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秦岭细鳞鲑稚鱼对底质颜色、光照强度 及光色的选择行为*

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摘要 光照、底质颜色是影响鱼类行为、生存的重要环境因子,为探究秦岭细鳞鲑(*Brachymystax tsinlingensis*)稚鱼对光照及底质颜色环境偏好,本研究以秦岭细鳞鲑子代为实验鱼[平均全长为(3.31±0.67) cm;平均体重为(0.42±0.18) g]开展了秦岭细鳞鲑稚鱼对底质颜色、光照强度及光照颜色的选择行为。结果显示,秦岭细鳞鲑稚鱼个体与群体均对黑色底质偏好明显;个体对3种光照强度(弱光区为1~5 lx,过渡区为5~10 lx,强光区为10~25 lx)均无明显趋向性($P>0.05$),而群体对强光(10~25 lx)有明显趋避性;在相同光照强度(1~3 lx)下,个体对4种光照颜色(黄、红、绿和蓝)无明显趋向性($P>0.05$),而群体对绿光有明显趋避性($P<0.05$)。秦岭细鳞鲑个体和群体对光照强度和光照颜色的差异性表现可能与其信息传递特征或环境反应机制不同有关,而个体和群体均偏好黑色底质,其偏好光照强度为1~10 lx,对绿光具有趋避性,这可能与该物种生活环境特征相关。本研究结论可进一步为秦岭细鳞鲑苗种培育和增殖放流环境选择提供参考。

关键词 底质;光照;选择行为;秦岭细鳞鲑;稚鱼

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鱼类的行为和生存状况受栖息水域中诸多环境因子影响,如温度、光环境、水流、底质等(蔡厚才等,1998)。光环境作为重要的环境因子之一,主要包括光照强度、光照颜色和光周期,有研究表明,强光(>340 lx)显著促进了大西洋鲑(*Salmo salar*)的生长(Oppedal *et al.*, 1997),随后证实连续光照也能促进大西洋鲑的生长,并随着光照强度的升高,生长率提高

(Stefansson *et al.*, 1993)。顾孝连等(2009)研究发现,长江口中华鲟(*Acipenser sinensis*)幼鱼摄食率受光照强度影响不明显,但对光照强度具有正趋向性,其正趋光性有利于寻找食物丰富的栖息环境;而川陕哲罗鲑(*Hucho bleekeri*)在弱光(1.11 lx)下受精卵孵化率显著高于强光(570 lx),且孵出时间早于强光(王成友等,2019)。与光照强度相似,光照颜色也可影响鱼类的

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食行为明显,摄食效果达到最佳,可认定为已完全适应实验环境。实验开始前 2 h 对实验鱼不进行投喂,避免摄食因素影响实验结果。

1.2 实验装置与方法

1.2.1 趋光性实验 将水族箱(长 1.80 m × 宽 0.45 m × 高 0.50 m)分成面积相等的 3 个区域,再以 2 只 15 W 白炽灯提供唯一光源放在水族箱一端,调节 2 个白炽灯与水族箱的距离,使水族箱 3 个等面积区域照度为弱光区为 1~5 lx,过渡区为 5~10 lx,强光区为 10~25 lx (图 1)。光照强度由 Spectrum LightScout 光量子计(3415F)多次重复测定。每组实验后调换强光区弱区位置,消除位置适应性误差。

