

Research Article

Combined effectiveness of light and bait to enhance trapping for monitoring and removal of invasive crayfish: virile crayfish example

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Abstract

Invasive populations of crayfish are a major threat to native aquatic ecosystems around the world. The virile crayfish (*Faxonius virilis*) has become problematic outside of its native range in North America. Use of minnow traps is a common method used to detect the presence of and reduce invasive crayfish numbers. The primary goal of this study was to determine if the effectiveness and practicality of control through trapping for invasive crayfish could be significantly improved with the addition of lights. From this study, we found virile crayfish were attracted to white light and avoided blue light in the laboratory. In pond trials, traps with white or blue lights had catch per unit effort (CPUE) greater than traps without light, and traps with white lights had a CPUE nearly twice that of traps with blue lights. The addition of white lights to traps with food led to a nearly three-fold increase in CPUE than white light alone or two-fold for food bait alone. We found a continued decline in capture rates from the same pond over 3 days of trapping where captured crayfish were not returned to the pond. The continued decline in catch rate of new individuals suggests that our trapping may have been having a significant effect on the density of crayfish remaining in the pond. In addition, the size distribution of the crayfish collected during these trapping studies showed that the effort appears to be effective at collecting both juvenile and adult crayfish across almost all sizes. This would suggest that the combination of white light and bait is effective in the management of invasive crayfish populations.

Key words: *Faxonius virilis*, invasive species, management methods, animal behavior, freshwater crayfish

Introduction

Because of their ability to alter ecosystems (Statzner et al. 2000) and compete with native species for resources, invasive crayfish can have detrimental effects on aquatic communities (Strayer 2010). In both Europe (Lozán 2000) and North America (Smith et al. 2019) invasive populations of crayfish have become established. In Europe, non-native crayfish species outnumber native species, potentially acting as disease vectors and competitors (Holdich et al. 2009). North America, in contrast to Europe, has a greater number of native crayfish species which tend to occupy smaller geographic ranges. This pattern of species distribution could lead to loss of species under

similar pressure from invasive species (Lodge et al. 2000). The likely vulnerability of North American crayfish and their economic importance in some regions, such as Louisiana, makes the development of methods for the control of invasive crayfish species imperative to limit the extent and impacts of invasions in North American waters (Larson and Olden 2011). Management strategies informed by knowledge of species behavior and physiology are more likely to be successful in controlling invasive species while limiting the deleterious effects of those strategies on native species (Lennox et al. 2015). Therefore, increasing our understanding of crayfish behavioral characteristics could aid in management of invasive populations. Two species of crayfish that have become the most problematic outside of their native range in North America are the virile crayfish (*Faxonius virilis* Hagen, 1870) and the red swamp crayfish (*Procambarus clarkii* Girard, 1852; Larson and Olden 2011). The native range of the virile crayfish is the north-central United States and southern Canada while the red swamp crayfish is native to the southern United States and northern Mexico; each species is considered invasive in the other's native range. Both species have been shown to negatively impact native crayfish populations and the aquatic communities where they have been introduced (James et al. 2016; Souty-Grosset et al. 2016), making early detection and effective management important. One method that is frequently used to detect the presence of and reduce invasive crayfish populations is trapping (Hein et al. 2007), so improving the efficiency of traps at catching these species may improve the effectiveness and practicality of control efforts.

One potential method of improving the effectiveness of crayfish trapping is the use of light as an attractant. Numerous studies have documented differing effects of light on behavior and capture of crayfish and other aquatic invertebrate species. The addition of lights to traps led to increased catch per unit effort in northern shrimps (*Pandalus borealis* Krøyer, 1838) with bycatch also being altered by the wavelength of light (Bouwmeester 2018). For red swamp crayfish, lighted traps in some cases caught more crayfish than un-baited traps but were outperformed by traps with fish bait (Ahmadi and Archdale 2008). Kozák et al. (2009) found that in some trials red swamp crayfish preferred lighted areas of an indoor trough, but a preference for the ends of the trough were more significant than any light response. Thomas et al. (2016) found that exposure to artificial lights led signal crayfish (*Pacifastacus leniusculus* Dana, 1852) to become less active and spend more time under cover. Another study found that exposure to both higher intensity lights up to 32 lux and ultraviolet light, altered the number, length, and intensity of agonistic interactions between individuals of two crayfish species (virile crayfish and rusty crayfish; *Faxonius rusticus* Girard, 1852; Jackson and Moore 2019). Additionally, ultraviolet light (10–400 nm) has also been shown to alter crayfish behavior and physiology (Jackson and Moore 2019).

The current understanding of movement in response to light can be used in conjunction with novel studies to conduct research focused on suppressing or eradicating populations of invasive species, e.g., virile, red swamp, and signal crayfish. Because of the variety of responses from different species of crayfish, increasing our understanding of how individual species respond to light is crucial to predicting the efficacy of light-based trapping for invasive species.

In addition to light as a potential attractant, food baits are also used to entice crayfish into traps. One study suggests that meat-based baits (chicken neck, fish, pork liver) and cereal-grain based dog food placed in traps could increase the overall size of individuals caught in traps for two crayfish species, common crayfish (*Cambarus bartoni* Fabricius, 1798) and virile crayfish (Somers and Stechey 1986). However, for Danube crayfish (*Pontastacus leptodactylus* Eschscholtz, 1823) non-baited traps had a greater catch per unit effort than fish baited traps (Bolat et al. 2011). There is also the potential for an interaction of bait and light which may increase trapping efficiency. In this study we investigated the effects of light on virile crayfish behavior using laboratory trials. We then used pond trials to test the effects of light, bait, and a combination of the two on the efficiency of crayfish traps for catching virile crayfish.

Objectives for the study were (1) observe and assess behavioral responses of virile crayfish to external stimuli (visible light) in a controlled environment to determine avoidance and/or attractant behavior. (2) Apply visible light stimuli (based on objective 1), with the addition of food as bait, to stationary minnow traps in an outdoor research pond and measure potential attractant behavior determined by catch per unit effort (CPUE) of virile crayfish.

Materials and methods

Study organisms and culture

During 2022 and 2023, we trapped and cultured virile crayfish from culture ponds at the U.S. Geological Survey Columbia Environmental Research Center (USGS CERC), Columbia, MO 65201 (38.911987°N, 92.276821°W) using minnow traps (Gee's G-40 Galvanized Minnow Trap; Tackle Factory: Fillmore, NY, USA) that were fed with extruded slow-sinking pellets (EXTR 450 Sturgeon Feeds; Rangen Connatural Products: Buhl, ID, USA). We trapped crayfish to be used for behavior tank trials and kept them in one indoor flow-through raceway (2.69 meters [m] × 0.55 m) with receiving water heated to 20 degrees Celsius (°C) that was supplied from a nearby well, which was the same water source for the experimental behavior tanks and research ponds. We placed polyvinyl chloride (PVC) pipe segments (15.24–20.96 centimeter [cm] lengths by 3.81–5.72 cm inner diameter) in the raceway to provide artificial shelter for crayfish, which we kept on a 12-hour light cycle. We fed crayfish 15 cubic centimeters (cm³) extruded slow sinking pellets three times per week until experiments began. We did not use any crayfish for more than one trial during the laboratory trials.

