Supplementary Information: Ecological adaptation of an F1 hybrid cross of carnivorous and herbivorous Cyprinidae fishes

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**Supplementary** [**method**](javascript:;)**s**

**Supplementary** [**method**](javascript:;) **1: Comparison of foraging habit**

In the first three animal food feeding experiments, each fish species was divided into 5 parallel groups, and 3 fishes in each parallel group were cultured in a 50 L tank with a water temperature of 20±1°C. The experiment was carried out for 5 days. These fishes fasted for the first two days and were fed with appropriate food for the next two days. On the last day, fishes were fed excessive food, and each parallel group was sampled 2, 4, 6, 8, and 10 hours after feeding. These fishes were then anaesthetized using MS-222 (3-aminobenzoic acid ethyl ester methanesulfonate), and the body weight and chyme weight of each fish were weighed and recorded. In [periphytic](javascript:;) [algae](javascript:;) feeding experiment, we put 15 fishes of each species into a concrete pond (3 m×3 m×0.6 m) filled with [periphytic](javascript:;) [algae](javascript:;), and on the fifth day, we caught all fishes [at](javascript:;) [noon](javascript:;) and dissected and weighed them.

**Supplementary** [**method**](javascript:;) **2: Hybrid vs *P. pingi* in** [**foraging**](javascript:;) **fish**

Each experimental fish was cultured separately in a 50 L tank with a water temperature of 20±1°C and fasted for 2 days. On the third day, we fed 10 small fishes (*S. taeniatus*) to each experimental fish separately; furthermore, to ensure there was an excess amount of food, the experiment ended when 5 small fishes were caught or after 30 min

**Supplementary** [**method**](javascript:;) **3: Hybrid vs *S. wangchiachii* in** [**foraging**](javascript:;) **periphytic algae**

These experimental fishes were placed respectively in a 65 L aquarium tank with circulating water at a water temperature of 18±1°C and fasted for 39 h. Next, we placed rocks with periphytic algae in the aquarium tank and collected 9 h of video. Then, we performed anaesthetic dissection and recorded the body weight and chyme weight.

**Supplementary** [**method**](javascript:;) **4: Whether the behaviour of hybrid fish vomiting fish is persistent**

Each PS (n=32) was cultured separately in a 50 L tank with a water temperature of 20±1°C and fasted for 1.5 days. In the afternoon of the second day of fasting, we fed 0.5 g of blood worms to each fish. In the following days, we fed the study fish 10 small fishes(*Carassius auratus*). The small fishes of *S. taeniatus* were used up in the previous experiment, but because it was *C. auratus’s* breeding season, we replaced *S. taeniatus* with *C. auratus*, and PS still had obvious vomiting behaviour after catching the small fishesof *C. auratus* provided to each PS at 9 a.m. (small fish were replenished regularly to ensure that they were provided in an excessive amount (more than 5)). After two hours, we counted the number of dead small fish and live small fish and cleaned up all of the small fish. We fed 0.5 g of blood worms to each fish every afternoon to simulate a palatable food shortage in the natural environment but not a complete absence.

**Supplementary** [**method**](javascript:;) **5: New ecological niche formation of hybrid fish**

In April 2020, a PP, an SW and a PS were cultured together in each transparent 50 L tank (n=8) with a water temperature of 20±1℃ and fasted for 2 days. In the next three days, each tank was overfed with only blood worms (0.0171±0.0006, Fig. 8b) for 30 min. We videotaped it and counted the number of effective attacks on blood worms per species. In the next three days, each tank was fed 10 small fishes (*C. auratus*, 0.0748±0.0023 g, Fig. 8a) and provided two rocks with periphytic algae (Fig. 8c). After one hour, excess blood worms and small fishes were added to each tank for 30 min. We videotaped it and counted only the number of effective attacks on blood worms per species and ignored the attacks on other prey.

**Supplementary** [**method**](javascript:;) **6: The influence of contradictory behaviour of hybrid fish on foraging**

For unique parental food, PS had inefficient or contradictory feeding behaviours and such behaviours of work without gain might dilute the energy of PS to forage intermediate ecological niche prey. To address this potential outcome, this study investigated the effects of PS foraging intermediate ecological niche prey (shrimp, 0.1093 ± 0.0227 g (Supplementary Fig. 3b); blood worms 0.0171 ± 0.0006 (Supplementary Fig. 3d)) in a foraging environment with small fish (*C. auratus*, 0.0748±0.0023 g (Supplementary Fig. 3a)) or periphytic algae (Supplementary Fig. 3d).

In April 2020, each PS was cultured separately in a transparent 50 L tank with a water temperature of 20±1°C and fasted for 2 days. Then, for the experiment simulating a foraging environment with small fish, we fed 10 shrimps at 9 a.m. and 10 shrimps and 10 fishes at 5 p.m. This experiment lasted for 2 h, during which we replenished small fishes and shrimps to ensure that they were provided in excess. After 2 h, we counted the number of remaining shrimps, live fishes and dead fishes and cleaned the tank. After two days, we changed the order of feeding, i.e., fed 10 shrimps and 10 fishes at 9 a.m. and fed 10 shrimps at 5 p.m., and used this pattern for two days. Next, we fed blood worms to PS using the same experimental method, except that each fish was initially fed blood worms (1 g ≈ 58 individuals). Similarly, for the experiment simulating a foraging environment with periphytic algae, we replaced only the small fish with periphytic algae and ignored the weight of the periphytic algae eaten by PS (in the above experiment, PS ate very little periphytic algae (Fig. 4f)), and the other experimental methods were the same as those described above.

To eliminate individual differences, we standardized the foraging weight of each fish and calculated the foraging proportion with fish (FP1) and foraging proportion without fish (FP2) of PS by the following formulas:

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where represents the total number of shrimp eaten over 4 days in the environment with fish; represents the total number of shrimp eaten over 4 days in the environment without fish; represents the total number of fish eaten over 4 days in the environment with fish; and the numbers represent the average individual weights of the corresponding food species.

Similarly, the same statistical methods were performed in the other three experiments, although we ignored the weight of periphytic algae eaten by PS. If there was a significant difference (P＜0.05) between the two PS subgroups in each of the above experiments, we used the corresponding parents as the control.

Finally, to investigate whether the behaviour of vomiting had a direct effect on the total food intake (TFI) of PS in the environment with fish, the correlation between TFI and the total number of vomiting fish (NVF) was calculated by Spearman’s correlation in SPSS 21.0. The TFI was calculated by the following formulas:

where represents the total number of shrimp or blood worms eaten over 4 days in the environment with fish; represents the total number of fish eaten over 4 days in the environment with fish. The numbers represent the average individual weights of the corresponding food species.

