Correlated evolution of phenotypic plasticity in metamorphic timing

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Abstract

Phenotypic plasticity has long been a focus of research, but the mechanisms of its evolution remain controversial. Many amphibian species exhibit a similar plastic response in metamorphic timing in response to multiple environmental factors; therefore, more than one environmental factor has likely influenced the evolution of plasticity. However, it is unclear whether the plastic responses to different factors have evolved independently. In this study, we examined the relationship between the plastic responses to two experimental factors (water level and food type) in larvae of the salamander *Hynobius retardatus*, using a cause-specific Cox proportional hazards model on the time to completion of metamorphosis. Larvae from ephemeral ponds metamorphosed earlier than those from permanent ponds when kept at a low water level or fed conspecific larvae instead of larval Chironomidae. This acceleration of metamorphosis depended only on the permanency of the larvae’s pond of origin, but not on the conspecific larval density (an indicator of the frequency of cannibalism) in the ponds. The two plastic responses were significantly correlated, indicating that they may evolve correlatively. Once plasticity evolved as an adaptation to habitat desiccation, it might have relatively easily become a response to other ecological factors, such as food type via the pre-existing developmental pathway.
Keywords: amphibian; cannibalism; desiccation risk; metamorphosis; phenotypic plasticity; water level
Introduction

Many organisms exhibit plasticity in their morphological and life-history traits (Pfennig et al., 2010). Although the evolution of phenotypic plasticity has long been a focus of research, the mechanisms of this evolution remain controversial (Pfennig et al., 2010).

As described in greater detail below, many organisms can exhibit a similar plastic response to multiple environmental factors, with this response mediated by different environmental cues. To advance the field of evolutionary biology, it is essential to reveal both the original selective factors favoring the evolution of phenotypic plasticity and the historical sequence in which plastic responses to different environmental cues have evolved (Gomez-Mestre et al., 2008).

Phenotypic plasticity has been extensively studied in amphibian larvae with complex life cycles. The larvae of many amphibian species cannot escape their aquatic environment until metamorphosis, which might be one factor indicating that these larvae exhibit phenotypic plasticity in response to variable environmental conditions. In fact, amphibian larvae exhibit phenotypic plasticity in their development and timing of metamorphosis (which affects their size at metamorphosis) in response to variation in biotic or abiotic environmental factors, such as larval density (Newman, 1998), the presence of predators (Laurila & Kujasalo, 1999; Lardner, 2000), the type and quantity
of available food (Hensley, 1993), habitat desiccation (Denver et al., 1998; Laurila &
Kujasalo, 1999), and water temperature (Walsh et al., 2008).

Therefore, more than one environmental factor has likely influenced the evolution
of plasticity, and interactions among different factors acting simultaneously may also be
important. However, it is unclear whether the plastic responses to different factors have
evolved independently. Developmental events in amphibians are regulated primarily by
the hypothalamus–pituitary–thyroid (HPT) axis, through the production of thyroid
hormone, which is produced enzymatically and regulates metabolic and developmental
processes (Rose, 2005). In particular, the metamorphosis of amphibian larvae is a
thyroid hormone-dependent developmental process (Rose, 2005). Sharing of the same
developmental pathways by the plastic responses might influence the capacity of a
population to evolve in response to selective factors (Derrickson & Ricklefs, 1988),
implying that it may not allow for their independent evolution.

Developmental plasticity is often adaptive. For example, on one hand, amphibian
larvae dwelling in a permanent water body can delay their metamorphosis and use the
extra time for additional growth in order to attain a larger size before metamorphosis
(Berven et al., 1979; Alvarez & Nicieza, 2002). Having a larger body size at
metamorphosis may directly increase an organism’s survival to maturity (Scott, 1994)
and size at reproduction (Altwegg & Reyer, 2003), which would, in turn, increase the individual’s fecundity and reproductive success (Altwegg & Reyer, 2003). On the other hand, developmental plasticity can allow larval amphibians inhabiting temporary or ephemeral water bodies to complete their metamorphosis more quickly, before their habitat dries up. In this case, acceleration of larval development may be adaptive in drying ponds because it reduces mortality due to desiccation (Laurila & Kujasalo, 1999), even though it is associated with a smaller size at metamorphosis, which can negatively affect the survival of juveniles and breeding success of adults (Altwegg & Reyer, 2003). The salamander *Hynobius retardatus*, which lives in Hokkaido, Japan, has long been noted to have variable life history (Iwasaki & Wakahara, 1999). This species spawns in ponds from early April to May, and has free-living aquatic larvae. Some individuals of this species born in permanent ponds retain certain larval features, such as external gills and tail fins, and overwinter once or twice in their aquatic habitat as larva, not metamorphosing until their second or third year of life (Iwasaki & Wakahara, 1999; Michimae, 2011). In contrast, most larvae spawned in small, ephemeral ponds created by melting snow metamorphose into terrestrial juveniles by late autumn (October) of the same year they are spawned (Iwasaki & Wakahara, 1999). Ponds of different permanency exert different selective pressures on organisms, which, in response, locally
evolve to attain different plastic responses (Leips et al., 2000; Lake, 2003). Hence, as *H. retardatus* utilizes both permanent and ephemeral ponds for spawning, it is possible that the species requires different reaction norms for adaptation to larval pond habitats of different permanency.

