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**REVIEW OF FISH BEHAVIOR RELEVANT TO
FISH GUIDANCE SYSTEMS**

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KEY WORDS

Hydroelectric dams, juvenile salmon, behavior, guidance, sensory systems

LIST OF ABBREVIATIONS

bls	=	body lengths per second
d	=	day
f	=	foot
fps	=	feet per second
h	=	hour
Hz	=	hertz
in	=	inch
L	=	liter
m	=	meter
milligrams	=	mg
min	=	minute
mm	=	millimeter
mo	=	month
s	=	second
SPL	=	sound pressure level
TL	=	total length
W	=	Watt
<	=	less than
>	=	greater than

PREFACE

Poor fish guidance at certain hydroelectric projects on the Columbia River has been a problem for some time. To date, little effort has been made to apply the principles of fish behavior when designing these fish guidance systems. The reason for undertaking this project was to review the principles of fish behavior relevant to fish bypass and apply this information to designing better bypass systems at dams on the Columbia River.

Information concerning fish behavior relevant to fish guidance systems was searched for at a variety of locations including: NMFS Montlake Library (Seattle, WA); and Fisheries-Oceanography, Fisheries Archives, Engineering, Health Sciences, Natural Sciences, and Forestry Libraries (University of Washington). Databases searched included: National Technical Information Service (NTIS), Aquatic Sciences and Fisheries Abstracts (ASFA), and Dissertation Abstracts (DISS).

The bibliography section at the end of this report is a complete listing of all references considered for this review, and is divided into sections roughly corresponding to the divisions in the review (abstracts were available only for those references downloaded from Compact Cambridge CD-ROM database). This bibliography, complete with abstracts and key words, is available on computer disk.

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INTRODUCTION

Safe and efficient passage of outmigrating juvenile Pacific salmon through fish guidance systems at hydroelectric projects on the Columbia River is essential if sufficient numbers of returning adults are to be maintained. Fish guidance efficiency (FGE) is variable between dams and between years at any given dam, and the reasons for this variability are not clear. This situation exists, in part, because significant differences between the systems make it difficult to extrapolate from one situation to the other.

A large body of literature exists concerning fish behavior and ecology, and this information can be applied to understanding the behavior of fish in response to the stimuli encountered at hydroelectric projects. A set of guidelines or minimum design criteria is necessary. Although it is not possible to design optimal guidance systems, there is sufficient information to establish minimum design criteria below which a system will not work. In the context of the immediate needs of fish guidance research, minimum design criteria can help identify and thus avoid the development of inadequate fish bypass systems. In a long-term context, minimum design criteria will facilitate improved behavioral guidance systems by identifying where additional work is required to develop design criteria for optimizing guidance systems.

This literature review examines five key parameters that we feel affect FGE the most: light and vision; sound and hearing; water currents and rheotaxis; turbidity; and temperature. All five of these factors interact simultaneously at times, so it is often difficult to “tease apart” the individual effects. Therefore, the information presented will often overlap or combine (or both) one or more of the five factors. For each factor we will provide a brief background with definitions, and then we will attempt to apply what is known about each factor to fish guidance at dams and minimum design criteria.

SOUND AND HEARING IN FISH

CHARACTERISTICS OF SOUND

There are two components to sound propagation through water: particle displacement and sound pressure. Particle displacement is the to-and-fro movement (on the order of nanometers) of water molecules and is a vector quantity, whereas sound pressure is the oscillatory change in pressure above and below hydrostatic pressure and is a scalar quantity acting in all directions.

UNITS OF MEASUREMENT

In a free sound field without physical obstructions to sound transmission, and with an advancing wavefront that is essentially a plane surface, particle velocity (the first derivative of particle displacement) is proportional to sound pressure in the following manner:

$$v = p/\rho c$$

where v = particle velocity,
 p = sound pressure,

ρ = the density of the medium, and
 c = the propagation velocity.

The product ρc is the acoustic impedance of the medium. However, sound levels are not usually expressed as particle velocity, rather the logarithmic decibel (dB) scale of sound pressure level (SPL) is used because a great range of sound levels are found in nature:

$$\text{sound pressure level (SPL)} = 20 \log_{10} p/p_{\text{ref}} \text{ dB}$$

where p = the measured sound pressure, and
 p_{ref} = the reference pressure.

A reference quantity is always associated with the dB in order to place sound levels in a reasonable range. The reference quantity for SPL in water is usually 1 Pascal (Pa). Twenty μPa of sound pressure is the reference (re.) pressure for the dB scale in humans, because 20 μPa is the amount of sound pressure the average human requires to hear. Therefore, 0 dB re. 20 μPa is the human threshold of hearing and 120 dB re. 20 μPa is the threshold of pain. For each 20-dB increase in SPL, regardless of the reference pressure, the increase in actual sound pressure is tenfold. Thus, a 40-dB increase in SPL is 100 times more pressure, 60 dB is 1000 times more and so on.

Sound pressure and particle displacement are essentially the same at substantial distances from the source. However, in the near-field ($\lambda/2\pi$ [λ = wavelength], from the sound source) where the wavefront is spherical rather than a plane surface, particle velocity is much higher for a given sound pressure—the “near-field effect.” The near-field can be thought of as the region where the greatest amount of bulk movement of water occurs in response to the sound source, which is not as pronounced after $\lambda/2\pi$ distance from the sound source. This near-field effect can extend up to 50 m from the source for low frequencies such as 5 Hz, which is perceivable by many fish.

Sound propagation through water, via either the pressure or displacement component, is a logarithmic function:

$$y = a + m(\log x)$$

where a = the source-sound pressure level (y-intercept),
 m = the logarithmic slope, and
 x = the distance from the source.

Therefore, rates of sound level increase close to the source are rapid compared to those far away.

SOUND PERCEPTION IN FISH

Literature on hearing in fish is abundant, and it is clear that fish detect and respond to sounds in their environment. Fish appear to use sound: to locate prey, evidenced by attraction to a sound stimulus (for example, sharks: Wisby et al. 1964, Nelson 1965; various teleosts and elasmobranchs: Richard 1968, and Nelson et al. 1969; rainbow trout,

Oncorhynchus mykiss: Abbott 1970); for social interactions (bicolor damselfish, *Pomacentrus partitus*: Myrberg 1972, and Myrberg and Riggio 1985; gudgeon, *Gobio gobio*: Ladich 1988); for encounters with fishing gear (Nomura 1980, Wardle 1983, Ona and Toresen 1988); and to signal the presence of danger, evidenced by fish avoiding a sound stimulus (steelhead trout, *O. mykiss*: VanDerwalker 1967; herring, *Clupea harengus* L.: Blaxter et al. 1981a, Schwarz and Greer 1984, and Blaxter and Batty 1985a and 1985b; alewife, *Alosa pseudoharengus*: Haymes and Patrick 1986). In addition, minimum audible field thresholds have been determined for many species of fish (Tavolga and Wodinsky 1963; Chapman and Hawkins 1973; Chapman and Sand 1974; Hawkins and Johnstone 1978; Coombs and Popper 1979; Saidel and Popper 1987). A few studies have investigated fish behavior in response to changes in SPL over time. Olsen (1971) found a positive correlation between the rate of sound pressure increase and the number of Atlantic herring that would avoid this stimulus (see Blaxter et al. 1981a). Schwarz and Greer (1984) obtained similar results on Pacific herring (*C. harengus pallasii*). However, these studies did not quantify rates of sound pressure increase or the fish's response to the sound stimulus.