**Supplementary results**

**Supplementary** **result 1: Specific morphological descriptions**

In external morphology, the head of the PP was relatively slender with a developed branchial membrane, lower lip with higher radian, lower jaw without keratinization, terminal mouth, deeper mouth crack, sparse gill-rakers, bulgier eyeballs and longer snout barbel and maxillary barbel. Comparatively, the head of SW was relatively round with an undeveloped branchial membrane, lower lip with a lesser radian, lower jaw with keratinization, inferior mouth, shallower mouth crack, serried gill-rakers, slightly bulging eyeballs and shorter snout barbel and maxillary barbel. In general, the head traits of PS were between those of PP and SW, but there were some special features. For example, PS had a longer maxillary barbel than both parents and a lower jaw without keratinization, which was the same as PP. In PCA of the external characteristics, PS was between PP and SW (Fig. 1m and Supplementary Tables 3-4).

In skeletal morphology, the traits of the three fishes were similar to their external morphologies, but there were some special features. For example, PP had a much more developed lower jaw but less developed upper jaw; SW had the opposite traits, and PS was somewhere in between. PP had a well-developed branchiostegal ray, SW had the opposite, and PS was somewhere in between. The relative size of the pharyngeal bone of PP was larger than that of SW, and it was long and narrow, which made the spacing of the pharyngeal teeth distributed above it larger; in contrast, the SW pharyngeal bone was shorter and wider, which made the spacing of the pharyngeal teeth distributed above it tighter, and PS was somewhere in between. In PCA of bone characteristics, PS was between PP and SW (Fig. 3m and Supplementary Tables 5-6).

In digestive morphology, PP had a chunky gut with thicker submucosa and muscularis and longitudinal mucosal folds, which made the longitudinally cut intestinal sections look messy; additionally, PP had a smaller liver with smaller hepatocytes without fat cavitation. Comparatively, SW had an elongated gut with thinner submucosa and muscularis and transverse mucosal folds, which made the longitudinally cut intestinal sections look orderly, and it had a larger fatty liver with larger hepatocytes with many fat cavitations.

**Supplementary result 2:** **Correlation analysis descriptions**

In the correlation analysis of foraging traits and foraging ability of PS (Supplementary Table 9), we did not find any correlation (P≥0.05) between the standardized traits of PS, and these indicators included the TNC, TNI, NVF and RVF. This result indicated that the shapes of those traits had no correlations with the above 4 indicators. Moreover, we did not find any correlation (P≥0.05) between any measured traits and NVF. However, we found that some measured traits were positively correlated (P<0.05) with TNC, TNI and NVF. Only mouth crack depth (MCD) was positively correlated with TNI (P<0.05). For TNC and NVF, these measured traits, including WL (whole length), SL (snout length), GL (gut length), PHA (articulation axis height of pharyngeal teeth), PHB (distance between external angle and articulation axes of pharyngeal teeth), and PHD (dorsal limb length of pharyngeal teeth), had positive correlations (P<0.05) with both. BW2 (body weight) and HL (head length) were positively correlated (P<0.05) with only TNC, and MBL (maxillary-barbel length) was positively correlated (P<0.05) with only NVF.

In the correlation analysis of the above 4 indicators (Supplementary Table 10), we found that TNC was extremely significantly positively correlated (P≤0.01) with TNI and NVF, TNI was extremely significantly positively correlated (P≤0.01) with NVF, and TNI was extremely significantly (P<0.01) [negative](javascript:;)ly correlated with RVF. Thus, we selected these individuals (TNC≥10, n=19) for the same analysis, and the results were similar to those above. However, the TNI and NVF no longer had significant correlations (P≥0.05), and the NVF and RVF re-established extremely significant positive correlations (P<0.01).

**Supplementary result 3：The influence of contradictory behaviour on foraging**

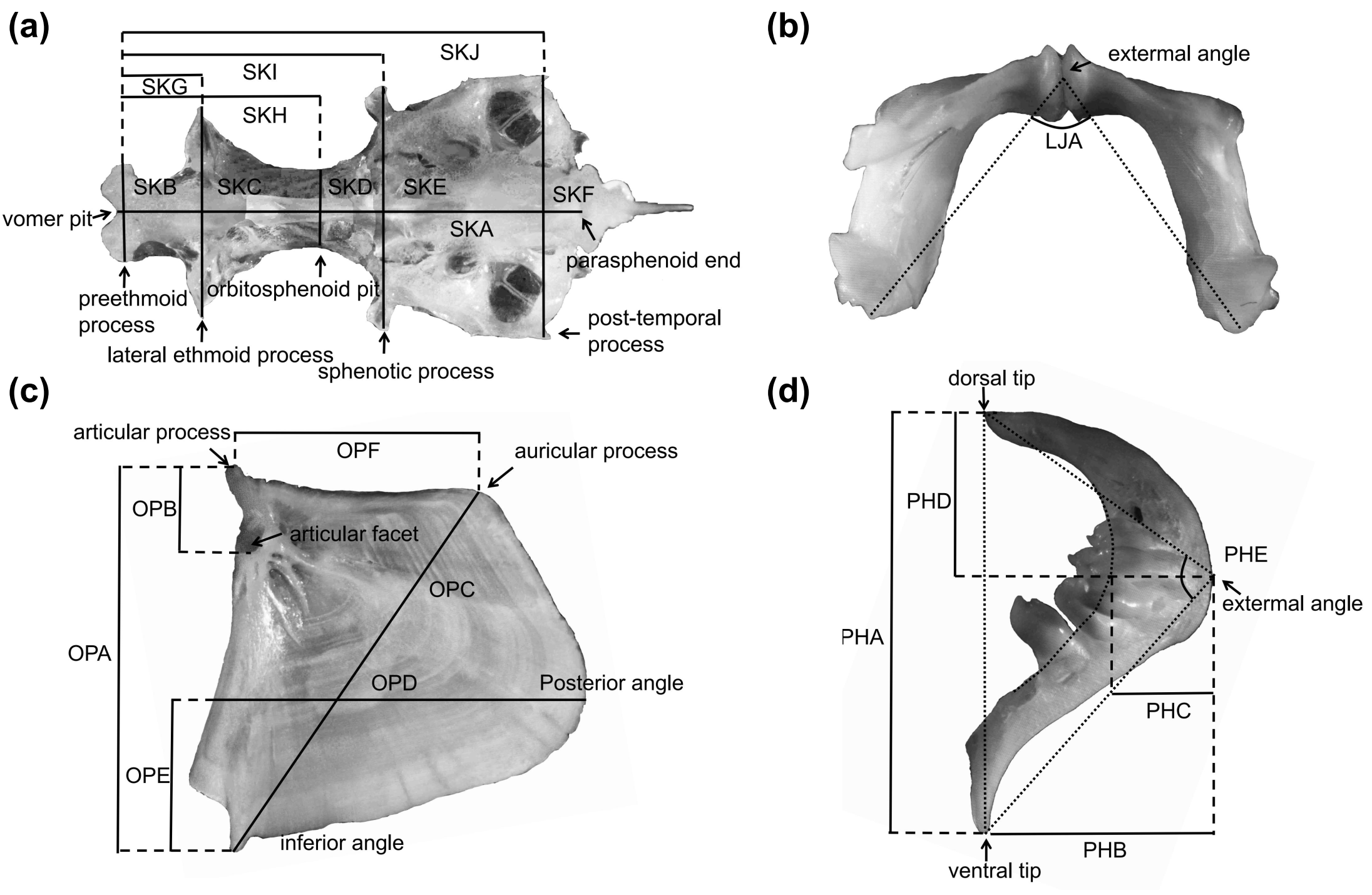
In the shrimp-only food environment, the FP of PS was extremely significantly higher (P<0.01) than that in the food environment with fish. Therefore, SW was used as a control. In the shrimp-only food environment, the FP of SW was significantly higher (P=0.033) than that in the food environment with fish, and the FP without small fish of PS was higher than that of SW, but there was no significant difference (P=0.191). Similarly, in the blood worm-only food environment, the FPs of SW and PS were both higher than those in the food environments with small fish, but the latter had an extremely significant difference (P<0.01), while the former had no significant difference (P=0.066); additionally, the FP without small fish of PS was higher than that of SW, but there was no significant difference (P=0.1, Supplementary Fig. 3e).

