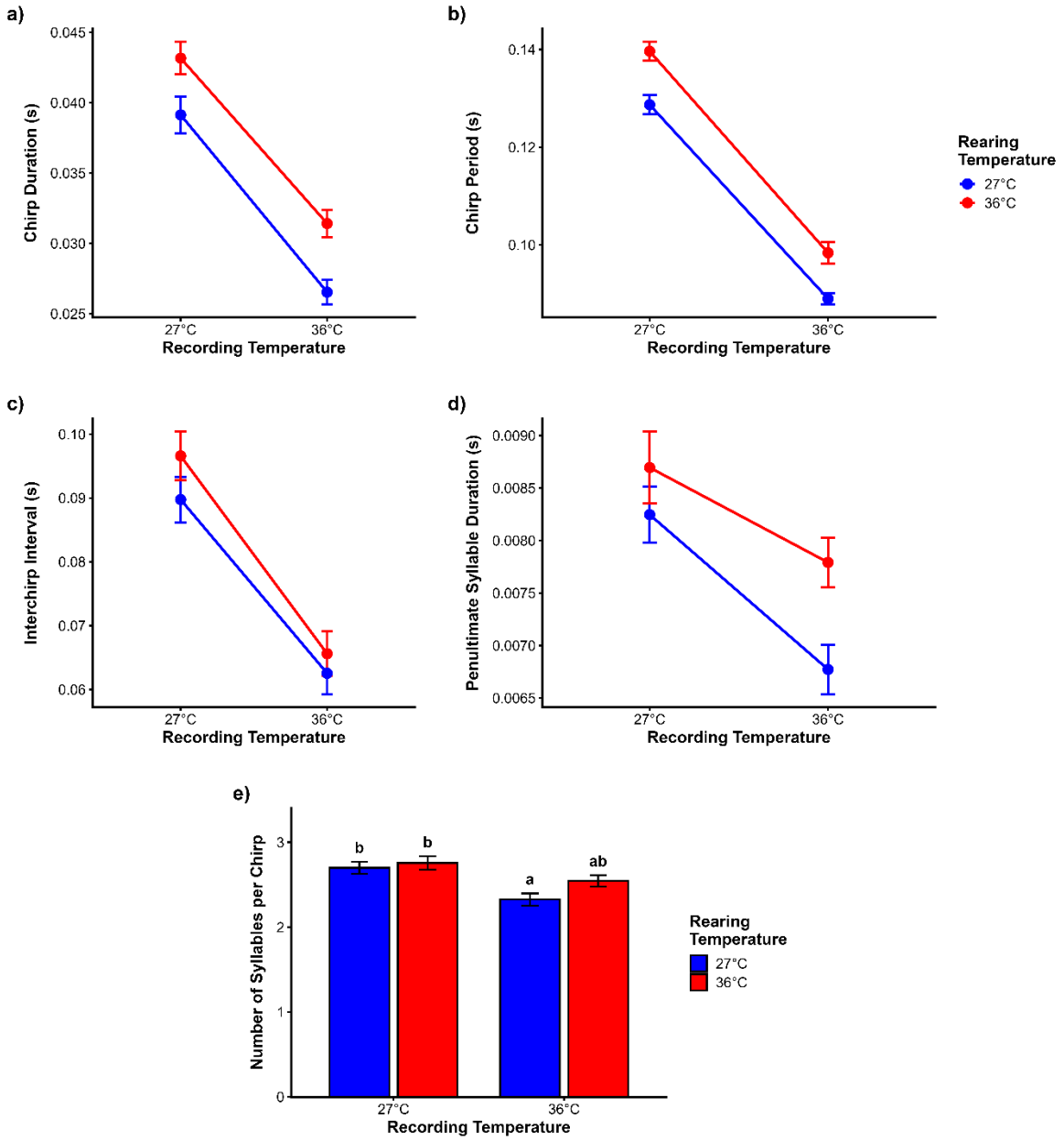

Figure 4: *Thermal effects on temporal patterns of the calling song. Males recorded at 36 °C had reduced chirp duration (a), chirp period (b), interchirp interval (c), penultimate syllable duration (d), and number of syllables per chirp (e) than those recorded at 27 °C. Conversely, males reared at 36 °C had longer chirp duration (a), chirp period (b), and interchirp interval (c) than those reared at 27 °C. Vertical bars indicate standard error (± SE) for plots a), b), d), e). For plot c), points represent posterior mean estimates of interchirp intervals. Vertical error bars represent the 95% Credible Intervals (CIs), indicating the range within which the true population means lie with 95% probability.*

