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Managing Water in the West

Descriptions of the Early Life Stages of Three Common Ictalurids from the Sacramento-San Joaquin River Delta, California

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by

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July 2010

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ABSTRACT

Early life stages of white catfish (*Ameiurus catus*), black bullhead (*Ameiurus melas*), and channel catfish (*Ictalurus punctatus*) from the Sacramento-San Joaquin River Delta and surrounding watershed are described. Stages were enumerated following Armstrong and Child's (1962) descriptions of brown bullhead (*Ameiurus nebulosus*). Eggs were collected from fishes that were provided spawning material and allowed to spawn naturally. Black bullhead eggs were the smallest at 3.5 mm in diameter compared to white catfish and channel catfish (4.4 and 4.3 mm, respectively). Newly hatched yolk-sac larvae of the channel catfish were the largest, averaging 10 mm TL at hatching, compared to white catfish and black bullhead (9 mm and 8.6 mm, respectively). The early life stages of three ictalurids were similar. Channel catfish early life stages were well-documented because of the species' importance in aquaculture. However, the early life stages of black bullhead and white catfish were not as well-documented.

Key words: Ictaluridae, ictalurids, catfish larvae, white catfish, black bullhead, channel catfish, Sacramento-San Joaquin River Delta

INTRODUCTION

North American catfishes, family Ictaluridae, are common freshwater fishes native to waters east of the Rocky Mountains, southern Canada, and parts of Mexico (Lundberg 1970, Moyle 2002). There are seven species in California: white catfish (*Ameiurus catus*), black bullhead (*Ameiurus melas*), brown bullhead (*Ameiurus nebulosus*), yellow bullhead (*Ameiurus natalis*), blue catfish (*Ictalurus furcatus*), channel catfish (*Ictalurus punctatus*), and flathead catfish (*Pylodictis olivaris*). In the Sacramento-San Joaquin River Delta (Delta), white catfish and channel catfish are most abundant, followed by black bullhead and brown bullhead. Blue catfish are also found in the Delta, but a reproducing population has not been confirmed (Wang 1986). Yellow bullhead and flathead catfish are found only in southern California (Moyle 2002).

At the southern region of the Delta (south Delta), water diversion projects operated by the U.S. Bureau of Reclamation's (Reclamation) Central Valley Project (CVP) and the State of California's State Water Project (SWP) divert the Delta's freshwater through large pumps (Bill Jones Pumping Plant and Harvey O. Banks Pumping Plant, respectively). The CVP is a multipurpose project intended to provide irrigation water to farmland, electrical power for large populations, and flood control protection for the Delta and low-lying areas near the Sacramento River (Stene 2008). Water pumped out of the Delta supplies most of the drinking water for over 22 million Californians inhabiting southern California and the San Francisco Bay Area (Brown and Moyle 2005). The CVP's Tracy Fish Collection Facility (TFCF; Byron, California) and the SWP's Skinner Delta Fish Protective Facility are fish salvage facilities located upstream of the pumping plants and are responsible for collecting fish (salvage) and transporting them downstream away from the influence of the pumps. White catfish was the most numerous ictalurid from the TFCF's salvage followed by channel catfish (Helfrich *et al.* 1999).

Ictalurids share similar physical characteristics, behaviors, and environmental tolerances. All have cylindrical bodies and scaleless skins, pectoral and dorsal fins have sharp spines along the leading edges, and barbels are arranged around the mouth (two above the jaws, four below the jaws, and one on each tip of the maxilla). Reproduction in ictalurids is characterized by adults attending offspring (Breder and Rosen 1966). Parental care is well-documented in brown bullhead, black bullhead, channel catfish, and white catfish, and is often provided by males (Blumer 1982, 1985a and b, 1986; Smith and Wootton 1995). Ictalurids inhabit a variety of habitats including hypoxic and heavily polluted waters. The blood of the brown bullhead has a greater affinity for oxygen and lesser sensitivity to carbon dioxide which helps explain how bullheads are able to inhabit hypoxic waters (Gerald and Cech 1970). In the south Delta, flow alterations due to agricultural practices create habitat conditions (*i.e.*, warm, stagnant, eutrophic waters) that are more favorable to non-native species (Saiki 1984, Brown 2000, Brown and Moyle 2005) such as ictalurids. Furthermore, ictalurids readily spawn in crevices and easily make use of anthropogenic debris such as discarded car tires, empty barrels, and submerged containers which are plentiful in the south Delta (TFCF trashrack debris records).

Although ictalurids have been widely cultured, only the channel catfish was shown to possess the best combination of characteristics of commercial importance (Dupree 1995). Therefore, most studies of ictalurids have and are still centered on channel catfish. Dietary requirements of farmed channel catfish are well-documented (*e.g.*, Tiemeier *et al.* 1969, Page and Andrews 1973, Garling and Wilson 1976) as well as biological and water chemistry requirements for successful propagation (*e.g.*, Brown 1942, Simco and Cross 1966, Allen and Avault 1969, Tucker and Robinson 1990, Lang *et al.* 2003, Pawiroredjo 2004). Early life stage requirements have also been well-documented for channel catfish in the context of aquaculture (*e.g.*, Marzolf 1957, Tucker and Robinson 1990, Small and Bates 2001). Aquaculture of the channel catfish was implemented by the California Department of Fish and Game in the mid-1950s (Geibel and Murray 1961); however, currently, most channel catfish farms in the state are privately run (Conte 1990). Although there is no processing industry for channel catfish in California, channel catfish aquaculture is profitable in the state (Conte 1990). In the Delta, a commercial fishery for the white catfish was abolished in 1953 when the catfish population showed signs of overfishing (Borgeson and McCammon 1967). White catfish compared favorably with channel catfish as a commercial species in earlier trials (Prather and Swingle 1960); however, white catfish along with black bullhead grew slower than channel catfish and therefore received less attention as candidates for aquaculture (Tucker and Robinson 1990). Black bullheads are not well-studied in California; however, the species was known to be resilient, has invaded new areas quickly, and are abundant in California's ditches, streams, and other temporary habitats (Moyle 2002).

Morphometric studies (studies of form relative to size) of the eggs and larvae of fishes are extremely valuable tools in larval fish taxonomy. The great morphological similarity among different taxonomic groups has been the main obstacle to identification of larvae. Analysis of morphometric measurements, together with other characteristics, allows us to compare the different developmental stages within and between species (Sanches *et al.* 1999). The objective of this report is to describe the morphology of the embryo and early life stages of the three most common ictalurids in the Delta: white catfish, channel catfish, and the black bullhead. Channel catfish early life stages have been described in the literature; however, descriptions of the white catfish and black bullhead early life stages have been very limited. Another objective is to identify differences between the three species at their early life stages. The identification and description of the early life stages of ictalurids in the Delta are part of Reclamation's proactive effort in cataloguing and identifying the early life stages of all fish species salvaged from the TFCF. Currently, the TFCF is required to record all fish that are 20 mm or greater; however, with improvements in the facility, identifying fishes smaller than 20 mm is likely (Wang and Reyes 2007). This report provides an illustrated document for biologists who study the early life histories of fishes in the Delta.

MATERIALS AND METHODS

Study Area

The Delta, consisting of over 1000 km of waterways with a drainage area encompassing approximately 40% of California's surface area (Nichols *et al.* 1986), is currently a network of dredged sloughs, channels, and canals connected to the Sacramento and San Joaquin Rivers (Figure 1). It was once an enormous tule marsh dissected by meandering river channels but has been transformed into islands of farmlands protected by earthen levees (Moyle 2002). Throughout the Delta, dead-end sloughs and agricultural barriers provide stagnant warm waters while agricultural runoffs create eutrophic environments, especially in the south Delta where two large water diversion projects (owned by the SWP and CVP) divert water from the Delta to mostly agricultural lands in the central and southern region of California.

Life-Stage Terminology

The terms used to describe life stages of fishes often vary according to author and study. In this study, the following conventions were used:

- *embryo*—period between fertilization and hatch, synonymous with the word 'egg'
- *yolk-sac larva*—period between hatch and the completion of metamorphosis, the fish may be free-swimming and feeding exogenously
- *juvenile*—period when the fish has fully absorbed all median fin folds
  note: the terms *larva(e)* and *larval* are used occasionally in this report and refers mainly to yolk-sac larva. Ictalurids do not have postlarval stages (*i.e.*, no protolarval, mesolarval, and metalarval stages).

Staging definitions follow Armstrong and Child's (1962) descriptions of the brown bullhead early life stages. Eggs collected were in different stages of blastulation and exact time of fertilization was not recorded; therefore, the age of the eggs was estimated and the term "days post spawn" (dps) was used rather than "hours post spawn."

Egg and Larval Collection

White catfish eggs were collected from barrels situated in stagnant waters of Discovery Bay (Contra Costa County). The 208-L black plastic barrels have a single crescent-shaped opening on one end for entry. The barrels were weighed down by a single rock and were marked by a buoy. Barrels were checked weekly starting the first week of May when temperatures reached 20°C during the day. Egg masses were collected in early June 2006 (two egg masses) and early June 2007 (one egg mass). Egg masses were gently removed from the wall of the barrel by hand. They were transported in 100-L coolers and driven 15 minutes (min) to the TFCF laboratory.

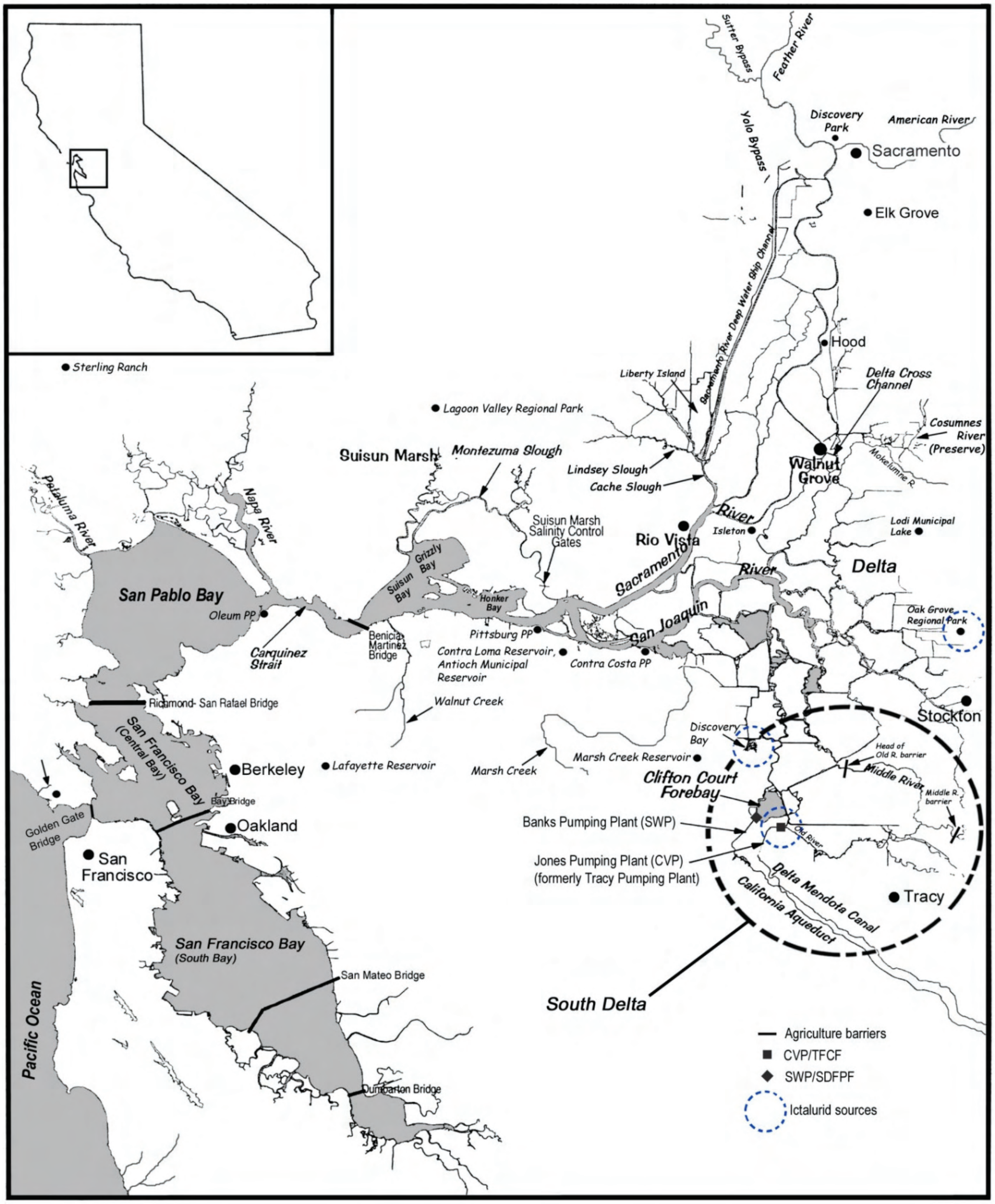

FIGURE 1.—Map of the study area.