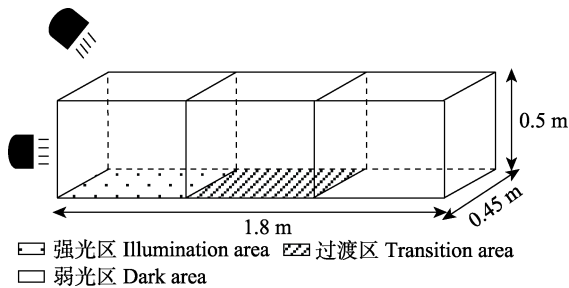


图 1 光照强度实验示意图

Fig.1 Sketch map for light intensity preference test

将水族箱进行清洗消毒后加入实验用水,水深为 20.06~21.50 cm,水质情况见表 1。

个体实验: 从暂养槽随机挑选 20 尾实验鱼进行实验,每次从水族箱中央(过渡区中央)放入 1 尾鱼,适应 2 min 后,利用摄像机连续录像 5 min,再新取出下一尾鱼按同样的方法进行实验;统计每尾鱼在 3 种不同照度区域中停留的时间,以实验鱼在不同照度区域中的时间百分比平均数作为个体对不同光照强度的选择性指标。

群体实验: 从暂养槽随机挑选 30 尾实验鱼并分为 5 组进行实验,每组 6 尾鱼同时放入水族箱中央,适应 2 min 后,每间隔 30 s 记录 1 次,记录在不同光照区域的实验鱼数量,每组记录 10 次,再新取出下一组实验鱼按同样的方法进行实验;计算不同光照强度区域中实验鱼的数量百分比,以各个区域中的数量百分比平均数作为群体对不同光照强度选择性的指标。

所有实验统计时,以实验鱼头部进入某个区域作为处于该区域的标准,开始计时或计数。

1.2.2 底质颜色选择实验 用白色、黑色、蓝色大小相等、不透光彩布(长 0.60 m × 宽 0.45 m)将水族箱底部铺设成面积相等的 3 个区域,再将 2 只 15 W 白

炽灯作为唯一光源置于水族箱的正上方,调节两灯间的位置,使 3 个等面积区域的光照强度均为 20~25 lx (图 2)。每组实验结束后交换底质位置,消除位置适应性误差。

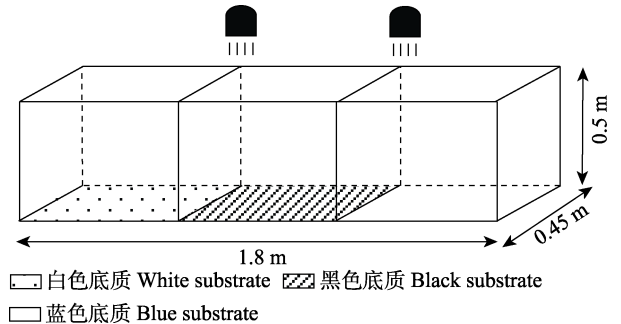


图 2 底质颜色实验示意图

Fig.2 Sketch map for substrate color preference test

底质颜色选择实验与趋光性实验类似。

个体实验: 随机选 20 尾实验鱼,每次放入 1 尾进行实验;统计每尾鱼在各个区域停留的时间,以实验鱼在各个区域的时间百分比平均数作为个体对不同底质颜色的选择性指标。

群体实验: 每组随机挑选 30 尾实验鱼,每次放入 6 尾进行实验;计算每次记录时各个区域实验鱼的数量百分比,以各个区域中的数量百分比平均数作为群体对不同底质颜色的选择性指标。

1.2.3 光照颜色选择实验 在水族箱内用 3 块面积相等的不透光挡板(长 0.45 m × 宽 0.20 m)将水族箱划分为 4 个等面积区域,再以 1 W 的黄色、红色、绿色和蓝色 4 种颜色的 LED 彩灯作为每个等面积区域内的唯一光源,置于水族箱正上方中心的同一平线上,使 4 个等面积区域的光照强度都为 1~3 lx (图 3)。每组实验结束后采用顺时针方向交换光色位置,消除位置适应性和光色组合带来的误差。