The larvae of *H. retardatus* are both carnivorous and cannibalistic (Michimae, 2006). In general, cannibalistic individuals develop faster, are larger, and have higher survivorship and enhanced reproductive success than non-cannibalistic individuals, and these beneficial effects of cannibalism on an individual’s life history may be more pronounced when food availability is low (Elgar & Crespi, 1992). Thus, organisms may adopt cannibalistic behavior mainly to enhance their mass and body condition. In amphibians, however, fast-developing larvae metamorphose at a smaller body size than do slowly developing larvae from the same cohort (Wilbur & Collins, 1973). In particular, *H. retardatus* larvae fed only conspecific larvae metamorphose much earlier and at a smaller size than those fed only their typical prey (freshwater oligochaetes and Chironomidae) (Michimae & Wakahara, 2002; Michimae, 2011). Therefore, cannibalism in *H. retardatus* leads to accelerated metamorphosis (Michimae & Wakahara, 2002; Michimae, 2011). Specifically, interpopulational variation in conspecific larval density (an indicator of the frequency of cannibalism in natural
habitat differences (Whiteman et al., 2003)) in natural ponds can promote population differences in cannibalism-mediated developmental plasticity.

Intraspecific studies of geographic variation in phenotypic plasticity have provided convincing evidence of both organismal adaptation to varying environmental conditions (Pigliucci, 2005) and the ecological consequences of environmentally induced plasticity (e.g., phenotypic plasticity can alter interactions between organisms and their abiotic and biotic environments; (Miner et al., 2005)). Therefore, we are interested in studying the relationship between habitat type and the reaction norm in *H. retardatus*, especially the geographical variation in phenotypic plasticity in metamorphic timing in response to a reduction in the water level, which can be used as a reliable cue indicating habitat desiccation. We are also interested in examining the interpopulational variation in phenotypic plasticity in the metamorphic timing of the species in response to being fed different food types (i.e., conspecific larvae and larval Chironomidae), corresponding to the diets available to *H. retardatus* larvae living in ponds with different larval densities.

In the present study, to analyze the evolution of the phenotypically plastic responses in the metamorphic timing of *H. retardatus*, we surveyed 9 ponds in Hokkaido, Japan (see Table 1), whose specific populations have been described.
previously (Iwasaki & Wakahara, 1999; Michimae, 2006; Michimae et al., 2009; Michimae, 2011). The preliminary surveys quantified the variability among the ponds in terms of pond permanency and the density of conspecific larvae (Table 1). The primary aims of our present study were as follows: (1) to identify phenotypically plastic responses in the metamorphic timing of *H. retardatus* larvae that are induced by either the experimental water level or food type, the latter of which was previously shown to affect metamorphic timing of larvae (Michimae & Wakahara, 2002; Michimae, 2011); (2) to examine whether each plastic response in metamorphic timing of *H. retardatus* larvae due to experimental changes in water level or food type is dependent on differences in the permanency of the natural pond from which the larvae were derived (permanent or ephemeral), on differences in conspecific larval density in their source pond, or both; and (3) to examine the spatial population heterogeneity and the relationships between these environmental conditions (i.e., pond permanency and conspecific larval density) and the reaction norm at the population level.

In addition, we are interested in determining whether the two plastic responses evolve independently. Thus, the secondary aim of this study was to estimate and interpret patterns of phenotypic correlation between the two plastic responses in metamorphic timing and the two different experimental factors of interest—water level
Materials and methods

Study populations and sites

We categorized Konuma, Tomaru, and Asari as permanent ponds because they never dried up during the years they were monitored (Table 1). In contrast, Okusawa, Atsuta, Kamitobetsu, Toyoha, Erimo, and Nopporo were categorized as ephemeral ponds because they dried up nearly every year that they were monitored (Table 1).