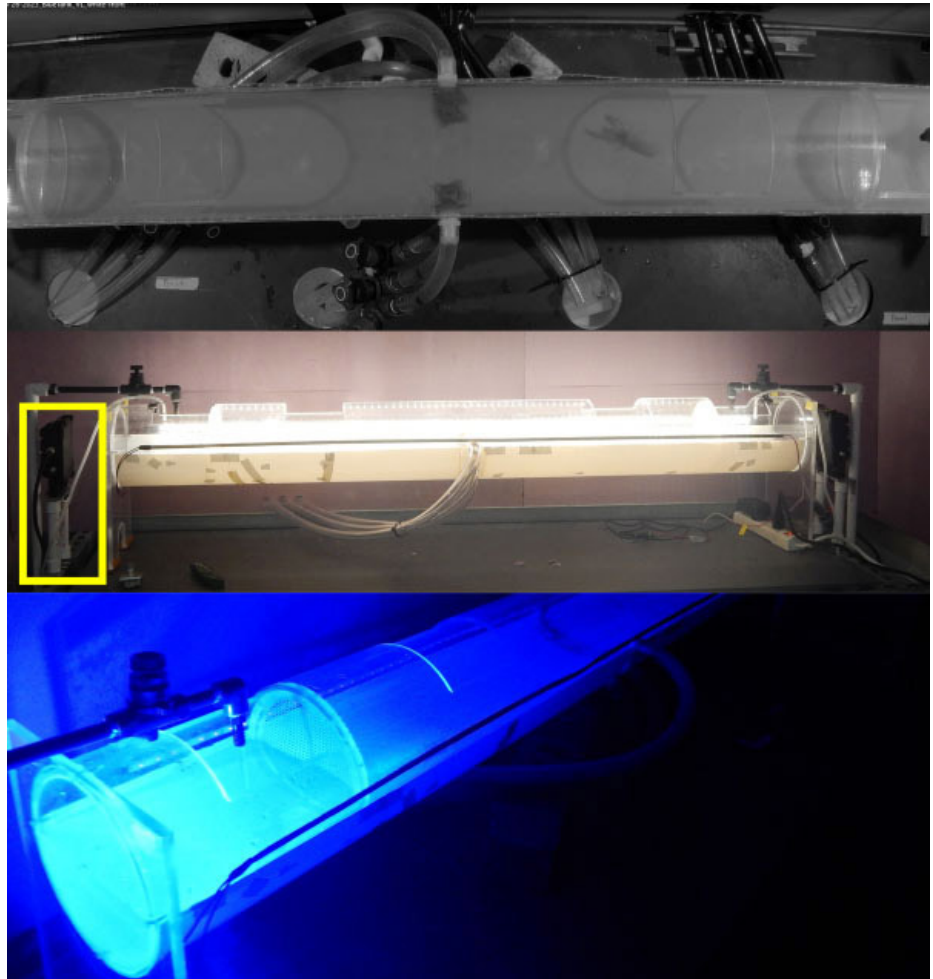


Figure 1. Tank used to test the responses of virile crayfish (*Faxonius virilis*) to light stimulus. Upper picture is the top down view with crayfish in tank, middle picture the side view with light source indicated by a yellow box, and lower picture shows end of tank with blue light treatment. See Figure 1 in Wildhaber et al. (2024) for a more detailed schematic of the experimental tank. Photos by Zachary D. Beaman and Mark L. Wildhaber.

Laboratory trials

To determine the effects of visible light, we used two plexiglass cylindrical tanks in an enclosed system that kept outside light and sound from interfering with trials (Figure 1). The tanks were isolated from each other by a 1.27 cm thick foam board insulation sheathing panel and a 0.64 cm thick foam board surrounding both tanks. Water filled each tank to roughly half (10 cm height) by an inflow of water controlled by a needle valve on both ends of the tank, then shut off prior to initiation of the trials. The tanks were designed to allow water to drain from the center by six drain tubes, three on each side vertically stacked. However, for this study the drains were closed during trials to ensure no movement of water through the tanks (Figure 1). Two infrared (IR) lights (Bosch EX12LED8W; Bosch Security Systems: Fairpoint, NY, USA) were mounted at each end of and above the tanks to allow subjects to be visible to an IR-detecting camera for tracking during periods with no visible light. There was one opening (window) (12.7 cm × 12.7 cm) at each end of the top of the tank for introduction of the

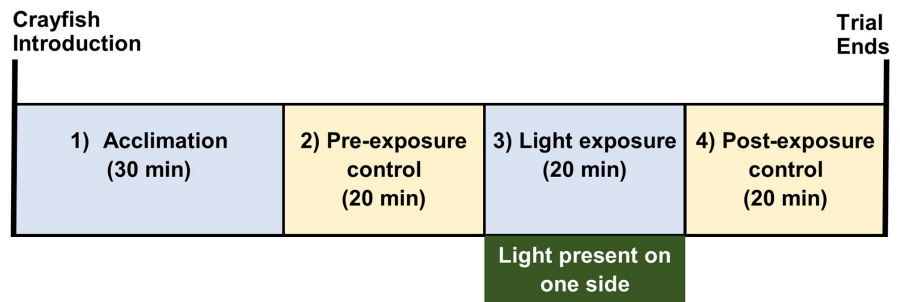


Figure 2. An illustration of time periods for each trial. Light tank trials consisted of a 30-minute acclimation period after crayfish were placed in the tank to allow the crayfish to acclimate to the tank. This was followed by a 20-minute control in which the crayfish was tracked for comparison to the light exposure period. At the beginning of the 20-minute light exposure period, an LED array was turned on to emit a specific color of light from one end of the tank. At the end of the light exposure period, the light was switched off and the crayfish was monitored for an additional 20-minute post-exposure control period.

study crayfish. To fill the tank for the trials we used well water set at a controlled temperature of 20 °C. At each end of the tank there was one LED light (10W 12V RGBW Flood Light [Model Number: FL-RGBCW10-MZ]; Super Bright LEDs: St. Louis, MO, USA) with adjustable color outputs that could be controlled separately.

Prior to the beginning of each trial and immediately after the trial concluded, we measured water quality (dissolved oxygen [milligrams per liter; mg/L] and temperature [°C]) at the flow-through raceway and at both ends of the experimental tanks (see below). Water temperature in the trail tanks ranged between 19.3 and 21.0 °C, dissolved oxygen ranged from 8.15 to 8.51 mg/L. We ran trials consisting of 4 time periods (acclimation, pre-exposure control, light exposure, and post-exposure control). The acclimation period began as soon as crayfish were introduced into the tank and lasted for 30 minutes (min). The pre-treatment control period began immediately after the acclimation period ended and lasted for a total of 20 min. The visible light exposure period began immediately after the pre-treatment control period ended and lasted 20 min. Lastly, the post-exposure control period began immediately after the visible light exposure period ended and lasted for a total of 20 min (Figure 2). For each test trial, we introduced crayfish into one of the tank windows (the introduction window was selected by a pre-determined, randomized order) of both of two tanks (152 cm length × 18 cm width × 18 cm height). We recorded crayfish movement behavior during pre-exposure control, exposure, and post-exposure control time periods. We compared pre-exposure control and post-exposure control period tank usage (proportion of time) and movement patterns (velocity [centimeters per second; cm/s], and acceleration [centimeters per square second; cm/s²]) to each other and to the exposure period to account for individual crayfish tank biases and residual effects of the exposure period.

