

Jiang H, Chen S S, Fu S J, *et al.* Associations of energy metabolism, personality traits, and social hierarchy in *Rhodeus ocellatus* [J]. *Acta Hydrobiologica Sinica*, 2026, 50(5): 052608. [蒋杭, 陈思思, 付世建, 等. 高体鲫能量代谢、个性特征与社群等级的关联 [J]. 水生生物学报, 2026, 50(5): 052608.]

高体鲫能量代谢、个性特征与社群等级的关联

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摘要: 本研究以繁殖期的高体鲫(*Rhodeus ocellatus*)为对象, 考察了能量代谢、个性特征与社群等级之间的关联, 并进一步分析了性别对上述关联的影响。结果发现: 雄性高体鲫的标准代谢率(SMR)、最大代谢率(MMR)与有氧代谢范围(AS)均显著高于雌性个体($P < 0.05$), 表明雄性高体鲫具备更强的代谢潜能。雄性高体鲫更强的代谢能力可能与其在繁殖期需执行各种高耗能活动有关。雌性个体的SMR与MMR及AS正相关($P < 0.05$); 雄性个体的SMR与活跃性正相关, 且MMR、AS均与攻击性呈显著正相关($P < 0.05$)。能量代谢与个性特征的关联存在显著的性别二态性, 这种差异可能源于两性在繁殖期面临不同的选择压力与行为适应策略。此外, 两种性别的个体均表现为仅活跃性与社群等级呈显著正相关($P < 0.05$), 而代谢率与社群等级不相关。结果提示, 高体鲫社群等级的形成更依赖于行为特征而非代谢水平, 性别差异影响高体鲫能量代谢与个性特征的关联, 但对其社群等级的决定机制无影响。

关键词: 能量代谢; 个性特征; 社群等级; 性别差异; 高体鲫

中图分类号: Q493 文献标识码: A 文章编号: 1000-3207(2026)05-052608-10

doi: 10.3724/1000-3207.2025.2025.0347 CSTR: 32229.14.SSSWXB.2025.0347



鱼类普遍存在显著的个体间差异, 尤其在能量代谢和个性特征这两个关键维度上。能量代谢参数中标准代谢率(Standard metabolic rate, SMR)反映鱼类个体维持最基本生命活动所需的能量消耗^[1], 最大代谢率(Maximum metabolic rate, MMR)代表鱼类在一定时间内所能达到的最高能量消耗水平, 二者的差值——有氧代谢范围(Aerobic scope, AS)才是鱼类能真正用于日常生命活动的“能量预算”^[2]。个性指动物个体间稳定的行为差异, 在鱼类中包括活跃性、攻击性、社会性和勇敢性等特征^[3]。代谢引擎(Metabolic engine)^[4]和生活节奏综合症(Pace-of-life syndrome, POLS)^[5]等假说认为, 动物的能量代谢与个性特征彼此应存在关联。但相关研究表明, 至少在鱼类中, 代谢与个性间的关系并不一

致。例如, 欧洲海鲈(*Dicentrarchus labrax*)的SMR与活跃性呈正相关^[6]; 而鳊(*Parabramis pekinensis*)幼鱼的SMR与活跃性不相关^[7]; 在褐鳟(*Salmo trutta*)中甚至二者的关联表现为负相关^[8]。一些研究将这种不一致性解释为物种特异性和环境依赖性^[6, 9, 10]。除此以外, 性别差异也可能影响二者的关联, 因为雌雄个体在繁殖过程中的能量分配模式存在差异。例如, 通常雌鱼在卵子产生上投入更高能量, 而雄鱼则在争夺配偶和领地时消耗更多能量^[11], 这可能导致鱼类在能量代谢水平和个性特征上表现出性别差异, 进而影响代谢与个性之间的关联。然而, 目前鲜有研究关注性别对代谢与个性关联的影响。

在社群动物内部, 不同个体可能会通过社会互

收稿日期: 2025-09-30; 修订日期: 2025-12-26

基金项目: 国家自然科学基金(NSFC 32370509); 重庆市自然科学基金(CSTB2025NSCQ-GPX1006); 重庆市教委科学技术研究重点项目(KJZD-K202500504)资助 [Supported by the National Natural Science Foundation of China (32370509); the Natural Science Foundation of Chongqing (CSTB2025NSCQ-GPX1006); the Science and Technology Research Key Program of Chongqing Municipal Education Commission (KJZD-K202500504)]