Black bullhead eggs were collected from an aboveground, flow-through pool (2,300 L, located onsite) that housed 12 mature, wild broodstock black bullheads collected from the TFCF. The spawning bullheads were offered various substrates such as 20-cm open-ended PVC pipes, gravel, 75-L plastic barrels with 20-cm opening, and used rubber tires.

The spawning substrates were checked weekly starting the third week of May once the water temperature reached 20°C. Eggs were collected in late May and late June 2008.

Channel catfish eggs were collected from San Joaquin County's Oak Grove Regional Park pond in north Stockton. Two 75-L white plastic barrels with crescent-shaped opening on one side were set the first week of June and submerged 0.9–1.5 m deep near the shoreline. Two egg masses were collected mid-June 2008. Egg masses were gently dislodged from both barrels and transported in 19-L buckets 45 min to the TFCF laboratory.

The three species of ictalurids hatched and grew in ambient temperature (20–21°C). At least 50 eggs from each egg mass were chosen for measurements by separating the egg mass into individual eggs or smaller clumps (2–10 eggs), gently mixing the eggs, and randomly siphoning 50 eggs with a pipet. Larvae were measured daily. Changes in morphology and pigmentation were recorded.

Laboratory Equipment

Eggs from the three species were treated similarly with malachite formalin (dip of 1 min in 5 mg/L solution) and incubated in ~21°C recirculating freshwater. Incubation periods were recorded as well as embryonic development. Eggs were photographed using a Leica™ DFC 420 digital camera attached to a Leica™ $MZ7_5$ stereomicroscope (Leica Microsystems, Bannockburn, Illinois). Photographs were calibrated, labeled, and archived for future reference. Because of the accumulation of images over time, an image database of the egg and early stages was created. During the incubation process, measurements and observations were made. Imaging analysis software (Image-pro© version 6.2 by Media Cybernetics, Inc., Bethesda, Maryland) was used to obtain accurate measurements. Eggs and larvae were preserved in 10% buffered formalin for future reference.

Photography Process

Live specimens were used for photographs. Eggs and larvae were placed in water in a microslide with a 1.0-mm depression. Brightfield technique was used to capture pigmentation structures in both eggs and larvae and also for counting myomeres. Larvae were anaesthetized using MS-222. Lateral images of the larvae were taken by situating part of the caudal fin on the moistened glass and the anterior part of the body in the depression. The caudal fin kept the rest of the body laterally positioned. Dorsal images were easily taken because ictalurid larvae are naturally positioned upright, even with their large yolk sacs.

Limitations

Descriptions of the eggs and larvae were from live specimens or freshly formalin-preserved specimens; therefore, there might be some difficulties in identifying eggs and larvae that are preserved in alcohol-based preservatives. Alcohol-based preservatives will tend to shrink a specimen and make the specimen opaque.

Eggs and larvae are subject to genetic and environmental influences. Size and condition factor of the spawning female strongly affect the number of eggs spawned and also affect the egg size (Meyer *et al*. 1973). Eggs used originated only from three locations of the Delta's watershed; therefore, the morphometric information gathered may not be applicable to specimens collected outside the watershed.

RESULTS AND DISCUSSION

Embryo Development

Embryonic development was similar. At initial stages of development (cleavage to blastula, stages 1–15), the embryo was mostly made of yolk. Eggs did not have oil globules. Eggs were enveloped in a gelatinous matrix and were attached to each other creating a flattened area called adhesion discs (Armstrong and Child 1962). Although there are chemicals that can be used to remove the matrix (Ringle *et al*. 1992), dissolving the matrix could rupture the chorion and therefore, was not implemented. White catfish had the largest egg, black bullhead had the smallest. Ictalurid eggs are one of the largest in the Delta, comparable with the acipenserids and the salmonids (Reyes 2010 *unpublished*). Yolk diameter was largest in white catfish and smallest in black bullhead; however, the proportion of yolk diameter to egg diameter was similar for the three species (~65–80%). Table 1 summarizes the egg information for the three species of ictalurid. The earliest stage that all three species were collected was blastula stage. Refer to Figure 2 for references to egg descriptions and development.

TABLE 1.—Incubation period, egg measurements, and yolk measurements for white catfish, black bullhead, and channel catfish collected from three locations in the Sacramento-San Joaquin River Delta and watershed, 2006–2008.

	White Catfish[1]	**Black Bullhead[2]**	**Channel Catfish[3]**
Incubation period	6–8 d at 21–22°C	8–9 d at 19–21°C	9–12 d at 19–21°C
Egg diameter range (mm)	3.9–5.1 (*n* = 151)	3.1–3.7 (*n* = 100)	3.5–4.9 (*n* = 101)
Avg. egg diameter (mm)	4.4	3.5	4.3
Yolk diameter range (mm)	2.7–3.8	2.5–3.0	2.8–3.3
Yolk color	yellow	cream	cream
Yolk:egg ratio	65–81% (*n* = 26)	70–82% (*n* = 26)	64–77% (*n* = 25)

[1] Three egg masses collected from Discovery Bay, Contra Costa County June 2006 and June 2007.
[2] Two egg masses collected from TFCF, Contra Costa County late-May and late-June 2008.
[3] Two egg masses collected from Oak Grove Regional Park, San Joaquin County mid-June 2008.

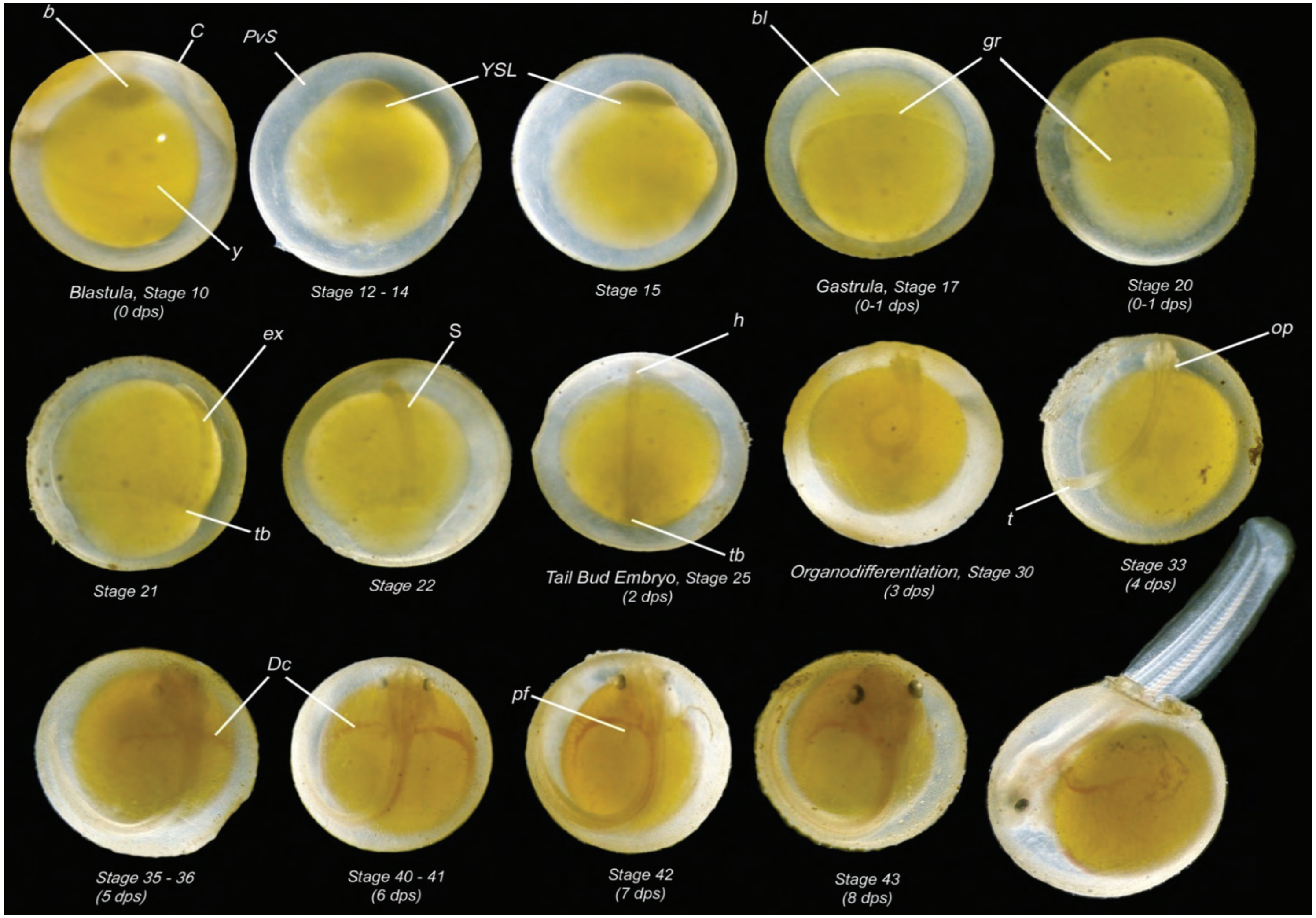

FIGURE 2.—Embryo development sequence and morphology of a white catfish *Ameiurus catus* egg from the Delta. Developmental stages are based on Armstrong and Child (1962). Not represented are the cleavage stages (Stages 1–7). *b*=blastodisc, *C* = chorion, y = yolk, *PvS* = perivitelline space, *YSL* = yolk synctial layer (Kimmel *et al.* 1995) or periblast, *bl* = expanding blastoderm, *gr* = germinal ring, *ex* = embryonic axis or shield, *tb* = tail bud, S = somites, *h* = head, *t* = tail, *op* = operculum, *Dc* = Duct of Cuvier, *pf* = pectoral fin, dps = days post spawn.