We conducted behavior trials in the laboratory using four wavelengths of visible light spectra: blue (450–495 nanometers [nm]), green (495–570 nm), red (620–750 nm), and white (400–700 nm) (10 trials per wavelength or 40 trials). Before each trial with the lights turned to their predetermined color, we placed a piece of white paper in front of the light and photographed it, then analyzed the photo with MATLAB to determine the overall red-green-blue (RGB) values (The MathWorks Inc. 2022). Before each trial, we used a lux meter to measure the intensity of the lights used during the trial. Light intensities ranged 150–180 lux. Using the lux meter, we were able to get the two lights within 10 lux of each other. We left IR lights on for all three time periods so that the crayfish could be monitored and tracked during the periods when the tanks were completely in the dark. To record crayfish movements, we used video monitoring software (Wisenet NVR [XRN-1610SA]; Hanwha Vision: Seongnam, South Korea) with one camera (Wisenet Q-series [QNO-7080R]; Hanwha Vision: Seongnam, South Korea) mounted above each tank. We collected data using video tracking software (Noldus EthoVision XT Version 15.0.1418; Noldus: Wageningen, The Netherlands) to track crayfish movement and behavior patterns post trials from the recorded videos.

After the completion of the trials we sexed, weighed in grams (g) using a scale (Mettler PM4800 Delta Range; Mettler-Toledo: Columbus, Ohio, USA), and measured carapace length to the nearest tenth of a millimeter (mm) with calipers (Kobalt 293883; Lowe's Companies, Inc.: Mooresville, NC, USA). Crayfish sex was determined by the presence of gonopods for males or the presence of a circular seminal receptacle for females (Huner and Barr 1991). We then placed crayfish into a sealable plastic bag to be humanely euthanized in a -20°C freezer.

Laboratory video capture and processing

Recordings were extracted and converted to MP4 format using software associated with the recording equipment (Wisenet Wave; Hanwha Vision: Seongnam, South Korea). Individual trial videos were analyzed at 10 samples/second using video tracking and analysis software, or “VTAS” (Multiple Body Points and Multiple Arenas Module within Ethovision XT Version 15.0.1418). Each tank was assigned one arena (a region in the video image where the subject will be tracked). The arena was divided into two equal segments (i.e., front and back ends of the tank). Three trial control settings were created to isolate the periods of the trial we wanted to track and analyze (pre-exposure control, light exposure, and post exposure control).

Field trials

Based on results from laboratory trials, we conducted two sets of night field trials, one focusing on effectiveness of light alone on trapping followed by a second set assessing the effectiveness of light color for trapping (see results)

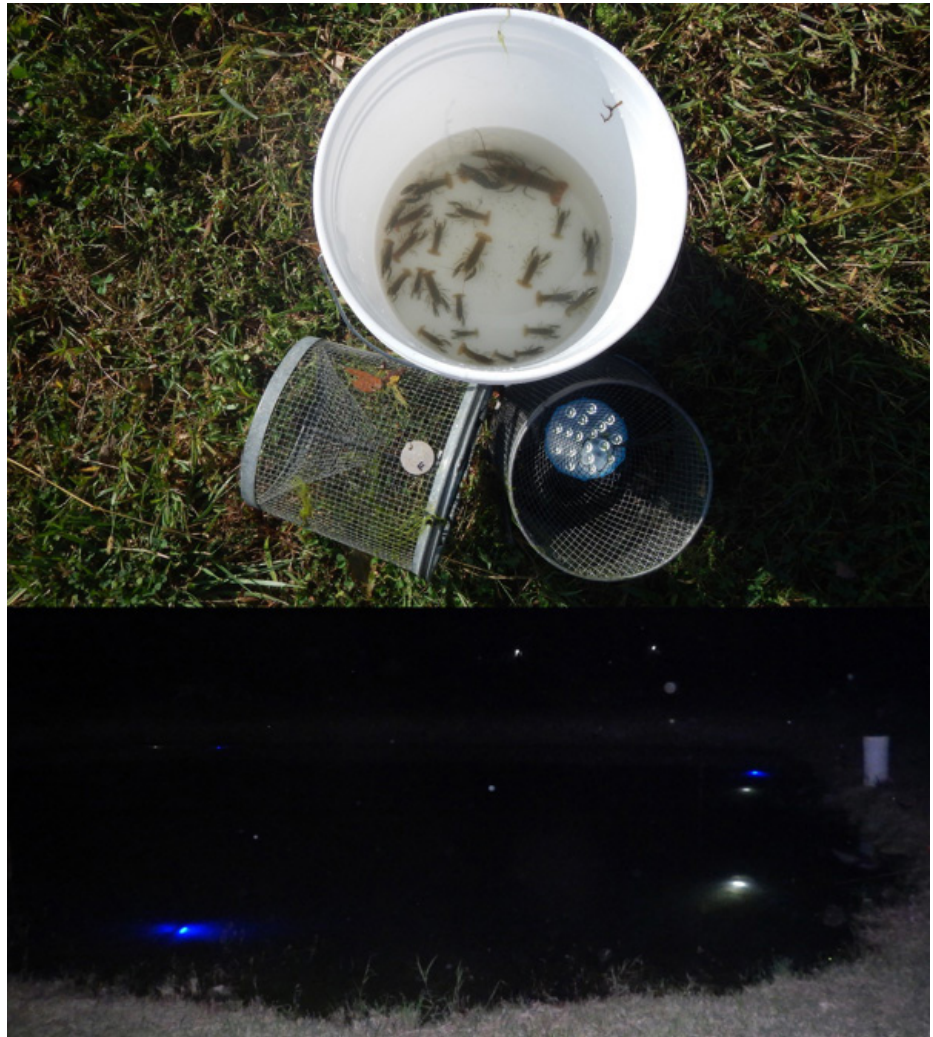


Figure 3. Lighted minnow traps used in pond trapping trials placement for pond trials. Upper picture shows a bucket containing virile crayfish (*Faxonius virilis*) trapped with white light turned on in the trap (lower right of picture). Lower picture is the Columbia Environmental Research Center, Columbia, Missouri, USA pond in which the traps were placed with the lights turned on and visible at night. Photos by Zachary D. Beaman (top) and Kendell R. Bennett (bottom).