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动形成稳定的等级结构,即社群等级(Social hierarchy)^[12,13]。社群等级对动物个体的资源获取、繁殖及生存等均具有深远影响^[14,15]。然而,目前动物社群等级的形成机制尚无统一论。以鱼类为例,个性特征(如攻击性)与种内竞争(如打斗)的胜负结果密切相关^[16]。此外,激烈的种内竞争也伴随着巨大的能量消耗^[17,18]。因此,个性特征和能量代谢可能是影响鱼类个体社群等级地位的重要因素^[19,20]。一些研究发现,高代谢水平的鱼类个体在种内竞争中更具优势,因而更易占据支配地位^[19];然而,亦有研究并未观测到二者存在显著关联,甚至发现了相反的趋势^[21]。个性特征同样如此,一般认为勇敢性或攻击性较强的个体更容易获得较高等级地位^[20,22],但在某些情况下,谨慎或胆小的个体也能通过社会经验在种内竞争中获胜,占据更高等级地位^[13,23]。因此,能量代谢、个性特征与社群等级之间的关系尚未完全明晰。值得注意的是,性别差异不仅限于繁殖能量投入与个性特征,更延伸至种内竞争的强度与策略^[24],这种差异可能进而调节代谢水平、个性特征与社群等级之间的关联。然而直至目前,相关研究仍然不足,性别是否会影响社群等级的决定机制尚不清楚。

高体鳊鱼(*Rhodeus ocellatus*)是一种广泛分布于东亚淡水水域的小型鲤科鱼类。在繁殖季节,雄鱼会披上美丽的婚姻色,雌鱼则通过一条可周期性收缩的产卵管,将卵产在河蚌的鳃腔内^[25]。这一特殊的繁殖策略导致雌雄个体在繁殖能量投入与竞争行为上表现出明显差异^[26,27]。同时,高体鳊鱼体型小、易于饲养,且在能量代谢、行为特征等方面均表现出较大的个体差异^[28]。上述代谢、行为特征等方面的性别间差异在高体鳊鱼的繁殖期尤为明显,为探讨代谢、行为与社群等级之间关联的性别间差异提供了关键研究窗口。因此,本研究选择繁殖期的高体鳊鱼为实验对象,旨在探讨能量代谢、个性特征与社群等级之间的关系,并进一步考察性别在其中的调节作用。该研究有望为揭示鱼类社群等级的决定机制及其性别差异提供新的证据。

1 材料与方法

1.1 实验鱼来源与驯养

本研究所用的实验鱼为繁殖期的高体鳊鱼(约120尾),购于四川成都(自当地池塘捕捞的野生种群)。高体鳊鱼运回实验室后先放入循环水养殖系统(鱼缸尺寸:39 cm×28 cm×29 cm,每缸约20尾)中以群体形式驯养1周以上,再将其转移至养殖单元格(12 cm×15 cm×29 cm;每个单元格1尾鱼)中隔离

驯养4周,以消除前期社会经历对代谢、个性及社群等级地位的影响^[29]。养殖单元格由不透明隔板组成,使高体鳊鱼个体形成视觉上的隔离,但不同单元格水体相通,允许化学信息的交流以降低社会隔离可能带来的胁迫。其间使用VIE (Visible implant elastomer)染料(青岛海星仪器有限公司)对高体鳊鱼进行体外颜色标记,便于后期的个体识别。养殖系统的水体为充分曝气的自来水,并使用充气泵不断往水中注入空气使水中溶氧水平维持在7.0 mg/L以上。水温控制在(27±1)°C。每天上午9:00使用颗粒饲料[通威鱼用膨化饵料,四川成都,组成:(42.3±0.8)%蛋白质,(8.8±0.5)%脂质,(23.6±0.1)%碳水化合物]对高体鳊鱼进行1次饱食投喂。30min后,用虹吸管清除残存的食物和粪便。每天换水1次,日换水量约为总体水量的10%。