White catfish eggs were collected from 24°C water. The large, yellow-colored eggs (~3.9–5.1 mm in diameter) were deposited in a large clump about 5–8 cm thick and over 20 cm wide on the walls of the plastic barrels. Eggs were adhesive to each other and the smooth substrate. Eggs hatched in 6 d at 21–22°C.

Black bullhead egg masses, deposited in one-layered clump about 13 cm in diameter, were collected from 23.8°C water and deposited on the inside wall of the open-ended PVC pipes. Eggs were whitish and cream in color and adhesive to each other and the smooth substrate. A few eggs were scattered about 20–30 cm from perimeter of the clump. Only 120 eggs (blastula stage) total were collected from 2 nests. One parent guarded the eggs and readily abandoned it when eggs were collected. Eggs hatched 8–9 d at 19–21°C.

Channel catfish eggs were deposited in a 6-cm-thick and 25-cm-wide mass. Eggs were whitish and adhesive to each other and to the smooth substrate. Eggs were collected from 22°C water. Eggs hatched 9–12 d at 19–21°C.

Cleavage, 0 Days Post Spawn — Cell division of the ictalurid egg was meroblastic where cleavage is limited to the blastodisc and not the yolk (stages 1–7 in Armstrong and Child 1962). In channel catfish, cell division progressed rapidly; the first cleavage furrow at the blastodisc was visible within 2 h (27–28°C) of fertilization (Makeeva and Emel'yanova 1993). The 64-cell division was attained within 5–7 h (24.7–26.8°C) after fertilization (Saksena *et al.* 1961). In the brown bullhead, this stage was attained within 6 h (no temperature provided; Armstrong and Child 1962). In the current study, no eggs at these early stages were collected; however, it is likely the cleavage stages occurred within the first few hours after fertilization.

Blastula, 0 Days Post Spawn (Figure 3) — Eggs were at various stages of blastulation at time of collection. In teleosts, the blastula stage is often achieved in the first few hours after fertilization. In the channel catfish, the blastula stage was attained in 6–8 h (Saksena *et al.* 1961, Makeeva and Emel'yanova 1993) and 6–9 h in the brown bullhead (Armstrong and Child 1962). Eggs collected were likely only a few hours old and certainly less than 1 d old; therefore, these eggs were labeled "0 dps." In all three species, the blastodisc resembled a tiny cap. The blastodisc was less obvious in the black bullhead because of the uniform paler coloration of the yolk and blastodisc. Towards the latter part of the blastula stage, the blastodic flattened as it started expanding over the yolk. The blastula phase is stages 8–15 in Armstrong and Child (1962).

Gastrula, 0–1 Days Post Spawn (Figures 4 and 5) — In teleosts, gastrulation begins when the blastodisc has flattened out into a thin layer of cells (blastoderm) and eventually covers a large surface of the yolk sphere (Kunz 2004). The blastoderm was observed migrating towards the vegetal pole during epiboly. The blastoderm also thickened around the yolk and differentiated. Early gastrulation is stages 16–19 in Armstrong and Child (1962).

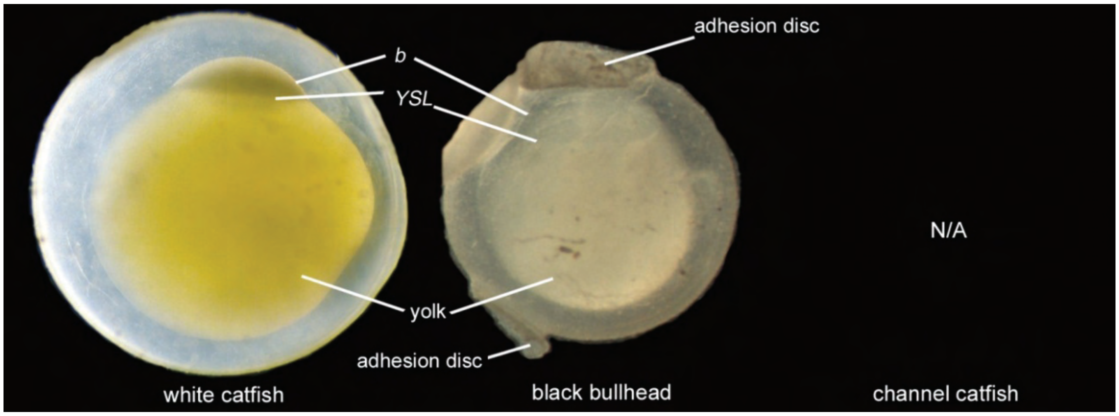

FIGURE 3.—Blastula stage: white catfish (4.9 mm, 0 days post spawn; dps) and black bullhead (3.5 mm, 0 dps) with cap-like blastodisc. The blastodisc for the white catfish is more obvious. Channel catfish (none photographed). *b* = blastodisc, *YSL* = yolk synctial layer (Kimmel *et al*. 1995) or periblast.

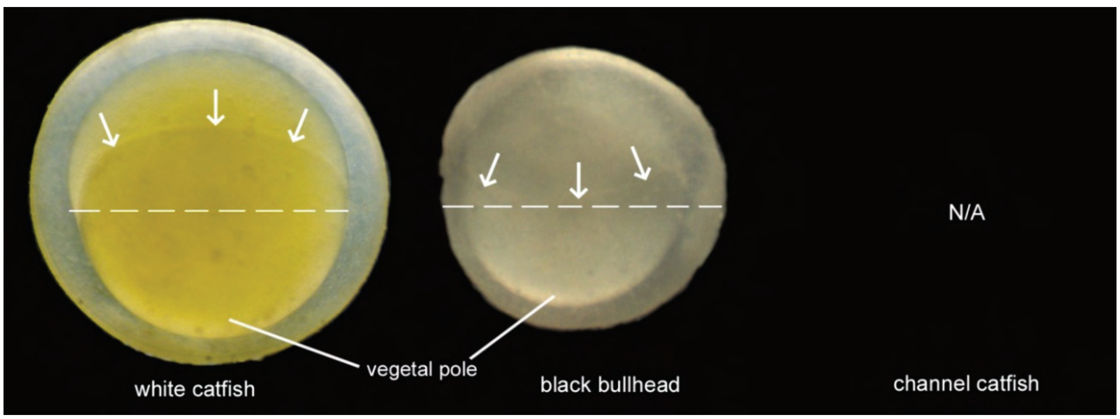

FIGURE 4.—Gastrula stage (early): white catfish (4.4 mm, 1 day post spawn; dps) with blastoderm covering one-third of the yolk. The white arrow points at the leading edge of the enveloping layer of the blastoderm and represents the direction of movement vegetally towards the equator (white dashed line). Black bullhead (3.4 mm, 1 dps) with the leading edge of the enveloping layer of the blastoderm reaching the equator (50% epiboly). Channel catfish (none photographed).

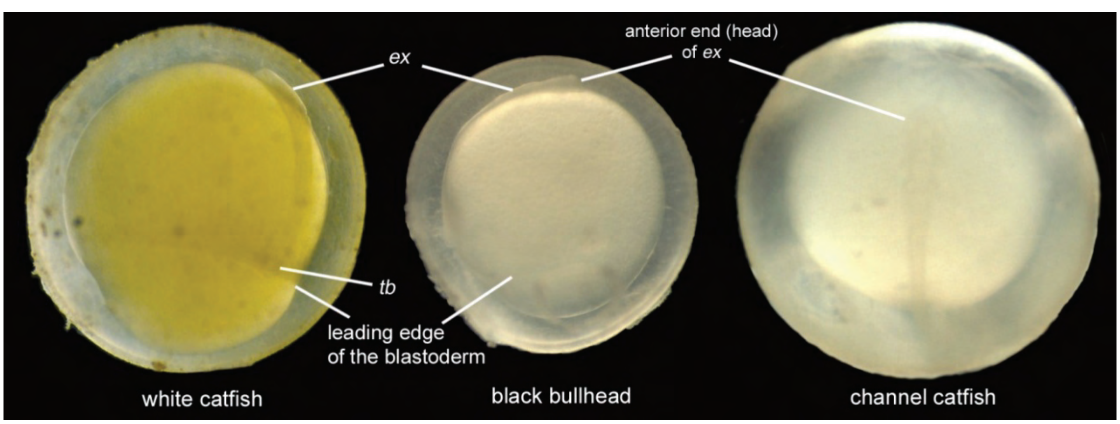

FIGURE 5.—Gastrula stage (late): white catfish (4.3 mm, 1 day post spawn; dps) oblique view; black bullhead (3.6 mm, 1 dps) lateral view; channel catfish (4.5 mm, 1 dps) dorsal view. The enlarged anterior end (head) of the embryonic axis is visible in the black bullhead. *ex* = embryonic axis or shield, *tb* = tail bud.

Eventually, the embryonic axis (or shield) became visible especially when viewed on the horizon of the egg (stages 20–24 in Armstrong and Child 1962). At this stage, the blastoderm was still extending over the yolk. Pictured in Figure 5, the white catfish and black bullhead embryos have 75–80% epibolized, and the channel catfish has fully epibolized. Complete epibolization was observed with the closure of the blastopore located in the vegetal pole. First somites appeared at this stage and the embryonic shield narrowed to form a keel as it lengthened towards the two poles. Tail bud was sometimes visible. The optic cups were rudimentary where the enlarged anterior end (the developing head) of the keel is located.

Tail-bud Embryo, 2 Days Post Spawn (Figure 6) — About 5–20 somites were visible at this stage. Tail bud was well-defined. The neural plate was thick along the embryonic axis which formed the spinal cord. The thickening was most prominent at the anterior edge of the axis where the head was forming. Optic cups were defined and auditory vesicles were visible. Midbrain started to differentiate with the appearance of furrows on the dorsal area of the head. Auditory vesicles were sometimes visible but no otoliths had formed. Embryonic axis was translucent and motionless. Heart was not visible. This stage of development is stages 25–27 in Armstrong and Child (1962).

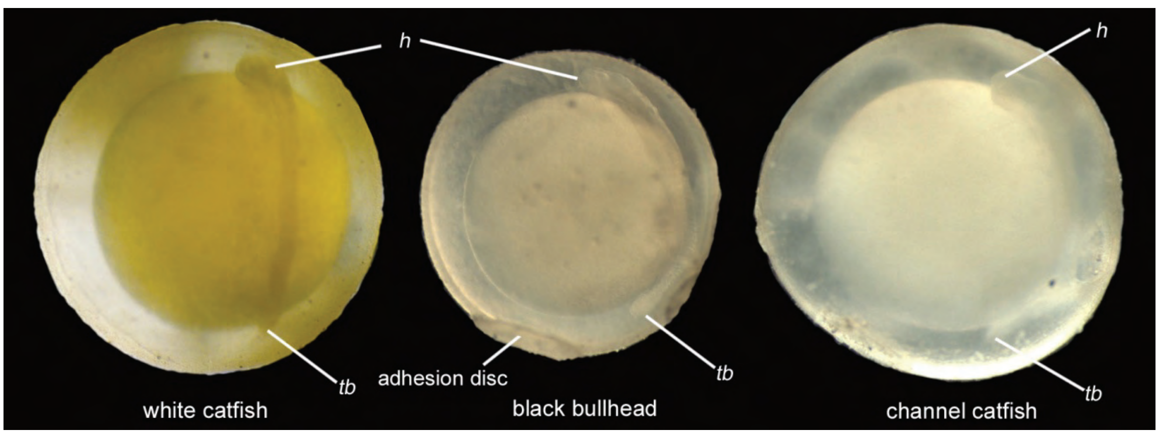

FIGURE 6.—Tail-bud embryo stage: white catfish (4.6 mm, 2 days post spawn; dps) oblique view; black bullhead (3.5 mm, 2 dps) lateral view; channel catfish (4.2 mm, 2 dps) lateral view. *h* = head, *tb* = tail bud.