from the first set compared to that of baited alone and baited plus light trapping. September 21 through 27, 2023 we conducted the first set of trials to determine the effects of visible light on the effectiveness of crayfish trapping. We conducted the trapping in a 0.02-hectare (ha; $\sim 17\text{ m} \times \sim 12\text{ m}$) rocky/silty-bottom outdoor research pond at USGS CERC, using the most effective light colors from the earlier trials set at maximum setting of 400 lumens (LyLmLe Rechargeable, 5.9" RGBW LED Submersible Pool Lights; Shenzhen Raypole Technology Co., Ltd.: Shenzhen, China). Prior to deployment, we fitted each trap with two rechargeable pool lights, both facing out in either direction towards the modified openings of the minnow trap (Figure 3). For the traps with lights present the opening was increased from approximately 3 cm to approximately 5 cm. For each trial, we randomly assigned traps to one of four treatments (i.e., blue light, white light, light present but turned off, and no light present) and distributed them in a randomized block design in four sets (i.e., 16 traps total) with traps

equidistantly apart (~ 3 m) around the pond. Traps with no lights and traps with lights present but switched off were included as controls to ensure that any measured difference was not due to the introduction of an obstruction in the trap by the addition of the pool lights. When we deployed traps in the pond, the openings of the traps were oriented parallel to the bank (approximately 2 m from shore). We deployed traps between 1550 and 1750 on each day and retrieved them shortly after 0900 the following morning. We recorded species, sex, and carapace length of each crayfish caught, and then released them into an on-site lagoon known to contain virile crayfish, located approximately 0.4 kilometers (km) from the study pond. For all field trials, we used total crayfish captured in traps for any overnight set as our measure of CPUE. We cleaned traps after every trial to ensure any debris that had gotten caught while pulling them from the ponds would not interfere with the next planned trials. Taking of water temperature on the days of the actual trials was not performed for this first set of trials. To obtain approximate water temperature during the September pond trials, we measured water temperature and turbidity at each corner of the pond on October 3, 2023, with depth estimates taken roughly where the traps would have been during these light trials. Based on historical air temperature records, obtained from the NOAA online weather data for Columbia Regional Airport, MO, USA, the air temperature when the measurements were taken were similar to the air temperatures when the September trials were conducted (NOAA 2025). Based on the recorded air temperature information, we assume water temperature for the September trials would have been similar to those recorded on October 3, 2023.

To further investigate the effects of light and bait on crayfish capture we conducted the second set of pond trials between November 7 and 17, 2023. We used 15 of the original 16 traps focusing on only white light with the additional element of bait in the form of dry pellet dog food (Ol' Roy Complete Nutrition Roasted Chicken & Rice Flavor Dry Dog Food; Ol' Roy: Brentwood, TN, USA). Traps baited with dog food had dog food pellets placed in a 4 oz/100 milliliter (mL) plastic vial with six holes drilled into them. For each trial, we randomly assigned traps to one of three treatments (i.e., white light only, dog food only, and white light with dog food) and distributed them in a randomized block design in five sets (i.e., 15 traps total) with traps equidistantly apart (~ 3 m) around the pond at depths ranging from 31.3 to 57.4 cm. In addition to the data collection described for the previous set of field trials, before collecting the traps, water temperature, depth, and turbidity were measured.

Data analysis

For laboratory trials, we conducted four primary analyses with post-hoc pairwise tests if model factors were significant (Wildhaber et al. 2025). For the first three analyses, we used a different response for each analysis, and

we calculated potential behavior responses as (value during exposure period) – (value during pre-exposure control). The first response variable was proportional usage i.e. the change in proportion of time spent on the side where the light stimulus was introduced. This metric addressed our prediction that crayfish would be attracted to certain visible light colors by spending more time in the side of the tank with the visible light stimulus than it had during the pre-exposure control period. A positive change in this value would indicate attraction, and a negative avoidance. The response variables for the second and third analyses were changes in mean velocity and mean acceleration, respectively, across individual trial periods. These metrics were used to assess how the light altered activity levels. The fourth laboratory trial analysis was developed after qualitatively observing an apparent residual effect of light on proportional usage from the exposure period to the post-exposure period. Therefore, we also calculated slope for each trial using pre-exposure control, exposure, and post-exposure control periods as x-values of 1, 2, and 3, respectively, and proportional usage for each period as y-values. This slope-based response variable was used to incorporate any residual effects of the light treatment on crayfish response.

All laboratory analyses were conducted as linear models with a single factor of light treatment; and they were interpreted as one-factor, type-III analyses of variance (ANOVAs; “lm” function in R [version 4.3.2] followed by the “Anova” function of the “car” R package [version 3.1-2]; Fox and Weisberg 2019; R Core Team 2024). A value of $\alpha = 0.05$ was used for ANOVAs. If the effect of light was statistically significant, we used a set of statistical software packages to perform pairwise comparisons of estimated marginal means (EMM) with a Tukey-method p-value adjustment (“emmeans” function of the “emmeans” package [version 1.8.6] and the “cld” function of the “multcomp” package [version 1.4-25]; Hothorn et al. 2008; Lenth 2021).

Compared to the laboratory trials, the field trials had two key differences that required modifications to data analyses. First, because our data comprised counts (number of crayfish captured in traps), we transformed the response variable to be square root of count to better meet ANOVA assumptions of constancy of variance and normality of residuals (Steel and Torrie 1980). Second, the ponds were not controlled environments, introducing heterogeneity beyond light and bait treatments. Therefore, we tested for the effects of two factors to attempt to account for this variability. Factor 1 was categorical date to account for effects such as day-to-day environmental changes and depletion of crayfish population from previous capture occasions. Factor 2 was spatial block to account for potential uneven distribution of crayfish within a pond.

We performed two sets of analyses for field trials: one used the September 2023 trials comparing the presence and color of light, and the other used the November 2023 trials comparing white light, bait, and the

Table 1. Stacked analysis of variance (ANOVA) tables based on linear models for tank trials of individual virile crayfish (*Faxonius virilis*) that were exposed to one of four colors of visible light (i.e., white, blue, green, and red). For each trial, light was emitted from an LED array at one end of the tank for 20 minutes after a pre-exposure control period where both halves of the tank were illuminated by only infrared light for 20 minutes. For the “Response” column, “Proportion of Time” was the change in proportion of time calculated between the exposure and pre-exposure period for the side from which light was emitted. “Velocity (cm/s)” and “Acceleration (cm/s²)” represent changes in the averages of these values. An average velocity or acceleration was calculated as the mean across each 20-minute period, and the change in velocity or acceleration was calculated as the difference between the light-exposure and pre-exposure period. “Slope of proportion of time” is the slopes from the regression lines of proportion of time spent on the lighted side of a tank across pre-exposure control (Pre), light exposure (Exp), and post-exposure control (Post) periods. The start of each ANOVA table is signified by a horizontal line. R² is the overall adjusted r² for a model. The overall p-value of the linear model is “p(model).” “Term” is the model term; for terms, Light = color of light (e.g., blue) as a factor, Error = error term. For the other columns, “df” = degrees of freedom, “SSE” = sum of squared errors, “MSE” = mean squared error, “F” = F-value of a variable, “p(var)” = p-value of a variable. “Signif.” Is blank if p(var) ≥ 0.05, ** if p(var) < 0.01.