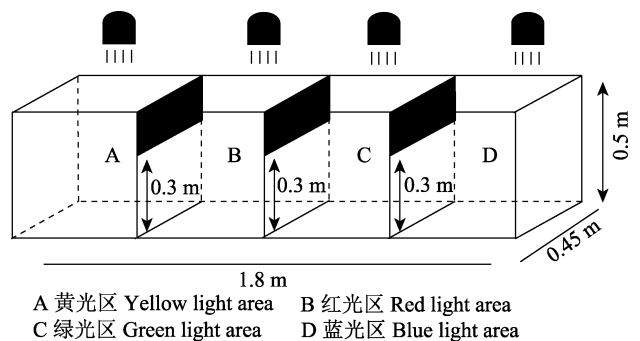


图 3 光照颜色选择实验示意图

Fig.3 Sketch map for light color preference test

个体实验：每次放入1尾实验鱼，共重复20次；统计每尾鱼在各个区域停留的时间，以实验鱼在各个区域的时间百分比平均数作为个体对不同光色的选择性指标。

群体实验：每次同时放入6尾实验鱼，共重复5次；计算每次记录时各个区域中实验鱼的数量百分比，以各个区域中的数量百分比平均数作为群体对不光色的选择性指标。该实验部分参照周显青等(2000)对鱼类光色偏好研究，光照颜色设计为黄色、红色、绿色和蓝色4种。

1.3 数据处理

运用非参数统计方法 Kruskal-Wallis Test 检验各区域内活动时间百分比和分布数量百分比差异显著性，利用单因素方差分析(one-way ANOVA)中 Duncan 法进行多重比较检验两两区域间显著性分析(王恒等, 2014)。数据使用 Excel 2016 和 SPSS 25 软件进行统计分析，结果均采用平均值±标准差(Mean±SD)表示。

2 结果

2.1 趋光性行为

秦岭细鳞鲑稚鱼在3个照度区域(强光区、过渡区和弱光区)内的个体停留时间百分比为(35.49±27.88)%、(27.14±16.71)%和(37.37±31.43)%，实验发现，20尾稚鱼中的3尾行为个性显著，再次统计分析其余17尾的个体停留时间百分比则为(35.60±20.23)%、(32.51±11.81)%和(31.89±21.38)%；以上各照度区差异均不显著($P>0.05$)。群体分布尾数数量百分比为(21.33±10.24)%、(36.00±5.08)%和(42.67±10.24)%，群体在强光区的分布尾数数量百分比低于弱光区和过渡区，且差异显著($P<0.05$)，弱光区和过渡区间无显著性差异($P>0.05$)，表明群体对强光有负趋向性(图4)。

2.2 底质颜色选择

实验照度范围为20~25 lx，秦岭细鳞鲑稚鱼在3种颜色底质(白色、黑色和蓝色)内，个体停留时间百分比依次为(22.13%±17.46)%、(55.48±20.62)%和(22.39±14.45)%，在黑色底质区域活动时间百分比显著高于其他区域($P<0.05$)；群体分布尾数数量百分比依次为(16.00±10.58)%、(58.33±17.16)%和(25.67±12.05)%，群体在黑色底质的数量百分数高于白色底质和蓝色底质，且差异显著($P<0.05$)，白色底质和蓝色底质间无显著差异($P>0.05$) (图5)。结果表明，秦岭细鳞鲑稚鱼偏好于黑色底质，对白色底质和蓝色底质均偏好不明显。

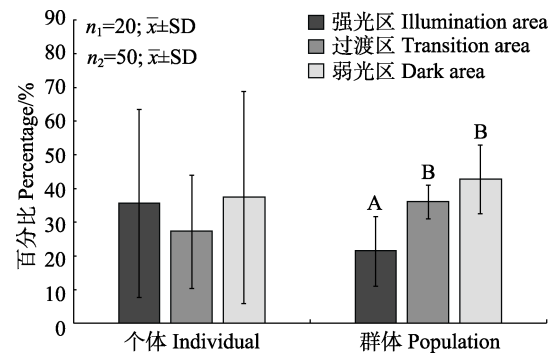


图4 秦岭细鳞鲑稚鱼趋光性

Fig.4 Preference for illumination intensity of juvenile *B. tsinlingensis*

n_1 表示个体实验的样本量； n_2 表示群体实验的样本量。

不同字母表示差异显著($P<0.05$)。下同。

n_1 denotes the sample size of individual experiments; n_2 denotes the sample size of population experiments. Different letters indicate significant differences ($P<0.05$).