1.2 实验方案

在驯养结束后,选取健康且体型相似的雌鱼[体重:(1.40±0.06) g;体长:(3.88±0.05) cm]、雄鱼[体重:(1.63±0.08) g;体长:(4.21±0.06) cm]各30尾进行正式实验。选择体型相似,旨在尽量控制体型差异这一混杂变量,从而更清晰地评估能量代谢和个性特征在社群等级形成中的作用。首先进行高体鳊鱼个体SMR和MMR的测量。代谢率测量完成后再使用个性行为观测装置对高体鳊鱼的个性特征依次进行测定,包括活跃性、攻击性、社会性和勇敢性。在个性特征测定完成后,允许高体鳊鱼个体恢复48h,随后按体长两两配对,进行社群等级地位的测定。每一对的两尾个体性别相同,且体长差异小于10%,以避免身体大小对社群等级地位的影响。雌鱼与雄鱼各15对。配对完成后将每一对高体鳊鱼分别转移至标准化水族箱中进行社群等级的判定,为确保等级序列数据的稳定性,48h后进行重复判定。为避免消化活动对高体鳊鱼能量代谢、个性等测量结果的影响,所有参数测量前高体鳊鱼均禁食24h^[30]。

1.3 参数测定方法

能量代谢 SMR使用实验室自行研制的间歇式代谢仪^[31]进行测定。代谢仪的运行包括代谢测定和换水两个模式:换水模式下外循环水泵开启,2min内完成>99%的水体置换,避免呼吸室内缺氧;代谢测定模式下外循环关闭,通过内循环保证呼吸室内水体混匀。呼吸室内的溶氧水平由溶氧仪(Oxy-10SMA; PreSens, 德国)每20s自动记录1次,并传输至计算机,用于计算代谢率。每个测量周期为10min (2min换水+8min测定),为减少换水时水体扰动对测定结果的影响,计算耗氧率(M_{O_2})时对于

8min的测定区间舍弃前后各1min数据。每个测量周期可得到一个耗氧率值。计算公式:

$$M_{O_2} = 60 \times (K - K_0) \times V \quad (1)$$

式中, K 为装有高体鲮鱼的呼吸室的溶氧下降斜率 [$\text{mg O}_2/(\text{L} \cdot \text{min})$], K_0 为空白呼吸室的溶氧下降斜率, V 为扣除了高体鲮鱼体积的呼吸室有效体积(假设1 g体重=1 mL体积)^[32]。测定前高体鲮鱼禁食24h以排除食物消化的影响,并提前一晚将高体鲮鱼转移至呼吸室适应。整个适应及代谢率测定期间使用不透明隔板遮挡每个呼吸室,使不同个体相互不可见以避免相互干扰,同时减少外界环境的影响。正式测定自次日9:30起连续记录24h,以期间所测定的所有 M_{O_2} 值的平均值作为SMR。为减小体重差异对代谢率的影响,SMR进一步按平均体重进行校正^[33, 34]。

在SMR测定完成后,将高体鲮鱼个体转移至实验室自行研制的Blazka式游泳代谢仪的游泳管中^[35],通过逐渐增加水流速度的方式诱导其进行逆流游泳至力竭。力竭标准为实验鱼无法维持游泳并被冲至末端挡板,停留 $\geq 10\text{s}$ ^[36]。力竭后立即将高体鲮鱼转移回间歇式代谢仪的呼吸室中,进行运动后耗氧率的测定,连续10min,用来计算MMR^[32]。MMR的计算公式与SMR相同,但其使用的溶氧下降斜率为连续滚动的2min回归窗口内所计算的下降率的最大值^[37]。MMR的体重校正方法与SMR相同,AS为MMR与SMR的差值^[2]。

个性特征 个性特征测定使用的方法和装置均参考已发表文献[38]。简而言之,活跃性的测定在长方体水槽(50 cm×35 cm×35 cm,水深10 cm)^[39]中进行,水槽上方安装高清摄像头(罗技C920)用以视频拍摄。先将单尾高体鲮鱼带水转移至装置中适应5min,之后打开摄像头对高体鲮鱼的自发运动进行视频拍摄,持续10min^[39, 40]。拍摄的视频使用行为学软件EthoVision XT 9.0 (Noldus, 荷兰)进行分析。活跃性以平均速度(cm/s)和运动时间比(%)来衡量,运动状态定义为实验鱼的质心移动速度 $> 1.75 \text{ cm/s}$ ^[41]。

攻击性的测定在活跃性测定之后完成,并使用同一实验水槽:该水槽的一个侧面安装有一面镜子(35 cm×20 cm),在活跃性测定期间使用白色隔板覆盖镜子,待活跃性拍摄完成以后,小心取出白色隔板,暴露出镜子。由于高体鲮鱼此时已经适应该测定环境,镜子中突然出现的自己的影子会被其视为入侵者而引起高体鲮鱼对镜子的攻击行为^[42]。白色隔板取出5min^[39]后即开始攻击性的拍摄,连续拍