3.3. Interactive Thermal Effect on Syllable Structure

Significant interactions between recording and developmental temperatures were observed in the last syllable duration, the intersyllable interval, and the syllable period. Last syllable duration was affected negatively by both the recording temperature (a 20.00% reduction; Estimate = -0.002, t_{95} = -4.36, p<0.001, Figure 5a) and the developmental temperature (a 10.00% reduction; Estimate = -0.001, t_{95} = -2.54, p = 0.012, Figure 5a). However, a strong positive interaction (Estimate = 0.002, t_{95} = 3.32, p = 0.001, Figure 5a) revealed that while males reared at 27 °C experienced a sharp reduction in last syllable duration when recorded at 36 °C, males reared at 36 °C maintained or slightly increased last syllable duration when recorded at 36 °C.

For the intersyllable interval and the syllable period, developmental temperature of 36 °C had a positive effect, lengthening the intersyllable interval by 20.00% (Estimate = 0.002, t_{95}= 4.72, p < 0.001, Figure 5b) and the syllable period by 16.67% (Estimate = 0.003, t_{95} = 7.15, p < 0.001, Figure 5c). In contrast, recording temperature of 36 °C had a negative effect, shortening the intersyllable interval by 20.00% (Estimate = -0.002, t95 = -4.445, p < 0.001, Figure 5b) and the syllable period by 2.22% (Estimate = -0.002, t95 = -9.65, p < 0.001, Figure 5c). Additionally, a significant negative interaction between the two temperature treatments for both intersyllable interval (Estime = -0.002, t_{95} = -3.104, p < 0.01, Figure 5b) and syllable period (Estimate = -0.002, t_{95} = -2.90, p < 0.01, Figure 5c) demonstrated that both traits shortened more steeply for males reared at 36 °C than males reared at 27 °C when

recorded at 36 °C.