Tail Elevation and Elongation, 3–4 Days Post Spawn (Figure 7) — This stage was marked by the elevation of the tail from the surface of the yolk. The optic cups were developed but not pigmented. Optic lenses were visible. Furrows of the head were observed defining the midbrain, cerebellar primordium, and hindbrain. Initial movement of the embryonic axis was observed in the anterior somites and also in the free tail. No melanophores were visible. Operculum was differentiated, and a pair of barbel buds was visible. Otoliths within the auditory vesicle were visible. This stage of development is stages 28–34 in Armstrong and Child (1962).

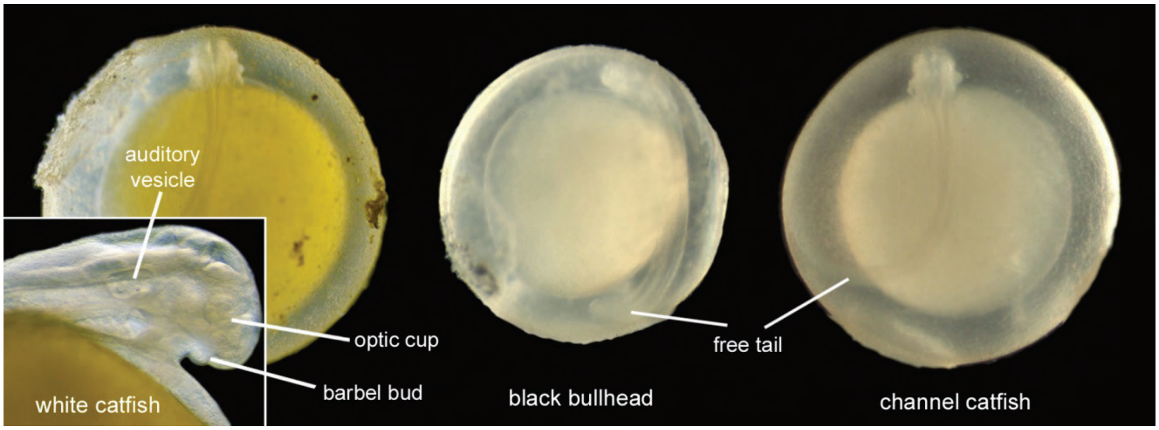

Figure 7.—Tail elevation stage: white catfish (4.3 mm, 4 days post spawn; dps) dorsal view; black bullhead (3.5 mm, 3 dps) lateral view; channel catfish (4.3 mm, 3 dps) dorsal view. Inset: Lateral view of white catfish head.

Eye Pigmentation and Blood Circulation, 5–6 Days Post Spawn (Figure 8) — Eye pigmentation began on the periphery of the eyes; however, the body remained pigmentless. The head doubled in size and barbel buds visibly lengthened. Pectoral fin buds were observed. Active undulation of free tail allowed embryo to turn. Vitelline circulation was observed with the movement of hemoglobin by the heart to the head, trunk, and yolk sac. Duct of Cuvier was prominent, supplying blood to the yolk sac. Hemoglobin circulation was visible along the length of the embryonic axis (trunk) through the arterial and venal caudalis. The functions of the yolk sac circulation are gaseous exchange, excretion, and uptake and distribution to the embryo of nutrients contained in the yolk (Kunz 2004). Faint red coloration of the blood was observed initially and became brighter towards the latter part of the stage. This stage of development is stages 35–42 in Armstrong and Child (1962).

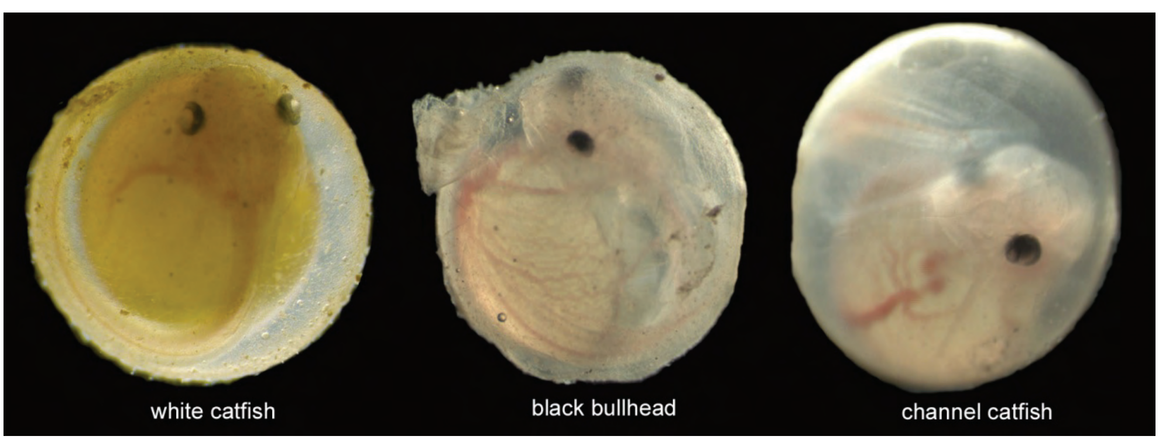

FIGURE 8.—Eye pigmentation and blood circulation stage: white catfish (4.6 mm, 6 days post spawn; dps) dorsal view; black bullhead (3.6 mm, 6 dps) dorsal view; channel catfish (4.0 mm, 5 dps) oblique view. *Dc* = Duct of Cuvier.

Prehatching to Hatching, 6–12 Days Post Spawn (Figure 9) — Before hatching, the embryo of all three species was very active, eyes fully pigmented, and the brain prominently sculpted. Melanophores on the dorsal region of the head were visible. These are stages 43–44 in Armstrong and Child (1962). In most teleosts, hatching enzyme dissolves the inner layers of the chorion and the lashing movements of the embryo eventually break the chorion (Kunz 2004). Breakthrough of the active embryo from the enveloping chorion was observed headfirst and tailfirst. White catfish hatched earliest (6–8 d), channel catfish hatched latest (9–12 d), and black bullhead was intermediate (8–9 d). Incubation period was expected to be shorter when eggs are in warmer water. For example, at temperatures of 27–28°C, the channel catfish incubation period averages 5 d (Makeeva and Emel'yanova 1993). In channel catfish, 16°C is below the thermal tolerance limit for normal embryonic development (Small and Bates 2001).

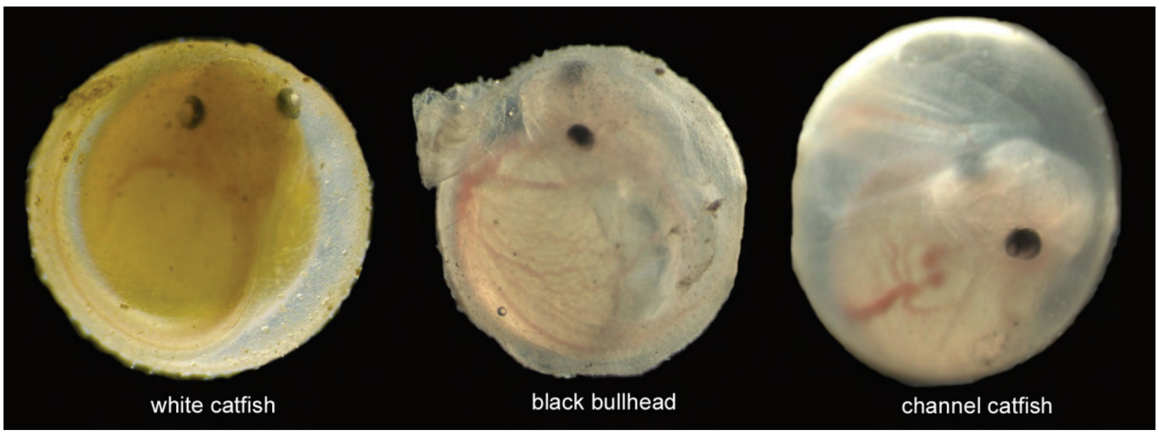

Figure 9.—Prehatching/hatching stage: white catfish (4.5 mm, 8 days post spawn; dps) dorsal view; black bullhead (3.7 mm, 9 dps) dorsal view; channel catfish (4.0 mm, 9 dps).

Yolk-sac Larval and Juvenile Development

Overlapping characteristics, with a few subtle differences, characterized the descriptions of the three ictalurid species. Selected anatomical features of ictalurid early stages, borrowed from Simon and Wallus (2004), are depicted in Figure 10. All three species hatched with large, bulbous yolk sac that was absorbed within the first 2 weeks after hatch. They also hatched with pigmented eyes, at least a pair of barbels, a visible flexion, all fin buds (except pelvic), and no oil globules. Ictalurids varied in size at hatching and, therefore, reached similar phases of life at different TL (Simon and Wallus 2004). As mentioned earlier, ictalurids do not have true postlarval stages because the fish resemble adults when the yolk sac disappears (Cloutman 1978, Wang 1986).

First melanophores were located on the occipital and the pectoral region dorsally of the yolk sac. Progression of melanophore coverage was similar for white catfish and black bullhead; however, degree of coverage was different. The black bullhead was initially a lightly pigmented yolk-sac larva that became dark within a week with melanophore coverage of the entire body. White catfish had melanophores everywhere except the ventral abdominal. Channel catfish had the lightest coloration of the three. Air bladder