In the correlation analysis between the TFI and the NVF, we did not find correlations with foraging shrimp (P=0.543) or blood worms (P=0.3, Supplementary Table 11).

In summary, the presence of small fishes can affect PS and SW, which forage these preys in the intermediate ecological niche. The reason why the FP of PS decreased more than that of SW was not because of vomiting fish but because of the negative predation after catching fishes. As shown in the Fig. 5, PS showed negative predation after the first catching fish, and this negative predation may spread to more prey.

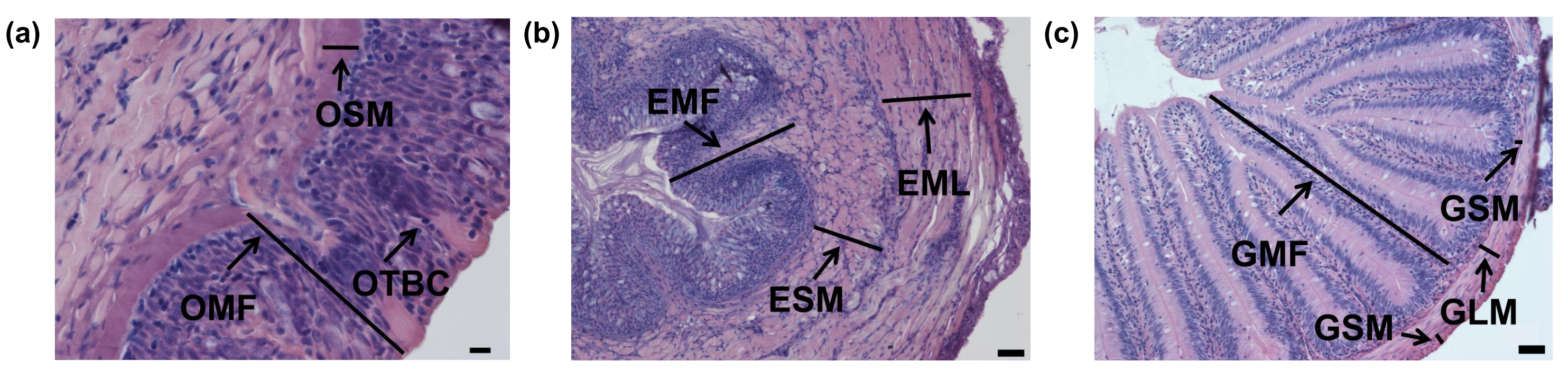
Whether in the shrimp-only or blood worm-only food environment, the foraging proportion of PS had no significant difference than the food environment with fish. Therefore, PP was not used as a control (Supplementary Fig. 3f).

**Supplementary Figure 1**



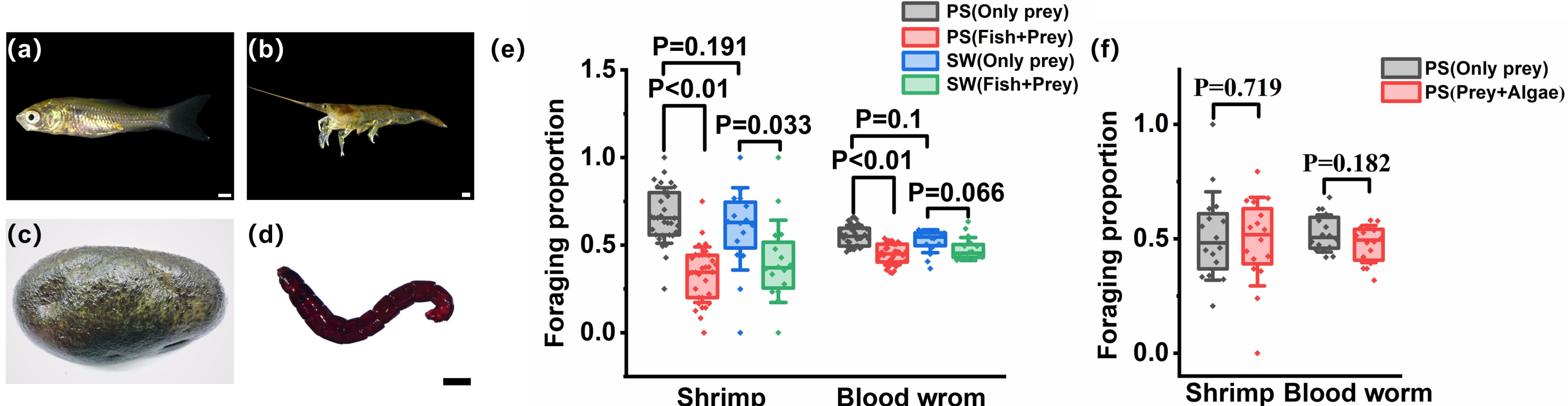
Reference figure for quantifying skeleton. (a) Reference figure for quantifying skull. (b) Reference figure for quantifying dentary. (c) Reference figure for quantifying opercular bone. (d) Reference figure for quantifying pharyngeal bone. These abbreviations are referred to in Supplementary Table S1.