The same as below.

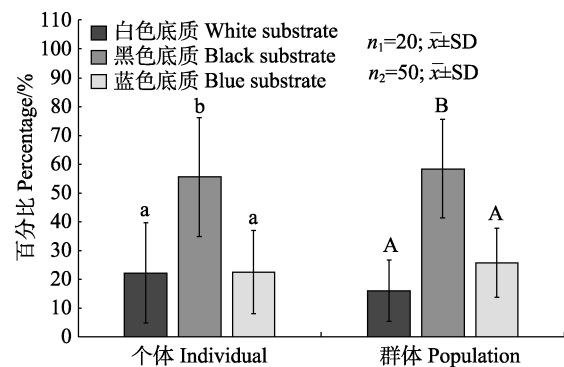


图5 秦岭细鳞鲑稚鱼对底质颜色的选择

Fig.5 Preference for substrate color of juvenile *B. tsinlingensis*

小写字母代表不同处理组个体之间的差异性；大写字母代表不同处理组群体之间的差异性。Lowercase letters represent the variability between individuals in different treatment groups, and uppercase letters represent the variability between groups in different treatment groups.

2.3 光照颜色选择

实验照度范围为20~25 lx，秦岭细鳞鲑稚鱼在黄、红、绿和蓝色4种光照颜色区域内，个体停留时间百分比依次为(26.15±23.72)%、(28.38±20.12)%、(24.29±17.81)%和(21.19±16.77)% (图6)，在蓝色区域的分布率(34.33±14.07)%最高，黄色(33.00±14.20)%次之，绿色区域的分布率最低，仅(12.67±3.65)%，蓝光和黄光显著高于绿光($P<0.05$)，对4种光照颜色的喜好排序：蓝色>黄色>红色>绿色。稚鱼在绿光分布尾数数量百分比低于其他光区，且差异显著($P<0.05$) (表2)，蓝

光和黄光区间无显著性差异($P>0.05$), 群体对绿光有负趋向性。

表2 秦岭细鳞鲑稚鱼在4种颜色区域的分布率及差异显著性

Tab.2 Distribution rate and significant difference of juvenile *B. tsinlingensis* in four kinds of color regions

光色 Color	分布尾数 Distribution number	分布率 F Distribution rate F /%	多重比较结果 Multiple comparison results
蓝色 Blue	103	34.33	A
黄色 Yellow	99	33.00	A
红色 Red	60	20.00	AB
绿色 Green	38	12.67	B

注: 不同字母表示差异显著($P<0.05$)。

Note: Different letters indicate significant differences ($P<0.05$).

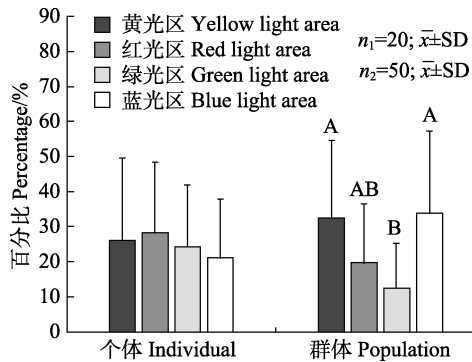


图6 秦岭细鳞鲑稚鱼对光照颜色的选择
Fig.6 Preference for light color of juvenile *B. tsinlingensis*