摄10min。使用EthoVision XT 9.0进行攻击性的分析,参数为高体鲮鱼个体与镜面平均距离(cm)和累计的攻击次数。

社会性的测定装置为长方体水槽(70 cm×35 cm×35 cm)^[43],通过两块透明隔板将水槽分隔为中间的选择区(50 cm×35 cm×35 cm)和两侧的两个刺激区(10 cm×35 cm×35 cm)。测定时随机挑选不纳入数据分析的3尾雌鱼和3尾雄鱼组成刺激鱼群,置于任意一侧的刺激区,另一侧的刺激区保持空白。随后,将单尾高体鲮鱼带水转移至选择区,适应5min后开始拍摄,持续10min。使用EthoVision XT 9.0进行社会性的分析,参数包括靠近鱼群(距刺激鱼群一侧透明隔板5 cm以内的空间范围)时间占比(%)和靠近鱼群次数。

用于勇敢性测定的主体水槽尺寸与社会性测定所用水槽一致^[43],该水槽由不透明隔板分隔为隐蔽区(10 cm×35 cm×35 cm)和开阔区(60 cm×35 cm×35 cm)两部分,隔板底部设一扇可开启的小门(10 cm×10 cm),小门打开时,高体鲮鱼可通过小门在隐蔽区和开阔区自由穿梭。隐蔽区内放置有塑料水草和鹅卵石,模拟庇护环境。实验时首先将单尾高体鲮鱼带水转移至隐蔽区适应10min,此时小门关闭。适应结束后打开小门并连续拍摄30min。勇敢性参数为高体鲮鱼个体在开阔区的累计停留时间占比(%)和出隐蔽所次数。

社群等级 社群等级的判定在配备了单株水草作为标准化隐蔽场所的小型水族缸(40 cm×20 cm×20 cm)中进行^[13, 44]。测定时将两尾大小接近的高体鲮鱼同时转移至缸内,经5min适应后,观察双方在30min内的互动行为,包括追逐(主动追击并迫使对方撤退)和驱离(撞击对方使其退避)等^[17, 45]。若某一个体在大部分时间内处于主动进攻地位,且持续占据隐蔽位点并多次迫使对手退避,则判定为高等级个体;相反,若某一个体频繁被追逐、驱赶至无水草庇护的区域,则判定为低等级个体^[2, 17, 46]。为检验社群等级序列的稳定性,两尾鱼在首次社群等级评定完成48h后重复上述实验流程。经对比,所有的30对个体前后两次社群等级判定结果均一致。

1.4 统计与分析

原始数据经Excel 2021整理与常规计算后,使用SPSS 17.0进行统计分析,显著性水平为 $P < 0.05$ 。在统计分析前,首先对各项参数进行正态性和方差齐性检验;若满足条件,各参数的性别间差异则采用独立样本 t 检验,否则采用非参数检验(Mann-Whitney U检验)。社群等级、代谢水平及个性参数

之间的关联则采用Pearson相关分析进行评估。

2 结果

2.1 高体鲮鱼能量代谢、个性特征的性别间差异

雄性高体鲮鱼的SMR、MMR和AS均显著高于雌鱼($P<0.05$; 图1)。雄性高体鲮鱼社会性参数中的靠近鱼群时间占比显著高于雌鱼, 但靠近鱼群次数显著低于雌鱼($P<0.05$; 图2)。其他个性特征在雌性与雄性个体之间均未表现出显著差异($P>0.05$; 图2)。

2.2 高体鲮鱼能量代谢与个性特征的关联

在雌性高体鲮鱼中, 代谢参数(SMR、MMR、AS)与所有个性特征均不相关($P>0.05$; 表1), 但SMR与MMR呈显著正相关($R=0.555, P=0.001$), MMR与

AS呈显著正相关($R=0.960, P<0.001$)。此外, 攻击性参数中的攻击次数与勇敢性参数中的开放区累计停留时间占比呈显著正相关($R=0.403, P=0.027$); 社会性参数中靠近鱼群次数与勇敢性参数中出隐蔽所次数呈显著正相关($R=0.450, P=0.013$; 表1)。

在雄性高体鲮鱼中, SMR与活跃性参数中的平均速度呈显著正相关($R=0.362, P=0.049$); MMR($R=0.469, P=0.009$)和AS($R=0.469, P=0.009$)均与攻击性参数中的攻击次数呈显著正相关, 且MMR与AS呈显著正相关($R=0.989, P<0.001$; 表2)。