Physiology of Hearing

Fish hearing in general is different from that of terrestrial organisms. Most fish hear with a primitive version of the terrestrial inner ear (located in the skull of fish) and with the lateral line that runs the length of each side of the fish and is often extensively routed on the head. The inner ear and the lateral line system is called the acoustico-lateralis system. The inner ear does not have a cochlea as in terrestrial vertebrates; rather there are three symmetrically paired structures with associated bony otoliths: the lagena, sacculus, and utriculus. The lagena and sacculus are directly involved with hearing, whereas the utriculus is mainly for three-dimensional orientation (Platt and Popper 1981). The mechanism for hearing is the differential displacement of high-density otoliths relative to the low-density bodies of fish, resulting in bending of sensory hair cells that line the lagena and sacculus. This mechanical stimuli is then converted to electrical stimuli in the hair cell body and sent to the brain for processing.

Audiograms (threshold SPL for various frequencies) of different species of fish are variable. Families of fish with the best hearing such as cyprinids and ictalurids (Ostariophysan fish) possess a physical connection (via a series of bones, the Weberian apparatus) between the swimbladder and the inner ear. Thus, the swim bladder acts as an amplifier. The hearing ability of other fish such as salmonids and flatfish is limited in bandwidth and intensity threshold compared to other teleosts: Atlantic salmon (*Salmo salar*) are functionally deaf above 380 Hz (Hawkins and Johnstone 1978, Fig. 1). These fish lack the physical connection between their swim bladder and inner ear that Ostariophysan fishes possess (Hawkins 1986). Fish with this type of hearing are most sensitive to particle velocity since the otoliths in the lagena and sacculus essentially respond to particle displacement (Hawkins and MacLennan 1976).

Compared to humans, salmonids have poor hearing on the basis of perceivable frequency range and sensitivity to sound pressure (Fig. 1). Human infants are capable of detecting sounds from 20-20,000 Hz, and at SPLs much lower than that of salmonids. For example, a human would require about -80 dBs re. 1 Pa SPL to hear a 160 Hz pure tone,

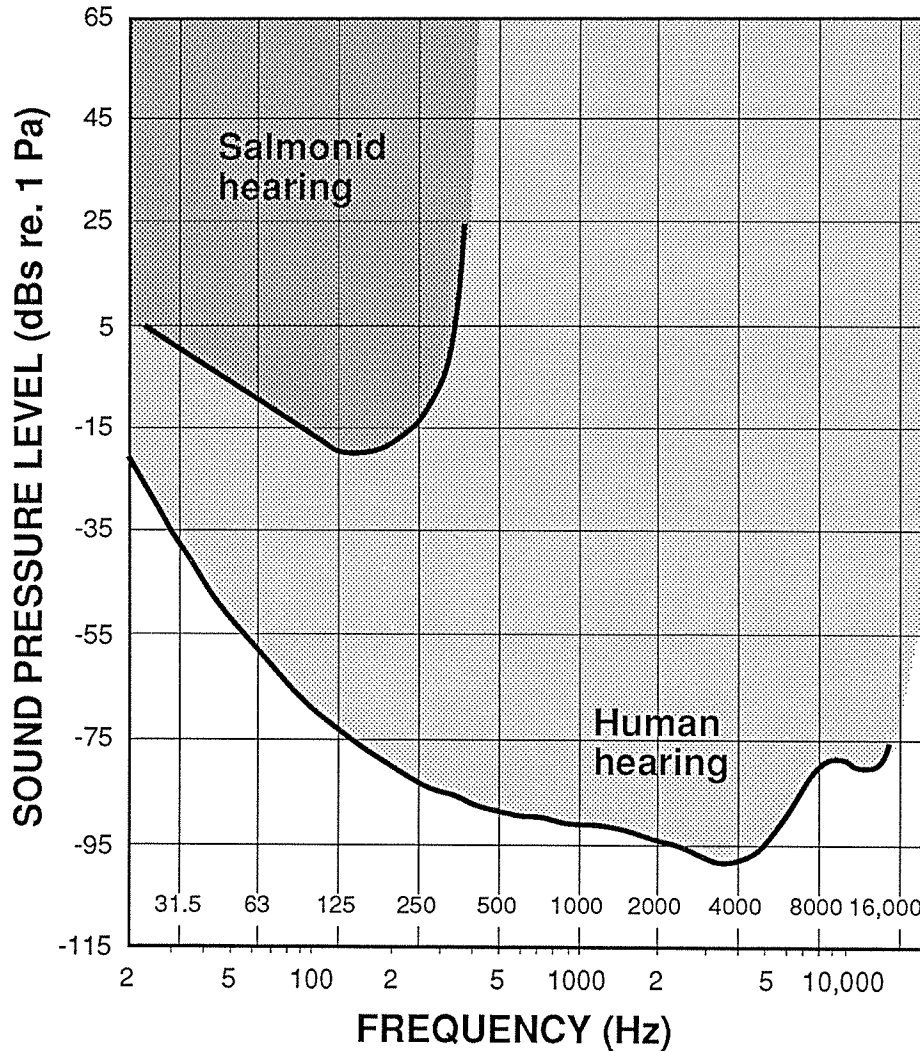


Figure 1. Comparison of Atlantic salmon, *Salmo salar* (Hawkins and Johnstone 1978, 11.88-12.6 in [30-32 cm] TL) and human sensitivity to sound.

while a salmonid would require about -20 dBs. Therefore, the salmonid requires close to a thousandfold increase in SPL to hear the same 160 Hz tone.

Minimum Requirements to Hear a Sound Stimulus

The minimum requirements for sound that will at least be audible to a juvenile salmon are as follows. First, SPL must be at least that of the minimum audible field of salmon in Figure 1 for all frequencies. Second, the ambient noise in the area where fish are to respond to the sound produced must be at least 24 dB less than the minimum audible field of the fish; otherwise “masking” will occur, and the fish will not hear the sound stimulus (Hawkins and Johnstone 1978). In addition, SPL should be at least 20-30 dB higher than ambient noise levels in order to be effective. Third, salmonids have a 183 Hz bandwidth for masking (Hawkins and Johnstone 1978). This means that any sounds within 90 Hz

above or below the stimulus frequency will mask the fish's detection of that frequency. Finally, noise or broad-band sound that is pulsed rather than continuous has been more aversive to other fish species than pure-tone continuous sound (see Hering 1968 in Olsen 1971; Olsen 1971; Blaxter et al. 1981b; Schwarz and Greer 1984).

FISH RESPONSES TO SOUND

The fright response of salmonids to sound is typically a “startle” or “start” behavior (Burner and Moore 1962, Moore and Newman 1956). Such behaviors involve sudden bursts of swimming that are short in duration and distance travelled. Few studies have shown that sound can attract or repel salmonids over great distances or for long lengths of time. Fish typically “habituate” to sound stimuli in their environment, evidenced by a rapid return to pre-stimulus behavior.