**Supplementary Figure 2**



Reference figure for quantifying digestive tract. (a) Reference histological figure for quantifying oral. (b) Reference histological figure for quantifying esophagus. (c) Reference histological figure for quantifying gut. These abbreviations are referred to in Supplementary Table S1.

**Supplementary Figure 3**



The influence of contradictory behavior of hybrid fish for foraging. (a) Small fish (*C. auratus*, experimental prey1). (b) Little shrimp (*Neocaridina denticulate*,experimental prey 2). (c) Rock with periphytic algae (Spirogyra, experimental prey 3). (d) Blood worm (Chironomidae larvae, experimental prey 4). (e) Comparison of the FP between SW and SP in an environment with only intermediate niche prey or in an intermediate niche prey and small fishes. (f) The FP of SP in an environment with only intermediate niche prey or in an intermediate niche prey and periphytic algae. The scale of all figures is 1 mm. The numbers above these boxes give the P-value based on Tukey test. The boxes give the first and third quartiles, the thick lines give the medians and whiskers indicate means ± SD.

**Supplementary Table 1** List of quantitative characters and their abbreviations

|  |  |
| --- | --- |
| Items | Abbreviation |
| **External characters** | |
| Whole length | WL |
| Body length | BL |
| Body width | BW1 |
| Body height | BH |
| Head length | HL |
| Dorsal fin anterior length | DFAL |
| Caudal peduncle length | CPL |
| Caudal peduncle depth | CPD |
| Snout length | SL |
| Mouth crack depth | MCD |
| Sub-head length (The distance from the posterior end of the gill cover to the anterior end of the lower lip) | SHL |
| Eye diameter | ED |
| Interorbital width | IW |
| Distance of eyeballs | DE |
| Snout-barbel length | SBL |
| Maxillary-barbel length | MBL |
| Number of gillrakers on outer row | GOR |
| Number of gillrakers on inner row | GIR |
| Whether have a sharp horny front jaw ([qualitative](javascript:;) [character](javascript:;), “have”=”1”, “none”=“0”) | SHJ |
| **Digestive characters** | |
| Body weight | BW2 |
| Liver weight | LW |
| Hepatocyte area | HA |
| Gut weight | GW |
| Gut length | GL |
| Oral mucosa fold height | OMFH |
| Oral sub-mucosa height | OSMH |
| Oral taste bud cell density (The number of taste bud cells on the 1mm cross section of the oral pharynx) | OTBCD |
| Esophageal mucosal folds height | EMFH |
| Esophageal sub-mucosa Height | ESMH |
| Esophageal muscular layer Thickness | EMLT |
| Foregut mucosal folds Height | FGMFH |
| Foregut sub-mucosa Height | FGSMH |
| Foregut longitudinal muscle Thickness | FGLMT |
| Foregut Circular muscle Thickness | FGCMT |
| Midgut mucosal folds Height | MGMFH |
| Midgut sub-mucosa Height | MGSMH |
| Midgut longitudinal muscle Thickness | MGLMT |
| Midgut Circular muscle Thickness | MGCMT |
| Hindgut mucosal folds Height | HGMFH |
| Hindgut sub-mucosa Height | HGSMH |
| Hindgut longitudinal muscle Thickness | HGLMT |
| Hindgut Circular muscle Thickness | HGCMT |
| Gut mucosal direction ([qualitative](javascript:;) [character](javascript:;), “[transverse](javascript:;)”=“1” , “longitudinal” =“0”) | GMD |
| **Skeletal characters** | |
| Opercular bone |  |
| Articular axis height | OPA |
| Length of articular process | OPB |
| Maximum height | OPC |
| Maximum length | OPD |
| Posterior angle height | OPE |
| Distance between superior angle and articulation axis | OPF |
| Pharyngeal bone |  |
| Articulation axis height | PHA |
| Distance between external angle and articulation axes | PHB |
| Maximum width of pharyngeal bone | PHC |
| Dorsal limb length | PHD |
| Angle within the limbs | PHE |
| Dentary |  |
| Angle within the dentary | DEA |
| Skull |  |
| Vomer pit to parasphenoid end | SKA |
| Distance between the two process of preethmoid | SKB |
| Distance between the two process of lateral ethmoid | SKC |
| Distance between the two pit of orbitosphenoid | SKD |
| Distance between the two process of sphenotic | SKE |
| Distance between the two process of post-temporal | SKF |
| Vertical distance between ateral ethmoid process and preethmoid process | SKG |
| Vertical distance between orbitosphenoid process and preethmoid process | SKH |
| Vertical distance between sphenotic process and preethmoid process | SKI |
| Vertical distance between post-temporal and preethmoid process | SKJ |