2.3 高体鲮鱼的个性参数与社群等级的关联

在雌性高体鲮鱼中, 活跃性参数的运动时间比与社群等级呈显著正相关($R=0.362, P=0.049$; 表1; 图3)。在雄性高体鲮鱼中, 活跃性参数中的平均速

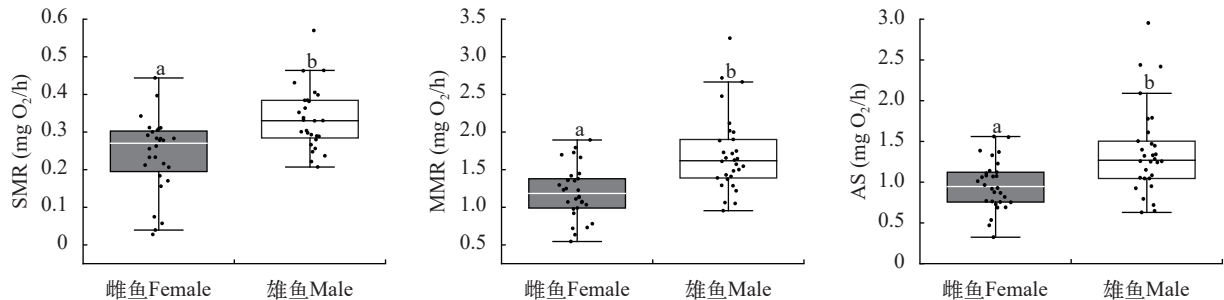


图1 高体鲮鱼代谢参数的性别差异

Fig. 1 Sex differences in metabolic parameters of *Rhodeus ocellatus* (Female $N=30$; Male $N=30$)

代谢参数(SMR, MMR, AS)均校正为平均体重下的代谢率, 不同的字母(a, b)表示雌雄之间差异有统计学意义($P<0.05$); 下同
Metabolic parameters (SMR, MMR, AS) are corrected to the metabolic rate at the average body weight; Different letters (a, b) denote significant differences between sexes ($P<0.05$); The same applies below

