Annual cycles of metabolic rate are genetically determined but can be shifted by phenotypic flexibility

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Running head:  
Annual variation in metabolic rate

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Summary

Birds have adjusted their life-history and physiological traits to the characteristics of the seasonally changing environments they inhabit. Annual cycles in physiology can result from phenotypic flexibility or from variation in its genetic basis. A key physiological trait that shows seasonal variation is basal metabolic rate (BMR). We studied genetic and phenotypic variation in the annual cycles of body mass, BMR and mass-specific BMR in three stonechat subspecies (Saxicola torquata) originating from environments that differ in seasonality, and in two hybrid lines. Birds were kept in a common garden set-up, under annually variable day length and at constant temperature. We also studied whether stonechats use the proximate environmental factor temperature as a cue for changes in metabolic rate, by keeping birds at two different temperature regimes. We found that the different subspecies kept in a common environment had different annual cycles of body mass, BMR (variance: Kazakh 4.12, European 1.31, Kenyans 1.25) and mass-specific BMR (variance: Kazakh 0.042, European 0.003, Kenyans 0.013). Annual variation in metabolic measures of hybrids was intermediate or similar to parental species. Temperature treatment did not affect the shape of the annual cycles of metabolic rate, but metabolic rate was higher in birds kept under the variable temperature regime. The distinct annual cycles in body mass and metabolic rate in stonechats subspecies kept in a common environment indicate different genetic backgrounds rather than merely a phenotypically flexible response to proximate environmental cues. Phenotypic effects of temperature are superimposed on this genetically orchestrated annual cycle.
Introduction

Seasonal changes in the environment influence metabolic rate of birds (McKechnie, 2008; Swanson, 2010) and have repercussions for their behavior, physiology and ecology. Seasonal variation in metabolic rate has been widely studied (for review see McKechnie 2008), often between two seasons (e.g. Ambrose and Bradshaw, 1988; Cooper and Swanson, 1994; Kvist and Lindström, 2001; Wikelski et al., 2003), but sometimes in more detail year-round (Piersma et al., 1995; Klaassen, 1995; Zheng et al., 2008; Vézina et al., 2011). The variety of patterns emerging from these studies indicates that annual cycles in metabolic rate differ among environments and/or with life history strategies. For example, resident birds in temperate zones generally have a higher metabolic rate in winter than in summer (Cooper and Swanson, 1994; Cooper, 2000; Dawson, 2003). Temperate or arctic breeding migrants, on the other hand, generally have a lower metabolic rate in winter than in summer (Kersten et al., 1998; Kvist and Lindström, 2001; Wikelski et al., 2003). Patterns of resident subtropical, tropical and desert birds are inconsistent, showing no annual variation (Bush et al., 2008; Maldonado et al., 2008; Doucette and Geiser, 2008), an increase (Chamane and Downs, 2009), or a decrease in metabolic rate in winter compared with summer (Maddocks and Geiser, 2000; Smit and McKechnie, 2010). Whether variation in annual cycles in metabolic rate found in birds results from genetic differences or phenotypic flexibility is largely unknown.

To compare seasonality of energy metabolism researchers use different measures of metabolic rate, including basal metabolic rate (BMR), resting metabolic rate or field metabolic rate. BMR is the most standardized measure, defined as the minimum energy expenditure of a post-absorptive normothermic animal, measured during the rest phase, at thermoneutral temperature (King, 1974). Mass-specific BMR, calculated as BMR divided by body mass (in kJ/day/g), is commonly applied in studies evaluating tissue-level processes, such as mitochondrial function, production of free radicals and other measures related to aging or intrinsic mortality (e.g. Speakman, 2005; Tieleman, Versteegh, Helm, et al., 2009). The relationships between BMR and activity (Deerenberg et al., 1998; Nudds and Bryant, 2001), food availability and diet (McNab, 1988; Mueller and Diamond, 2001), organ sizes and body composition (Daan et al., 1990; Piersma et al., 1996; Tieleman et al., 2003), and daily energy expenditure (Daan et al., 1990; Nilsson, 2002; Tieleman et al., 2008) make it an interesting trait for researchers studying seasonal variation.
BMR is influenced by seasonally variable environmental factors such as temperature and food availability (Swanson and Olmstead, 1999; Tieleman et al., 2003; Broggi et al., 2007; Swanson, 2010), but also by seasonally variable life cycle traits and physiology (Klaassen, 1995; Ricklefs and Wikelski, 2002; Wikelski et al., 2003; Vézina et al., 2007). There are several hypotheses about the mechanisms underlying the adjustment of BMR to the annual cycle of energetic needs and challenges. Annual cycles of BMR could have a genetic basis, indicating that annual cycles in metabolism have evolved to be adaptive in particular environments and not in others (Piersma and Drent, 2003; Hahn and MacDougall-Shackleton, 2008). Alternatively, or superimposed on a genetically orchestrated pattern, annual cycles in BMR could result from phenotypically flexible adjustments (Piersma and Drent, 2003; Hahn and MacDougall-Shackleton, 2008). This would allow birds to adjust their cycles in BMR at short notice to the needs of any environmental conditions that they encounter. Whether annual cycles in metabolic rate have a genetic basis or result solely from phenotypic flexibility can be investigated by placing species from seasonally different environments in a common environment (Turesson, 1922; Gwinner, König, and Haley, 1995). If the annual cycles have a genetic basis, differences among species will be maintained. However, if annual cycles of metabolism result solely from phenotypic flexibility, birds will adjust their metabolism to the common environment and no difference will be detected among the species. Additional means to investigate genetic and phenotypically flexible components of annual cycles include studying hybrids created from birds with different annual cycles, or altering environmental conditions at which birds are kept.