Most salmonids can be attracted to or repelled from sound through classical conditioning (Abbott 1973), but they habituate rapidly or do not respond at all when there is no conditioned response, regardless of SPL (Burner and Moore 1962, Moore and Newman 1956). “At no time did a sound frequency or intensity influence the action of the trout enough to be utilized in guiding young salmon into safe passages around dams and diversions” (Burner and Moore 1962). An explanation for this is that salmon have poor hearing, and the nature of the sounds presented to them in experiments has not been biologically relevant. Other species of fish with better hearing capabilities than salmon have been shown to jump out of the water or swim rapidly away from or towards sound stimuli (Moulton 1956; Hashimoto and Maniwa 1966).

Studies conducted on the response of salmonids to sound have direct application at hydroelectric projects. Fish guidance efficiency is low at certain projects, and many outmigrants pass through the project turbines (Williams et al. 1988). It is estimated that up to 33% of juvenile salmonids passing through the turbines are killed (Long et al., unpublished in Giorgi et al. 1988).

Bypass screens may produce some stimulus that fish avoid (Williams et al. 1988), and this stimulus might be sound (Anderson 1988a,b; Anderson et al. 1989). The acoustic environment at hydroelectric projects has been measured extensively (Anderson et al. 1989). However, we do not know how juvenile salmonids react to these sounds. Research on the response of salmonids to sounds analogous to those found at hydroelectric projects would be useful in assessing the impact sound has on outmigrant salmonids at hydroelectric projects. On the basis of studies concerning salmonid audition, sound is unlikely to be useful for attracting or repelling fish at hydroelectric projects.

Salient Research on Fish Hearing

The reviews of fish hearing in Hawkins (1981, 1986), Hawkins and Myrberg (1983), Fay (1988), Kalmijn (1988), Rogers and Cox (1988), and Popper et al. (1988) provide an unsurpassed wealth of information concerning fish hearing and behavior. In addition, Hawkins and Johnstone (1978) have established much of the fundamental knowledge base concerning minimum audible fields for Atlantic salmon. Particularly important case studies are Moore and Newman (1956), Burner and Moore (1962), Haymes and Patrick (1986), and Loeffelman (1990)

In summary, further research directed at salmonid hearing would yield little useful information to increase bypass efficiency at hydroelectric projects. Given the turbulent hydraulics at turbine intakes, we consider that using sound to divert outmigrating juveniles is unlikely to be successful.

LIGHT AND VISION

CHARACTERISTICS OF LIGHT

Light is characterized by both intensity and wavelength. The propagation of sunlight through water can be described by the equation

$$I = I_0 e^{-kz}$$

where I = intensity at depth z ,
 I_0 = surface intensity, and
 k = an extinction coefficient.

The intensity of a point source light at distance r from the source can be approximated by the equation:

$$I = \mu N_0 (r_0/r)^2 e^{-a(r-r_0)}$$

where a = volume absorption coefficient,
 N_0 = surface radiance-per-unit-area, and
 r_0 = the radius of the source.

The values of a for distilled water are 0.04 (1/m) and 0.3 (1/m) for Lake Pend Oreille water in the spring.

UNITS OF MEASUREMENT

Light intensity measurements generally integrate light over a specific range of wavelengths for a unit length of time and area of illumination. The result is an energy flux over a unit area. Table 1 provides a conversion for some of the common light measurements. Some are approximate because the energy content of light depends on wavelength, and different measures cover different ranges of wavelength. When characterizing the response of fish to light, the problem is further complicated because fish have different sensitivities to different wavelengths, and this spectral sensitivity is different from that of measuring instruments. Tables 1 and 2 describe the relationship of different measures of light and typical light levels.

PHYSIOLOGY OF VISION

As in most fish, salmon have paired, image-forming eyes. Accommodation is accomplished by moving the lens relative to the retina as opposed to altering the shape as in the case of human accommodation. Adaptation to various light intensities is mainly accom

Table 1. Conversions of different measurements

10.76 lux	=	1 footcandle
1000 lux	=	1 lambert
1 lux	=	1 lumens/m ²
98 lux	~	1 watt/m ²
41 lux	~	1 mE/m ² /s
1 μ Einstein	=	6.02 x 10 ¹⁷ photons
1 mwatt/cm ²	=	1 watt/m ²

Table 2. Intensities of different light sources

Condition	Lux	Watt/m ²	mE/m ² /s
Sky at noon	81,667	834	~2000
Direct sunlight	5.19 x 10 ⁸	5.3 x 10 ⁶	~1.3 x 10 ⁷
Dusk-dawn	5	0.05	~0.1
Starlight	0.03	0.0003	~0.0007
Fluorescent lamp (40 watt)	2100	21	~51
Mercury lamp (100 watt)	9.4 x 10 ⁷	9.6 x 10 ⁵	~2.3 x 10 ⁶

plished by moving the outer segments of retinal receptors relative to the pigment layer (retinomotor response). The large number of rods ($18 \pm 2/100 \mu\text{m}^{-1}$) and cones ($14 \pm 2/100 \mu\text{m}^{-1}$) in all *Oncorhynchus* spp. shows that the eye is adapted for vision in both bright and dim light (Brett and Ali 1958). However, even under optimal conditions, maximum sight distance for most pelagic fish is probably well under 50 feet (15.2 m). Less than 75% of blue-green light is absorbed by the retinas of many marine fish, compared to 30% absorption in humans (Woodhead 1966).

LIGHT AND FISH ECOLOGY

Light levels and photoperiodism can affect the ecology of fish (feeding, shelter seeking, etc.). Photoperiodism may influence smolt timing through its action on the pituitary (Hoar 1953). Minnows, *Phoxinus phoxinus* (L.), are more active in general at night than during the day when cover is available (Jones 1956). When there is no cover, the activity pattern is reversed. This situation held when fish were tested individually or in groups, and with or without food. The minnows avoided light intensities >0.08-0.17 meter-candles (m-c), and shoaling behavior (dependent on vision) broke down from 0.0240-0.0034 m-c. Feeding (on *Daphnia*) efficiency was 90% at intensities >0.008 m-c, but decreased to 40% in total darkness (Jones 1956).

Changes in photoperiod can have long term effects on salmonids. When exposed to advanced photoperiod schedules in experimental raceways, juvenile steelhead trout (*O.*

mykiss) exhibited initiation of migratory movements and elevated gill Na^+ , K^+ -adenosine triphosphatase activity (Na^+ , K^+ -ATPase) 1 mo earlier than controls (Zaugg 1981).

Level of light intensity is not a good measure of whether fish can see each other well enough to maintain schools (Whitney 1969).

Feeding efficiency of "young" coho salmon (*O. kisutch*) on Daphnia began to decline at intensities of 0.01 footcandles and dropped logarithmically with light intensity to no feeding in total darkness (Brett and Groot 1963). Glare from light of 9000 footcandles did not have any impact on feeding.

Steelhead trout from upper river drainages of the Columbia River may respond to changes in photoperiod analogous to that of winter steelhead trout (Zaugg and Wagner 1973; Wagner 1974).