**Supplementary Table 2** Standard characters of four fishes

|  |  |  |  |
| --- | --- | --- | --- |
| Items | PP | SW | PP×SW |
| WL/BL | 1.1988±0.0126a | 1.2214±0.0137b | 1.2577±0.0157c |
| BW1/BL | 0.1296±0.0068b | 0.1221±0.0014a | 0.1294±0.0055b |
| BH/BL | 0.2096±0.0104a | 0.2221±0.0102b | 0.2081±0.0082a |
| HL/BL | 0.2844±0.0084c | 0.2195±0.0083a | 0.2409±0.0093b |
| DFAL/BL | 0.5410±0.0136c | 0.5081±0.0122a | 0.5083±0.0110a |
| CPL/BL | 0.1494±0.0113a | 0.1633±0.0144b | 0.1514±0.0123a |
| CPD/CPL | 0.6195±0.0525a | 0.6139±0.0632a | 0.6298±0.0618a |
| SL/HL | 0.2459±0.0139a | 0.2732±0.0167c | 0.2629±0.0105bc |
| MCD/HL | 0.2252±0.0174d | 0.0843±0.0066a | 0.1640±0.0147c |
| SHL/HL | 1.0253±0.0101c | 0.8776±0.0296a | 0.9284±0.0198b |
| IW/DE | 0.5155±0.0124a | 0.6778±0.0093c | 0.5863±0.0105b |
| ED/HL | 0.2319±0.0172a | 0.2602±0.0179b | 0.2561±0.0167b |
| IW/HL | 0.2354±0.0091a | 0.3924±0.0207c | 0.3174±0.0210b |
| SBL/HL | 0.2504±0.0149a | 0.1218±0.0208c | 0.2155±0.0183b |
| MBL/HL | 0.2548±0.0189b | 0.1542±0.0211a | 0.2718±0.0234bc |
| NOGR | 17.9667±0.8899a | 25.6000±1.2205d | 20.2000±1.0306b |
| NIGR | 10.6000±0.4983a | 17.8667±1.6526d | 12.7000±1.0554b |
| SHJ | 0 | 1 | 0 |
| OPB/OPA | 0.2067±0.0164a | 0.2378±0.0126b | 0.2349±0.0153b |
| OPC/OPA | 1.1279±0.0381ab | 1.0833±0.0357a | 1.1512±0.0306b |
| OPD/OPA | 1.0072±0.0486b | 0.8057±0.0409a | 0.8418±0.0805a |
| OPE/OPA | 0.4119±0.0638a | 0.4147±0.0226a | 0.5063±0.0513b |
| OPF/OPA | 0.6225±0.0420b | 0.5538±0.0339a | 0.5840±0.0181ab |
| PHB/PHA | 0.3933±0.0244a | 0.4866±0.0141b | 0.4922±0.0214b |
| PHC/PHA | 0.1587±0.0115a | 0.2544±0.0285b | 0.2343±0.0151b |
| PHD/PHA | 0.2462±0.0279a | 0.4519±0.0275c | 0.3611±0.0392b |
| PHE | 92.8319±3.0941b | 91.3234±2.5501b | 87.1146±1.6831a |
| SKB/SKA | 0.1846±0.0172a | 0.2187±0.0087b | 0.1969±0.0148a |
| SKC/SKA | 0.3585±0.0353a | 0.4644±0.0179c | 0.4173±0.0343b |
| SKD/SKA | 0.1270±0.0133a | 0.1954±0.0201b | 0.1663±0.0238b |
| SKE/SKA | 0.5036±0.0276a | 0.5409±0.0246b | 0.5193±0.0179ab |
| SKF/SKA | 0.5259±0.0379a | 0.5702±0.0181b | 0.5428±0.0167ab |
| SKG/SKA | 0.1563±0.0158a | 0.1625±0.0121a | 0.1726±0.0172a |
| SKH/SKA | 0.4098±0.0309a | 0.4074±0.0197a | 0.4229±0.0206a |
| SKI/SKA | 0.6037±0.0462b | 0.5617±0.0163a | 0.5758±0.0096ab |
| SKJ/SKA | 0.9625±0.0409a | 0.9297±0.0132a | 0.9500±0.0177a |
| DEA | 32.3061±4.4547a | 57.463±3.3247c | 42.4467±4.1244b |
| LW/BW2 | 0.0071±0.0017a | 0.0264±0.0049b | 0.0231±0.0074b |
| HA | 103.41±26.7652a | 258.06±41.4878b | 372.50±62.4964c |
| GW/BW2 | 0.0336±0.0040c | 0.0281±0.0034bc | 0.0203±0.0044a |
| GL/BL | 1.0787±0.0660a | 1.4277±0.0916c | 1.2421±0.0669b |
| OMH | 0.0079±0.0015a | 0.0093±0.0033a | 0.0094±0.0012a |
| OSMH | 0.0059±0.0019c | 0.0014±0.0011a | 0.0037±0.0014bc |
| OTBCD | 1.0400±0.3554a | 3.2290±0.8671ab | 3.8453±2.0382b |
| EMFH | 0.0317±0.0046a | 0.0251±0.0031a | 0.0270±0.0041a |
| ESMH | 0.0209±0.0077a | 0.0140±0.0062a | 0.0172±0.0049a |
| EMLT | 0.0270±0.0097a | 0.0196±0.0040a | 0.0203±0.0018a |
| FGMFH | 0.0594±0.0043a | 0.0620±0.0100a | 0.0697±0.0052a |
| FGSMH | 0.0024±0.0006b | 0.0010±0.0005a | 0.0016±0.0005ab |
| FGLMT | 0.0026±0.0010a | 0.0021±0.0003a | 0.0022±0.0002a |
| FGCMT | 0.0058±0.0009a | 0.0050±0.0008a | 0.0047±0.0011a |
| MGMFH | 0.0474±0.0037a | 0.0422±0.0055a | 0.0488±0.0028a |
| MGSMH | 0.0042±0.0008b | 0.0011±0.0003a | 0.0018±0.0005a |
| MGLMT | 0.0018±0.0003a | 0.0013±0.0002a | 0.0015±0.0004a |
| MGCMT | 0.0050±0.0006b | 0.0034±0.0007a | 0.0035±0.0008a |
| HGMFH | 0.0399±0.0028b | 0.0271±0.0039a | 0.0337±0.0017b |
| HGSMH | 0.0035±0.0008b | 0.0020±0.0010a | 0.0019±0.0007a |
| HGLMT | 0.0019±0.0003b | 0.0012±0.0002a | 0.0014±0.0003ab |
| HGCMT | 0.0024±0.0004a | 0.0021±0.0003a | 0.0022±0.0004a |
| GMD | 0 | 1 | 1 |

The full name of abbreviation should refer to Supplementary Table S1. Values in the table are represented as Mean ± SD. a,b Values within a row with different superscripts differ significantly at P < 0.01 based on Tukey test. IW/DE is an indicator defined in this study, it can represent the degree of eyeball protrusion, which is related to feeding habits. SHL/HL is an indicator defined in this study, it can represent the location of mouth, which is related to feeding habits. Some of the external trait data we have used in previous study [[1](#_ENREF_1)].

**Supplementary Table 3** Total variance of the interpretation of external characters

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Component | Initial eigenvalue | | | Sums of squared loadings | | |
| [sums](javascript:;) | Variance% | Aggregate% | [sums](javascript:;) | Variance% | Aggregate% |
| 1 | 9.049 | 50.273 | 50.273 | 9.049 | 50.273 | 50.273 |
| 2 | 2.275 | 12.64 | 62.913 | 2.275 | 12.64 | 62.913 |
| 3 | 1.327 | 7.374 | 70.288 | 1.327 | 7.374 | 70.288 |
| 4 | 1.188 | 6.601 | 76.888 | 1.188 | 6.601 | 76.888 |
| 5 | 1.016 | 5.645 | 82.533 | 1.016 | 5.645 | 82.533 |
| 6 | 0.739 | 4.106 | 86.639 |  |  |  |
| 7 | 0.576 | 3.198 | 89.837 |  |  |  |
| 8 | 0.539 | 2.994 | 92.831 |  |  |  |
| 9 | 0.339 | 1.884 | 94.715 |  |  |  |
| 10 | 0.269 | 1.497 | 96.211 |  |  |  |
| 11 | 0.16 | 0.891 | 97.102 |  |  |  |
| 12 | 0.125 | 0.695 | 97.797 |  |  |  |
| 13 | 0.102 | 0.568 | 98.365 |  |  |  |
| 14 | 0.082 | 0.455 | 98.82 |  |  |  |
| 15 | 0.071 | 0.394 | 99.213 |  |  |  |
| 16 | 0.053 | 0.292 | 99.505 |  |  |  |
| 17 | 0.046 | 0.254 | 99.759 |  |  |  |
| 18 | 0.043 | 0.241 | 100 |  |  |  |