Stonechats (Saxicola torquata) provide an ideal study system to address the evolutionary physiology of annual cycles in metabolic rate because we can build on extensive knowledge from previous studies of their physiology and life history. Stonechats, widespread small passerines (Urquhart, 2002), occur in environments that vary considerably in seasonal cycles of environmental conditions, which is reflected in distinct annual cycles and life history traits (Gwinner, König, and Haley, 1995; König and Gwinner, 1995; Helm et al., 2009; Helm, 2009). They are easily kept and bred in captivity, and hybrid lines between subspecies can be created. Differences in life history traits among stonechat subspecies remain present when birds are born and held in captivity (Gwinner, König, and Haley, 1995; König and Gwinner, 1995; Helm et al., 2009; Helm, 2009). Kenyan stonechats had the lowest, European stonechats had intermediate and Kazakh stonechats had the highest mass-specific metabolic rate when kept at the same
temperature and the same or varying light regimes (Klaassen, 1995; Wikelski et al., 2003; Tieleman, 2007). In addition, repeated measures, inclusion of pedigree information and hybridization among subspecies have revealed that BMR in stonechats has a repeatable, heritable component (Versteegh et al., 2008; Tieleman, Versteegh, Fries, et al., 2009; Tieleman, Versteegh, Helm, et al., 2009). A logical extension of these stonechat studies is to investigate if annual cycles in metabolism differ among birds from different environments, and if differences in annual cycles have a genetic basis or result solely from phenotypic responses to annual environmental and life cycle variation.

We studied the genetic and phenotypic backgrounds of annual cycles in body mass, BMR and mass-specific BMR of Kazakh, European and Kenyan stonechats, and their hybrids, bred and held in a common environment. We compared variability (i.e., differences between life cycle stages with the highest and the lowest value) and also shape (i.e., the particular pattern of up- and downregulation) of annual cycles between subspecies. The rationale is that the subspecies can upregulate or downregulate traits (i.e. BMR) in different life cycle stages, resulting in different shapes, or display similar shapes, but differ in variability (e.g. Gwinner, König, and Zeman, 1995). If annual cycles in body mass and metabolic rate have a genetic background, we expect that shape and/or variability differ among subspecies, and that hybrid lines show values intermediate to their parent groups. To investigate whether phenotypic flexibility has an (additional) effect on annual cycles, we kept European stonechats under two different temperature regimes, either at year-round constant temperature or at annually fluctuating temperature.

**Methods**

**Birds and keeping conditions**

Stonechats originated from three different locations: Kazakhstan (n=17) (*S. t. maura*), Europe (n=61) (*S. t. rubicola*), and Kenya (n=22) (*S. t. axillaris*). Kazakh stonechats migrate over long distances and have a short breeding season during which they typically lay a single clutch with five to six eggs; European stonechats are short-distance migrants that typically lay two to three clutches with five eggs per clutch; Kenyan stonechats are resident birds and lay generally one clutch with three eggs (Helm et al., 2006; Urquhart, 2002; Flinks and Pfeifer, 1987; Helm, 2009). Birds were from first (n=30), second (n=48) or third (n=28) generation, bred and hand-
raised at the Max Planck Institute for Ornithology, Andechs, Germany, or had been taken as
nestlings from the field, moved to the institute and hand-raised (n=32) (Gwinner et al., 1987). In
addition to the three subspecies, we bred and studied hybrids between Kazakh and European
subspecies (n=17) and between European and Kenyan subspecies (n=21). All individuals were
fully grown, ranging in age from 0 (age > 158 days) to 12 years, but most individuals were 0 to
4 years old (n=128). To investigate if birds of age 0 had reached adult level metabolic rates, we
tested whether they differed significantly from older birds (age 1-12) in body mass, BMR, and
mass-specific BMR; they did not (F_{1,237} < 2.59, P < 0.11). Therefore we concluded that birds had
reached adult level metabolic rates.