Response	r ²	p(model)	Term	df	SSE	MSE	F	p(var)	signif
Proportion of time	0.11	0.1512	Light Color	3	0.26	0.09	1.86	0.1512	
			Residuals	43	1.98	0.05			
Velocity (cm/s)	0.11	0.1811	Light Color	3	0.65	0.22	1.7	0.1811	
			Residuals	43	5.46	0.13			
Acceleration (cm/s ²)	0.03	0.6731	Light Color	3	0.0001	4.37×10 ⁻⁵	0.52	0.6731	
			Residuals	43	0.0036	8.46×10 ⁻⁵			
Slope of proportion of time	0.27	0.0031	Light Color	3	0.12	0.04	5.37	0.0031	**
			Residuals	43	0.32	0.01			

combination of the two. For both analyses, we used treatment as a single factor; it had four levels of the former (blue light, white light, light turned off, no light installed), and three levels for the latter (white light, bait, and white light + bait). We performed iterative analyses of each set. For initial analyses, we used a multi-factor ANOVA with square root of count as the response variable, a main effect of treatment, and an interaction between categorical date and spatial block (“lm” function in R [version 4.3.2] followed by the “Anova” function of the “car” R package [version 3.1-2]; Fox and Weisberg 2019; R Core Team 2024). If the interaction was not statistically significant at our threshold value of $\alpha = 0.05$, we re-analyzed the data without the interaction, that is, main effects of treatment, categorical date, and spatial block. If either categorical date or spatial block was not a statistically significant factor, we dropped those main effects from our final model. Like the analyses of the laboratory data, we performed pairwise comparisons of all statistically significant main effects and interactions in our final models using estimated marginal means (EMM) with a Tukey-method p-value adjustment (“emmeans” function of the “emmeans” package [version 1.8.6] and the “cld” function of the “multcomp” package [version 1.4-25]; Hothorn et al. 2008; Lenth 2021).

Results

Laboratory trials

Overall, there was no significant difference in proportional usage, velocity, or acceleration among light treatments (Table 1). However, individual t-tests for each light treatment indicated marginal evidence for proportional usage of blue and green light being less than zero (i.e., avoidance; Table 2).

Table 2. Results of multiple-testing adjusted one-way *t*-tests with zero as the hypothesized mean for tank trials of individual virile crayfish (*Faxonius virilis*) that were exposed to one of four colors of visible light (i.e., white, blue, green, and red). For each trial, light was emitted from an LED array at one end of the tank for 20 minutes after a pre-exposure control period where both halves of the tank were illuminated by only infrared light for 20 minutes. For the “Response” column, “Proportion of Time” was the change in proportion of time calculated between the exposure and pre-exposure period for the side from which light was emitted. “Velocity (cm/s)” and “Acceleration (cm/s²)” represent changes in the averages of these values. An average velocity or acceleration was calculated as the mean across each 20-minute period, and the change in velocity or acceleration was calculated as the difference between the light-exposure and pre-exposure period. “Slope of proportion of time” is the slopes from the regression lines of proportion of time spent on lighted side of a tank across pre-exposure control (Pre), light exposure (Exp), and post-exposure control (Post) periods. The data are from trials testing behavioral responses of virile crayfish to of four colors of light. The “*t*” column is the *t*-test statistic; df = degrees of freedom for *t*-test; *p* = unadjusted *p*-value for *t*-test. The “98.75% CI” column shows confidence; this interval was chosen based on a Bonferroni-adjusted $\alpha = 0.05/4 = 0.0125$. The “signif.” Column contains “marginal” if $p > 0.0125$ and ≤ 0.10 , and is otherwise blank.

Variable	Light Color	<i>t</i>	df	<i>P</i>	98.75% CI	signif
Proportion of time	Red	0.065	12	0.9493	−0.1603 to 0.1672	
Proportion of time	Green	−2.053	11	0.0646	−0.3304 to 0.0674	marginal
Proportion of time	Blue	−2.785	9	0.0212	−0.3570 to 0.0275	marginal
Proportion of time	White	−0.066	11	0.9486	−0.2268 to 0.2173	
Velocity (cm/s)	Red	−0.741	12	0.4732	−0.5499 to 0.3353	
Velocity (cm/s)	Green	2.404	11	0.0350	−0.0549 to 0.4303	marginal
Velocity (cm/s)	Blue	−0.958	9	0.3631	−0.3809 to 0.2075	
Velocity (cm/s)	White	0.104	11	0.9188	−0.2101 to 0.2247	
Acceleration (cm/s ²)	Red	0.605	12	0.5565	−0.0040 to 0.0059	
Acceleration (cm/s ²)	Green	0.280	11	0.7844	−0.0081 to 0.0098	
Acceleration (cm/s ²)	Blue	−0.702	9	0.5003	−0.0166 to 0.0107	
Acceleration (cm/s ²)	White	0.726	11	0.4830	−0.0048 to 0.0077	
Slope of proportion of time	Red	−0.724	12	0.4827	−0.0682 to 0.0420	
Slope of proportion of time	Green	0.719	11	0.4874	−0.0674 to 0.1080	
Slope of proportion of time	Blue	−2.578	9	0.0298	−0.1578 to 0.0182	marginal
Slope of proportion of time	White	2.691	11	0.0210	−0.0115 to 0.1612	marginal

Additionally, there was marginal evidence for decreased velocity under green light. On a closer examination of a graph of the results, there appeared to be a residual effect of light treatment on proportional usage (Figure 4, upper four plots). Because of this apparent relationship we analyzed the slope across pre-exposure, exposure, and post-exposure (Figure 4, lower four plots). We found that the slope of proportion of time per trial period significantly differed among light treatments (Table 1). There was marginal evidence for a slope greater than zero for white light and less than zero for blue light (Table 2, Figure 5).

Field trials

Analysis of pond trial trapping results produced significant differences in number of crayfish collected under different combinations of light and bait. In the pond trials with only light as a potential attractant, traps where the light was emitting white or blue light both caught significantly more crayfish than traps where the light was turned off and those with no light in the trap (Table 3, Figure 6). On average, traps with white light collected more than twice the number of crayfish as traps with blue light (Table 4, Figure 6). The combination of white light and bait in a trap resulted in an average of more than 2 times more crayfish caught than in traps with bait alone and more than 3 times with white light alone (Tables 3 and 4, Figure 7).