**Supplementary Table 4** Component matrix of external characters

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Items | Component | | | | |
| 1 | 2 | 3 | 4 | 5 |
| Z-score（WL/BL） | 0.206 | 0.818 | -0.015 | 0.272 | -0.209 |
| Z-score（BW/BL） | -0.465 | -0.214 | 0.334 | 0.622 | -0.237 |
| Z-score（BH/BL） | 0.453 | -0.482 | 0.225 | 0.438 | 0.322 |
| Z-score（DFAL/BL） | -0.622 | -0.136 | -0.029 | -0.395 | 0.444 |
| Z-score（HL/BL） | -0.895 | -0.258 | 0.049 | -0.066 | 0.066 |
| Z-score（CPL/BL） | 0.414 | 0.055 | 0.711 | -0.085 | 0.100 |
| Z-score（CPD/CPL） | 0.010 | 0.053 | -0.565 | 0.488 | 0.542 |
| Z-score（SHL/HL） | -0.872 | -0.308 | -0.01 | -0.049 | 0.056 |
| Z-score（SL/HL） | 0.402 | -0.259 | -0.569 | -0.039 | -0.389 |
| Z-score（MCD/HL） | -0.949 | -0.135 | -0.043 | 0.079 | -0.033 |
| Z-score（ED/HL） | 0.357 | 0.451 | 0.077 | 0.150 | 0.300 |
| Z-score（IW/HL） | 0.924 | 0.095 | -0.033 | 0.074 | 0.030 |
| Z-score（IW/DE） | 0.945 | 0.133 | 0.020 | -0.071 | 0.023 |
| Z-score（SBL/HL） | -0.772 | 0.460 | 0.037 | -0.167 | 0.180 |
| Z-score（MBL/HL） | -0.718 | 0.604 | -0.032 | 0.037 | 0.004 |
| Z-score（NIGR） | 0.911 | 0.097 | -0.008 | -0.184 | 0.117 |
| Z-score（NOGR） | 0.938 | 0.058 | -0.022 | -0.137 | 0.11 |
| Z-score（SHJ） | 0.842 | -0.486 | -0.011 | -0.062 | 0.03 |

**Supplementary Table 5** Total variance of the interpretation of skeletal characters

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Component | Initial eigenvalue | | | Sums of squared loadings | | |
| [sums](javascript:;) | Variance% | Aggregate% | [sums](javascript:;) | Variance% | Aggregate% |
| 1 | 7.924 | 41.706 | 41.706 | 7.924 | 41.706 | 41.706 |
| 2 | 2.13 | 11.212 | 52.918 | 2.13 | 11.212 | 52.918 |
| 3 | 1.948 | 10.25 | 63.168 | 1.948 | 10.25 | 63.168 |
| 4 | 1.535 | 8.077 | 71.245 | 1.535 | 8.077 | 71.245 |
| 5 | 0.963 | 5.07 | 76.315 |  |  |  |
| 6 | 0.881 | 4.637 | 80.952 |  |  |  |
| 7 | 0.807 | 4.248 | 85.2 |  |  |  |
| 8 | 0.586 | 3.083 | 88.283 |  |  |  |
| 9 | 0.524 | 2.759 | 91.042 |  |  |  |
| 10 | 0.463 | 2.436 | 93.479 |  |  |  |
| 11 | 0.32 | 1.685 | 95.164 |  |  |  |
| 12 | 0.308 | 1.621 | 96.785 |  |  |  |
| 13 | 0.201 | 1.059 | 97.844 |  |  |  |
| 14 | 0.121 | 0.638 | 98.482 |  |  |  |
| 15 | 0.091 | 0.48 | 98.962 |  |  |  |
| 16 | 0.078 | 0.412 | 99.374 |  |  |  |
| 17 | 0.062 | 0.326 | 99.699 |  |  |  |
| 18 | 0.033 | 0.172 | 99.871 |  |  |  |
| 19 | 0.025 | 0.129 | 100 |  |  |  |

**Supplementary Table 6** Component matrix of skeletal characters

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Item | Component | | | |
| 1 | 2 | 3 | 4 |
| Z-score (OPD/OPA) | 0.686 | 0.05 | 0.01 | 0.424 |
| Z-score (OPE/OPA) | -0.35 | 0.719 | -0.077 | 0.181 |
| Z-score (OPF/OPA) | -0.847 | -0.105 | 0.234 | -0.2 |
| Z-score (PHB/PHA) | 0.114 | 0.627 | -0.524 | 0.313 |
| Z-score (PHC/PHA) | -0.613 | 0.28 | 0.253 | 0.175 |
| Z-score (PHD/PHA) | 0.826 | 0.306 | -0.193 | -0.212 |
| Z-score (PHE) | 0.894 | 0.117 | -0.098 | 0.028 |
| Z-score (SKB/SKA) | 0.869 | -0.004 | -0.061 | 0.021 |
| Z-score (SKC/SKA) | -0.351 | -0.557 | 0.269 | 0.348 |
| Z-score (SKD/SKA) | 0.71 | 0.128 | 0.303 | 0.294 |
| Z-score (SKE/SKA) | 0.846 | 0.084 | 0.178 | 0.361 |
| Z-score (SKF/SKA) | 0.748 | -0.171 | 0.109 | -0.134 |
| Z-score (SKG/SKA) | 0.535 | 0.018 | 0.639 | 0.18 |
| Z-score (SKH/SKA) | 0.603 | -0.099 | 0.536 | -0.222 |
| Z-score (SKI/SKA) | 0.301 | 0.382 | 0.227 | -0.681 |
| Z-score (SKJ/SKA) | 0.071 | 0.562 | 0.455 | -0.259 |
| Z-score (DEA) | -0.513 | 0.304 | 0.549 | 0.26 |