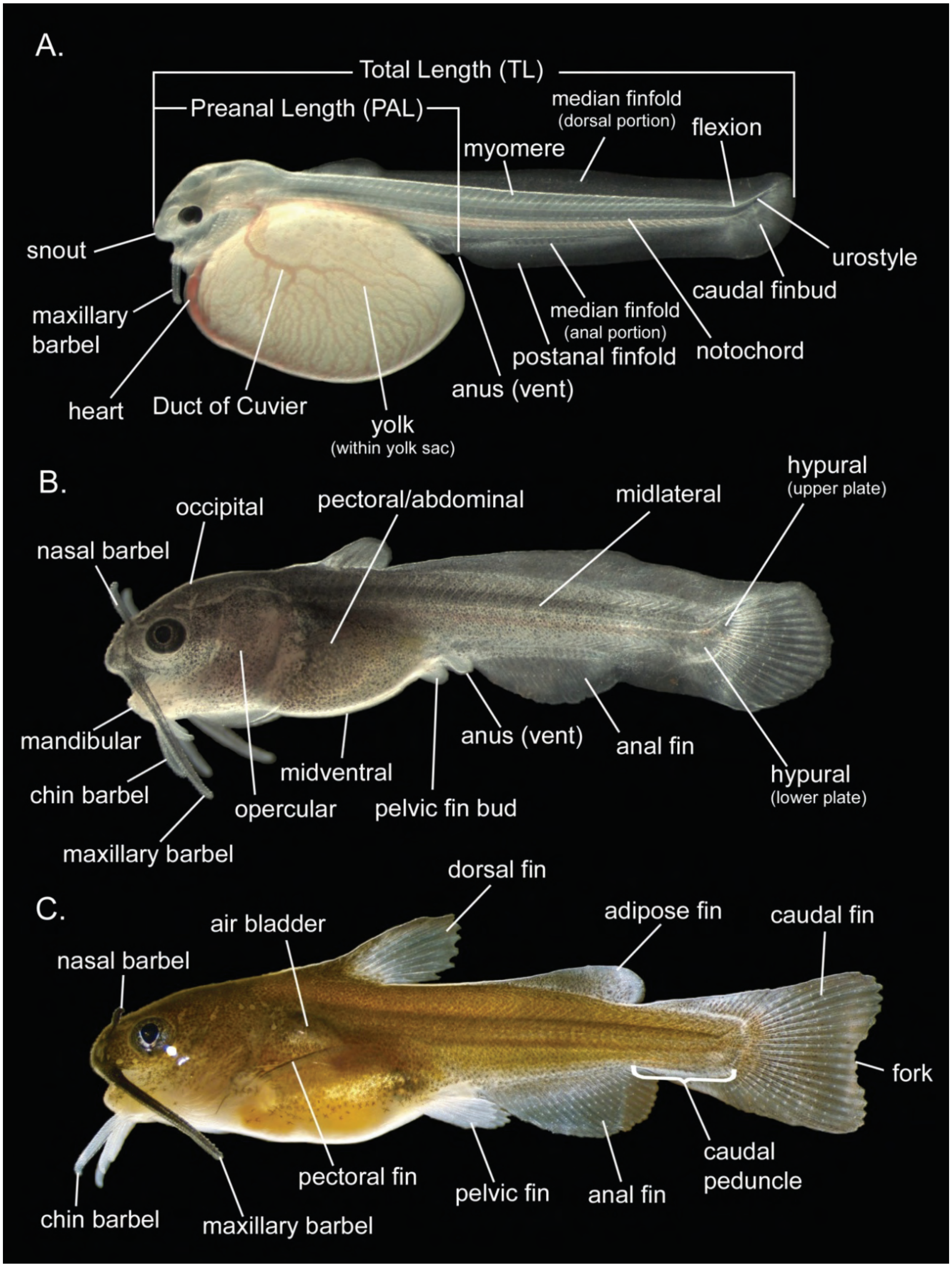

FIGURE 10.—Morphology of an early-stage ictalurid: (A) yolk-sac larva, (B) yolk-sac larva (advanced), (C) juvenile.

was observed in black bullhead as early as 10.5 mm TL and appeared in channel catfish between 14–15 mm TL. Active foraging occurred around 8–16 days post hatch (dph), about the same time that yolk sac was fully absorbed. Yolk-sac larval and juvenile stages of the three ictalurid species are summarized in Table 2. As a visual aid in identifying the species, estimating age, and staging of development, developmental series for the three ictalurids are located in Appendices 1–3.

TABLE 2.—Descriptions of yolk-sac larval and juvenile stages white catfish, black bullhead, and channel catfish from the Sacramento-San Joaquin River Delta and watershed.

	White Catfish	**Black Bullhead**	**Channel Catfish**
Yolk-sac larvae			
Hatch range (mm)	7.0–11.9 (*n* = 50)	8.0–9.1 (*n* = 50)	10.3–13.2 (*n* = 50)
Avg. hatch size (mm)	9.1	8.6	10.6
Newly hatch PAL/TL (%)[1]	47–52	47–51	45–48
Yolk-sac larvae PAL/TL (%)	47-52 (7-15 mm TL, *n* = 65)	48–50 (9.8–12.6 mm TL, *n* = 30)	45–47 (11.7–14.7 mm TL, *n* = 50)
Eye pigmented at hatching?	yes	yes	yes
Preanal myomeres	16–21	15–18	16–19
Postanal myomeres	20–25	21–26	26–30
Total myomeres	37–43	38–42	43–49
Length when air bladder visible (mm TL)	12–13	~10.5	14–15
Length when caudal fin fork visible (mm TL)	~14.5	n/a	~14
Length when nasal barbels visible (mm TL)	~15	~9.5–10.5	~25
Length when body darkens (mm TL)	~12–13	~12	~15
Length when yolk absorbed (mm TL)	~15	12–13	15–16
Length at first exogenous feeding	14.7–16 (8–14 dph)	13–14 (9–10 dph)	16.5–18 (14–16 dph)
Juveniles			
Chin barbel color	white	black or gray	clear or cream
Caudal fin shape	forked	rounded	forked

[1] PAL/TL (preanal length/total length) represents the location of the anus relative to the total length of the larvae.

Yolk-sac Larva (Newly Hatched), 0 Days Post Hatch (Figure 11) — Newly hatched ictalurid larvae were large, 7–13.2 mm TL, with pigmented eyes but very

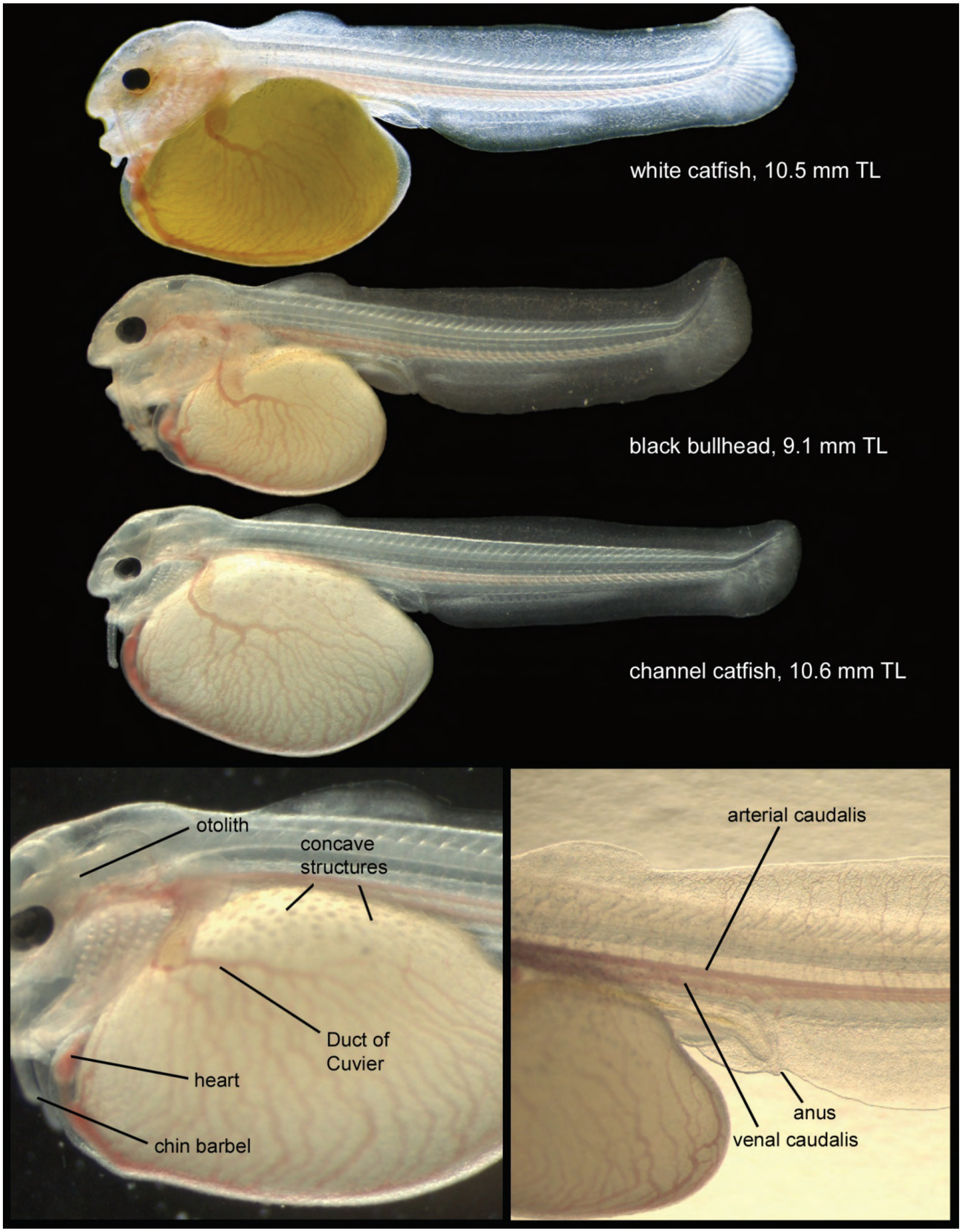

FIGURE 11.—Newly hatched larvae: lateral view of white catfish, 10.5 mm TL; black bullhead, 9.1 mm TL; channel catfish, 10.6 mm TL. **Inset**: On the left is a channel catfish newly hatched with chin barbels that are visible as buds growing at ventral head region; Duct of Cuvier and heart showing circulating blood; concave structures on dorsal region of yolk sac. On the right shows locations of arterial caudalis and venal caudalis that run along length of the larvae.

minimal amount of body pigmentation. First melanophores observed on the body were on the midbrain region of the head and on the pectoral region. Channel catfish had very light pigmentation on the midbrain; black bullhead had heavy pigmentation on the head and pectoral region (see Appendix 4). Similar to salmonids, ictalurids hatched with large bulbous yolk sacs and visible dorsal, anal, and caudal fin buds. Yolk sac was smallest in the black bullhead. White catfish had the largest and roundest yolk sac. Black bullhead, on average, had the shortest newly hatched larvae, and the channel catfish had the longest. For the three species, maxillary barbels were elongated, nasal barbels were not visible, and chin barbels were visible as tiny buds.

Vitelline circulation was most visible at this stage for the three species since the larva were translucent and contrasted with the bright red hemoglobin of the circulating blood. Blood movement was observed in the heart, the Duct of Cuvier, the yolk sac, body and fin folds, and the arterial and venal caudalis. There were dimple-like concave structures found only in channel catfish located on the dorsal region of the yolk sac adjacent to the pectoral fin bud. These structures are associated with the vitelline vein network which may have something to do with yolk absorption and nutrient flow from the yolk sac to the larva (T. Simon 2009, personal communication). The dimple-like concave structures were only present the first 2 dph.

Newly hatched larvae were sometimes on their sides but were also seen right side up. Black bullhead newly hatched larvae had wide heads compared to the other ictalurids but their yolk sacs were smaller (see Appendix 1). Newly hatched channel catfish larvae had elongated yolk sacs. Unlike in the Ohio River drainage where white catfish and black bullhead pectoral fin buds were absent at hatching (Simon and Wallus 2004), all white catfish and black bullhead observed in this study hatched with pectoral fin buds. The newly hatched larvae had motile pectoral fin buds at hatching; however, the larvae were mostly on the bottom because of their bulbous yolk sac. Newly hatched black bullhead and channel catfish larvae congregated or “huddled” in a bunch and showed swim bursts when disturbed. White catfish newly hatched larvae placed in an open container did not scatter even when disturbed. For all three species, initial folds of the pelvic fin buds sometimes did not develop until 1–2 dph.

Yolk-sac Larva (Initial Pigmentation), 0–3 days post hatch (Figure 12) — Darkening of the melanophores occurred initially on the occipital region of the head and on the pectoral abdominal region. Nasal barbels were visible as buds in the black bullhead as early as 9.5 mm TL; the white catfish and channel catfish did not have visible nasal barbels until later in development. Shape of the yolk sac was less bulbous and more irregular due to yolk absorption. Channel catfish had a pointed yolk sac posteriorly. Pelvic fin buds were visible. Initial stages of air bladder inflation were visible the first 3 dph for black bullhead and white catfish; however, air bladder inflation for channel catfish was not visible until ~7 dph. These are stages 44–47 in Armstrong and Child (1962).