Birds were housed with 8-12 individuals per room and individuals were kept in separate
cages. They were randomly assigned to rooms with respect to subspecies. Standard conditions in
all rooms consisted of year-round constant temperatures of 20-22˚C and day length following
natural day length of the European population (cf. Helm et al., 2009). In addition to this standard
treatment we also kept a subset of European birds (n=14) under a weekly changing temperature
regime, that mimicked the average natural temperature cycles of free-living European stonechats
reconstructed from ringing recovery locations (Helm et al., 2006; Fig. 2).

Measurements
We performed measurements during five life cycle stages, between February 2005 and March
2006: The spring migration period (27 February to 24 March), breeding (10 May to 2 June),
moult (21 July to 19 August), autumn migration (30 September to 7 November) and winter (24
November to 14 February). During the migration period birds are active during the night (Helm
et al. 2005), which we monitored by a constant infrared light-beam. Kenyan stonechats show
migratory restlessness when held in captivity, even though free living Kenyan stonechats do not
migrate. We defined winter as the quiescent period after the autumn migration period and before
spring migration. Stonechats were unpaired during the breeding season, but they do
physiologically prepare for breeding after nighttime activity (due to spring migration) stops, and
before moult starts (Gwinner, König, and Zeman, 1995; Helm et al., 2005). Birds were checked
twice a week for moult. One hour before the start of experiments, we removed water and food
from cages to ensure birds were post-absorptive. We placed birds in 13.5 l metal metabolic
chambers with Plexiglas lids that closed airtight. We set the metabolic chambers inside a
climatic chamber with a constant temperature of 35°C±0.5°C, a temperature within the
thermoneutral zone of the stonechat subspecies (Tieleman, 2007).

We measured body mass and BMR of Kazakh, European and Kenyan stonechats and the
two hybrid lines. Metabolic rate was measured by standard flow-through respirometry methods
(Gessaman, 1987). Details about experimental set up, measurement protocol and data analysis
are described elsewhere (Tieleman, 2007; Versteegh et al., 2008; Tieleman, Versteegh, Fries, et
al., 2009). To assure that birds were not active, we only used measurements obtained at least
three hours after birds were put in the metabolic chambers, and only when O₂ consumption had
been stable for at least ten minutes. Before and after the metabolic measurement we measured
body mass and we calculated mass-specific BMR by dividing BMR by the average of the two
body masses. We normally measured 6 to 17 individuals per life cycle stage per group kept at
standard conditions. Because of a combination with other studies (Versteegh et al., 2008;
Tieleman, Versteegh, Fries, et al., 2009) some sample sizes for winter are larger (Europeans n =
45, European-Kenyan hybrids n = 21). We measured 7 to 13 individuals per life cycle stage of
European stonechats kept at variable temperature.

Statistical analysis

We used R version 2.8.0 for statistical analyses (R development core team, 2010). Variables
were normally distributed (Kolmogorov-Smirnov D < 0.09, P > 0.10), and we used mixed effects
models for body mass, BMR and mass-specific BMR. We also analyzed BMR with body mass as
covariate, but we do not report the results because they did not differ from the analyses of mass-
specific BMR. In all mixed effects models we used log-likelihood-ratio tests and χ²-statistic to
evaluate statistical significance (P<0.05). We investigated whether the annual cycles of body
mass, BMR and mass-specific BMR of different subspecies (including hybrid lines) or treatment
groups differed in shape (given by interactive effects of subspecies and life cycle stage) and/or
variability (given by variance, see below). We first analyzed variation among life cycle stages
and subspecies in birds kept at standard conditions with models including subspecies, life cycle
stage, sex, age and the interactions life cycle stage*subspecies, life cycle stage*sex and
subspecies*sex. We analyzed the response to temperature treatment in European stonechats with
models including treatment, life cycle stage, sex, age and the interactions life cycle
stage*treatment, life cycle stage*sex and subspecies*sex. Because we measured the same
individuals during multiple life cycle stages, we included individual as random effect in all models.