**Supplementary Table 7** Total variance of the interpretation of digestive characters

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Component | Initial eigenvalue | | | Sums of squared loadings | | |
| [sums](javascript:;) | Variance% | Aggregate% | [sums](javascript:;) | Variance% | Aggregate% |
| 1 | 8.772 | 38.139 | 38.139 | 8.772 | 38.139 | 38.139 |
| 2 | 3.333 | 14.493 | 52.632 | 3.333 | 14.493 | 52.632 |
| 3 | 1.752 | 7.618 | 60.25 | 1.752 | 7.618 | 60.25 |
| 4 | 1.659 | 7.213 | 67.463 | 1.659 | 7.213 | 67.463 |
| 5 | 1.202 | 5.228 | 72.69 | 1.202 | 5.228 | 72.69 |
| 6 | 1.149 | 4.996 | 77.687 | 1.149 | 4.996 | 77.687 |
| 7 | 1.033 | 4.492 | 82.179 | 1.033 | 4.492 | 82.179 |
| 8 | 0.808 | 3.511 | 85.69 |  |  |  |
| 9 | 0.655 | 2.849 | 88.539 |  |  |  |
| 10 | 0.613 | 2.667 | 91.206 |  |  |  |
| 11 | 0.463 | 2.012 | 93.217 |  |  |  |
| 12 | 0.385 | 1.676 | 94.893 |  |  |  |
| 13 | 0.326 | 1.417 | 96.31 |  |  |  |
| 14 | 0.296 | 1.288 | 97.598 |  |  |  |
| 15 | 0.229 | 0.995 | 98.593 |  |  |  |
| 16 | 0.134 | 0.581 | 99.174 |  |  |  |
| 17 | 0.074 | 0.322 | 99.496 |  |  |  |
| 18 | 0.056 | 0.243 | 99.739 |  |  |  |
| 19 | 0.032 | 0.14 | 99.879 |  |  |  |
| 20 | 0.017 | 0.073 | 99.953 |  |  |  |
| 21 | 0.007 | 0.031 | 99.984 |  |  |  |
| 22 | 0.004 | 0.016 | 100 |  |  |  |
| 23 | 2.07E-05 | 8.99E-05 | 100 |  |  |  |

**Supplementary Table 8** Component matrix of digestive characters

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Item | Component | | | | | | |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Z-score (LW/BW2) | -0.829 | 0.146 | -0.187 | -0.093 | -0.196 | 0.226 | 0.167 |
| Z-score (HA) | -0.742 | 0.207 | 0.344 | 0.07 | -0.293 | 0.226 | 0.135 |
| Z-score (GMD) | 0.931 | -0.246 | 0.036 | -0.061 | -0.018 | -0.1 | 0.018 |
| Z-score (GW/BW2) | 0.528 | -0.648 | -0.134 | -0.112 | 0.277 | -0.155 | 0.024 |
| Z-score (GL/BL) | -0.739 | -0.141 | -0.083 | 0.003 | 0.193 | 0.06 | 0.427 |
| Z-score (OMH) | -0.337 | -0.503 | 0.377 | 0.075 | 0.147 | 0.174 | -0.383 |
| Z-score (OSMH) | 0.719 | -0.265 | 0.397 | -0.158 | 0.038 | 0.097 | -0.102 |
| Z-score (OTBCD) | -0.584 | 0.416 | 0.202 | 0.118 | 0.082 | 0.148 | -0.033 |
| Z-score (EMFH) | 0.465 | 0.442 | -0.314 | 0.496 | -0.127 | -0.016 | -0.188 |
| Z-score (ESMH) | 0.47 | -0.379 | 0.444 | 0.351 | 0.309 | 0.38 | 0.135 |
| Z-score (EMLT) | 0.528 | 0.02 | 0.026 | 0.665 | 0.126 | 0.179 | 0.283 |
| Z-score (FGMFH) | -0.139 | 0.684 | 0.497 | 0.033 | 0.296 | -0.061 | -0.021 |
| Z-score (FGSMH) | 0.679 | 0.566 | -0.131 | 0.103 | 0.081 | 0.257 | -0.108 |
| Z-score (FGLMT) | 0.392 | 0.59 | -0.065 | -0.539 | 0.022 | 0.118 | -0.048 |
| Z-score (FGCMT) | 0.479 | 0.323 | -0.429 | -0.281 | 0.426 | 0.208 | 0.109 |
| Z-score (MGMFH) | 0.309 | 0.327 | 0.585 | -0.456 | 0.058 | -0.053 | 0.169 |
| Z-score (MGSMH) | 0.891 | -0.104 | 0.098 | -0.168 | -0.218 | 0.014 | -0.015 |
| Z-score (MGLMT) | 0.581 | -0.076 | -0.162 | -0.037 | -0.315 | 0.548 | 0.168 |
| Z-score (MGCMT) | 0.708 | -0.386 | 0.045 | -0.248 | -0.322 | 0.226 | 0.174 |
| Z-score (HGMFH) | 0.675 | 0.488 | -0.02 | 0.048 | 0.173 | 0.146 | -0.198 |
| Z-score (HGSMH) | 0.707 | 0.046 | -0.063 | 0.099 | 0.194 | -0.375 | 0.387 |
| Z-score (HGLMT) | 0.651 | 0.094 | 0.117 | 0.227 | -0.306 | -0.192 | -0.291 |
| Z-score (HGCMT) | 0.426 | 0.416 | 0.293 | 0.17 | -0.339 | -0.302 | 0.353 |