3 讨论

3.1 秦岭细鳞鲑稚鱼的光照强度选择

鱼类对光刺激产生定性运动的特征称为趋光性, 不同鱼类对光强的敏感性不同, 朝向光源运动称为正趋光性, 背离光源运动称为负趋光性(俞文钊, 1981)。鱼类对光照强度的选择是其对栖息选择的适应表现, 许多中上层鱼具有正趋光性, 如罗非鱼(*Oreochromis niloticus*) (杨弘等, 2011)、大西洋鲟(*Acipenser sturio*) (Kynard *et al*, 2002)、鲫(巩建华等, 2016)等。而底栖性鱼类由于栖息、索饵、繁殖于河底, 光线对其作用较弱, 对光照刺激呈现负趋光性(茅绍廉, 1985), 如瓦氏黄颡鱼(*Pelteobagrus vachelli*) (路波等, 2012)、大西洋鲑(Pinhorn *et al*, 1965)。本研究发现, 秦岭细鳞鲑稚鱼对光照强度呈负趋向性, 与秦岭细鳞鲑自然种群喜好遮蔽度高的山涧溪流深潭等昏暗环境相吻合。鱼

类的趋光性是鱼类探寻适宜照度的结果, 并经常在该照度的水域内集群(蔡厚才等, 1988), 四川裂腹鱼(*Schizothorax kolzovi*)常在10.0~39.5 lx照度范围内集群明显(董登攀等, 2021), 与秦岭细鳞鲑稚鱼在1~10 lx照度区域集群明显不一致。行为是生物长期进化的结果, 鱼类所选择的生活条件及行为也是其长期进化的结果(Clarke *et al*, 1981), 集群行为可以更快获取信息、有效躲避敌害、增强适应能力(周应祺等, 2013)。秦岭细鳞鲑稚鱼对光照强度的负趋向性以及弱照度下的集群行为都是其对栖息地选择的自然进化表现。鱼类视觉器官中视网膜形态组合与其生存的环境相适应, 其中, 视柱细胞对光照强度较为敏感, 可以分辨明暗(蔡厚才等, 1988), 秦岭细鳞鲑趋向弱光与视网膜形态结构的关系还有待后续研究。

3.2 秦岭细鳞鲑稚鱼的底质颜色选择

秦岭细鳞鲑稚鱼游经黑色底质的水族箱区域时游动缓慢、停留时间长, 说明其对黑色底质有明显偏好, 与依靠嗅觉夜间摄食的革胡子鲶(*Clarias gariepius*) (汪留全等, 1990)、黑斑原鲌(席杰等, 2021)、黄颡鱼(*Pseudobagrus fulvidraco*) (路波等, 2012)偏好一致。施德亮(2012)对秦岭细鳞鲑的摄食习性观察发现, 黄昏或黑暗条件下摄食效果最佳, 而此条件下难以依靠视觉发现食物或捕获饵料, 间接说明选择黑色底质可能更多作为寻找安全栖息地的信号。本研究中, 秦岭细鳞鲑稚鱼偏好黑色底质, 这可能是由于在光照环境下当光穿过水层照射在黑色底质时能形成相对较暗的水域环境, 有利于提供安全的藏匿环境。吴金明等(2017)研究表明, 秦岭细鳞鲑自然种群常选择两岸植被茂盛、遮蔽度高、石砾底质的山涧溪流深水区栖息, 而当光穿过栖息地同样会形成昏暗的环境。因此, 秦岭细鳞鲑稚鱼对黑色底质的偏好性是对栖息地适应性的选择, 其适应性意义主要是为了躲避敌害避免被捕食、提高生存能力。

3.3 秦岭细鳞鲑稚鱼的光照颜色选择

秦岭细鳞鲑稚鱼在黄色、红色、绿色和蓝色4种光色区域具有选择性停留, 并且会尝试其他区域, 当其游经绿色区域时表现为游动突然加速通过该区域或者选择回避该区域, 表现出惊慌不安远离逃窜, 趋避行为明显; 在黄色区域表现出游泳缓慢、有序游动, 自主巡游, 活动稳定; 以上说明秦岭细鳞鲑对黄光具有正趋向性, 而对绿光具有负趋向性, 充分证明秦岭细鳞鲑具有一定的辨色能力。根据光谱理论可知, 由于水的吸收和反射作用, 太阳光穿过水层时, 大部分