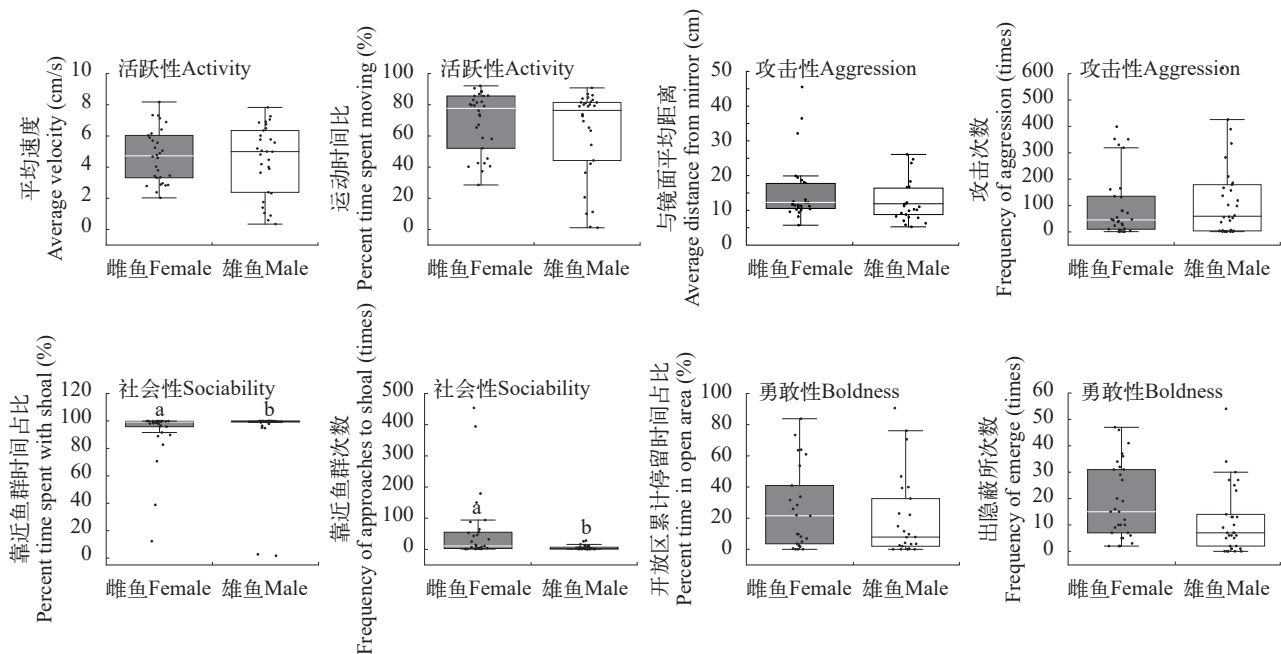


图2 高体鲮鱼活跃性、攻击性、社会性和勇敢性的性别差异

Fig. 2 Sex differences in activity, aggression, sociability, and boldness between female and male *Rhodeus ocellatus* (Female $N=30$; Male $N=30$)

接近次数。雄性个体长时间停留在鱼群附近可能与其繁殖需求有关。因为雄性个体往往需要主动

接近雌性, 以便更好地获取交配机会, 因此表现出更高的社会依附性^[55]。雌性个体表现为更高频率

表 2 雄性高体鲮社群等级、代谢和个性之间的关联

Tab. 2 Correlation between social hierarchy, metabolism, and personality in male *Rhodeus ocellatus* (N=30)

| 参数 Parameter | 代谢Metabolic rate | | | 活跃性Activity | | 攻击性Aggression | | 社会性Sociability | | 勇敢性Boldness | |
|---|--------------------|--------------------|-------------------------------------|----------------------------------|-------------------------------------|--------------------|----------------------------------|--------------------|--------------------|--------------------|-------------------------------------|
| | 标准代谢率 | 最大代谢率 | 有氧代谢范围 | 平均速度 | 运动时间比 | 与镜面平均距离 | 攻击次数 | 靠近鱼群时间占比 | 靠近鱼群次数 | 开放区累计停留时间占比 | 出隐蔽所次数 |
| 社群等级 Social hierarchy | R=0.073 P=0.701 | R=0.052 P=0.785 | R=0.040 P=0.835 | R=0.407 P=0.026 | R=0.429 P=0.018 | R=0.085 P=0.653 | R=0.111 P=0.560 | R=0.266 P=0.156 | R= P=0.460 | R= P=0.835 | R=0.119 P=0.531 |
| 代谢 Metabolic rate | | R= P=0.423 | R= P=0.115 | R=0.362 P=0.049 | R=0.276 P=0.139 | R=0.005 P=0.980 | R= P=0.600 | R= P=0.513 | R= P=0.494 | R= P=0.788 | R= P=0.866 |
| 标准代谢率 SMR (mg O ₂ /h) | | -0.152 | -0.294 | | | | -0.100 | -0.124 | -0.130 | -0.051 | -0.032 |
| 最大代谢率 MMR (mg O ₂ /h) | | | R=0.989 P<0.001 | R=0.302 P=0.104 | R=0.320 P=0.085 | R=0.125 P=0.511 | R=0.469 P=0.009 | R=0.139 P=0.463 | R= P=0.291 | R= P=0.137 | R= P=0.169 |
| 有氧代谢范围 AS (mg O ₂ /h) | | | | R=0.240 P=0.202 | R=0.269 P=0.150 | R=0.120 P=0.527 | R=0.469 P=0.009 | R=0.153 P=0.421 | R= P=0.359 | R= P=0.165 | R= P=0.195 |
| 活跃性 Activity | | | | | R=0.927 P<0.001 | R=0.116 P=0.540 | R=0.074 P=0.699 | R=0.224 P=0.234 | R= P=0.847 | R=0.149 P=0.432 | R=0.301 P=0.106 |
| 平均速度 Average velocity (cm/s) | | | | | | | | | | | |
| 运动时间比 Movement time ratio (%) | | | | | | R=0.071 P=0.710 | R=0.055 P=0.774 | R=0.231 P=0.219 | R= P=0.682 | R=0.198 P=0.294 | R=0.355 P=0.055 |
| 攻击性 Aggression | | | | | | | R= P=0.743 | R=0.186 P=0.326 | R=0.025 P=0.894 | R= P=0.927 | R= P=0.157 |
| 与镜面平均距离 Average distance from mirror (cm) | | | | | | | | | | | |
| 攻击次数 Frequency of aggression (times) | | | | | | | | R=0.112 P=0.554 | R=0.069 P=0.716 | R= P=0.278 | R= P=0.275 |
| 社会性 Sociability | | | | | | | | | R=0.062 P=0.744 | R=0.202 P=0.285 | R=0.161 P=0.397 |
| 靠近鱼群时间占比 Proportion of time spent with shoal (%) | | | | | | | | | | | |
| 靠近鱼群次数 Frequency of approaches to shoal (times) | | | | | | | | | | R=0.197 P=0.297 | R= P=0.892 |
| 勇敢性 Boldness | | | | | | | | | | | R=0.717 P<0.001 |
| 开放区累计停留时间占比 Proportion of cumulative time spent in the open area (%) | | | | | | | | | | | |
| 出隐蔽所次数 Frequency of emerge (times) | | | | | | | | | | | / |