**Supplementary Table 9** Correlation analysis of foraging traits and foraging ability of hybrid fish

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Item | TNC | | TNI | | TNVF | | RVF | |
| ρ | P-value | ρ | P-value | ρ | P-value | ρ | P-value |
| BW2 | **0.364\*** | 0.041 | 0.311 | 0.083 | 0.27 | 0.135 | -0.030 | 0.903 |
| BL | 0.262 | 0.148 | 0.183 | 0.315 | 0.168 | 0.357 | 0.056 | 0.820 |
| WL | **0.399\*** | 0.024 | 0.274 | 0.129 | **0.355\*** | 0.046 | 0.163 | 0.505 |
| BH | 0.332 | 0.063 | 0.270 | 0.134 | 0.252 | 0.164 | -0.02 | 0.935 |
| BW1` | 0.271 | 0.133 | 0.170 | 0.353 | 0.208 | 0.254 | 0.08 | 0.745 |
| HL | **0.395\*** | 0.025 | 0.255 | 0.159 | 0.407 | 0.021 | 0.284 | 0.239 |
| SL | **0.427\*** | 0.015 | 0.239 | 0.188 | **0.378\*** | 0.033 | 0.178 | 0.466 |
| ED | 0.234 | 0.198 | 0.133 | 0.468 | 0.172 | 0.347 | 0.251 | 0.300 |
| DE | 0.294 | 0.103 | 0.254 | 0.160 | 0.135 | 0.460 | -0.061 | 0.805 |
| IW | 0.292 | 0.105 | 0.216 | 0.236 | 0.148 | 0.418 | 0.031 | 0.901 |
| SBL | 0.109 | 0.551 | -0.05 | 0.786 | 0.218 | 0.230 | 0.327 | 0.172 |
| MBL | 0.309 | 0.085 | 0.183 | 0.317 | **0.366\*** | 0.039 | 0.259 | 0.284 |
| MCD | **0.448\*\*** | 0.010 | **0.351\*** | 0.049 | 0.33 | 0.065 | -0.025 | 0.918 |
| GW | 0.341 | 0.056 | 0.27 | 0.136 | 0.234 | 0.198 | -0.143 | 0.559 |
| GL | **0.484\*\*** | 0.005 | 0.427 | 0.015 | **0.372\*** | 0.036 | -0.041 | 0.868 |
| PHA | **0.433\*** | 0.013 | 0.276 | 0.126 | **0.449\*\*** | 0.010 | 0.359 | 0.131 |
| PHB | **0.445\*** | 0.011 | 0.324 | 0.071 | **0.390\*** | 0.028 | 0.257 | 0.287 |
| PHC | 0.303 | 0.091 | 0.314 | 0.080 | 0.181 | 0.322 | 0.008 | 0.974 |
| PHD | **0.392\*** | 0.027 | 0.171 | 0.349 | **0.488\*\*** | 0.005 | 0.431 | 0.066 |
| PHE | 0.042 | 0.818 | 0.03 | 0.871 | 0.070 | 0.705 | 0.026 | 0.915 |
| WL/BL | 0.185 | 0.311 | 0.118 | 0.522 | 0.233 | 0.200 | 0.173 | 0.479 |
| BH/BL | 0.132 | 0.470 | 0.11 | 0.550 | 0.129 | 0.480 | 0.046 | 0.853 |
| BW1/BL | 0.109 | 0.554 | 0.067 | 0.716 | 0.083 | 0.652 | 0.094 | 0.702 |
| HL/BL | 0.081 | 0.658 | 0.033 | 0.857 | 0.162 | 0.377 | 0.199 | 0.414 |
| SL/HL | 0.213 | 0.242 | 0.07 | 0.703 | 0.161 | 0.378 | -0.012 | 0.96 |
| ED/HL | -0.168 | 0.359 | -0.162 | 0.375 | -0.207 | 0.255 | 0.013 | 0.957 |
| DE/IW | -0.217 | 0.234 | -0.212 | 0.245 | -0.077 | 0.677 | 0.055 | 0.822 |
| IW/HL | 0.137 | 0.454 | 0.107 | 0.561 | -0.031 | 0.866 | -0.153 | 0.533 |
| SBL/HL | -0.048 | 0.796 | -0.141 | 0.440 | 0.095 | 0.605 | 0.234 | 0.334 |
| MBL/HL | 0.146 | 0.426 | 0.076 | 0.680 | 0.213 | 0.241 | 0.082 | 0.737 |
| MCD/HL | 0.07 | 0.702 | 0.06 | 0.745 | 0.014 | 0.938 | -0.175 | 0.475 |
| SHL/HL | -0.091 | 0.620 | -0.14 | 0.445 | -0.017 | 0.927 | 0.217 | 0.373 |
| GL/BL | 0.171 | 0.351 | 0.168 | 0.357 | 0.100 | 0.585 | -0.183 | 0.454 |
| GW/BW2 | 0.295 | 0.101 | 0.244 | 0.178 | 0.248 | 0.171 | -0.025 | 0.92 |
| PHB/PHA | -0.023 | 0.898 | -0.042 | 0.819 | -0.027 | 0.885 | 0.025 | 0.918 |
| PHC/PHA | -0.009 | 0.961 | 0.124 | 0.498 | -0.161 | 0.380 | -0.273 | 0.258 |
| PHD/PHA | 0.104 | 0.570 | -0.028 | 0.878 | 0.217 | 0.233 | 0.146 | 0.552 |

TNC: Total number of capture. TNI: Total number of ingestion. TNVF: Total number of vomiting fish. RVF: Rate of vomiting fish. \* indicates P<0.05, significant correlation, \*\* indicates P<0.01, extremely significant correlation. “ρ”: correlation coefficient. These abbreviations are referred to in Supplementary Table S1.

**Supplementary Table 10** Correlation analysis between TNC, TNI, NVF and RVF of hybrid fish

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Item | TNC | | | TNI | | | NVF | | | RVF | | |
| ρ | P-value | | ρ | P-value | | ρ | P-value | | ρ | P-value | |
| TNC | 1.000 | | / |  | |  |  | |  |  | |  |
| TNI | **0.844\*\*** | | 0.000 | 1.000 | | / |  | |  |  | |  |
| NVF | **0.844\*\*** | | 0.000 | **0.482\*\*** | | 0.005 | 1.000 | | / |  | |  |
| RVF | -0.234 | | 0.197 | **-0.637\*\*** | | 0.000 | 0.211 | | 0.246 | 1.000 | | / |
| These individuals (TNC≥10, n=19) participated in the following correlation analysis | | | | | | | | | | | | |
| Item | TNC | | | TNI | | | NVF | | | RVF | | |
| TNC | 1.000 | | / |  | |  |  | |  |  | |  |
| TNI | **0.546\*** | | 0.016 | 1.000 | | / |  | |  |  | |  |
| NVF | **0.740\*\*** | | 0.000 | -0.078 | | 0.752 | 1.000 | | / |  | |  |
| RVF | 0.274 | | 0.257 | **-0.601\*\*** | | 0.006 | **0.823\*\*** | | 0.000 | 1.000 | | / |

TNC:Total number of capture. TNI:Total number of ingestion. NVF:Total number of vomiting fish. RVF:Rate of vomiting fish. \* indicates P<0.05, significant correlation, \*\*indicates P<0.01, extremely significant correlation. “ρ”: correlation coefficient. In calculating the correlation between RVF and those traits, we selected only individuals whose TNC was greater than 10 in 9 days to eliminate individuals with few catches but high RVF.

**Supplementary Table 11** Correlation analysis between TNFV and TFI of hybrid fish

|  |  |  |
| --- | --- | --- |
| Item | NVF | |
| correlation coefficient | P-value |
| TFI([Shrimp](D:/Dict/8.9.3.0/resultui/html/index.html#/javascript:;)) | 0.112 | 0.543 |
| TFI([Blood](D:/Dict/8.9.3.0/resultui/html/index.html#/javascript:;) [worm](D:/Dict/8.9.3.0/resultui/html/index.html#/javascript:;)) | -0.189 | 0.300 |

TFI: Total food intake. NVF: total number of vomiting fish.

**References**

1. Gu HR, Wan YF, Yang Y, Ao Q, Cheng WL, Deng SH, Pu DY, He XF, Jin L, Wang ZJ: **Genetic and morphology analysis among the pentaploid F-1 hybrid fishes (Schizothorax wangchiachii female x Percocypris pingi male) and their parents.** *Animal* 2019, **13:**2755-2764.