Ten egg clutches were collected from each pond. The annual density of conspecific larvae in each pond was estimated by multiplying the mean size of the collected clutches by the estimated density of clutches in the pond (see Michimae, 2006). The mean density of conspecific larvae (individuals/m² ± SD) in each pond was calculated each year, and the mean total annual density of conspecific larvae in each pond was calculated by dividing the sum of the annual total larval densities by the number of years that clutches were collected. Using data from 2 to 5 years (from 2002 to 2007, except for 2005) and a calculation method previously detailed by Michimae (2006), we determined the mean density of conspecific larvae (Table 1). The conditions of natural ponds, i.e., pond permanency and larval density, were the covariates in the

and food type.
evaluation of the effects in the following experiment.

Rearing experiment

We collected 20 fertilized egg clutches of *H. retardatus* from each of the 9 ponds during the spawning season (early April to late May) in 2006. Each clutch was placed in a stock tank filled with 1.6 L of dechlorinated tap water and was kept with a natural light/dark schedule in an incubator at 4 °C or in the laboratory at 20–21 °C until hatching (because the hatching day of the embryos was controlled). After the egg clutches hatched, 5 newly hatched larvae from each clutch were reared as a group for 2 weeks in the laboratory at 20–21 °C, with each group in a plastic tank (30-cm long × 25-cm wide × 17.5-cm deep) containing 5 L of dechlorinated tap water. The larvae were maintained in the plastic tank until the experiment described below was established. The experimental larvae were fed on days 3, 5, 7, 9, 11, and 13 by being offered frozen Chironomidae from 20:00 to 22:00. The larvae were always given enough food to eat within 2 h, and any food remaining in their tanks after the feeding period was removed. The rearing water in each tank was also exchanged after each feeding period.

We established four experimental treatments by crossing two water levels (low vs. high) and two food types (Chironomidae vs. conspecific salamander larvae). For each
pond, we randomly assigned five sets of the five 2-week-old larvae to one of the experimental treatments. Hence, each treatment group contained 225 larvae (45 clutches) in total, including 25 (5 clutches) larvae from each of the 9 ponds. The rearing experiment was designed to have five cages (clutches) for each treatment. Five cages were hung in each experimental tank. In each of the two water-level treatments, five larvae were raised as a group in a cage (15-cm long × 15-cm wide) with plastic mesh sides (mesh size, 3 mm) and a plastic plate bottom (1.6-mm thick) that hung from the edge of the experimental tank (86-cm long × 66-cm wide × 27-cm deep) containing 145 L of dechlorinated tap water. For the high water-level treatment, the distance from the bottom of each cage to the water’s surface (i.e., the water depth) was approximately 25 cm, whereas it was approximately 2 cm for the low water-level treatment. Larvae in the cages were individually fed with one of the two food types (one conspecific larva or frozen Chironomidae) from 20:00 to 22:00 every other day, until they completed metamorphosis. During feeding, larvae in the cages of each experimental treatment were individually transferred from the experimental tank to another tank (8 cm × 8 cm × 8 cm), allowed 2 h to eat the food, and then transferred back to their cages in the experimental tanks. Both diets had constant and similar wet weights, as all larvae used for feeding were about the same size, and enough frozen Chironomidae were fed to
match the mass of the larvae used for feeding. The wet weight of each food type was measured to the nearest 0.01 g with an electronic balance. The water in the experimental tanks was changed every other day during the experiment. Four experimental tanks and five cages in experimental tanks were randomly redistributed after every water exchange. The time to event (days from hatching to the completion of metamorphosis or larval death) was recorded for each larva.

Each new metamorph was anesthetized by immersion in 0.01% MS222 (Sandoz), and its snout-vent length (SVL) was measured to the nearest 0.05 mm with calipers, and its body mass was measured to the nearest 0.01 g with an electronic balance. SVL measurements were made from the tip of the snout to the anterior end of the cloaca. Body mass was transformed to the same linear scale as SVL in all analyses by taking its cube root before analysis.

**Analyses**

A cause-specific Cox proportional hazards model was used to assess the effects of the two experimental factors (water level and food type), the two environmental factors (pond permanency as a categorical covariate and pond larval density as a continuous covariate), and their interactions on time to completion of metamorphosis. Identities for
the egg clutch were also incorporated into the Cox proportional hazards model as a random effect, accounting for the within-clutch correlation. We used a general strategy for model selection, as recommended by Collett (2003), rather than information theoretic criteria such as Akaike's Information Criterion (AIC) or Bayesian Information Criterion (BIC). The analysis results are reported as hazard ratios with the 95% confidence interval (CI).