If the interaction life cycle stage*subspecies or life cycle stage*treatment was significant, we tested the significance of life cycle stage in each subspecies or treatment group separately. If life cycle stage was significant in these separate analyses, we subsequently used a post-hoc Tukey test to compare shape and variability of annual cycles in body mass, BMR and mass-specific BMR. Additionally, we calculated the averages per life cycle stage for each subspecies or treatment group separately. To investigate differences in variability of the traits, we calculated annual means and variances using these life cycle stage averages. We compared the variances in a pair-wise fashion among subspecies, with a one-tailed F-test. We first compared annual cycles of Kazakh, European and Kenyan subspecies, to investigate whether they are based on genetic or solely on phenotypic differences. To further investigate genetic components of annual cycles, we then compared hybrid stonechats (Kazakh x European or European x Kenyan) with their parental subspecies. We report averages of body mass, BMR and mass-specific BMR per subspecies based on models without the interaction terms life cycle stage*subspecies. We visualized results of statistical analyses on the subspecies by plotting residuals from models including subspecies as fixed effect.

Results

Subspecies differences in annual cycles of mass and metabolism

Confirming previous work, mass-specific BMR was highest in Kazakh, intermediate in European and lowest in Kenyan stonechats, and body mass was lowest in Kazakh and highest in Kenyan stonechats (Table 1). Annual cycles in body mass, BMR and mass-specific BMR differed in shape ($\chi^2 > 38.59$, d.f. = 16, $P < 0.001$; Table 2A; Fig. 1) as well as in variability (Table 1) among subspecies and hybrid lines of stonechats kept in a common environment. Male stonechats were significantly heavier and had a lower mass-specific BMR than females (Table 2A).

Comparing subspecies in a common environment - The shape of annual cycles of body mass was similar in Kazakh and Kenyan stonechats, but Europeans deviated, especially in the breeding season (Fig. 1A, Table A1). Relative to the subspecies’ average, Kazakh and Kenyan birds were
especially heavy in the two migration periods, and lighter during breeding, moult and winter. European stonechats were also heavier in the migration periods, and lighter during moult and winter, but differences among these life cycle stages were less pronounced and not significant (Table A1). However, in the breeding period, Europeans were relatively heavy, unlike Kazakh and Kenyan stonechats. Despite the impression of a smaller seasonal variation in the European birds, the variability did not significantly differ among subspecies (Table 1).

Annual cycles of BMR differed in shape among subspecies (Fig. 1B, Table A1). Kazakh stonechats had relatively high BMR during breeding and low BMR during the autumn migration period. In contrast, in European stonechats BMR was not elevated during breeding, and relatively low during both moult and the autumn migration period. Contrary to both Kazakh and European birds, BMR of Kenyan stonechats was especially elevated during moult. Although the Kazakh birds appeared to have the largest variation among life cycle stages, the variability did not significantly differ among subspecies (Table 1).

The shape of annual cycles of mass-specific BMR differed among subspecies (Fig. 1C, Table A1). Kazakh stonechats had low values during spring and especially the autumn migration period, and high values in the breeding period. European stonechats showed little variation in mass-specific BMR throughout the year. In Kenyan stonechats mass-specific BMR was elevated during moult and reduced during the autumn migration period. The other life cycle stages did not differ from each other. The variability was significantly different among subspecies: Kazakh had higher variance than European stonechats ($F_{4,4} = 12.37, P = 0.02$; Table 1), while Kenyan stonechats were intermediate.

Comparing hybrids with parent lines - Body mass, BMR and mass-specific BMR of hybrids showed intermediate values to parental subspecies in some seasons, and in other seasons resembled one of the parent lines (Fig. 1; Table 1; Table 2). Body mass of Kazakh x European stonechats showed an annual cycle similar in shape to that of Kazakhs, but lacked the high values in the spring migration period and showed a larger dip during moult, more resembling European birds (Fig. 1A). There was no significant difference in body mass variability among Kazakh x European hybrids and their parental subspecies (Table 1). Body mass of European x Kenyan hybrids were intermediate to both parent groups during breeding, the autumn migration period and winter. The European x Kenyan hybrids showed an increase in body mass from moult to the
autumn migration period, similar in shape but smaller in magnitude compared with that of Kenyan stonechats (Fig. 1A). The variability was not intermediate and appeared even to be lower in the European x Kenyan hybrids than in either of the parental subspecies (Table 1).