LIGHT AND MIGRATION

Juvenile Pacific salmon (*Oncorhynchus* spp.) appear to migrate out of their natal streams and rivers at night. However, the time during darkness that fish migrate varies. Pink (*O. gorbuscha*), chum (*O. keta*), coho (*O. kisutch*), spring chinook (*O. tshawytscha*), and sockeye salmon (*O. nerka*) fry released at the head of an impoundment migrated at night, primarily from 1.5 h after sunset to 1.5 h before sunrise, and their migration velocity was much faster than the average water velocity (MacKinnon and Brett 1955). Brett and Ali (1958) found that sockeye salmon smolt evening migration peaked between 1900 and 2100 h in the Lakelse River, British Columbia. The downstream migration of chum, sockeye, pink, and coho salmon was initially nocturnal and was regulated closely by light intensity (approximately 0 footcandles); migration was most active 2-5 h after dark, decreasing until dawn (McDonald 1960). Downstream movement seemed to occur when fish lost visual reference to their surroundings.

While most juvenile salmonids outmigrate in the darkness, there are instances of migration during daylight. Lengthy migrations of pink and chum salmon can extend into daylight, and chum salmon migrations can occur during daylight under certain conditions like high flow (McDonald 1960). Durkin (1981) found most coho salmon outmigration was associated with daylight hours and increased from late March to mid-May.

Outmigrating sockeye salmon exhibit pulsed movements around dawn and especially dusk. The general hypothesis on the nature of sockeye salmon outmigration is: "Celestial phenomena are used in the time-compensated orientation of migrating sockeye which, by an unknown inherited mechanism, provides a direction appropriate to the particular escaped route from the lake" (Brett and Groot 1963). Because light reflects differentially off many things, it is a good way for salmon to navigate if there is no particulate interference (Brett and Groot 1963).

Nocturnal outmigration of juvenile salmonids is thought to be partially caused by loss of visual and contact stimuli at night, which decreases their rheotactic response intensity and leads to downstream migration (Hoar 1951; McDonald 1960). Atlantic salmon seem dependent on a light-dark cycle for timing their activity patterns (Varanelli and McCleave 1974). However, using chinook salmon (1.6 in [41.1 mm] mean TL) and bluegill (*Lepomis macrochirus*, 2.5 in [64.2 mm] mean TL) with high (1×10^3 footcandles) and low ($<1 \times 10^{-4}$ footcandles) light intensities, Hanson and Jacobson (1985) found that visual cues did not play a significant role in the fish's orientation to water currents (0-0.08

fps [0-2.5 cm/s]). Thus the nighttime seaward migration of salmon was thought not to be initiated by a loss of ability to detect and respond to water currents at night. However, the velocities used in this study were extremely slow and are not necessarily indicative of the flow conditions found in a river or stream.

Experiments on two stocks of rainbow trout (above- and below-waterfall stocks) found that both stocks had similar responses to current in the light, but the below-falls stock showed more downstream movement in darkness than did the above-falls stock (Northcote 1981). In one study, chum salmon fry preferred bright light and moved into strong currents by day (Hoar 1953). Coho and Atlantic salmon, and steelhead trout defended territories during the day, and sought deeper water and became inactive at night; this behavior is believed to facilitate seaward movement.

Coho salmon smolts adapt rapidly to current (MacKinnon and Hoar 1953). Turbulence produced no changes in distribution of fish between light and dark sides of a tank in tests of smolts and fry of coho, pink, chum, and sockeye salmon, but the presence of rocks helped fish hold position more strongly (Hoar et al. 1957).

ATTRACTION AND REPULSION TO LIGHT

As with sound, light can attract or repel fish. In general, fish are more affected by pulsing (strobe) rather than continuous light (Brett and MacKinnon 1953; Craddock 1956; Patrick et al. 1985). Light intensity has been examined, and minimum intensity thresholds along with attraction/repulsion behaviors have been established. The level of light to which fish are adapted, the species studied, and the developmental stage of fish seem to be three key parameters affecting fish response to light.

The level of light to which fish are adapted affects response to light. Puckett and Anderson (1988) found for trout that if part of their environment was suddenly darkened, attraction to the remaining lighted region was strongest if the light level was the same as they were previously adapted to. Light levels dimmer or brighter than their previous surrounding produced weaker attraction. Sockeye left in darkness for 4 d before exposure to a 6300 footcandle light at night were almost completely light-adapted in 20-25 min; those acclimated to the 6300 footcandle light continuously for 4 d showed a slower adaptation of 55-60 min to sudden dark (Brett and Ali 1958).

A directional light (6 Volts, 50 candle power) 3.3-9.8 ft (1-3 m) deep, was found to attract *Lateolabrax japonicus* (catch was doubled) in a trap at night, especially if the lights were in strings and lit in succession (Sasaki 1959). In the Gulf of Mexico, coastal pelagic fish have been led away from obstructions such as oil rigs (1000-W mercury vapor lamps, Wickham 1973). Sequential leading with the lamps only worked if the lamps were <32 ft (10 m) apart. A drifting lamp led 5 tons (4.5 metric tons) of *Sardinella anchovia* 0.6 miles (1 km) before being captured (Wickham 1973). If fish went out of the lamp beam in either sequential or leading strategies, they were lost. Ten (400-W) underwater floodlights were tested at Jenkins Creek on outmigrating, 0-aged coho salmon, and an average of 81% of the fish were diverted by the lights at night (Craddock 1956). However, the author felt that the results might have been different if lights were left on all night.

Response to lights varies between species or stock studied and water velocity. Anderson and Nemeth (1987) observed differences in the behavior of coho and chinook salmon smolts to strobe lights in raceways. Freshwater (alewife; smelt, *Osmerus mordax*;

and gizzard shad, *Dorosoma cepedianum*) and estuarine (white perch: *Morone americana*, spot: *Leiostomus xanthurus*, menhaden: *Brevoortia tyrannus*) fish all exhibited avoidance behavior to strobe lights, which varied with water velocity, flash rate, and acclimation of fish (Patrick et al. 1985). Gizzard shad showed strong avoidance to lighted runways at velocities ranging from 0.5-1.0 fps (0.15-0.32 m/s), less so at higher velocities. White perch were slightly attracted to lights at the higher velocities although, like the gizzard shad, they avoided other lighted conditions (Patrick et al. 1985). Hoar et al. (1957) found that coho salmon smolts were uniformly photonegative. When sockeye salmon smolts were suddenly exposed to light (150 footcandles), they displayed the most marked negative response compared to chum, coho or sockeye salmon fry or coho salmon smolts. At sudden exposure to 1000 footcandles, all species of smolts tested (coho, chum, pink, and sockeye salmon) were photonegative, as determined by a >50% negative response.

Fish response to light is known to change with developmental stage. Sensitivity to light was found to increase during smolting in both coho and sockeye salmon, as evidenced by their seeking cover or deeper water (Hoar et al. 1957). Kwain and MacCrimmon (1969) found that until rainbow trout were 7 mo old, there were no behavioral responses to overhead light. At 10 mo, light between 0.010 and 0.005 lux was the minimum threshold for response, but by 24 mo 0.005 lux could be discriminated from total darkness, but not 0.001 lux. When given a choice between light and dark sides of a tank, at intensities from 0-500 footcandles, pink and chum salmon fry (which school) were consistently photopositive whereas coho salmon fry were indifferent to light intensities >45 footcandles (Hoar et al. 1957). This behavior in coho salmon coincides with their rapid adaptation to current (MacKinnon and Hoar 1953) and to alarming stimuli (Hoar unpublished). At 1000 footcandles, all groups in the study were photonegative, as determined by a >50% negative response to sudden light. Sensitivity to light increased during smolting in both coho and sockeye salmon, which then retreated to deeper water or cover (Hoar et al. 1957).