We also characterized the completion of metamorphosis over time using the cumulative incidence function, i.e., the overall probability of metamorphosis in the presence of death (Fine & Gray, 1999).

To examine the correlation between the plastic responses in metamorphic timing at the population level, we conducted correlation analysis based on the difference between the median times to metamorphosis for the level of each experimental factor for each population.

To examine the correlation between phenotypic plasticity in body size (SVL and body mass) at metamorphosis with the two experimental factors at the population level, we conducted multivariate analysis of covariance (MANCOVA) and correlation analysis as follows. The mean body size at metamorphosis with each treatment was calculated for each population. The effects of the two experimental factors, the two
environmental factors (pond larval density as a covariate), and their interactions on the
mean body size at metamorphosis were calculated using MANCOVA. This test was
carried out by re-running the models excluding the interaction terms. If there was no
interaction between the two experimental factors, we conducted correlation analysis
based on the difference between the mean body sizes for the level of each experimental
factor for each population. If a larva of a treatment had died, we deleted the associated
measurements of body size before calculating the mean body size.

To examine the relationship between body size (SVL and body mass) at
metamorphosis and age at metamorphosis (days from hatching to the completion of
metamorphosis), we conducted correlation analysis. For this analysis, larval
measurements of body size were averaged to calculate the treatment means, and the
median time to metamorphosis was estimated by each treatment for each population. If
a larva of a treatment had died, we deleted the associated measurements of body size
before calculating the mean body size.

This study was approved by the Hokkaido University Animal Committee, and the
animals were maintained in accordance with the Hokkaido University Guidelines for the
Care and Use of Laboratory Animals.
Results

Time to metamorphosis

Table 2 summarizes the results of variable selection in the Cox proportional hazards model for time to metamorphosis. The final model comprised the two experimental factors (water level and food type), one environmental factor (pond permanency), two interactions (water level by pond permanency and food type by pond permanency), and the identities of the egg clutches.

The two interactions indicate that the effects of the two experimental treatments on time to completion of metamorphosis differed between the types of pond permanency (permanent vs. ephemeral). For permanent environments, the estimated hazard ratio of low water level to high water level was 11.3 (95% CI, 8.1–15.7), and the estimated hazard ratio of conspecific larvae to Chironomidae was 7.5 (95% CI, 5.4–10.5) (Fig. 1a). For ephemeral environments, the estimated hazard ratio of low water level to high water level was 58.5 (95% CI, 35.1–97.5), and the estimated hazard ratio of conspecific larvae to Chironomidae was 16.6 (95% CI, 10.0–27.6) (Fig. 1b).

The hazard ratios and the lower limit of the associated 95% CIs were more than 1, indicating that the time to metamorphosis for both permanent and ephemeral environments was shortened both by a decrease in the water level from high to low and
by feeding larvae the conspecific larvae instead of Chironomidae (Fig. 1). The variance of the random effect for clutches was estimated to be 0.134, which shows weak within-clutch correlation (Kendall rank correlation coefficient = 0.062, $P < 0.0001$).

**Two plastic responses in metamorphic timing at the population level**

There was no interaction between the two experimental factors on time to the completion of metamorphosis (Table 2). Therefore, we calculated two plastic responses in metamorphic timing to water level and food type at the population level, as described in the Analyses section. Correlation analysis showed a significant relationship between the two plastic responses in metamorphic timing to water level and food type at the population level ($R = 0.775$, $n = 9$, $P = 0.0115$; Fig. 2a).

**Two plastic responses in body size at the population level**

Based on MANCOVA results, we found no higher interactions, including the interaction between the two experimental factors on body size (SVL and body mass) at metamorphosis (results not shown). We found only two significant experimental factors on body size: water level (Walks’ lambda = 0.064, $F_{2,30} = 219.197$, $P < 0.0001$) and food type (Walks’ lambda = 0.255, $F_{2,30} = 43.857$, $P < 0.0001$). Thus, we calculated
phenotypic plasticity in body size in response to water level and food type at the 
population level, as described in the Analyses section. Correlation analysis showed a 
significant relationship between plastic responses in SVL to water level and food type 
($R = -0.721, n = 9, P = 0.0258$; Fig. 2b), but not in body mass to water level and food 
type ($R = -0.468, n = 9, P = 0.2140$; Fig. 2c), likely because of the use of a small 
sample size for this analysis.