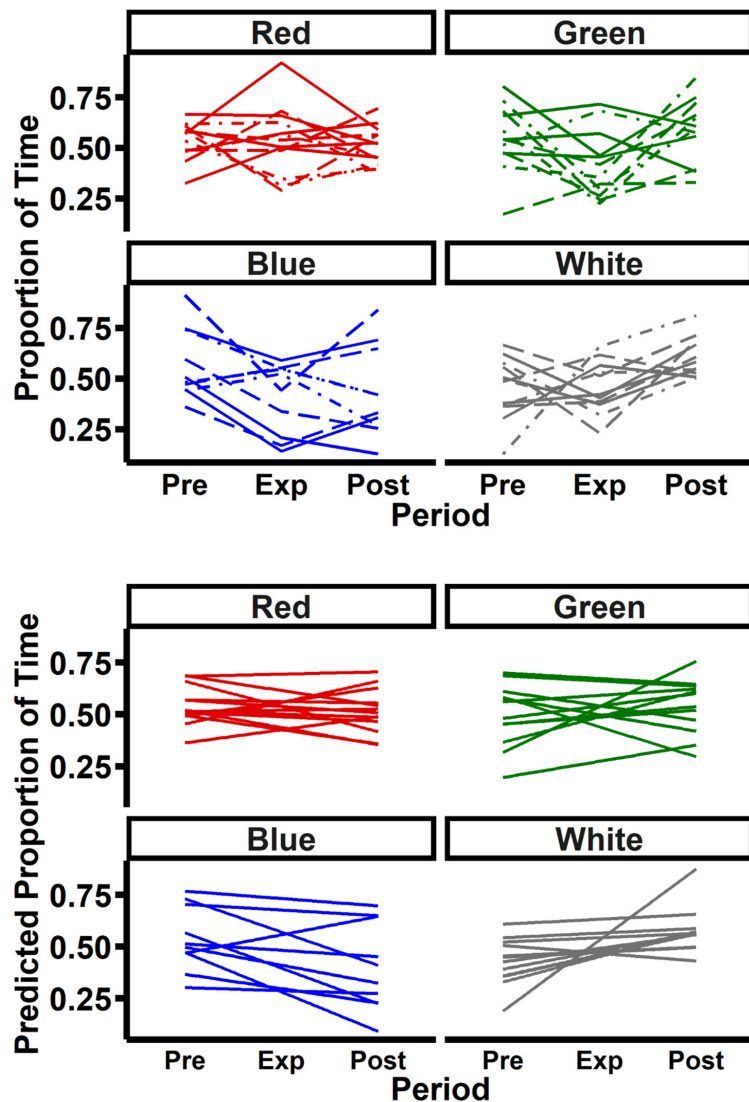


Figure 4. Actual (upper four plots) and predicted (lower four plots) proportion of time spent on lighted side of a tank by virile crayfish (*Faxonius virilis*) during pre-exposure control (Pre), light exposure (Exp), and post-exposure control (Post) periods (10 trials per light color or 40 trials). In upper four plots different line types are used to help distinguish trials; some line types are repeated. In the lower four plots are the regression lines from associated linear regressions of proportions for those three periods.

Additionally, there appeared to be a trend of decreased number of crayfish collected over consecutive days of crayfish removal through trapping from the same pond (Table 4, November 7, 2023, November 9, 2023, and November 17, 2023). Across all trapping trials we caught crayfish ranging in size from 10.3 to 51.1 mm (Figure 8).

Discussion

In this study, we found evidence that, in the laboratory, virile crayfish were attracted to white light and avoided blue light. These laboratory trials provided the impetus for field trapping trials using white and blue light. Among field treatments using light as the only attractant, white light attracted the most crayfish. Somewhat contrary to the laboratory trials, blue light attracted more

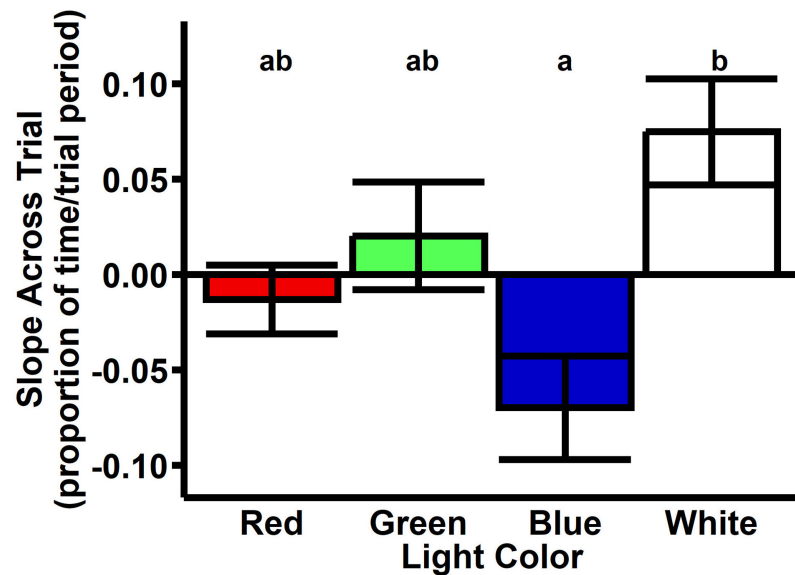


Figure 5. Slope of proportion of time spent on side of tank with light treatment by virile crayfish (*Faxonius virilis*). Slopes from the regression lines of proportion of time spent on lighted side of a tank across pre-exposure control (Pre), light exposure (Exp), and post-exposure control (Post) periods. Error bars represent 95% confidence intervals. The bars represent the color of light to which the crayfish were exposed to from one side of the tank (i.e., red, green, blue, and white light) (10 trials per light color or 40 trials). The letters above the bars represent compact letter display significance groups with significant differences indicated by not sharing a letter.

Table 3. Stacked analysis of variance (ANOVA) tables based on linear models for pond trapping trials of virile crayfish (*Faxonius virilis*) using light and/or bait as an attractant. For each trial, traps were deployed in the pond overnight and collected the following morning. Trial type refers to trials using only light or light and bait as potential attractants. R^2 is the overall adjusted r^2 for a model. The overall p-value of the linear model is “p(model).” “Coefficient” is the model term; for terms, treatment = presence of attractant (i.e., light and/or bait) as a factor, Date = date of the trial as a factor, Residuals = residual term. For the other columns, “df” = degrees of freedom, “SSE” = sum of squared errors, “MSE” = mean squared error, “F” = F-value of a variable, “p(var)” = p-value of a variable. “Signif.” Is blank if $p(\text{var}) \geq 0.05$, *** if $p(\text{var}) < 0.001$.