EFFECT OF LIGHT AT DAMS AND STRUCTURES

Working at McNary Dam, Fields (1966) found that ten times more salmonid migrants (all species) were caught in surface traps when the lights were on than on dark nights; the subsurface catches were not decreased in these cases. In addition, no significant difference in total number or vertical distribution of migrants occurred in the six submerged nets on light or dark nights. This suggests that the experimental guiding lights in this study attracted and concentrated migrants from all directions and did not simply pull migrants from the turbine entrance. Fields also found that significantly larger numbers of downstream migrants were recovered from lighted emergency slots than dark slots, and this number did not increase when turbines were inoperative. Slots with 200-W lamps attracted fish best; however, migrants avoided brighter 1000-W lamps in swiftly flowing water. There was no interaction between lighting conditions in the forebay and that in the slots. Chinook salmon and steelhead trout were caught more in lighted slots but sockeye salmon showed no preference. Guidance was especially effective at McNary because fish were light acclimated as they passed through the powerhouse, and the "swim towards the light response" was in effect after they entered the turbines (Fields 1966).

Collins and Elling (1960) noted that adult chinook salmon and steelhead trout swim slower in dark channels than light channels but swim faster in dark fishways (<1 foot-

candle) than light (800 footcandles). The authors felt, however, that this was probably due to the laminar flow in the channels versus the turbulence of a fishway. In the same study, light-adapted adult steelhead trout exhibited a marked preference (80%) for dark channels over light, whereas chinook salmon showed no preference. In addition, rate of ascent of fishways in the dark compared favorably with ascent during the day.

Atlantic salmon and sea trout (anadromous brown trout, *Salmo trutta*) ascended a tunnel 7250 feet (2208 m) long, 20 feet (6.25 m) high and 18 feet (5.50 m) wide despite the lack of lights and the very low velocity (<0.92 fps [28 cm/s], Rogers and Cane 1979).

In experiments with glass tubes and/or chains suspended vertically in the path of downstream migrating sockeye salmon, the visual response to the chain clearly was the cue for stream orientation in low light, rather than deflection of current around an unseen obstacle (glass) (Brett and Groot 1963).

Adult spring chinook salmon passage through the Bonneville Dam, Washington, ladder was tested. During the lights-on condition at Washington Gate number one (two 150-W thallium iodide lights installed on the powerhouse wall directed through the trash and ice sluiceway) the exit to entry rate was 82%; at lights-off it was neutral. Sluiceway number one had a higher net entry during dark periods (Shew et al. 1984).

When exposed to various trashrack bar spacing at an average water velocity of 1.0 fps (32 cm/s) in an oval swim tank, juvenile chinook salmon exhibited changes in rheotaxis orientation and a hesitancy to pass through bar-spacing <5.9 in (15 cm), under light intensities of 14.0 and 1.0×10^{-2} footcandles (Hanson and Li 1983).

A reduction to about one third of the expected catch of outmigrating salmon was achieved with either a continuous or flashing light. No difference was seen in the movement of trout through similar conditions (Brett and MacKinnon 1953).

Patrick (1981), studying gizzard shad, smelt, and alewife, found that in the absence of light, most diversion barriers were ineffective. The addition of a strobe light not only reduced fish passage but kept fish from the vicinity of barriers. These barrier/light combinations were effective at water velocities of 0.5 and 1.0 fps (0.15 and 0.32 m/s) and at strobe intensities of at least 10 lux. Shad sped up upon encountering the barrier, and passage was significantly higher in the dark. In contrast to shad, smelt displayed a high order of rheotaxis. In the presence of a strobe light, alewife appeared disoriented and often ran into the wall trying to escape. For all barrier types, passage increased by a factor of 2.4, with an increase in velocity from 0.5-1.0 fps (0.15-0.32 m/s). Generally, the fish showed no evidence of behavioral adaptation to the light over a 12-h period (Patrick 1981).

It is important to determine preferred wavelengths of fish around well-lit industrial structures, so fish are not inadvertently attracted to dangerous places (i.e., intakes, etc., Sager and Hocutt 1985). Zaugg (1981) felt that in order to compensate for the migratory inhibition induced by dams, hatchery smolts should be exposed to advanced photoperiods. In addition, flood lighting of streams changed sockeye salmon behavior, and also increased predation on the concentrated schooling fish (Brett and Groot 1963).

TURBIDITY

Turbidity levels on the Columbia River are variable, and the effect of turbidity on fish passage at hydroelectric projects is difficult to determine. Continuous monitoring of

turbidity levels at the entrance to bypass systems is unnecessary. However, turbidity in the river tends to increase during the spring runoff, and modifications of bypass parameters might be appropriate during these times.

UNITS OF MEASUREMENT

There are three different units for turbidity used in this paper: nephelometric turbidity units (NTU), formazin turbidity units (FTU), and mg/L (milligrams per liter). No standard conversion is available between NTU/FTU and mg/L. The conversion varies with particle size and type. For example, Gradall and Swenson (1982) used 2 μm diameter particle size, and the conversion for mg/L to FTU was: $\text{mg/L} = 0.61 \text{ FTU} + 0.16$. Because the references for measuring NTU and FTU are different, a simple conversion for these units is not available.

FISH RESPONSE TO TURBIDITY

Fish do respond to turbidity, and this response is a result of a combination of sensory inputs. Vision and rheotaxis are probably the most important sensory modalities affecting turbidity response. The olfactory and acoustico-lateralis systems of fish are unaffected by turbidity (Brett and Groot 1963).

Interspecific Responses

There are interspecific differences in response to turbidity. Creek chubs (*Semotilus atromaculatus*) prefer highly turbid water (56.6 FTU) to moderately turbid water (5.8 FTU), while brook trout (*Salvelinus fontinalis*) show no preference (Gradall and Swenson 1982). In addition, schooling behavior of the creek chubs was not affected by the above turbidity levels.

Turbidity Acclimation

The turbidity that fish are acclimated to has an effect on the turbidity the fish will respond to. Juvenile coho salmon that were acclimated to clear water (<0.3 NTU) initially avoided water of 70 NTU (sublethal levels) and above, but this behavior ceased after about 5 min. Such behavior was thought to occur in response to maintaining visual contact with potential food items (Bisson and Bilby 1982). Juvenile coho salmon that were acclimated to slightly turbid (2-15 NTU) water initially avoided water of 100 NTU and above, but this behavior also ceased after about 5 min. In addition to this response, some fish exhibited a "fright huddle" by darting rapidly, hiding in corners, and huddling together at times, all within the turbid areas of the experimental tank. When the "fright huddle" behavior occurred, virtually all fish were involved (Bisson and Bilby 1982). The authors concluded that juvenile coho salmon may not avoid moderate turbidity increases over low background levels, but this could not be fully justified until fish could be tested in their native streams (Bisson and Bilby 1982).