The shape of the annual cycle in BMR of Kazakh x European hybrids was similar to that of European stonechats, lacking the pronounced high and low values during breeding and the autumn migration period, respectively, of the Kazakh birds (Table A1; Fig. 1B). The variability among life cycle stages of BMR was significantly lower in Kazakh x European hybrids than in Kazakh stonechats ($F_{4,4} = 7.27, P = 0.04$; Table 2). In European x Kenyan hybrids BMR resembled European stonechats during the spring migration period, Kenyan stonechats during breeding and the autumn migration period, and was intermediate between parent lines during moult (Fig. 1B). The variability was not significantly different between European x Kenyan stonechats and their parental subspecies (Table 1).

Mass-specific BMR of Kazakh x European hybrids was similar to that of Kazakh birds during breeding, moult and the autumn migration period, but close to values of European stonechats during the spring migration period and winter (Fig. 1C). Mass-specific BMR of Kazakh x European hybrids did not differ significantly in variability from either Kazakh or European stonechats. The fact that the two parental subspecies did differ from each other implies that annual variation of this hybrid line is intermediate to that of its parental subspecies (Table 1).

In European x Kenyan hybrids mass-specific BMR was high during moult and low during the autumn migration period, a similar shape as Kenyan stonechats (Fig. 1C). During the spring migration period, breeding and winter mass-specific BMR varied little in either European x Kenyan hybrids, or their parental subspecies. The variability of BMR of European x Kenyan hybrids did not differ from European and Kenyan stonechats (Table 1).

**Phenotypic flexibility of annual cycles of mass and metabolism: response to temperature**

We found that the shape and variability of the annual cycles of body mass and mass-specific BMR did not differ between European stonechats kept at different temperature treatments (Figs 2B, 2D, Table 2B, Table 3). After removing the non-significant interaction term treatment*life cycle stage, we found that mass-specific BMR differed between treatment groups, whereas body mass did not (Table 2B). The effect of life cycle stage was significant for both body mass and mass-specific BMR (Table 2B). Taking the significant term life cycle stage into account,
stonechats kept at variable temperature had an 8% higher mass-specific BMR than birds kept at constant temperature (Fig. 2D).

For BMR, the annual cycles differed between treatment groups, as indicated by the significant interaction treatment*life cycle stage (Table 2B; Fig. 2C). We first compared the shape of the annual cycles using post-hoc Tukey tests comparing life cycle stages with each other per treatment, and found that the difference occurred in the autumn migration period. During the autumn migration period, stonechats kept at variable temperature had a BMR close to the treatment group’s average, while stonechats kept at constant temperature showed a relatively low value (Table A1). The variances of BMR did not differ among treatment groups (Table 3). Because different temperature regimes can also result in overall differences in BMR between groups in some or all life cycle stages, we also explored for each life cycle stage if treatment groups differed from each other. During the spring migration period ($\chi^2 = 3.87, \text{d.f.} = 1, P = 0.049$) and the autumn migration period ($\chi^2 = 12.49, \text{d.f.} = 1, P < 0.001$) stonechats kept at constant temperature had a significantly lower BMR than stonechats kept at variable temperature. In the other life cycle stages the treatment groups did not differ from each other ($\chi^2 < 2.21, \text{d.f.} = 1, P > 0.14$).

**Discussion**

Three subspecies of stonechats originating from environments that differ in seasonality maintained different annual cycles in body mass, BMR and mass-specific BMR, when reared and kept in a common environment in captivity. In addition, two hybrid lines bred between subspecies displayed different annual cycles, with values often intermediate to the parent lines. Keeping stonechats at two temperature regimes, one constant and one variable throughout the year, did not affect the shape or variability of the annual cycles of body mass and mass-specific BMR. However, mass-specific BMR was 8% higher throughout the year in the birds kept at variable temperatures, and BMR was higher in birds kept at variable temperatures in two life cycle stages. These findings show that variation in the shape and variability of annual cycles in body mass and metabolic measures stem from genetic differences, and that phenotypic flexibility contributes modest variation superimposed on the genetic program.