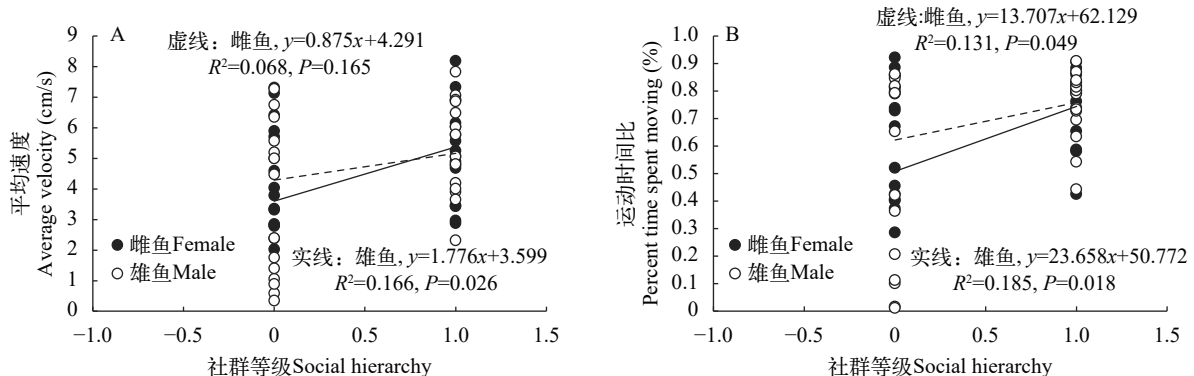


图 3 高体鲮社群等级与活跃性之间的关联

Fig. 3 Correlation between social hierarchy and activity in *Rhodeus ocellatus* (Female N=30; Male N=30)

的接近鱼群,可能体现了其在社会互动中更倾向于短暂接触而非持续依附。这种模式在孔雀鱼中也有类似发现,即雌性更倾向于与多个个体建立短暂的互动,以降低被单个雄性骚扰的风险^[56]。

3.2 高体鲮鱼能量代谢与个性特征关联的性别间差异

代谢引擎假说认为,动物个体的SMR可能与其MMR存在正相关关系,因为大的“代谢引擎”需要更高的维持能量消耗,即“空转”成本更高^[4]。在本研究中,雌性个体的SMR与MMR呈正相关,与青鱼(*Mylopharyngodon piceus*)^[57]、鲤(*Cyprinus carpio*)^[58]的研究结果一致,符合代谢引擎假说。但雄性个体的SMR与MMR无显著关联,我们推测有两种可能:一是雄性个体因为性内竞争较为激烈,MMR较低的一部分个体可能因为应激反而表现出更高的SMR,进而掩盖了二者间的关联。二是雄性个体在繁殖竞争和领地防御中常依赖短时爆发性游动,在其力竭后测得的MMR很可能受运动后过量耗氧(无氧代谢后的氧债偿还)所影响,导致其与传统意义上反映鱼类心-鳃供氧极限的最大有氧代谢潜能不一致或相关性较弱^[59]。

动物所有的日常生命活动都依赖于能量代谢的支持^[1],因此,POLS等假说提出,个体的能量代谢与个性等表型特征之间应当存在一定的关联^[4,60]。例如,拥有较高SMR的个体可能也更活跃、更勇敢且更具攻击性^[31,39]。本研究中雄性高体鲮鱼的SMR与活跃性呈正相关,且MMR、AS与攻击性呈正相关,研究结果与上述假说相符^[60]。这也与以往大西洋鲑(*Salmo salar*)^[61]、热带豆娘鱼(*Pomacentrus amboinensis*)^[2]等研究的结果一致,表明代谢潜力能够影响个体的行为表达。然而代谢与个性的关联在雌性个体中并不存在。一种可能的解释是,在雌性高体鲮鱼中,个体间的个性差异并不依赖或受制于代谢水平的变异,个性与代谢可能作为相互独立的性状,在演化过程中分别受到不同的选择压力而独立演化^[62]。