红光会被滤掉(Volpato *et al.*, 2001; 张延青等, 2020), 水体底层主要以蓝绿光为主。秦岭细鳞鲑常栖息于黑色底层, 其视觉特征与自然栖息环境相适应。罗会明(1985)研究表明, 鱼类在游动过程中会对看到的灯光感到好奇, 因而产生探索性反射, 趋向光源。当红光突然出现时可能会与秦岭细鳞鲑喜好的栖息环境出现较大反差, 产生探索性反射而趋向光源。因此, 秦岭细鳞鲑对红光具有探索性趋向, 而对绿光具有趋避性, 在培育过程中避免使用红色和绿色光源, 可以降低秦岭细鳞鲑对环境的探索和趋避行为, 从而有效减少应激反应、提高成活率。

3.4 秦岭细鳞鲑稚鱼个体、群体间选择行为差异

鱼类个体行为在不同情境下表现出稳定的差异称为“个性”, 群体间的个体行为差异有利于集体协同作用(张东等, 2021)。本研究表明, 秦岭细鳞鲑个体、群体间的底质颜色选择结果保持一致, 而光照强度和光照颜色选择实验中个体、群体间的结果有趋向性分歧; 秦岭细鳞鲑稚鱼个体对光照强度和光照颜色趋向性不明显, 而群体对强光和绿光负趋向性明显。张婧等(2017)认为, 具有“冒险型个性”的个体能对环境进行快速探索, 因此, 在群体中通常占据主导地位。秦岭细鳞鲑与褐鳟(*Salmo trutta*)、虹鳟等群体中也有“冒险型”的个体(Fredrik *et al.*, 2004; Sneddon, 2003)。同时, 鱼类在集群中可以通过个体间相互传递信息(周应祺等, 2013), 秦岭细鳞鲑群体中“冒险型”个体将环境信息传递给其他鱼, 使其更快地趋避不利环境, 即减少探索时间, 有更多时间停留在适宜照度和光色区域, 导致群体趋避性明显(任为公, 1992)。个体和群体不同的现象原因有多种, Chan等(1997)对海湾鲟(gulf sturgeons)研究发现, 群体间由于存在种内斗争会对卵石回避或无选择, 而个体选择卵石; 大型鱼类中华鲟群体由于部分进入亮光区的幼鱼进行适应性圆周运动, 迫使其他幼鱼更多停留在过渡区, 而个体更多停留在亮光区(王恒等, 2014)。本研究中, 秦岭细鳞鲑稚鱼群体能更快趋避强光区和绿光区, 停留时间较短, 而个体停留时间较长, 这可能是集群后群体与个体信息传递特征或环境反应机制不同所导致。

4 结论

秦岭细鳞鲑属冷水性鱼类, 生长缓慢, 应激性强, 基于研究结果并结合秦岭细鳞鲑早期生物学特性, 建议在秦岭细鳞鲑苗种培育与资源增殖过程中, 尤其是

在稚鱼期, 其光照强度设置为 1~10 lx, 使用黑色或深色底质的养殖设施, 避免使用绿色和红色光色的光源, 以上措施将会利于秦岭细鳞鲑稚鱼集群行为产生, 降低应激行为频次和减少能量消耗, 从而使其生长发育、摄食和存活率等方面得到改善。需要强调的是, 本研究仅针对秦岭细鳞鲑早期发育关键阶段, 关于其他发育阶段及其行为规律有待于后续进一步研究。

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Selective Behavior of Juvenile *Brachymystax tsinlingensis* Depends on Substrate Color, Light Intensity, and Light Color