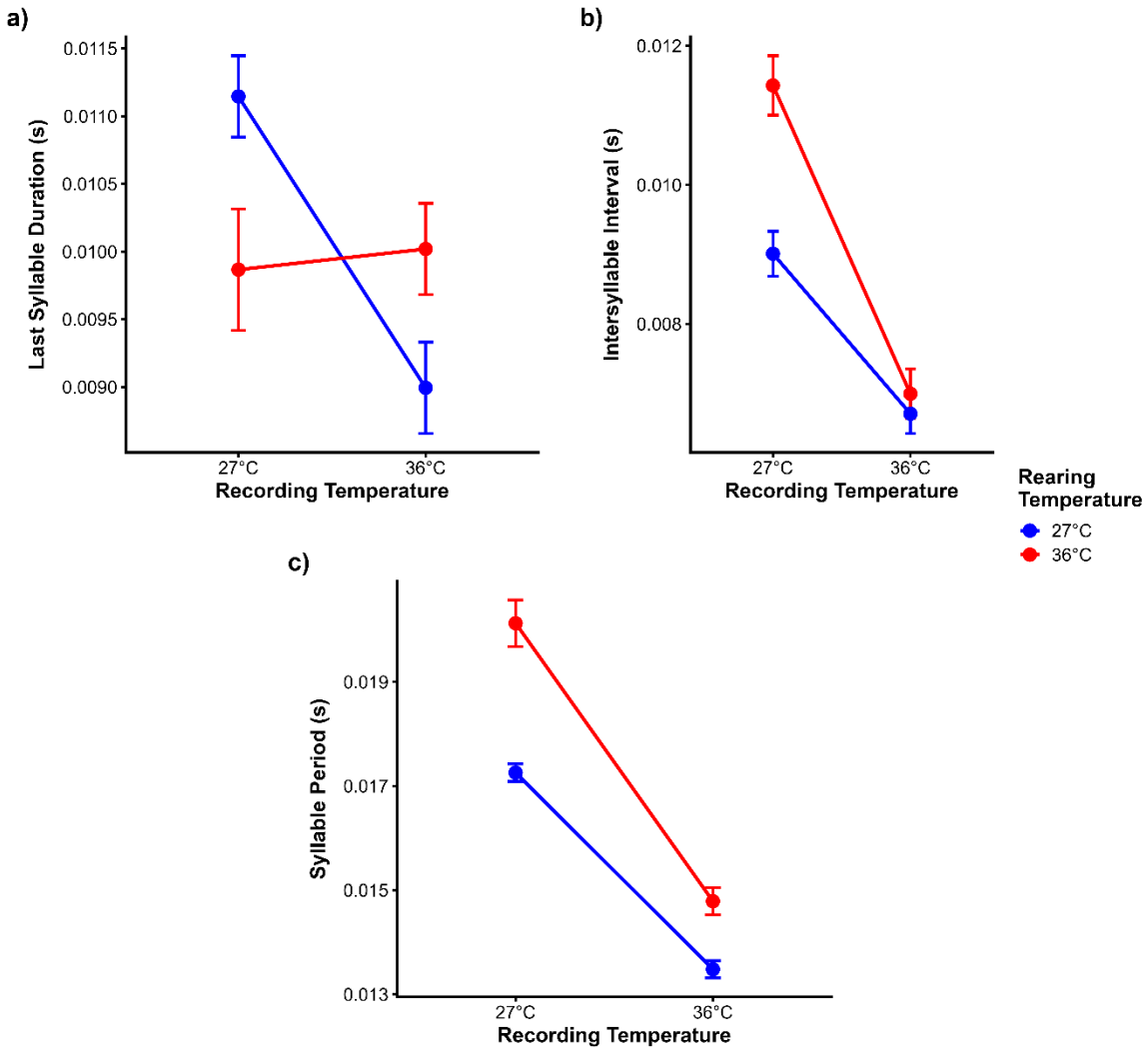

***Figure 5**: Interactive thermal effect of rearing and recording temperature on syllable structure. Males reared at 36 °C had slightly longer last syllable duration when recorded at 36 °C (a), while males reared at 27 °C showed a sharp decrease in last syllable duration when recorded at 36 °C (a). Additionally, at a recording temperature of 36 °C, males reared at 36 °C had a sharper decrease in intersyllable interval (b) and syllable period (c) than those developed at 27 °C. Overall, males recorded at 36 °C had shorter intersyllable interval (b) and syllable period (c) than those recorded at 27 °C. Asymmetry between lines in all plots indicates an interactive effect. Vertical bars indicate standard error (± SE) for all plots.*

Remarks

Across all models, male body weight had no significant effect on any measured parameter ($p > 0.05$ for all traits).

Discussion

In this study, we investigated the interactive and independent effects of developmental and ambient temperature on the calling song of the decorated cricket, *Gryllodes sigillatus*. To

disentangle these effects, we conducted full-factorial recordings of crickets under the hypothesis that the various parameters of the cricket song would be influenced independently by developmental and ambient temperature conditions, or interactively by both. Our results reveal that all the various properties of the cricket calling song we studied were influenced by developmental temperature, ambient temperature, or both. Moreover, both treatment temperatures had an interactive effect on some song properties (the duration of the last syllable, syllable period, and intersyllable interval).