Chronic Responses

High turbidity or surges of turbidity seems to correspond to outmigration, however, it is often difficult to differentiate between the effects of increased water velocity and turbid-

ity. McDonald (1960) found that the largest daytime catches of young migrant pink salmon were observed during periods of increased water velocity and turbidity. However, on the Kalum River, British Columbia, where the water is always turbid, the run is essentially constant over time despite water level fluctuations. Peaks in the outmigration of chinook and sockeye salmon from the middle reaches of the Susitna River in Alaska correlated with peaks of river flow and discharge of sediment (Hale 1987). McDonald (1960) found that the daily migration period of Pacific salmon was extended if waters were turbid, and migration continued in muddy waters. All of this suggests turbidity as a factor in fish migration and movement in general.

Acute Responses

There are also acute effects from both sudden changes in or high levels of turbidity. Juvenile coho salmon exhibit "alarm" responses to rapid increases in turbidity, whereby they hide in the gravel, swim sporadically or head downstream (Berg and Northcote 1985). High levels of turbidity increased the rate of downstream migration in juvenile chum salmon during the day (McDonald 1960; Noggle 1978). Lake trout (*Salvelinus namaycush*) have been shown to avoid turbid water (Swenson 1978). Raising the turbidity level above 30 NTU caused juvenile coho salmon to move closer to the substrate, decreased capture success and reaction distance to brine shrimp from 11.8 to 4.7 in (30 to 12 cm), deactivated dominance hierarchies, and discontinued territorial behavior (Berg and Northcote 1985). Brook trout (*S. fontinalis*) and creek chubs exhibited decreased use of fixed overhead cover, increased activity, and reduced association with the substrate in response to increased turbidity (Gradall and Swenson 1982). Juvenile coho salmon, when given a choice, prefer "moderately" turbid water, but exhibit no preference for "slightly" (10-20 NTU) turbid water (Bisson and Bilby 1982).

The findings of turbidity effects on fish are variable, however. Noggle (1978), found that juvenile coho salmon do not avoid suspended sediment concentrations that are normally found in nature. Turbidity can be lethal if levels are high enough, but turbidity levels found in nature rarely reach lethal levels (Herbert and Merkens 1961). Avoidance in juvenile coho salmon has been observed at 4000-8000 mg/L of sediment, which is above the 96-hour LC50 (lethal concentration to kill 50% of the fish in 96 h) for coho salmon (Noggle 1978). In the same study, fish preferred low to medium (0-2000 mg/L) levels of turbidity in a laboratory setting for short periods of time, and avoidance occurred at high concentrations (4000-8000 mg/L) of suspended sediment.

WATER CURRENTS AND RHEOTAXIS

The response of fish to water currents (rheotaxis) in conjunction with their swimming abilities seems to hold the most promise for understanding and improving FGE's at dams. The complex hydraulic environment found at the entrance to fish bypass systems should be characterized at each project and correlated with what is known about fish response to hydraulics and swimming ability.

PHYSIOLOGY OF SWIMMING

There are a few key words and concepts regarding fish swimming that must first be defined. Swimming experiments conducted on fish typically examine three types of swimming or swimming speeds: burst, critical, and sustained. Burst swimming speed is the maximum velocity a fish can swim for 15 sec or less, analogous to sprinting in humans. Burst swimming velocities consume tremendous amounts of energy. Puckett and Dill (1984) found that the metabolic rate (based on oxygen consumption) required for burst swimming was 40 times higher than that required for sustained swimming. Critical swimming velocity is determined by increasing water velocity in experimental flumes by a constant interval every 15 min and noting the velocity at which the subject becomes exhausted. And finally, sustained swimming is the velocity a fish can maintain for an hour or more without variation in performance, analogous to walking in humans.

Fish use about 10% of their total oxygen consumed to operate their gills; this percentage is probably less in small fish than large. In contrast, oxygen use for breathing is about 3% in humans (Lindsey 1978).

Fish have two functionally different types of muscles for swimming: dark or red muscle, and white muscle. Red fibres of fish muscle are thought to be involved in aerobic, slow swimming (Bone 1966; Hudson 1973; Webb 1975; Johnston et al. 1977), whereas white fibres are associated with anaerobic, burst or fast swimming in fish. Hudson (1973) found that the white muscle may be more involved with intermediate speeds than burst swimming.

Orientation in moving water (rheotropism) is accomplished mainly with visual and tactile sensation (Lyon 1905; Dijkgraaf 1962; Pavlov 1966) along with the lateral line system. Because of this, most teleost fish (especially the young) invariably have a lower critical velocity in darkness than in light. Rheotropism is thought to be maintained in fish by an optomotor reaction that is actually an unconditioned reflex movement as a function of moving reference points in the field of vision (Lyon 1905; Jones 1963; Pavlov 1966).

UNITS OF MEASUREMENT

Swimming velocity is usually expressed in body lengths per sec (bls), where body length is total length (length from tip of head to tip of tail, TL). Body lengths per sec are used in order to standardize velocities since the length of a fish governs its ability to swim. Sometimes swimming velocity is expressed as fork lengths per sec, fork length being the distance from the tip of the snout to the fork of the caudal fin.

Tail beat frequency is the number of beats the caudal fin of a fish makes per-unit-of-time. In general, lower tail beat frequencies for a given velocity are equated with increased swimming efficiency (Flagg and Smith 1981). Tail beat frequency increases linearly with swimming velocity for a given fish at a given temperature (Bainbridge 1958).

PHYSICAL CHARACTERISTICS OF WATER

Physical characteristics of water have an effect on fish swimming. Water viscosity is the dominant factor in larval fish locomotion with associated low Reynolds numbers. Water viscosity is 30% greater at 50°F (10°C) than at 68°F (20°C, Bernatchez and Dodson 1985). For large fish, inertial forces of the water are the dominant factor; thus it is more

difficult to accelerate and easier to glide. With larval fish, acceleration is less difficult, but gliding is more difficult (Lindsey 1978). For example, smaller fish (about 4 in [10 cm] TL) can attain burst speeds of 25 bls (at 57°F [14°C]), whereas larger fish (about 40 in [100 cm] TL) can reach 6 bls (Wardle 1977). The power needed for propulsion equals the drag that the fish has to overcome, and fish morphology and locomotion are the main factors affecting drag (Webb 1975).

SWIMMING PERFORMANCE

In addition to the physical constraints of living in a fluid medium, a number of other factors contribute significantly fish's ability to swim: temperature, size or age, species, stock, ecology/behavior, and physiological status (such as smolting). Vision and the lateral-line system of fish are the key sensory inputs for a fish's response to currents. However, we will first consider the basic swimming abilities of fish, and then discuss how the aforementioned variables affect swimming.

Many studies have determined swimming "performance" of various species of Pacific salmon at various temperatures and sizes of fish. For the most part, swimming speeds of 2-3 bls can be achieved by most fish for some time (4 bls for salmonids, Blaxter 1969).