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Abstract *Brachymystax tsinlingensis* is a unique cold water fish locally distributed in China, belonging to Salmoniformes, Salmonidae and *Brachymystax*. It is mainly distributed in the mountain streams of the Qinling

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mountain range, including the Shitouhe River in the northern foothills, the Heihe River in the eastern foothills and the Taibaihe and Xushuihe rivers in the southern foothills. *B. tsinlingensis* has high sensitivity owing to demanding natural habitat conditions and special biological properties. In the past few decades, environmental pollution, a variety of human-caused threats, and reduced resources has caused drastic declines in the wild populations of *B. tsinlingensis*. In 1998, the species was listed as a second-class state-protected wild animal in the China Red Data Book of Endangered Animals. Due to environmental disruption and human impacts, wild numbers of this species have declined quickly. In China, researchers have focused on *B. tsinlingensis* conservation. Artificial propagation is one of the most effective methods to restore the natural populations of *B. tsinlingensis*. In recent years, initial breakthroughs in artificial propagation techniques have aided this species, but the fry survival rate remains relatively low. During artificial breeding experiments, we identified the light environment and substrate conditions that are important factors affecting the survival rate of fry. Fry behavioral selection of light and substrate characteristics was highly significant. The aim of this study was to identify the habitat preferences and associated behavior of *B. tsinlingensis*. Behavioral experiments were conducted on the progeny of *B. tsinlingensis* in response to the light environment and substrate color. In this study, we randomly selected healthy juveniles from the same offspring batch obtained through artificial propagation as the experimental fish. The fry total length ranged from 2.23–4.57 cm, with an average of (3.31±0.67) cm. Fry weight ranged from 0.21–0.77 g, with an average weight of (0.42±0.18) g. The experimental fish were not fed 2 h before initiating the experiment. We undertook a combination of individual tests and population tests to investigate three different behavioral selection experiments on juveniles: substrate color preference with the substrate colors of black, white, and blue; light intensity preference with the light intensity of dark (from 1 lx to 5 lx), transition area (from 5 lx to 10 lx), and illuminated area (from 10 lx to 25 lx); light color preference with the light colors of yellow, red, green, or blue. The statistical analysis of the percentage of residence time and the distribution number of experimental fish in each area, enabled analysis using a selective index for the different light intensities, different light colors, and different substrate colors. All analyses used Excel 2016 and SPSS (V 25.0) software, and the statistical values were expressed as the mean ± standard deviation. The results showed that the percentage of time the individuals resided in the black substrate area was significantly higher than that in the white or blue area ($P<0.05$). The percentage of the population distributed in the black substrate area was also significantly higher than that in the white or blue area ($P<0.05$). Therefore, the majority of the fish preferred the black substrate. The fish swam slowly through the black substrate area in the substrate color experiments. Secondly, in the phototropism experiment, there was no significant variation in the duration of each individual in the three light intensity areas ($P>0.05$), and the percentage of the population in the illuminated area was significantly lower than that in the dark area and the transition area ($P<0.05$). There was no significant difference between the dark area and the transition area. The population had a negative tendency to the illuminated area, and fish were observed clustering in the dark area and the transition area. Moreover, individuals did not differ significantly in the percent of time they resided in the four light color areas ($P>0.05$). However, the percentage of individuals in the green light area was significantly lower than that in other areas ($P<0.05$). The population had a negative tendency towards the green light, and fish displayed sudden acceleration when swimming through the green area in the light color selection experiment. Consequently, the population had a more pronounced avoidance than the individual experiments, this might be related to the mutual transmission of information when residing in clusters, and the speed of information transmission in groups encouraging individuals to avoid the adverse environment. Juvenile *B. tsinlingensis* preferred a black substrate, avoided green light, and their optimum illumination range was 1–10 lx. The results provide scientific guidance for environmental fry rearing and releasing of *B. tsinlingensis*.

Key words Substrate environment; Light; Behavior selectivity; *Brachymystax tsinlingensis*; Juvenile