Our results demonstrate a clear divergence between ambient and developmental thermal effects on the overarching pattern of the calling song. Ambient heat stress increased the chirp rate, a trend also observed in vertebrates such as frogs and birds, where higher temperatures lead to faster song speed. On the other hand, ambient heat stress decreased the chirp duration, chirp period, and interchirp interval. The accelerating effect of high ambient temperatures on signalling rates reflects a general trend observed across crickets (Pires and Hoy, 1992) and anurans such as frogs (Ziegler et al., 2016) and toads (Lörcher, 1969). Similar ambient heat stress effects on temporal patterns of the calling song, such as shortened durations, intervals, and periods, have been shown in other cricket species (Ciceran et al., 1994; Walker and Cade, 2003; Hedrick et al., 2002; Doherty, 1985) and in katydids (Cusano et al., 2016). Conversely, developmental acclimation to heat stress led to a decrease in the chirp rate while increasing the chirp duration, chirp period, and interchirp interval, which align with a previous study in *Acanthogryllus asiaticus* (Singh et al., 2020). These divergent shifts in the chirp properties can have profound consequences on intersexual selection. Females rely on the specific pattern of the male calling song to distinguish conspecific males from heterospecific males and environmental noise. (Wendler, 1990; Moiseff et al., 1978). While ambient heat stress compresses the entire song structure into an accelerated pattern that could disrupt signal recognition, developmental heat stress appears to act as a counter, by stretching the intervals and durations back out. This suggests that developmental plasticity may help maintain structural signal recognition and preserve mate-locating dynamics when the ambient temperature rises. Such compensatory effects reflect a broader pattern across insects, where developmental thermal history induces plastic responses that modulate or counteract adult sensitivity to acute thermal stress (Mira et al., 2026). Additionally, females may assess male quality partly through the calling song, as temporal properties of the song can indicate the male's underlying phenotypic state, particularly nutritional condition, with faster chirp rates and shorter interchirp intervals indicating higher nutritional content (Scheuber et al., 2003). Variations in chirp rate due to temperature can decouple the song structure from the male's actual physical condition, generating a potentially dishonest signal of the male's quality to a female.

We found that the number of syllables per chirp decreased when individuals were recorded at a heat-stress ambient temperature. Such temperature dependence in syllable number is highly variable across crickets; while similar reductions occur in a few species (Doherty, 1985; Olvido & Mousseau, 1995; Walker & Cade, 2003), others show no thermal sensitivity to ambient heat in syllable count per chirp or trill (Ciceran et al., 1994; Martin et al., 2000; Singh et al., 2020). There is some evidence that female crickets prefer males with a higher number of syllables in a chirp, as it serves as a reliable signal of the male's immune function (Ryder and Siva-Jothy, 2000). Acute heat stress can reduce males' immune function (Karl et al., 2011; Franke and Fischer, 2013). Hence, the decrease in the number of syllables per chirp at higher ambient

temperatures may indicate reduced immunity and serve as an honest signal to females. While high ambient temperature decreased the number of syllables per chirp, it increased syllable rate, consistent with previous findings (Walker and Cade, 2003; Martin et al., 2000; Beckers, 2020). Syllable rhythm and chirp rhythm are controlled by different pattern generators, and the timing of both generators is set independently (Bentley, 1969; Kutsch, 1969). Our results indicate that the mechanism behind the timing of both generators is sensitive to ambient temperature, but the mechanism modulating the timing of the pattern generator responsible for syllable rhythm is not developmentally plastic, remaining strictly canalised across the developmental thermal environments.

We found particularly interesting results for the penultimate syllable duration, the last-syllable duration, the syllable period, and the intersyllable interval between the two. Penultimate syllable duration was affected only by the ambient temperature, which is consistent with other studies (Walker and Cade, 2003; Martin et al., 2000). On the contrary, developmental temperature and ambient temperature had substantial effects on the other three properties studied, and an interaction effect was observed between them. To date, studies of this type have been conducted only on *Acanthogryllus asiaticus* (Singh et al., 2020), in which syllable duration and syllable period showed interaction effects between developmental and ambient temperatures. Changes in the intersyllable interval result from changes in the rate at which wings open, whereas changes in syllable duration result from the rate at which wings close (Bennet-Clark, 2019). Furthermore, cricket songs are controlled by a central pattern generator, where separate groups of neurons trigger the wing-opening and wing-closing muscles (Bentley, 1969). The males that had been reared under heat stress conditions showed a slight increase in the duration of the last syllable relative to the control group as the recording temperature increased from the control temperature to the heat-stress treatment temperature. This may be attributed to the developmental modifications in the neuromuscular architecture responsible for wing closure, resulting in a fine-tuning of the final closing stroke that enables males to thermally optimize their ability to either maintain or increase the duration of the last syllables. Alternatively, males reared under heat stress have a bigger reduction in their syllable period and intersyllable intervals at a heat stress ambient temperature as compared to males who were reared at the control temperature. This suggests that development at different temperatures can tune the rate of wing opening, with higher temperatures during development sensitizing the neural circuitry to higher temperatures in the environment, thus making wing opening happen faster. The difference here indicates decoupling of song components, with developmental plasticity optimizing the final closing stroke of the wings but increasing the sensitivity of the neural circuitry involved in wing opening.