The genetic background of the differences in annual cycles among Kazakh, European and Kenyan stonechats suggests evolutionary modification. Evolution of annual cycles in body mass
or metabolic rate could be a direct response to the changing environmental conditions that
different subspecies encounter throughout the year (e.g. food availability, pathogen and predation
risk, temperature), but could also be connected with variation in other life history characteristics
(Daan et al., 1990; Ricklefs and Wikelski, 2002). One might expect more variation in the annual
cycle of birds that encounter larger environmental differences during the year or that vary their
work levels more during the year. Because it is challenging to provide the bird’s perspective on
the environmental conditions encountered, especially by migrant birds, we first explored if life
history differences could explain the annual cycle differences among stonechats. Because
Kazakh stonechats breed in a continental environment, lay the largest clutch and migrate the
longest distance (Raess, 2008), we expected that they would experience the largest differences in
energy expenditure among life cycle stages. We expected European stonechats to be
intermediate, because they breed in temperate climates, have an intermediate clutch size, a longer
breeding season, and a shorter migration distance (Helm, 2009). Free-living Kenyan stonechats
may experience the least variation among life cycle stages because they do not migrate and only
produce one small clutch per year (Dittami and Gwinner, 1985). Therefore, if the evolution of
body mass and metabolic measures is mainly influenced by life history traits, we would expect
that Kenyans would have evolved the least, Europeans intermediate and Kazakhs the most
variability, because of their respective migratory and reproductive characteristics. In agreement
with these ideas, long-distance migrant Kazakh stonechats indeed had the highest annual
variability in all measures. However, in contrast to predictions European and not Kenyan
stonechats showed the lowest variability in mass-specific BMR. We conclude that differences in
variability among subspecies are hard to generalize, but subspecies differ substantially in specific
life cycle stages, such as migration and moult. This may indicate that, in addition to specific life
cycle stage demands, local environmental factors like temperature and food availability also play
important roles in the evolution of the annual cycles of mass and metabolic rate.

During the autumn migration period all three stonechat subspecies increased body mass
and decreased BMR and mass-specific BMR. During the spring migration period body mass
generally increased, BMR increased in Kazakh and European stonechats, and mass-specific
BMR decreased in Kazakh stonechats. Increases in body mass just before and during migration
periods are commonly found in many captive and free-living bird species, and are related to fat
deposition (e.g. Gwinner, 1996; Schaub and Jenni, 2000; Vézina et al., 2007). This could present
an explanation for the decrease of mass-specific BMR during the autumn migration, but not for
the variation among subspecies in metabolic rates during spring migration. The finding of lower
metabolic rate during autumn than during spring migration is also found in free-living migrating
yellow-rumped warblers (Swanson and Dean, 1999). In several waders BMR was lower during
autumn migration than during winter in the tropics, but higher than during breeding in the arctic
(Lindström, 1997; Kvist and Lindström, 2001). BMR depends to a large extent on body and/or
organ composition (Hume and Biebach, 1996; Piersma et al., 1999; Dietz et al., 1999; Tieleman
et al., 2003). In free-living birds spring migration is often faster (and more urgent) than autumn
migration (Pearson and Lack, 1992), and in spring different organs may be important than in
autumn (e.g. reproductive organs, see Bauchinger et al., 2005), leading to a difference in BMR in
the two migration periods.

BMR and mass-specific BMR of Kenyan stonechats was remarkably high during moult, a
finding that was lacking in the other subspecies. Klaassen (1995) showed that Kenyan stonechats
had a higher total plumage mass than European stonechats. This is in concordance with the
finding of Tieleman (2007) that the insulation of Kenyan stonechats was better than that of
Europeans and Kazakhs. Basal metabolic rate has been shown to be correlated with the amount
of feathers produced per day (Dietz et al., 1992; Lindström et al., 1993). Therefore, our results
support Klaassen’s (1995) hypothesis of a higher increase in BMR between moult and the
preceding and following life cycle stages in Kenyan than in European stonechats.

Body mass, BMR and mass-specific BMR of the two hybrid lines were intermediate to
parental subspecies in some life cycle stages, but also sometimes resembled one of the parental
subspecies or deviated from both. This supports a genetic basis for the annual cycles of these
traits, but also shows that the underlying genetic mechanisms are not simple. Metabolic rate is
determined by the size of the metabolically most active organs, mitochondrial density and
mitochondrial function (Daan et al., 1990; Tieleman et al., 2003; Tieleman, Versteegh, Fries, et
al., 2009; Vézina and Williams, 2005; Zheng et al., 2008), that all may have a genetic basis.
Changes in organ size, mitochondrial density or mitochondrial function may contribute to annual
changes in metabolic rates (Piersma et al., 1999; Dietz et al., 1999; Tieleman et al., 2003; Zheng
et al., 2008). Previous work on stonechat hybrids has shown that metabolic rate is affected,
presumably through mitochondrial function, by the mix of mitochondrial genes (inherited only
from the mother) and nuclear genes (inherited from both parents), and is not a linear intermediate
between parent lines (Tieleman, Versteegh, Fries, et al., 2009). Likewise, the inheritance patterns
of annual changes in body composition or in mitochondrial density from parental to hybrid
stonechats may be complex. Such complicated genetic backgrounds may have resulted in the
dissimilar shapes and variabilities that characterised the annual cycles of the two hybrid lines.