Relationships between body size and age at metamorphosis

Correlation analysis showed significant relationships both between SVL at 
metamorphosis and age at metamorphosis ($R = 0.882, n = 36, P < 0.0001$; Fig. 3a), and 
between body mass at metamorphosis and age at metamorphosis ($R = 0.901, n = 36, P < 
0.0001$; Fig. 3b), indicating a trade-off between body size and the developmental rate.

Discussion

The salamander species *H. retardatus* experiences greater variability in the risk for 
desiccation in ephemeral ponds than in permanent ponds (Iwasaki & Wakahara, 1999). 
In this study, we experimentally shortened the duration of the larval period of *H. retardatus* by raising the larvae at a low water level, indicating that this species exhibits
phenotypic plasticity in metamorphic timing in response to water level (Fig. 1). This
decrease in the duration of the larval period was dependent on the permanency of the
source pond (ephemeral or permanent) of the larvae, but not on the conspecific larval
density of the source pond; thus, the interaction between water level and pond
permanency was included in our final model (Table 2). This interaction shows that, in
this species, there is geographical variation in the plastic response in metamorphic
timing in response to water level (Fig. 1). These results imply that when populations
experience a drying pond, individuals from ephemeral habitats may alter their
physiological and developmental traits more than individuals from permanent habitats.

The acceleration of metamorphosis offers clear advantages to many pond animals,
which might face catastrophic mortality if their habitat were to dry up (Laurila &
Kujasalo, 1999; Altwegg & Reyer, 2003). However, this acceleration also has an
associated cost because of the trade-off between developmental rate and body size at
metamorphosis (Fig. 3). Therefore, in animals living in ephemeral ponds, evolution may
favor individuals with highly plastic developmental systems. At the other extreme,
however, theoretical study predicts that homogeneous environments can lead to the
evolution of specialists (Moran, 1992). Evolution may favor the development of
specialist phenotypes with limited phenotypic plasticity in animals living in permanent
water bodies, thus reducing the fitness costs of being phenotypically plastic (Relyea, 2002). In this study, individuals from permanent ponds displayed less plasticity in response to water level (Fig. 1a), as indicated by the larger estimated hazard ratio (low water level to high water level) for larvae from ephemeral ponds (58.5) than for larvae from permanent ponds (11.3). Nevertheless, larvae from permanent ponds still produced a plastic response in metamorphic timing in response to water level (Fig. 1a). These results may suggest that individuals from permanent ponds do not experience selective forces strong enough to produce specialist phenotypes. Furthermore, there may have been alternating selection over time that has periodically selected against specialist phenotypes (Relyea, 2002).

It is interesting that although the duration of the larval period of *H. retardatus* was shortened by feeding the larvae conspecific larvae instead of Chironomidae, this decrease in the larval period due to cannibalism depended not on the larval density of the ponds from which the larvae were derived but instead on the pond’s permanency. This was indicated by the exclusion of the interaction between food type and pond conspecific larval density from the final model, and the inclusion of the interaction between food type and pond permanency (Table 2). These results imply that the selective factor favoring the evolution of phenotypic plasticity in metamorphic timing in
response to food type may be pond permanency, even though the frequency of

cannibalism itself depends on the pond conspecific larval density (Michimae, 2006).

One question that remains is why plasticity in response to food type interacts with the
selective factor pond permanency instead of conspecific larval density.

Conspecifics are assumed to provide a better balance of nutrients than
heterospecific foods, with the result that cannibalism can greatly enhance an
individual’s growth or rate of development (Elgar & Crespi, 1992). However, in this
study, *H. retardatus* larvae fed only conspecific larvae metamorphosed much earlier but
at a smaller size than those fed only Chironomidae (Fig. 3). These results suggest that
cannibalism in *H. retardatus* larvae may have increased the rate of development but did
not increase the growth rate (Fig. 3). The fast development associated with cannibalism
might result in amphibian larvae metamorphosing before the ephemeral ponds they
inhabit dry up. Therefore, in the case of amphibians, cannibalism may also be an
important mechanism by which the larvae reach the necessary developmental stage
before the pond in which they were spawned dries up, thus reducing larval mortality due
to desiccation (Lannoo & Bachmann, 1984). In particular, *H. retardatus* larvae spawned
in ephemeral ponds must metamorphose as soon as possible after the ponds begin
drying up (Iwasaki & Wakahara, 1999); therefore, such larvae may have secondarily
utilized their cannibalism-mediated developmental plasticity to cope with the risk of
desiccation. Thus, it follows that the cannibalism-mediated developmental plasticity that
evolved to enhance the rate of development and conditions also depends on the pond
permanency. However, the lack of dependence of the cannibalism-mediated
developmental plasticity on the pond conspecific larval density still requires
explanation.