3.3 高体鲮鱼能量代谢、个性特征与社群等级关联的性别间差异

在鱼类群体中,个体的能量代谢水平和个性特征通常被认为是影响社群等级的重要因素^[1]。然而,本研究结果显示,不论在雌性还是雄性高体鲮鱼中,所有代谢参数(SMR、MMR、AS)均未与社群等级呈现显著相关性。这可能因为在实验室条件下,食物和庇护所等资源的供给相对均衡,这种环境会显著削弱代谢水平在竞争中的作用。已有研究指出,代谢率对个体行为和竞争表现的影响往

往依赖于资源是否有限^[63]。在资源匮乏的情况下,高代谢个体可能更积极、更具攻击性以获取资源,从而获得更高的社会地位;而在资源充足时,不同代谢水平个体均能满足能量需求,从而减弱了代谢对社会等级形成的影响^[61]。此外,在隔离驯养期间,所有个体均处于高度一致的环境条件下,这可能导致不同个体之间的代谢差异趋于减小,从而削弱了代谢率与社群等级之间可能存在的关联。本研究中不同个体间相对较小的体型差异也会弱化二者的关联,因为在自然环境中,鱼类个体的体型大小通常与社群等级地位直接相关^[64]。

当然,就高体鲮鱼而言,代谢与社群等级地位之间可能本就不存在关联。因为鱼类社群等级的形成可能更多依赖于行为特质而非代谢水平,即“行为驱动”在此类鱼群中扮演了比“代谢驱动”更核心的角色^[63]。与代谢不同,两种性别的高体鲮鱼的活跃性均与社群等级正相关,这与以往相关研究的结果类似^[65]。这种较高的活跃性可能与高等级个体频繁的领地巡视、积极的探索和获取食物、更为积极的求偶展示有关^[66]。

高体鲮鱼在繁殖期表现出独特的繁殖行为模式:雄性个体需要建立并保卫繁殖领地以控制用于产卵的河蚌,而雌性个体则通过产卵管完成在河蚌中的产卵^[25]。对于雌鱼而言,其繁殖策略更侧重于产卵决策而非直接参与社会冲突^[67],这也可能是其大部分代谢特征及个性参数与社群等级地位无显著相关的重要原因。相比之下,维持较高的等级地位对于雄鱼获取优质繁殖领地至关重要。然而仅活跃性与雄鱼的社群等级地位呈正相关,这与一般预期有所不同,因为获得并维持较高等级地位通常需要频繁的攻击行为,并伴随较高的能量消耗。可能的解释是,在高体鲮鱼的雄性竞争中,活跃性可能通过更高效的领地巡逻、展示行为或择机攻击策略来提升社会地位,而不一定完全依赖高频率、高能耗的直接冲突,从而在能量消耗与等级维持之间达到一定平衡。

(作者声明本文符合出版伦理要求)

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ASSOCIATIONS OF ENERGY METABOLISM, PERSONALITY TRAITS, AND SOCIAL HIERARCHY IN *RHODEUS OCELLATUS*

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Abstract: This study investigated the relationships among energy metabolism, personality traits, and social hierarchy in breeding-season rosy bitterling (*Rhodeus ocellatus*), with further analysis of sex-specific differences. The results showed that male *R. ocellatus* had significantly higher standard metabolic rate (SMR), maximum metabolic rate (MMR), and aerobic scope (AS) than females ($P < 0.05$), indicating a greater metabolic potential in males, likely linked to the high-energy-demand activities during reproduction. In females, SMR was positively correlated with both MMR and AS ($P < 0.05$). In males, SMR was positively correlated with activity, while MMR and AS showed significant positive correlations with aggressiveness ($P < 0.05$). The observed sexual differences in the relationships between metabolism and personality may stem from the distinct selective pressures and behavioral strategies experienced by males and females during reproduction. In both sexes, only activity was significantly and positively correlated with social hierarchy ($P < 0.05$), while metabolic rates showed no correlation with hierarchy. These findings suggest that social hierarchy in *R. ocellatus* is determined more by behavioral traits than by metabolic levels, and while sex influences the relationship between energy metabolism and personality, it does not affect the mechanism determining social hierarchy.

Key words: Energy metabolism; Personality traits; Social hierarchy; Sex differences; *Rhodeus ocellatus*