The shape and variability of the annual cycles of European stonechats were unaltered by
temperature treatments, at least for body mass and mass-specific BMR, and differed only during
the migration periods for BMR. Yet, the stonechats kept at variable temperature had a higher
mass-specific BMR in all life cycle stages than birds kept at constant temperature. This suggests
that European stonechats adjust their metabolic rates to variability as such, and not so much to a
fixed or current temperature. In contrast, red knots (Calidris canutus) kept at variable outside
temperatures had a BMR similar to warm-acclimated conspecifics in summer and to cold-
acclimated conspecifics in winter (Vézina et al., 2011). Also, free-living temperate resident birds
are found to adjust their BMR and/or mass-specific BMR according to winter temperatures
(Swanson and Olmstead, 1999; Broggi et al., 2007). Vézina et al. (2011) proposed that the
adjustments in the annual cycle of metabolism of red knots stem from the highly variable
ambient conditions (e.g. high and low temperatures) that knots face during the annual cycle, a
fact that may also apply to temperate resident species (Swanson and Olmstead, 1999; Broggi et
al., 2007). Free-living European stonechats may keep their thermal environment relatively
constant throughout the year, because they breed in central Europe and winter in southern Europe
and northern Africa, where winters are mild (Helm et al., 2006). The necessity of flexibility in
the annual cycles of BMR and body mass may be less strong than in birds facing large
temperature changes, and therefore annual cycles may be more rigid.

In summary, the variation in annual cycles of body mass, BMR and mass-specific BMR
among stonechat subspecies that we found indicates that these cycles have a genetic component.
This genetic component is unlikely to be solely an adaptation to the energy demands and costs of
life history characteristics. Environmental factors may have contributed to the evolution of
annual cycles of BMR as well. The fact that hybrids differ from parent lines confirms that there
is a genetic component determining annual cycles of metabolic rate. However, the complexity of
the patterns shows that heritability is not simple. When birds were exposed to different
temperature regimes, they adjusted their metabolic rate. This shows that, although annual cycles
in metabolic rate are genetically determined, annual cycles of metabolic rate are also phenotypically flexible.

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References


Table 1: Variance of the means per life cycle stage and overall subspecies means ± standard errors for body mass, BMR and mass-specific BMR of Kazakh, European and Kenyan stonechat and two hybrid lines. Different letters indicate significant differences (F-test, P < 0.05).

<table>
<thead>
<tr>
<th>Subspecies</th>
<th>Body Mass (g)</th>
<th>BMR (kJ/day)</th>
<th>Mass-Specific BMR (kJ/day/g)</th>
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<td></td>
<td>Variance of life cycle stage means</td>
<td>Subspecies mean ± s.e.m.</td>
<td>Variance of life cycle stage means</td>
</tr>
<tr>
<td>Kazakh</td>
<td>1.636 a</td>
<td>13.8 ± 0.56 a</td>
<td>4.120 a</td>
</tr>
<tr>
<td>Kazakh x European</td>
<td>1.104 ab</td>
<td>14.4 ± 0.40 ab</td>
<td>0.567 b</td>
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<tr>
<td>European</td>
<td>0.474 ab</td>
<td>14.3 ± 0.47 a</td>
<td>1.311 ab</td>
</tr>
<tr>
<td>European x Kenyan</td>
<td>0.184 b</td>
<td>15.6 ± 0.52 b</td>
<td>0.568 b</td>
</tr>
<tr>
<td>Kenyan</td>
<td>0.967 ab</td>
<td>17.7 ± 0.58 c</td>
<td>1.249 ab</td>
</tr>
</tbody>
</table>
Table 2: Degrees of freedom, $\chi^2$- and P-values of log-likelihood ratio tests for body mass, BMR and mass-specific BMR of (A) Kazakh, Kazakh x European, European, European x Kenyan and Kenyan stonechats and (B) European stonechats kept at constant and variable temperature. Results are from linear mixed models with individual as random effect, after backwards elimination of non-significant (P>0.05) terms. Whenever an interaction was significant, statistics of main effects cannot be meaningfully interpreted, and they are not shown.