The plastic responses in metamorphic timing to experimental changes in water
level and food type were correlated (Fig. 2a), which indicates that these two plastic
responses may have evolved correlative. Unfortunately, our present data cannot
resolve which plastic response evolved first in *H. retardatus*, the one to water level or
that to food type, but the plastic response in metamorphic timing to water level appears
to be a relatively ancient trait. The ability to accelerate metamorphosis in response to a
reduction in water level is present in most amphibian species and is widely conserved in
the genus *Hynobius* (Misawa & Matsui, 1997; Mori & Natuhara, 2004). However,
plastic response in metamorphic timing to food type, especially cannibalism, might
represent an apomorphic trait found only in the species *H. retardatus*, because
cannibalism-mediated developmental plasticity, particularly cannibalism-mediated
acceleration of metamorphosis, has been reported in no other species in the genus
Hynobius. Thus, in H. retardatus, phenotypic plasticity in metamorphic timing may have been initially selected in response to risk of habitat desiccation, as indicated by a water level reduction, which is the most reliable and informative cue for pond drying. Once the initial plasticity evolved in this ecological context, the evolution of a response to additional ecological factors (e.g., food type), utilizing pre-existing developmental pathways, might have been relatively easy. There is some evidence showing how environmental factors modulate the HPT axis under desiccation stress and the availability of alternative food types (Pfennig, 1992; Denver, 1997; Ledon-Rettig et al., 2010). Western spadefoot toad (Scaphiopus hammondii) tadpoles respond to decreasing water levels by increasing production of corticotropin-releasing hormone (CRH, Denver, 1997; Denver, 1998). CRH stimulates not only thyroid hormone production in tadpoles, but also production of the stress hormone corticosterone in Spea multiplicata, which accelerates metamorphosis by converting thyroxine to the more potent triiodothyronine (Rose, 2005). Carnivore morphs in southern spadefoot toad (Scaphiopus multiplicatus) tadpoles are induced directly by thyroxine in conspecific larvae, which accelerates their development (Pfennig, 1992). In short, the acceleration to a reduction in the water level may involve an endogenous sensory and hormonal response that leads to activation of the developmental pathways. Experimental changes in food type may involve activation
of the developmental pathways by exogenous hormones obtained by eating conspecific
larvae. The two plastic responses in metamorphic timing might use the same
downstream developmental pathways. In addition, plastic responses in SVL to
experimental changes in water level or food type were negatively correlated (Fig. 2b),
indicating that plastic responses in SVL may have a shared downstream developmental
pathway. Although the reduction of the larval period caused by being reared in low
water level or eating conspecifics also caused the larvae to have a smaller body size at
metamorphosis, plastic responses in body size to water level or food type might be
directly and partially regulated by the developmental pathways overlapping with the
HPT axis (Rose, 2005). However, the upstream regulation of the stress response to
water level and the regulation of eating conspecific larvae or not may be different from
each other. Nevertheless, the plastic responses in metamorphic timing to experimental
changes in water level and food type were correlated (Fig. 2a). Although the impact of
the upstream regulation or the decision-making process on the evolution of plastic
responses in metamorphic timing is not known, phenotypically plastic responses
triggered by different environmental cues might evolve correlatively because of
constraints imposed by their shared downstream developmental pathways. The main
selective factor, pond permanency, might have favored the evolution of phenotypic
plasticity in metamorphic timing, with the degree of expressed plasticity dependent on
the ecological context. As a result, the phenotypic plasticity in metamorphic timing does
not depend on pond conspecific larval density.

Furthermore, a correlation between evolutionary changes in two traits can exist if
the selection factors giving rise to the traits are correlated. Thus, the correlation we
found between the two different plastic responses in metamorphic timing might be due
to their selections factors being correlated or even the same. For example, pond
permanency may be strongly correlated with pond conspecific larval density in ponds.

For amphibians, informative cues of environmental drying include an increase in
conspecific density, a decrease in swimming volume, a decrease in food, and changes in
the chemical and physical properties of the water (Denver et al., 1998). Furthermore, an
increase in conspecific larval density caused by an ephemeral pond drying up may be a
reliable cue of pond drying to a larva (Newman, 1998).