Trial type	r^2	P (model)	Term	df	SSE	MSE	F	P (var)	signif
Light only	0.64	< 0.0001	Treatment	3	63.109	21.036	26.410	0	***
			Residuals	44	35.047	0.797			
Bait and light	0.5	< 0.0001	Date	3	12.268	4.089	7.848	< 0.0002	***
			Treatment	2	16.009	8.004	15.361	0	***
			Residuals	54	28.139	0.521			

crayfish than unlit control traps, but it attracted fewer crayfish than white light. There could be multiple reasons for this difference between the pond and laboratory trials. Perhaps the most obvious difference between the two environments is the higher turbidity of the pond water compared to the water in the behavior tank. This increased turbidity would affect the way crayfish perceive and interpret the light stimulus. Since crayfish have been shown to exhibit opposite responses to light depending on the intensity (Fernández-De-Miguel and Aréchiga 1992), if the crayfish in the pond perceived the light as less intense this could lead to a difference in behavior. At a light intensity approximately one third those used in our laboratory trials and approximately one sixth those used in the pond trials, some avoidance of green and white lights based on decreased trap CPUE has been found in signal crayfish (Ruokonen et al. 2021). Though both the signal and virile crayfish are considered non-burrowing crayfish, the differences in

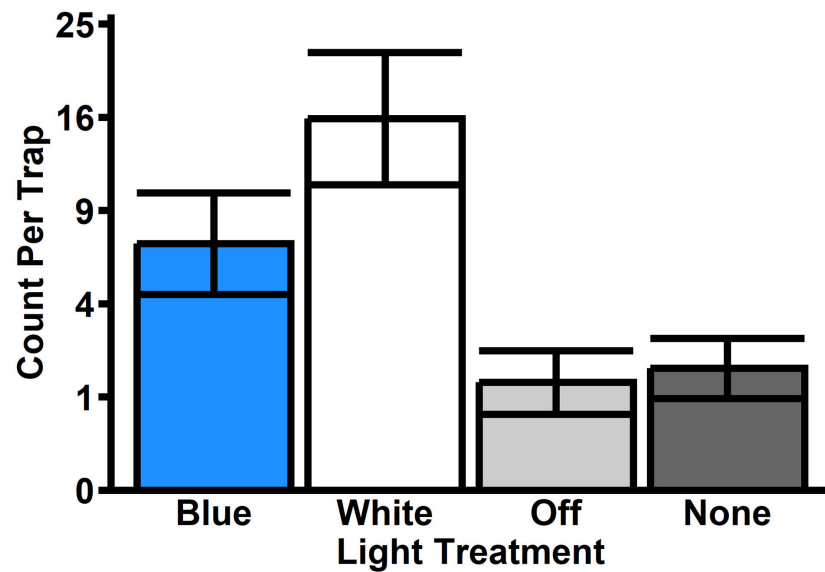


Figure 6. Square root transformed count of virile crayfish (*Faxonius virilis*) caught in traps during pond trials using only light as an attractant. The trials ran from September 21 through 27, 2023 in ponds at the Columbia Environmental Research Center, Columbia, Missouri, USA (4 traps per light treatment over 3 nights or 48 traps). +Error bars represent 95% confidence intervals. Y-axis ticks are evenly spaced based on a square root scale; values displayed on y-axis ticks are back transformed from a square root scale to the count scale. Treatments included traps with LED's emitting blue light (blue), traps with LEDs emitting white light (white), traps where the LED's were present but turned off (off), and traps with no LED arrays in the trap (none).

Table 4. Pairwise comparisons for square root transformed virile crayfish (*Faxonius virilis*) pond trapping trials conducted at the Columbia Environmental Research Center, Columbia, Missouri, USA from September 21 through November 17, 2023. Trial type refers to trials using “Light only” or “Bait and light” as potential attractants. Term refers to the independent variable tested in the individual pairwise comparison. “Treatment” main effect of either light alone or light and bait combination. State refers to the state of the independent variable considered. “Off” = light in trap, but turned off. “None” = no light in trap. “Blue” = blue light turned on in trap. “White” = white light turned on in trap. Date = date of the morning on which the traps were retrieve after having been in pond overnight. Date = November 8, 2023 trapping done the same as other dates, but in a similar but different nearby pond at the Columbia Environmental Science Center. “EMM” refers to the estimated transformed marginal mean. For other columns “SE” = Standard error, “df” = degrees of freedom, 95% CI = the 95% confidence interval, for groups tests with significant differences based upon non-overlapping 95% CI's are indicated by differing group numbers.

Trial type	Term	State	EMM	df	95% CI	Group
Light only	Treatment	Off	1.3	44	0.4 to 2.8	1
Light only	Treatment	None	1.7	44	0.6 to 3.3	1
Light only	Treatment	Blue	7.0	44	4.5 to 10.0	2
Light only	Treatment	White	15.9	44	12.0 to 20.3	3
Bait and light	Treatment	White light; no bait	2.3	54	1.4 to 3.4	1
Bait and light	Treatment	Light off; baited	2.9	54	1.9 to 4.2	1
Bait and light	Treatment	White light; baited	7.31	54	5.7 to 9.2	2
Bait and light	Date	November 17, 2023	1.5	54	0.8 to 2.6	1
Bait and light	Date	November 9, 2023	4.0	54	2.6 to 5.6	2
Bait and light	Date	November 8, 2023	5.3	54	3.7 to 7.1	2
Bait and light	Date	November 7, 2023	5.7	54	4.1 to 7.7	2

response to light may suggest that signal crayfish avoid white light while virile crayfish are attracted to it. However, it may also be that the difference in response between signal crayfish and virile crayfish may be due to differences in intensity between the previous study and this study. We did not test differences in response of virile crayfish to different light intensities in laboratory or field trials; that would require further study. The pond environment is also obviously much more complex than the behavior

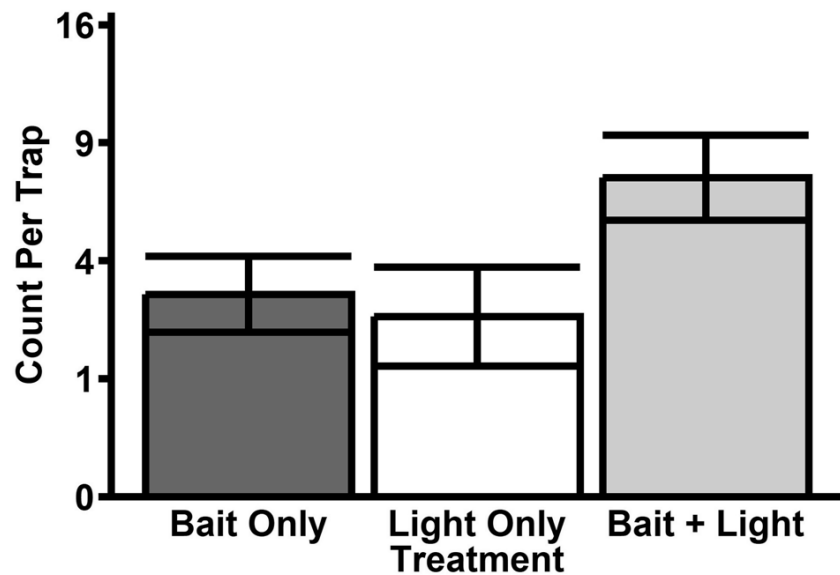


Figure 7. Count of virile crayfish (*Faxonius virilis*) caught in pond trials using white light and dog food bait as attractants. Error bars represent a 95% confidence interval. Y-axis ticks are evenly spaced based on a square root scale; values displayed on y-axis ticks are back transformed from a square root scale to the count scale. The trials ran November 6 through 17, 2023 in ponds at the Columbia Environmental Research Center, Columbia, Missouri, USA (5 traps per treatment over 4 nights or 60 traps). The bait only bar refers to traps with only dog food as an attractant. The light only bar represents traps with white light emitted from LEDs as an attractant. The bait + light bar represents traps which contained both dog food and LEDs emitting white light.