Yolk-sac Larva (Dorsal Fin Bud), 3–6 Days Post Hatch (Figure 13) — Dorsal fin bud was differentiating from the dorsal fin fold. Initial receding of the dorsal fin fold

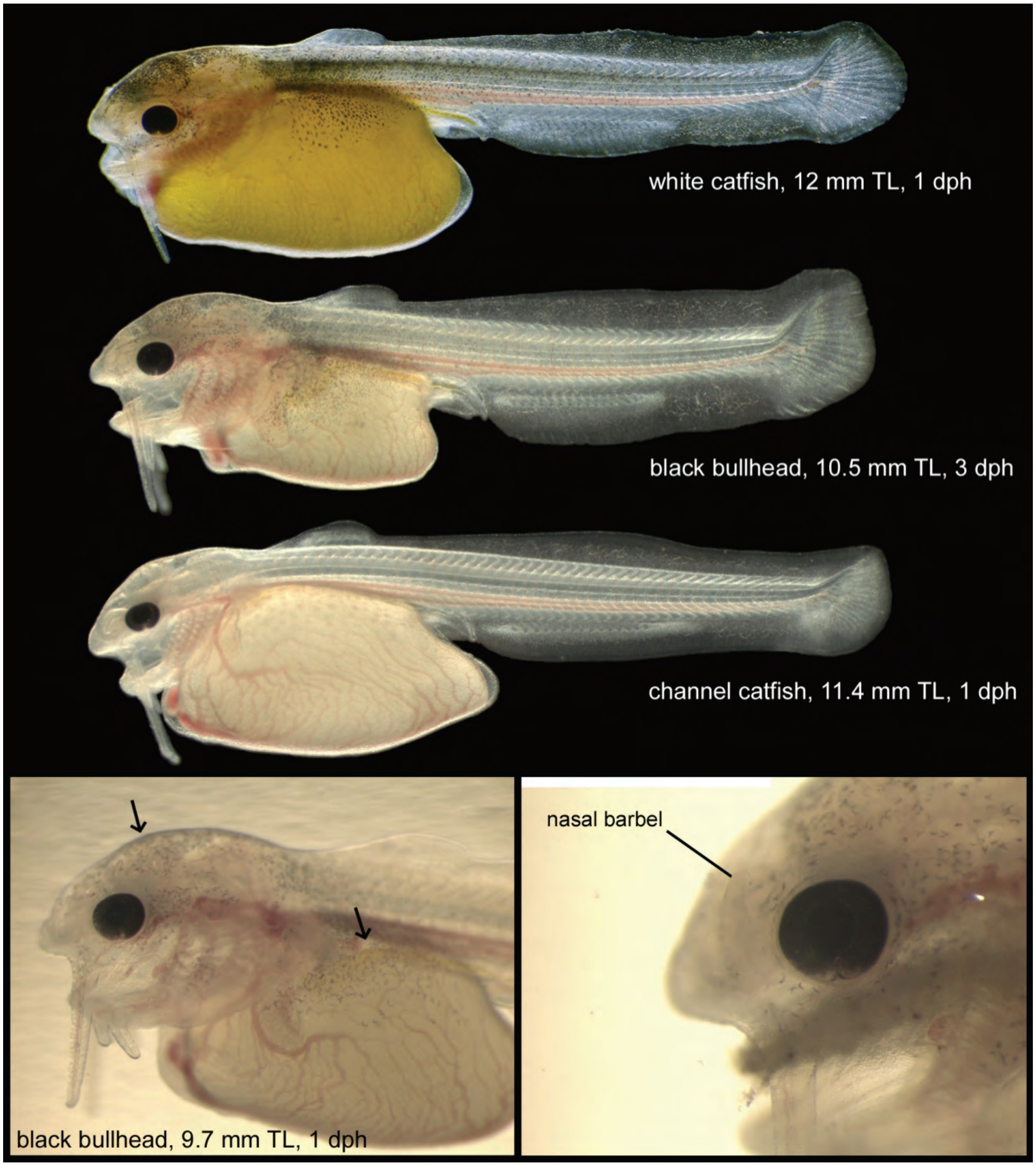

FIGURE 12.—Initial pigmentation (stages 44–47): lateral view of white catfish, 12 mm TL, 1 day post hatch (dph); black bullhead, 10.5 mm TL, 3 dph; channel catfish, 11.4 mm TL, 1 dph. **Inset**: left, arrows point to the first congregation of pigments along occipital or the midbrain and pectoral abdominal region on the yolk sac; right, location of the nasal barbel bud in black bullhead.

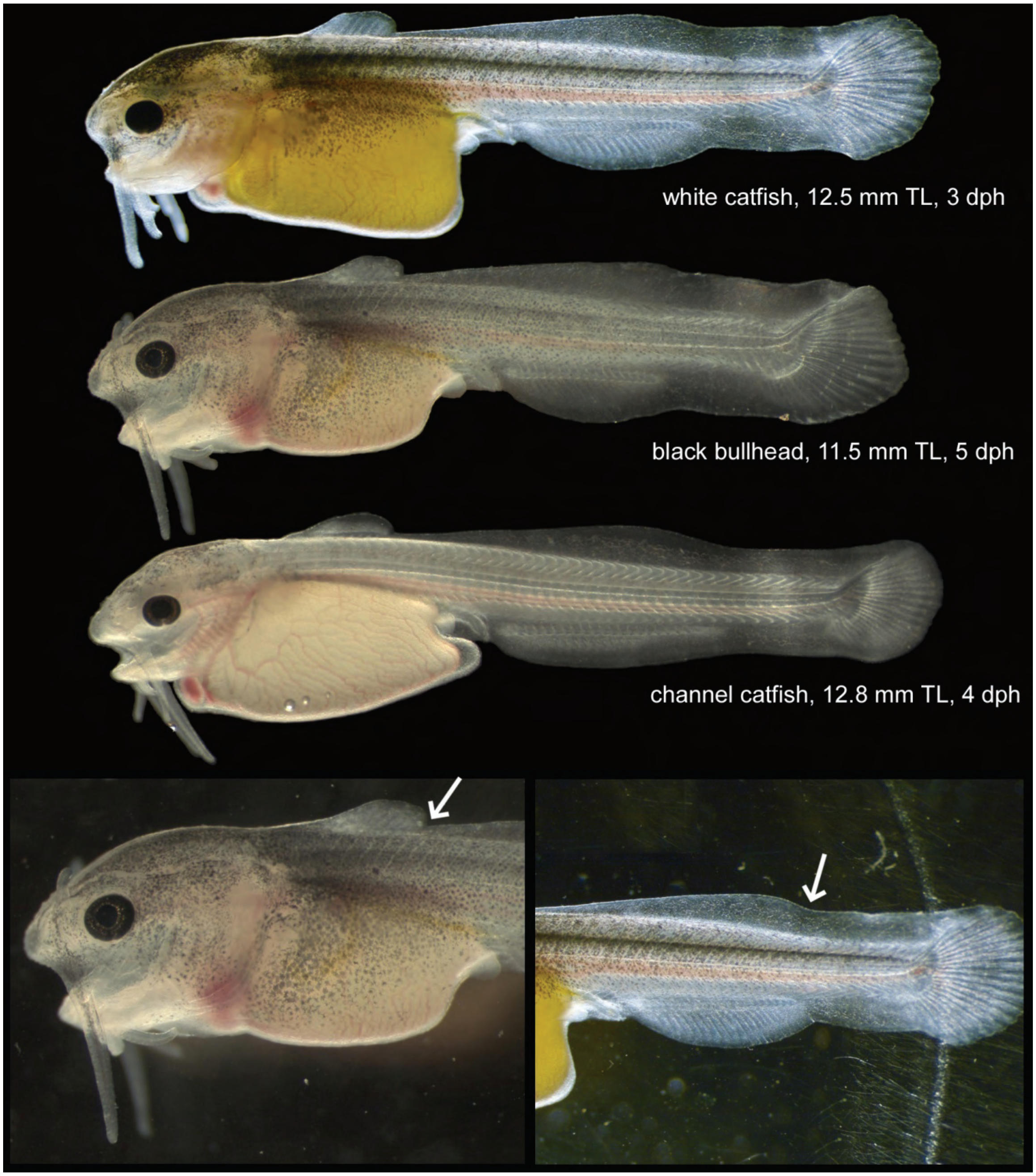

FIGURE 13.—Dorsal fin bud (Stages 48–49): lateral view of white catfish, 12.5 mm TL; black bullhead, 11.5 mm TL; channel catfish, 12.8 mm TL. **Inset**: Left, arrow points to the cleavage which separates the dorsal fin from the dorsal fin fold; right, arrow points at the initial receding of the dorsal fin fold where the cleavage will divide the adipose fin from the caudal fin.

was observed which will divide the fin fold into the adipose fin and the caudal fin. Pigmentation was observed along length of body, mostly along dorsal length of body, especially for white catfish and black bullhead. Channel catfish was mostly pigment-free along the body. The body of channel catfish was slender and the snout sharper compared to other two ictalurids. Also, when viewed dorsally, head of the channel catfish was smaller relative to width of yolk sac (see Appendix 1). Yolk sac of channel catfish was still pointed posteriorly. Nasal barbels were obvious in black bullhead but not visible in the other two ictalurids. These are stages 45–49 in Armstrong and Child (1962).

Yolk-sac Larva (Pigmenting Body), 6–10 Days Post Hatch (Figure 14) — A week after hatching, the ictalurid larvae darkened, especially on the dorsal region. Pigmentation on the yolk sac was most pronounced in the black bullhead, intermediate in the white catfish, and least in the channel catfish. Although pigmentation at the preanal/ventral region was observed only in the black bullhead, its midventral region was still pigment-free. Initial development of caudal fork was visible in the channel catfish but not in the two other ictalurids. Channel catfish air bladder was visible at ~7 d. In an indepth study of the development of channel catfish swim bladder, Al-Rawi (1967) observed a swim bladder in an 8.3-mm larva as early as 110 h post fertilization, ~4.5 dps. Channel catfish larvae have been collected as drifting organisms in rivers, perhaps as a consequence of their diel feeding activity (Armstrong and Brown 1983). Even though yolk-sac was present, foraging behavior and exogenous feeding were observed at this stage in the laboratory for all three species.

Several taste buds developed on the lips and barbels of the three species. Scanning electron micrograph of a 1-week-old channel catfish also showed numerous taste buds resembling elevated tubercles in the skin of the head and trunk (Northcutt 2003). These developments are stages 49–53 in Armstrong and Child (1962).