<table>
<thead>
<tr>
<th></th>
<th>Body mass</th>
<th></th>
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<td></td>
<td>d.f.</td>
<td>$\chi^2$</td>
<td>P</td>
<td>$\chi^2$</td>
<td>P</td>
<td>$\chi^2$</td>
<td>P</td>
</tr>
<tr>
<td>A</td>
<td></td>
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</tr>
<tr>
<td>Life cycle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>stage*subspecies</td>
<td>16</td>
<td>38.59</td>
<td>0.001**</td>
<td>48.71</td>
<td>&lt;0.001**</td>
<td>48.89</td>
<td>&lt;0.001**</td>
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<tr>
<td>Subspecies*sex</td>
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<td>1.66</td>
<td>0.80</td>
<td>4.04</td>
<td>0.40</td>
<td>4.11</td>
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<td>Life cycle stage*sex</td>
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<td>1.72</td>
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<td>1.69</td>
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<tr>
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<tr>
<td>Sex</td>
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<td>16.13</td>
<td>&lt;0.001**</td>
<td>1.73</td>
<td>0.19</td>
<td>5.58</td>
<td>0.02*</td>
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<td>Age</td>
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<td>0.14</td>
<td>0.71</td>
<td>0.93</td>
<td>0.33</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>stage*treatment</td>
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<td>7.01</td>
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<td>10.26</td>
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<tr>
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<td>0.35</td>
<td>0.55</td>
<td>0.05</td>
<td>0.82</td>
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<td>Life cycle stage*sex</td>
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<td>5.71</td>
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<td>12.61</td>
<td>0.01*</td>
<td>4.28</td>
<td>0.37</td>
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<td>0.33</td>
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<td>-</td>
<td>10.01</td>
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<tr>
<td>Sex</td>
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<td>15.21</td>
<td>&lt;0.001**</td>
<td>-</td>
<td>-</td>
<td>6.73</td>
<td>0.01</td>
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<tr>
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<td>1.12</td>
<td>0.29</td>
<td>0.08</td>
<td>0.78</td>
<td>1.06</td>
<td>0.30</td>
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</table>
Table 3: Variance of means of the five life cycle stages for body mass, BMR and mass-specific BMR of European stonechats kept at variable and constant temperature. Different letters indicate significant differences (F-test, \( P < 0.05 \)).

<table>
<thead>
<tr>
<th></th>
<th>Body mass (g)</th>
<th>BMR (kJ/day)</th>
<th>Mass-specific BMR (kJ/day/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant temperature</td>
<td>0.474 \text{a}</td>
<td>1.311 \text{a}</td>
<td>0.003 \text{a}</td>
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<tr>
<td>Variable temperature</td>
<td>1.092 \text{a}</td>
<td>1.775 \text{a}</td>
<td>0.002 \text{a}</td>
</tr>
</tbody>
</table>
Figure legends:

Figure 1: Annual variation of (A) body mass and (B) BMR and (C) mass-specific BMR of Kazakh, European and Kenyan stonechats, and Kazakh x European and European x Kenyan hybrid lines. Stonechats were kept at constant temperature and annually fluctuating day length. Bars represent means ± standard errors of residuals of a linear model with subspecies as fixed effect. Letters represent life cycle stages; S=spring migration period, B=breeding season, M=moult, A=autumn migration period and W=winter.

Figure 2: (A) Annual variation in temperature in constant and variable temperature treatment groups. The dotted line represents the temperature birds were exposed to, the solid lines the measurement periods. (B) Body mass (C) BMR and (D) mass-specific BMR of European stonechats kept at constant (white diamonds) and variable (black circles) temperature treatments and measured during five life cycle stages. Symbols represent means ± standard error. Letters represent life cycle stages; S=spring migration period, B=breeding season, M=moult, A=autumn migration period and W=winter.
**A**

Temperature chart with data points for Mar, May, Jul, Sep, Nov, and Jan.

**B**

Graph showing body mass (g) with data points for S, B, M, A, and W.

**C**

Graph showing BMR (kJ/day) with data points for S, B, M, A, and W.

**D**

Graph showing mass-specific BMR (kJ/day/g) with data points for S, B, M, A, and W.