It is possible that the correlation between the plastic responses in metamorphic
timing is due to an adaptive response to desiccation risk in ephemeral ponds, favoring
the evolution of the plasticity based on one or more of the environmental cues described
above. However, our results related to metamorphic plasticity in *H. retardatus* may not
be congruent with this scenario. Although desiccation of ephemeral ponds can lead to
an increase in conspecific larval density, conspecific larval density in permanent ponds is not necessarily low, as indicated by the high conspecific density in the permanent pond Tomaru examined in this study, as well as in other permanent ponds. Phenotypic plasticity in metamorphic timing in response to food type, therefore, may not depend on the conspecific larval density of the source pond but instead on the pond permanency, because the two plastic responses are correlated as a constraint caused by their sharing the same downstream developmental pathway (Rose, 2005).

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<table>
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<th>Sampling site</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Monitoring period for pond permanency (year)</th>
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<th>Monitoring period for larval density (year) except for 2005</th>
<th>Mean density of conspecific larvae (individuals/m² ± SD)</th>
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<td>permanent5 (from 2002 to 2007)</td>
<td>12.0 15.0 13.6 17.1 18.8</td>
<td>15.3 ± 2.7</td>
</tr>
<tr>
<td>Nopporo</td>
<td>43.0651</td>
<td>141.5039</td>
<td>9 (from 2000 to 2009)</td>
<td>ephemeral5 (from 2002 to 2007)</td>
<td>82.0 75.0 76.0 73.4 82.9</td>
<td>77.9 ± 4.3</td>
</tr>
<tr>
<td>Tomaru</td>
<td>43.1907</td>
<td>140.5151</td>
<td>7 (from 2002 to 2009)</td>
<td>permanent5 (from 2002 to 2007)</td>
<td>2034.6 1997.9 2366.3 2243.5 2484.0</td>
<td>2225.3 ± 209.3</td>
</tr>
<tr>
<td>Atsuta</td>
<td>43.4445</td>
<td>141.4144</td>
<td>6 (from 2003 to 2009)</td>
<td>ephemeral4 (from 2003 to 2007)</td>
<td>1560.0 1378.6 1579.2 1347.1</td>
<td>1466.2 ± 120.3</td>
</tr>
<tr>
<td>Kamitobetsu</td>
<td>43.2333</td>
<td>141.4819</td>
<td>6 (from 2003 to 2009)</td>
<td>ephemeral4 (from 2003 to 2007)</td>
<td>290.8 355.5 200.9 165.7</td>
<td>253.2 ± 86.2</td>
</tr>
<tr>
<td>Okusawa</td>
<td>43.1447</td>
<td>140.9605</td>
<td>9 (from 2000 to 2009)</td>
<td>ephemeral4 (from 2003 to 2007)</td>
<td>74.9 49.7 56.0 91.3</td>
<td>68.0 ± 18.9</td>
</tr>
<tr>
<td>Toyoha</td>
<td>42.9811</td>
<td>141.1599</td>
<td>9 (from 2000 to 2009)</td>
<td>ephemeral4 (from 2003 to 2007)</td>
<td>110.0 115.7 111.3 135.6</td>
<td>118.1 ± 11.9</td>
</tr>
<tr>
<td>Asari</td>
<td>43.0524</td>
<td>141.0412</td>
<td>18 (from 1992 to 2009)</td>
<td>permanent 2 (2006 and 2007)</td>
<td>149.8 135.6</td>
<td>142.7 ± 10.1</td>
</tr>
</tbody>
</table>

Table 1: Features of the 9 discrete sites (ponds) where Hynobius retardatus samples were collected.
Table 2 Values of $-2\log L$ for models fitted to the data of time to metamorphosis. Experimental treatments were water level (w) and food type (f), and covariates were pond permanency (p; as a categorical covariate) and pond conspecific larval density (as a continuous covariate). Identities for egg clutch were included as a random effect, accounting for the within-clutch correlation.