Yolk-sac Larva (Transition Stage), 9–14 Days Post Hatch (Figure 15) — The three species displayed juvenile characteristics but still had median fin folds and yolk-sac. Fin rays had developed in all fins; however, adipose and anal fins were still fused with median folds of the caudal fin. The lateral profile of the adipose fin fold and anal fin were more symmetrical in the channel catfish compared to white catfish and black bullhead. Pelvic fin buds differentiated into pelvic fins; pectoral spines and dorsal spines were partially ossified. Initial fork of white catfish caudal fin was observed. Air bladder was more visible and shaped like a circular bubble above the origin of the pectoral fins. Nasal barbels were visible as buds in the white catfish, elongated in the black bullhead, and absent in the channel catfish. Remnants of yolk sac were visible in all three ictalurids with the white catfish retaining the bright yellow coloration. In brown bullheads, and likely black bullheads, development of photomechanical properties of retina allowed embryo to adapt to light and to leave nest (Armstrong 1964). Active foraging was observed in the three species at this stage. Kalmijn (1988) found that ictalurids are able to sense the low frequency alternating or direct current electric fields emanated by prey (Kalmijn 1988). In channel catfish, onset of feeding seemed to correlate with the morphological maturity of the electrosensory lateral line (Lannoo and Lannoo 1996). Black bullhead larvae fed during daylight hours and were highly selective feeders on amphipods, ostracods, and copepods (Campbell and Branson 1978).

FIGURE 14.—Pigmenting body (Stages 50–53): lateral view of white catfish, 13.2 mm TL, 7 days post hatch (dph); black bullhead, 12.2 mm TL, 7 dph; channel catfish, 14 mm TL, 7 dph. **Inset**: Left, arrows point to a narrow, pigment-free midventral region of black bullhead (12.2 mm TL). Pigments are observed ventrally on the head; right, a 15.4-mm TL white catfish showing pigment-free ventral region, including the head. Channel catfish also do not have pigments ventrally.

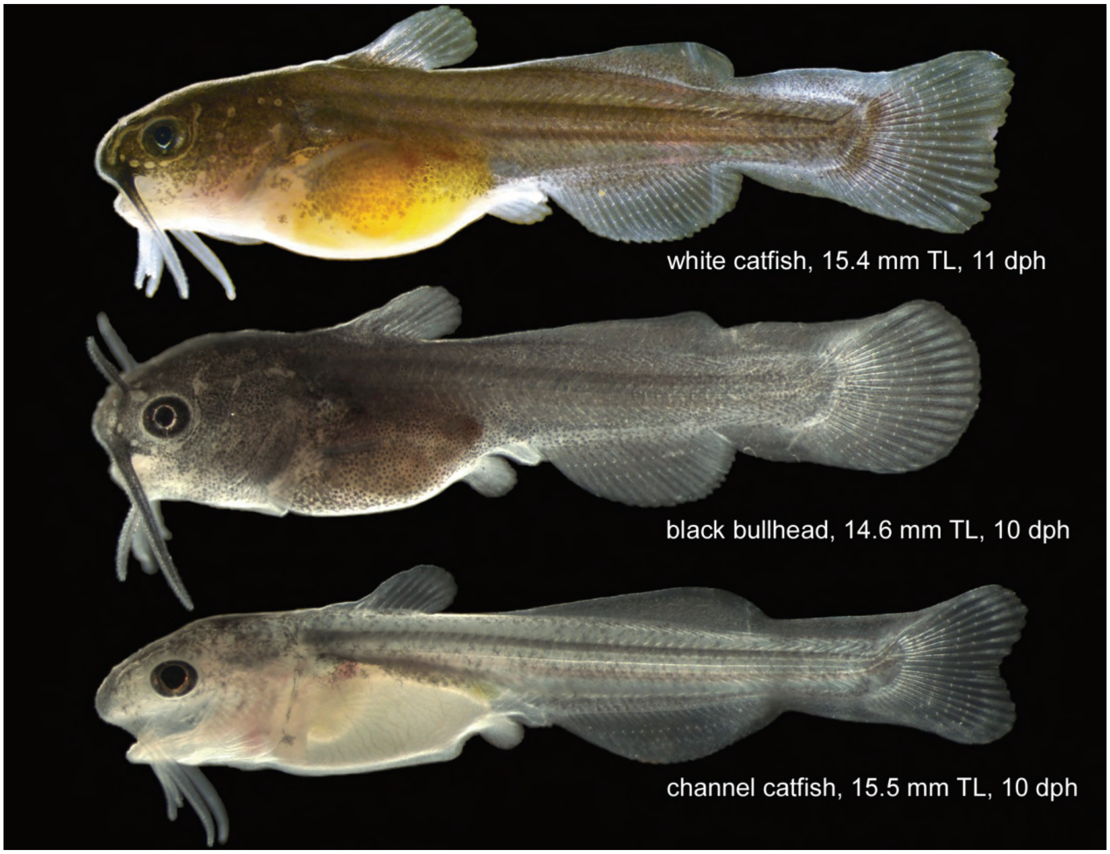

FIGURE 15.—Transition stage: lateral view of white catfish, 15.4 mm TL, 11 dph; black bullhead, 14.6 mm TL, 10 dph; channel catfish, 15.5 mm TL, 10 dph.

Juvenile, 14–21 Days Post Hatch (Figure 16) — Juvenile ictalurids had characteristics similar to adults. White catfish had a forked caudal fin, black bullhead a rounded caudal fin, and channel catfish a deeply forked caudal fin. Pectoral and dorsal spines were observed in all three species. There were four sets of barbels on the head. Nasal barbels were most prominent in the black bullhead. Dark body due to melanophores was greatest in black bullhead; least in channel catfish. White catfish and black bullhead had wide heads with flatter snout; channel catfish had a protruding, pointed snout. White catfish and black bullhead had a more robust and thick body; channel catfish were streamlined in comparison with a thinner caudal peduncle. All fins were developed, including the pelvic fin, which is the last to develop.

In the wild, black bullheads school, accompanied by one or two adults, and are abandoned once they reach ~25 mm (Forney 1955). Channel catfish and white catfish also school as juveniles (Wang 1986, Moyle 2002). Channel catfish juveniles were observed schooling in the daytime or in the absence of cover (Brown *et al*. 1970). Dichotomous keys for ictalurid juveniles were completed by Cloutman (1978) and Tin (1982).

FIGURE 16.—Juvenile: lateral view of white catfish, 20 mm TL, 30 days post hatch (dph); black bullhead, 20.5 mm TL, 21 dph; channel catfish, 20 mm TL, 21 dph.

There was a pigmentation and coloration difference between the cultured juveniles and wild juveniles (Figure 17). Similar to other cultured species at the larval and juvenile stages, pigmentation was heavy in cultured ictalurids. In example below, the laboratory-raised channel catfish was darker in coloration and had more distinct circular and stellate melanophores on head and body. The wild-caught channel catfish of the same size and life stage was more pinkish white with less distinct body melanophores. This coloration contrast in cultured and wild ictalurids was also observed in white catfish.

FIGURE 17.—Morphological difference between a cultured channel catfish (a) and a wild channel catfish (b). Both specimens were 16.7 mm TL.

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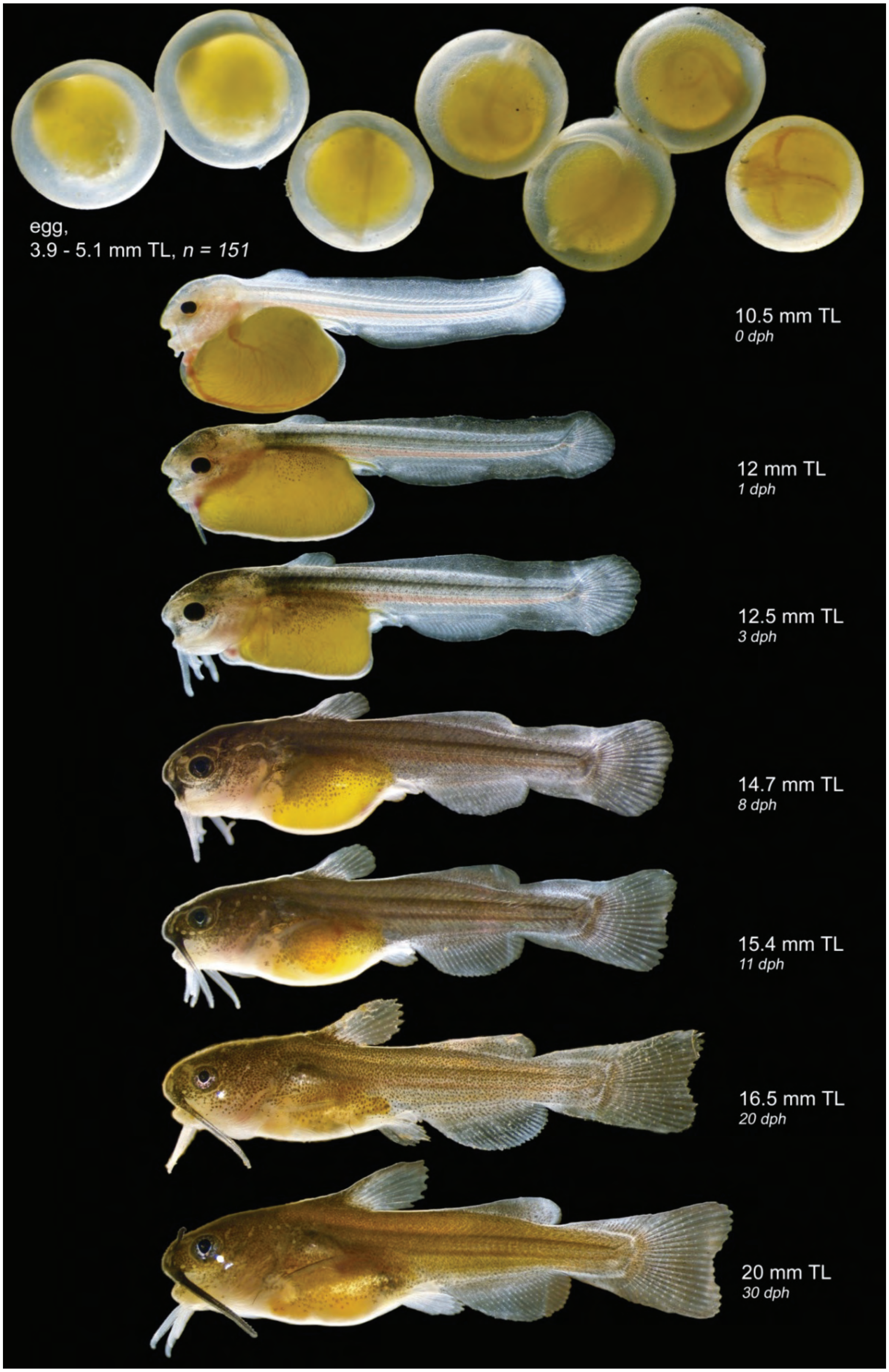
Appendix 1