A current of 3 feet per sec (fps, 0.9 m/s) was believed to be too rapid to permit trout fry to swim out of a deflection zone (Brett and MacKinnon 1953). Optimal velocity for chinook salmon (1.25-1.50 in TL) was concluded to be 1 fps (92% maintained this velocity for 10 min). Kerr (1953) stated: "Even though the salmon might be impinged on screens for short periods of time, they will still survive upon release," and impingement for 10 min was not harmful.

Maximum burst speeds of are generally on the order of 10 bls (Blaxter 1969). Rainbow trout had burst speeds of 10 bls, steelhead trout 7-13 bls, adult coho salmon 6-9 bls, adult chinook salmon burst 7-11 bls. Burst speeds in the rainbow and steelhead trout could only be maintained for 10-20 sec, after which it dropped to 4 bls (Blaxter 1969). Coho salmon (1.9 in [48.3 mm] TL, 59°F [15°C]) reached burst swimming velocities of 1.4 fps (43.5 cm/s) or 9 bls, and travelled an average distance of 7.4 in (18.8 cm) during the burst (Puckett and Dill 1984). Gray (1953, 1957) found that burst swimming velocities of coho salmon (mean TL of 3.7 in and 4.0 in [9.4 cm and 10.1 cm]) at 54-59°F (12°-15°C) were 4.5-5.0 fps (140-150 cm/s), or about 15 bls.

Blaxter (1969) noted that sustained swimming speeds for sockeye and coho salmon were 3.0 and 3.4 bls, respectively. Recovery of an exhausted coho salmon was estimated at 5 h (Blaxter 1969). Kerr (1953) found that 1.2- to 2.0-in (3- to 5-cm) TL spring chinook salmon could swim at 1.0- to 1.5-fps velocities for up to 10 min in a flume, but would continue swimming in 1.0- to 1.2-fps velocities for an hour or more.

Brown, brook, and lake trout, and Atlantic salmon (1.6-2.0 in [40-50 mm] TL) had critical velocities >1.6 fps (0.5 m/s [Brett et al. 1958]). "Approach velocities above dams which exceed 1.0 fps will cause increased difficulty in guiding young salmon into safe by-passes if more than 20 to 30 min elapse during which the fish are forced to stem the current. Fatigue from exceeding the cruising speed is likely to occur (65-71°F [18.5-21.5°C])" (Brett et al. 1958).

In addition to swimming performance, there is information of jumping performance in salmonids. Symons (1978) found that juvenile coho and Atlantic salmon could leap water

falls at least 5 body lengths in height. There were no seasonal changes in leaping behavior, but temperatures near optimal for the species produced maximum jumping heights.

FACTORS AFFECTING SWIMMING PERFORMANCE

Temperature

Temperature has a tremendous impact on a fish's swimming ability (Figs. 2 and 3). For any given species of fish, there is an optimum temperature for swimming. In general, 59°F (15°C) is considered the optimum temperature for most Pacific salmon (Beamish 1980). However, temperature optima vary for different activities (food digestion, swimming, etc.).

The best swimming temperature for sockeye salmon was 59°F (15°C [5.1 bls]), and swimming ability dropped off greatly outside this temperature preferendum (Blaxter 1969). The optimum temperature for sustained swimming speed in yearling and subyearling coho salmon (3.5 and 2.1 in [8.9 and 5.4 cm] mean TL, respectively) was 68°F (20°C). Maximum sustained velocities at these temperatures were 1.0-1.5 fps (30-45 cm/s). Brett (1964) and Bernatchez and Dodson (1985) also found that the cost of swimming at high, sustained speeds was independent of temperature. Fry and Hart (1948) found that the sustained swimming speed of thermally adapted goldfish (*Carassius auratus*) at 41°F (5°C) was about 0.7 fps (0.2 m/s), rising rapidly to 1.7 fps (0.5 m/s) at 68°F (20°C), levelling out until 86°F (30°C), above which, swimming speed decreased to 1.25 fps (0.4 m/s) at 95°F (35°C). Fish acclimated at different temperatures also gave different curves for swimming speeds at specific temperatures.

Critical swimming speeds increased by 1.6 fps (0.5 m/s) for each 7°C increase in temperature for brown, brook, and lake trout, and Atlantic salmon fry (Brett et al. 1958). Once temperature optima are exceeded, however, critical swimming velocity presumably decreases (Fry and Hart 1948; Heggenes and Traaen 1988). Change in water temperature mainly affects critical swimming velocities by altering metabolic processes. However, oxygen content and water viscosity are also affected by water temperature, thus altering swimming ability (Pavlov et al. 1972). Temperature appears to have little effect on burst swimming speed (Blaxter 1969).

Rheotaxis and migratory behavior may be influenced by temperature. Hoar (1953) found that chum salmon fry swam with the current as temperature increased. He felt that this effect might be due to thyroid stimulation, which occurs when fish are held too long in freshwater (immersion of chum salmon in thyroxine significantly alters their swimming speed [Hoar 1953]). Pink salmon are assumed to exhibit the same response. Juvenile steelhead trout, when exposed to 55.4 °F (13°C) for 20 d experienced continued migratory behavior impairment and a decrease in gill Na⁺,K⁺-ATPase activity (Zaugg 1981). In experimental raceways, migrant summer steelhead trout exposed to 55.4°F (13°C) for 20 d exhibited serious impairment of migratory behavior and a reduction in gill Na⁺,K⁺-ATPase activity (Zaugg 1981). Higher water temperatures increased gill Na⁺,K⁺-ATPase activity and inhibited downstream migration of winter steelhead trout (Zaugg and Wagner 1973).