<table>
<thead>
<tr>
<th>Variables in model</th>
<th>$-2\log L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>9870.017</td>
</tr>
<tr>
<td>Pond permanency</td>
<td>9858.272</td>
</tr>
<tr>
<td>Pond conspecific larval density</td>
<td>9870.016</td>
</tr>
<tr>
<td>Pond permanency + pond conspecific larval density</td>
<td>9857.400</td>
</tr>
<tr>
<td>Pond permanency + water level</td>
<td>9332.887</td>
</tr>
<tr>
<td>Pond permanency + food type</td>
<td>9622.808</td>
</tr>
<tr>
<td>Pond permanency + water level + food type</td>
<td>8761.745</td>
</tr>
<tr>
<td>Pond permanency + water level + food type + w*f</td>
<td>8761.739</td>
</tr>
<tr>
<td>Pond permanency + water level + food type + f*p</td>
<td>8677.528</td>
</tr>
<tr>
<td>Pond permanency + water level + food type + w*f + p</td>
<td>8737.330</td>
</tr>
<tr>
<td>Pond permanency + water level + food type + w<em>p + f</em>p</td>
<td>8648.875</td>
</tr>
<tr>
<td>Pond permanency + water level + food type + w<em>p + f</em>p + clutch</td>
<td>8466.763</td>
</tr>
</tbody>
</table>

NOTE: First, 2 environmental factors were selected, ignoring the treatment effects. Pond permanency led to the reduction in $-2\log L$ by 12.745 ($P = 0.0036$), while pond conspecific larval density led to the reduction in $-2\log L$ by 0.001 ($P = 0.97$). Second, we built a Cox model based on the 2 environmental factors. When pond permanency was omitted, $-2\log L$ increased by 12.616 ($P = 0.00038$), whereas when conspecific larval density was omitted, $-2\log L$ increased by 0.872 ($P = 0.35$). Hence, larval density was not considered further for inclusion. Third, we considered the effects of the 2 experimental factors. In this way, any differences between the 2 groups that arose as a result of differences between the distributions of the covariates were adjusted. When water level was added to the model containing pond permanency, the $-2\log L$ value was reduced by 524.385 ($P < 0.0001$). When food type was added, the reduction was 234.464 ($P < 0.0001$). Finally, the interactions among the 3 significant variables were considered. The interaction of water level by food type was not significant, whereas the other two were significant. Therefore, the final model comprised the 2 experimental factors (water level and food type), 1 environmental factor (pond permanency), and 2 interactions (water level by pond permanency and food type by pond permanency).
Table 3 MANCOVA results for the effects of experimental factors (water level and food type) and environmental factors (pond permanency and pond conspecific larval density as covariate) on body size (snout-vent length and body mass).

<table>
<thead>
<tr>
<th>Factor</th>
<th>Walks’ lambda</th>
<th>d.f.</th>
<th>$F$</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water level</td>
<td>0.064</td>
<td>2, 30</td>
<td>219.197</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Food type</td>
<td>0.255</td>
<td>2, 30</td>
<td>43.857</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Pond permanency</td>
<td>0.936</td>
<td>2, 30</td>
<td>1.030</td>
<td>0.3694</td>
</tr>
<tr>
<td>Pond conspecific density</td>
<td>0.958</td>
<td>2, 30</td>
<td>0.656</td>
<td>0.5262</td>
</tr>
</tbody>
</table>
Figure 1

(a) Permanent
- High water level & Chironomidae
- High water level & conspecifics
- Low water level & Chironomidae
- Low water level & conspecifics

(b) Ephemeral
- High water level & Chironomidae
- High water level & conspecifics
- Low water level & Chironomidae
- Low water level & conspecifics
Figure 2

(a) Plastic response in metamorphic timing (day) to food type

(b) Plastic response in SVL (cm) to food type

(c) Plastic response in body mass (g) to food type

Symbols: ● permanent, ■ ephemeral

Correlation coefficients:

- (a) $R=0.775$
- (b) $R=-0.721$
- (c) $R=-0.468$
Figure 3

(a)

(b)

Median time to metamorphosis (day)

Body mass (g)

SVL (cm)

high water level & chironomidae

high water level & conspecifics

low water level & chironomidae

low water level & conspecifics

R = 0.882

R = 0.901
**Figure legends**

**Fig. 1** Cumulative incidence functions (%) for time to metamorphosis with each experimental treatment of larvae from permanent ponds (a) or ephemeral ponds (b).

**Fig. 2** Results of correlation tests between two plastic responses in metamorphic timing (a; days), snout-vent length (A; cm), and body mass (B; g) to water level and food type at the population level. Two points (Kamitobetsu and Nopporo) in Fig. 2a are overlapping. Body mass was transformed by taking its cube root before analysis.

**Fig. 3** Results of correlation tests between snout-vent length (SVL) at metamorphosis and age at metamorphosis (a), and between body mass at metamorphosis and age at metamorphosis (b). Body mass was transformed by taking its cube root before analysis.