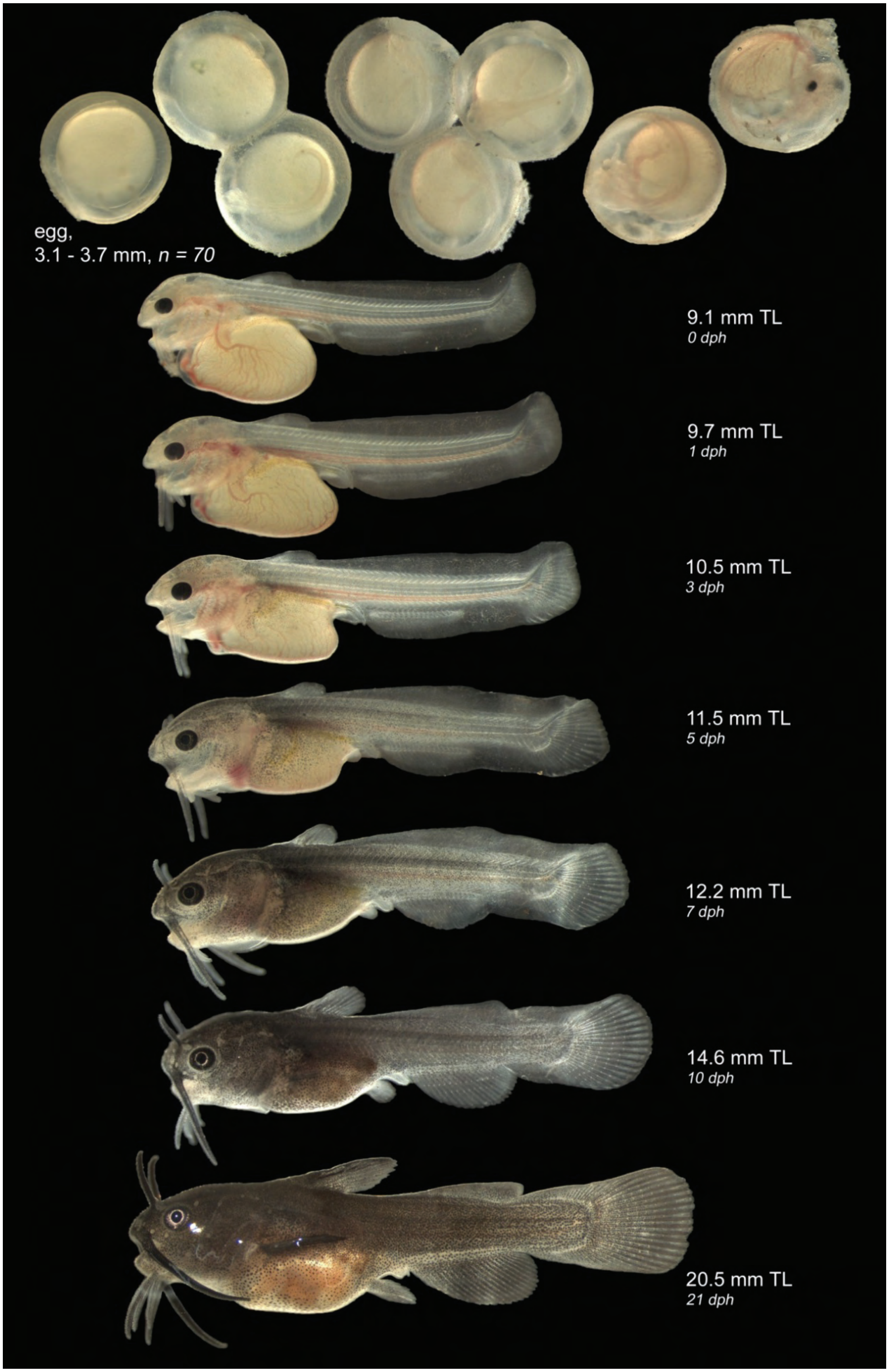
Life Stage Series of White Catfish



APPENDIX 1.—White catfish life stage developmental series.

Appendix 2

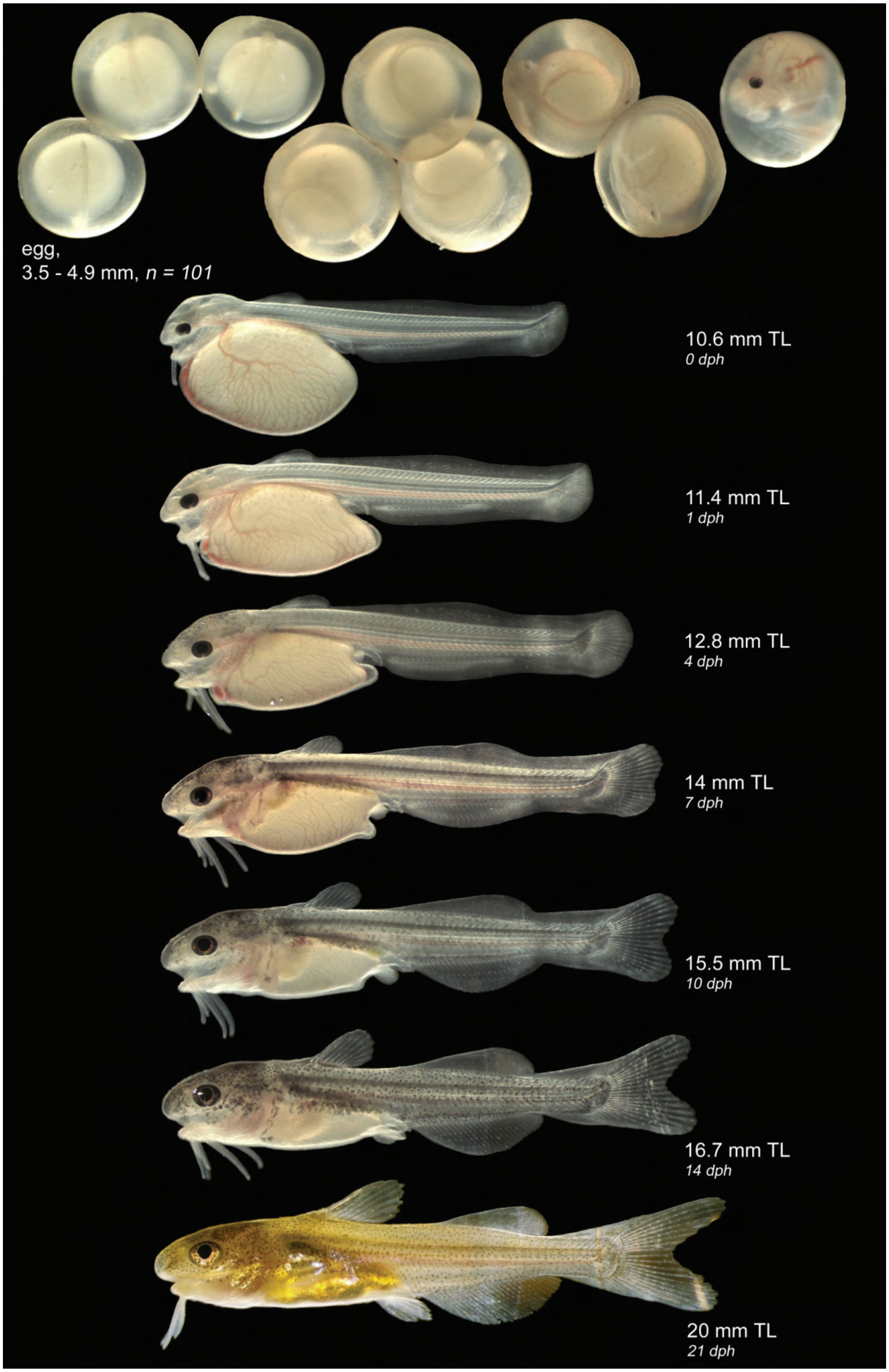
Life Stage Series of Black Bullhead



APPENDIX 2.—Black bullhead life stage developmental series.

Appendix 3

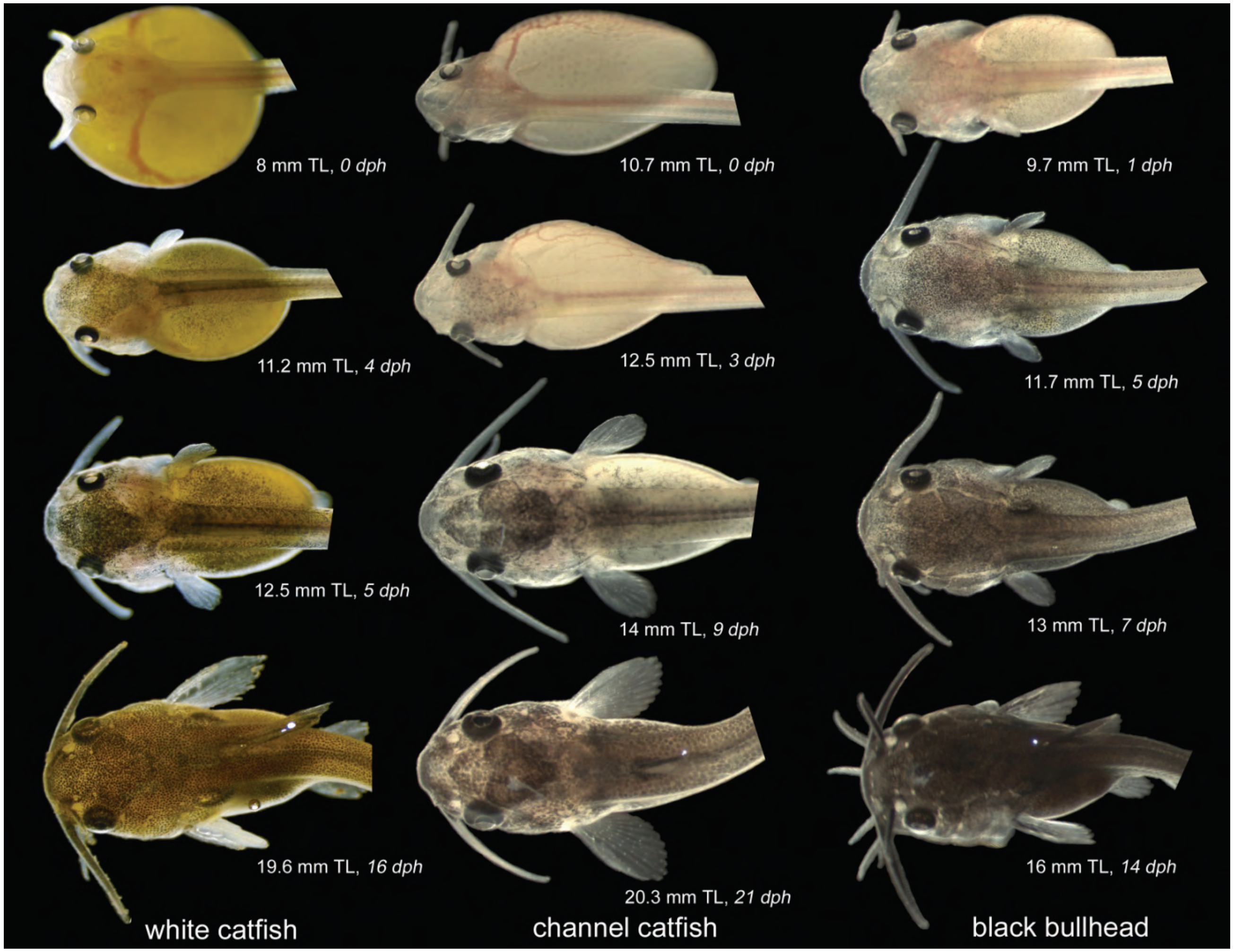
Life Stage Series of Channel Catfish



APPENDIX 3.—Channel catfish life stage developmental series.

Appendix 4

Dorsal View Progression of Larval Ictalurids



APPENDIX 4.—Dorsal view progression of morphology of white catfish (left column), channel catfish (center column), and black bullhead (right column). On the first row, yolk sac profile is most circular in white catfish and elongate in channel catfish. Head width relative to yolk sac is also most prominent in black bullhead. Second row shows initial pigmentation on the occipital region of the head of all three species. Third and fourth rows show white catfish retaining its yellow coloration, channel catfish exhibiting a sharper snout-profile, and the black bullhead developing numerous melanophores and prominent nasal barbels.