The calling song serves as a phonotactic cue, allowing both males and females to recognise conspecific males (Roy et al., 1982). In terms of intersexual selection, females have been shown to prefer more pulses per trill, shorter inter-trill intervals (Wagner Jr. et al., 1995), and higher chirp rates (Wagner and Reiser, 2000). Particularly in *Gryllodes sigillatus*, female preference has been reported for shorter syllable durations (Champagnon and Castillo, 2008). Female mating preferences can thus shift or become mismatched as the temporal properties of the male calling song are altered by developmental or ambient temperature. Consequently, a significant change in song structure under heat stress may cause males to drift outside the female preference envelope, potentially reducing their ability to find a mate. Moreover, crickets can exhibit parallel plasticity, wherein, as temperature changes, female preferences shift in

accordance with traits expressed by males (Becker et al., 2019; Grace and Shaw, 2004). However, if developmental temperature affects male song and female preference at different rates, it could disrupt the direction of sexual selection in response to global warming.

To summarise, our results provide strong evidence for the effects of both rearing and ambient temperature on various temporal properties of the cricket calling song. This can result in altered mating choices, ultimately influencing individuals' fitness. Therefore, it is essential, ecologically and evolutionarily, to understand how developmental temperature influences acoustic signalling and mating pair-formation strategies in response to climate change.

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Data and Code Availability Statement

The datasets generated and analysed for the current study are available on https://doi.org/10.5281/zenodo.22668264

Author Contributions

DS: Conceptualisation, Data Curation, Methodology, Software, Formal Analysis, Investigation, Project Administration, Visualisation, Writing - Original Draft, Writing - Review and Editing (supporting) **TR:** Conceptualisation, Methodology, Project Administration, Supervision (supporting), Writing - Review and Editing (supporting) **KR:** Conceptualisation, Funding Acquisition, Methodology, Project Administration, Resources, Supervision (lead), Writing - Review and Editing (lead)

Conflict of Interest Declaration

The authors declare no competing interests.

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Supplementary Material

S1: *Summary of Linear Models for the effects of developmental temperature, recording temperature, and their interaction on chirp rate, syllable rate.*

Model / Predictor	**Estimate**	**Std. Error**	**t value**	**p - value**
Chirp Rate (R^2 = 0.83)				
(Intercept)	3.927	0.197	19.920	< 0.001
Developmental Temperature (36 ^{0}C)	**-0.343**	**0.114**	**-3.018**	**0.003**
Recording Temperature (36 ^{0}C)	**1.659**	**0.109**	**15.271**	**< 0.001**
Male Weight	0.830	0.734	1.131	0.261
Developmental Temperature x Recording Temperature	-0.135	0.155	-0.870	0.386
Syllable Rate (R^2= 0.34)				
(Intercept)	11.343	1.014	11.192	< 0.001
Developmental Temperature (36 ^{0}C)	-0.674	0.584	-1.154	0.251
Recording Temperature (36 ^{0}C)	**2.323**	**0.558**	**4.159**	**< 0.001**
Male Weight	-0.713	3.776	-0.189	0.851
Developmental Temperature x Recording Temperature	0.766	0.798	0.961	0.339

S2: *Summary of Linear Models for the effect of developmental temperature, recording temperature, and their interaction on chirp duration, chirp period, penultimate syllable duration, and number of syllables per chirp.*

Model / Predictor	**Estimate**	**Std. Error**	**t value**	**p - value**
Chirp Duration (R^2 = 0.59)				
(Intercept)	0.040	0.003	13.862	< 0.001
Developmental Temperature (36 ^{0}C)	**0.004**	**0.002**	**2.482**	**0.015**
Recording Temperature (36 ^{0}C)	**-0.013**	**0.002**	**-8.010**	**< 0.001**
Male Weight	-0.001	0.011	-0.120	0.905
Developmental Temperature x Recording Temperature	0.001	0.002	0.354	0.724
Chirp Period (R^2 = 0.83)				
(Intercept)	0.132	0.005	26.416	< 0.001
Developmental Temperature (36 ^{0}C)	**0.011**	**0.003**	**3.938**	**< 0.001**