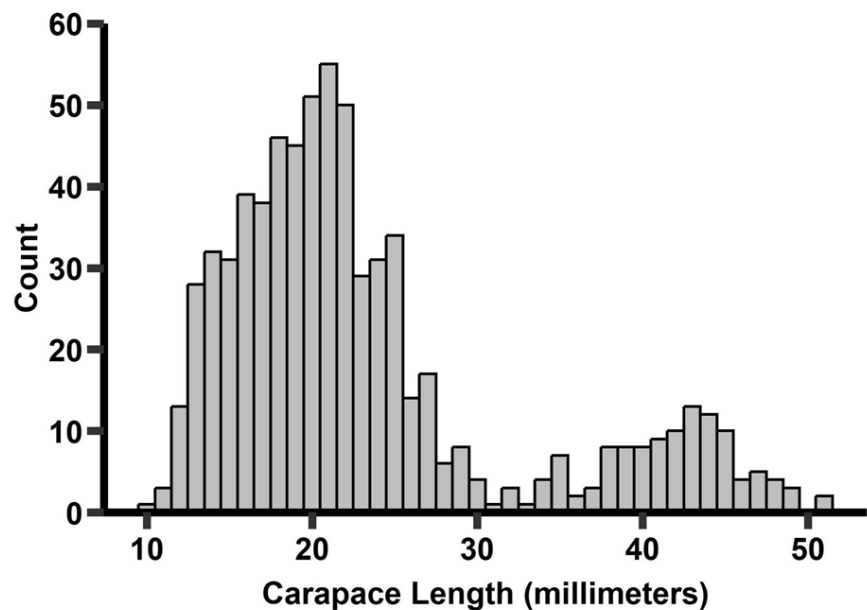


Figure 8. Histogram of carapace lengths of virile crayfish (*Faxonius virilis*) caught throughout the pond trapping trials in Columbia Environmental Research Center, Columbia, Missouri, USA between September 21 and November 17, 2023.

tanks, including other individual crayfish, other aquatic organisms such as minnows and tadpoles, and other factors. The crayfish held in the indoor tank prior to testing in the behavior tank may have also adapted to different light levels than the crayfish in natural settings such as a pond. As crayfish photoreceptor cells exposed to intense, orange-adapting exposures

undergo change in light-sensitive proteins (Cummins and Goldsmith 1986), this could lead to differences in perception and behavior when exposed to light.

Among the trials testing different combinations of a food bait and white light, the combination of bait and white light had the highest CPUE. The effectiveness of food alone in attracting crayfish has also been documented by Ahmadi and Archdale (2008) for red swamp crayfish using box traps with four openings; however, they did not test light and food combined. In our study, the addition of lights to traps with food bait increased the efficiency of these traps, leading to more than three-fold and more than two-fold increase in CPUE than either light or food bait alone, respectively. The spectral sensitivity for photosensitive neurons found in the ganglion of the red swamp crayfish has been found to peak at 570 nm or green (500–570 nm) light (Bruno and Kennedy 1962), and virile crayfish have a similar maximum wavelength absorption of 530 nm (Cronin and Goldsmith 1982; Goldsmith 1978), suggesting the reaction to light may be similar for these species. Because of the ongoing use of trapping and the ineffectiveness of other methods such as rotenone added to water (Recsetar and Bonar 2015), this increased catch rate could prove useful to managers attempting to reduce the numbers of invasive crayfish through trapping. In support of that idea, we found a unidirectional decline in capture rates from the same pond over 3 days of trapping where captured crayfish were not returned to the pond. Though the initial and final densities of crayfish were not known in this pond, the unidirectional trend of declining catch rate of new individuals suggests that our trapping may have been decreasing the density of crayfish remaining in the pond.

The size distribution of crayfish we collected appears to suggest we were catching all but maybe the very smallest crayfish (Figure 8). Our traps appeared to catch two size classes of individuals, one with a carapace length below 30 mm and one above. Based on Momot (1967) where the average juvenile had a carapace length around 24 mm and average yearling around 30 mm, we appear to have juvenile size class and a yearling and adult size class. Virile crayfish lay eggs once a year in the spring in their second year of life when they average around 30 mm. As is seen in other virile crayfish populations (Momot 1967) the greatest number of individuals fall in the younger age class. The ratio of the smaller size class to the larger size class was 5.6:1 in our study which is greater than the population-estimate ratio of 2.7:1 using population estimates reported by Momot (1967) in Michigan. Not knowing the true size distribution of the virile crayfish population we sampled meant that we could not determine if our traps were more efficient at catching a particular age class. These results may suggest that the combination of white light and bait may be an effective tool in removal of most sizes of virile crayfish, being especially effective for juveniles.

To further help managers of invasive species, future research into the use of light in crayfish trapping could look at the attraction to or avoidance of

light by different species of crayfish. Because of the interspecific difference in responses to light that have been documented in crayfish (e.g., Kozák et al. 2009), it may be possible to use these differences to preferentially catch invasive species over native species. As with light, there appears to be some interspecific variation in the preferences for certain types of bait among crayfish species (Kutka et al. 1992). More research could determine if specific baits may allow for invasives to be trapped at a higher rate than native species.

Conclusions

Ultimately, this research demonstrated the multi-fold value of adding white light to standard, baited minnow traps used for sampling and removal of virile crayfish as a means of controlling invasive populations. This research provides support for a novel enhancement of current control technologies for virile crayfish where they have become invasive in the form of high intensity underwater lights originally designed for application to swimming pools. The result is a new tool that can be used by resource agencies to manage virile crayfish invasions. The next step is to test whether these enhanced traps provide the same increased collection effectiveness for other invasive crayfish, such as the red swamp crayfish. This research complements other control technologies to strengthen their overall effectiveness and provide documentation of behavioral responses of crayfish to light stimuli.

Authors' contributions

Mark L. Wildhaber contributed to the study conception. All authors contributed to study design, material preparation, and data collection. Analyses were performed by Benjamin L. Bates, Benjamin M. West and Mark L. Wildhaber. The first draft of the manuscript was written by all authors and all authors commented on subsequent versions of the manuscript. All authors read and approved the final manuscript.

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Data availability

The data presented in this study are openly available as a U.S. Geological Survey data release Wildhaber ML, Bates BL, Beaman ZD, West BM, 2025 Behavioral response of crayfish to light and the effects on trapping success, laboratory and pond trials, Missouri 2022-2023: U.S. Geological Survey data release found at <https://doi.org/10.5066/P14H38CD>.

Ethics statement

The care and use of experimental animals complied with animal welfare laws, guidelines and policies as approved by the Institutional Animal Care and Use Committee of the U.S. Geological Survey Columbia Environmental Research Center. During collection of behavior data, the crayfish were transferred from their holding tank using a net then placed in the behavior tanks. At the end of a trial, crayfish were humanely euthanized via placement into a –20 C° freezer in a sealed bag.

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