Recording Temperature (36 ^{0}C)	**-0.039**	**0.003**	**-14.299**	**< 0.001**
Male Weight	-0.013	0.019	-0.690	0.492
Developmental Temperature x Recording Temperature	-0.002	0.004	-0.541	0.590
Penultimate Syllable Duration (R^2 = 0.22)				
(Intercept)	0.008	0.001	11.339	< 0.001
Developmental Temperature (36 ^{0}C)	0.0004	0.0004	1.024	0.308
Recording Temperature (36 ^{0}C)	**-0.002**	**0.0004**	**-3.900**	**< 0.001**
Male Weight	0.001	0.003	0.446	0.657
Developmental Temperature x Recording Temperature	0.001	0.001	1.128	0.262
Number of Syllables per Chirp (R^2= 0.19)				
(Intercept)	2.826	0.186	15.178	< 0.001
Developmental Temperature (36 ^{0}C)	0.058	0.107	0.538	0.592
Recording Temperature (36 ^{0}C)	**-0.373**	**0.103**	**-3.634**	**< 0.001**
Male Weight	-0.480	0.694	-0.692	0.491
Developmental Temperature x Recording Temperature	0.163	0.146	1.111	

S3: *Summary of Bayesian Robust Linear Regression Model with Student - t distribution for the effects of developmental temperature, recording temperature, and their interaction in interchirp interval.*

Parameter	**Estimate**	**Est. Error**	**Lower 95% CI**	**Upper 95% CI**	**Rhat**	**Bulk ESS**
(Intercept)	0.09	0.00	0.08	0.10	1.00	9696
Developmental Temperature (36 ^{0}C)	**0.01**	**0.00**	**0.00**	**0.01**	**1.00**	**7436**
Recording Temperature (36 ^{0}C)	**-0.03**	**0.00**	**-0.03**	**-0.02**	**1.00**	**8571**
Male Weight	-0.01	0.02	-0.05	0.02	1.00	8671
Developmental Temperature x Recording Temperature	-0.00	0.00	-0.01	0.00	1.00	6818
sigma (Residual SD)	0.01	0.00	0.01	0.01	1.00	6503
nu (Degrees of Freedom)	10.85	8.00	3.24	32.83	1.00	6605

572 ***S4:*** *Summary of Linear Models for the effects of developmental temperature, recording temperature,*
573 *and their interaction on last syllable duration, intersyllable interval, and syllable period.*

Model / Predictor	**Estimate**	**Std. Error**	**t value**	**p - value**
Last Syllable Duration (R^2 = 0.17)				
(Intercept)	0.010	0.001	11.334	< 0.001
Developmental Temperature (36 ^{0}C)	**-0.001**	**0.0005**	**-2.540**	**0.012**
Recording Temperature (36 ^{0}C)	**-0.002**	**0.0005**	**-4.363**	**<0.001**
Male Weight	0.003	0.003	0.754	0.452
Developmental Temperature x Recording Temperature	**0.002**	**0.001**	**3.320**	**0.001**
Intersyllable Interval (R^2 = 0.53)				
(Intercept)	0.010	0.001	10.469	< 0.001
Developmental Temperature (36 ^{0}C)	**0.002**	**0.0005**	**4.724**	**< 0.001**
Recording Temperature (36 ^{0}C)	**-0.002**	**0.0005**	**-4.445**	**< 0.001**
Male Weight	-0.002	0.0034	-0.651	0.517
Developmental Temperature x Recording Temperature	**-0.002**	**0.001**	**-3.104**	**0.002**
Syllable Period (R^2 = 0.78)				
(Intercept)	0.018	0.001	24.874	< 0.001
Developmental Temperature (36 ^{0}C)	**0.003**	**0.0004**	**7.146**	**< 0.001**
Recording Temperature (36 ^{0}C)	**-0.004**	**0.0004**	**-9.650**	**< 0.001**
Male Weight	-0.001	0.003	-0.400	0.690
Developmental Temperature x Recording Temperature	**-0.002**	**0.001**	**-2.901**	**0.004**

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