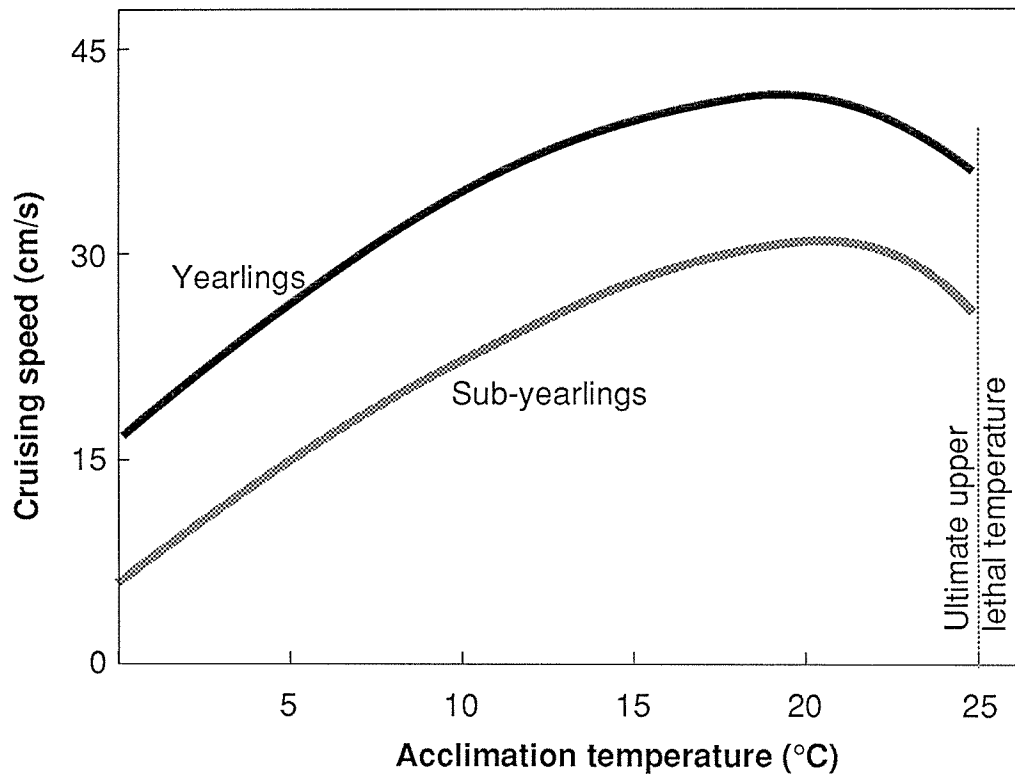


Figure 2. Effect of temperature on cruising speed of yearling and subyearling coho salmon, adjusted to common mean lengths of 3.5 and 2.1 in (8.9 and 5.4 cm), respectively (Brett et al. 1958).

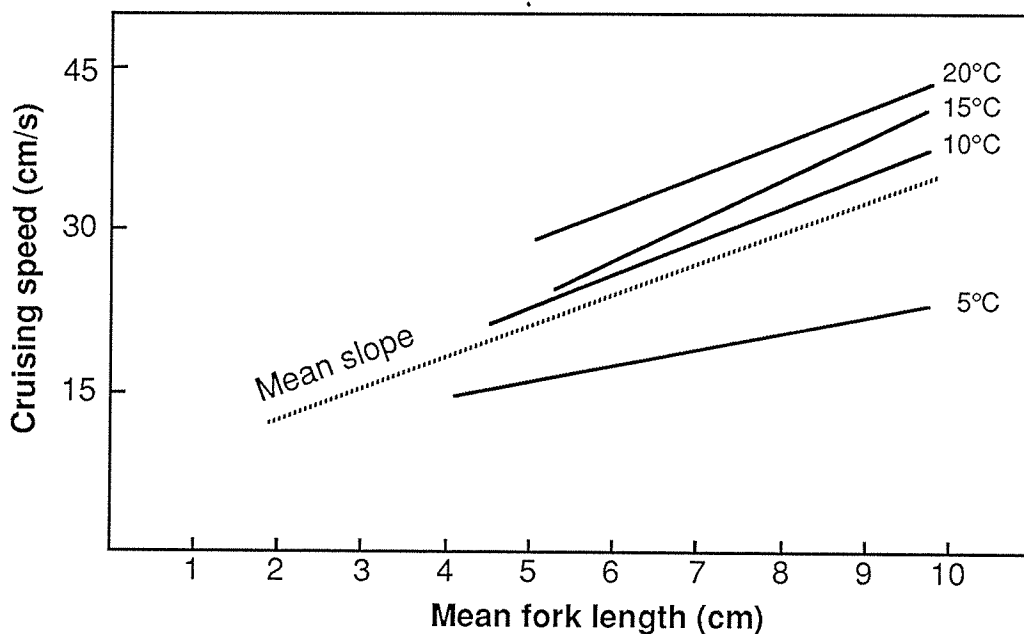


Figure 3. Relationship between yearling and subyearling coho salmon cruising speeds as a function of TL at various temperatures. On the basis of the mean slope, cruising speed increasing about 0.1 fps (3 cm/s) for each 0.4 in (1 cm) increase in TL (Brett et al. 1958).

Fish Length and Maneuverability

The ability of fish to avoid a bypass screen or other structures is a function of their maneuverability as characterized by their turning radius. Webb (1983) found that the minimum turning radius for rainbow trout (10.1 in [25.7 cm] TL) was independent of speed and acceleration. Minimum turning radius was $0.18 \pm 0.2 L$. The equation $R/L = 2V/AL$ predicts minimum turning radius where R is turning radius, L is fish length, V is velocity, and A is wet surface area. Maximum acceleration was found to be 262 fps^2 (80 m/s^2), and maximum turning speeds were 8.2 fps (2.5 m/s) (Webb 1983).

Fish Length and Swimming Velocity

The length of a fish not only governs its ability to maneuver, but also its burst, sustained, and critical swimming speed, and time to exhaustion (Figs. 2 and 3). For juvenile coho salmon (4.4-8.3 in [111-212 mm], FL) swimming in a flume with a minimum velocity of 1.6 fps (0.5 m/s) (computed velocity based on flow was 3.4 fps [1.0 m/s]), the mean difference in mean FL of fish swimming after 15 h versus fish impinged in the first 15 min was 0.75 in (19.2 mm, Fields et al. 1954a). Therefore, fish still swimming after 15 h were, on average, 13.6% longer than those impinged within 15 min. When the velocity was increased to 4.0 fps (1.2 m/s) throughout the flume, fish (3.4-10.3 in [87-262 mm] FL) were all impinged within 15 min. Fish with mean FL of 4.2 in (108 mm) were swept out in 5 min, whereas those of 8.5 in (217 mm) mean FL were swept out within 12 min.

Fish Length and Migration Status

The size of fish may indicate their tendency to migrate. Larger coho salmon tend to migrate downstream before smaller individuals do in any given season, and larger coho salmon usually come from hatcheries, while the smaller fish are usually wild (Durkin 1981). Zaugg (1981) found more migrants than nonmigrants among juvenile steelhead trout with fork lengths ≥ 6.3 in (16 cm).

Cardiovascular and Muscular Efficiency

The "physical fitness" of a fish also affects its ability to swim. Coho salmon smolts from two different stocks were exercised at 0.2, 1.0, 1.5, and 2.0 body fork lengths/s and assessed for their swimming performance changes on the basis of swimming characteristics and critical velocities; the two stocks exhibited differences in their swimming endurance (Besner and Smith 1983). Endurance increased in the exercised fish compared to controls, and this increase in stamina was maintained after a period of rest for the fish. Long-term exercise in the laboratory also increased the strength of muscular contractions in the caudal peduncle of Alaska coho salmon stock (Besner and Smith 1983).

Nahhas et al. (1982) exercised rainbow trout (2.4-2.7 in [6-7 cm] TL) in flowing water at 0, 1.4, 2.2, and 3.5 bls for a period of 46 d. The group exercised at 3.5 bls exhibited an increase in swimming ability as measured by oxygen consumption and increase in white muscle mass. White muscle mass also increased at the 2.2-bls water velocity. Training at 3.5 bls increased time to fatigue by about 420% compared to fish exercised at lower velocities, which exhibited little or no improvement. Fish trained at 1.4, 2.2 and 3.5 bls had white/red muscle ratio increases of 4.7, 35.6, and 71.7%, respectively. The standard

metabolic rate of trained fish was higher than that of untrained fish, and trained fish had lower oxygen consumption rates than untrained fish. The oxygen consumption rates were not significantly different when the training velocity dropped below 1.4 bls (Nahhas et al. 1982). Training also increases the ability of fish to resist fatigue when confronted with sudden drastic changes in water velocity (Nahhas et al. 1982).

Exercising fish increases their stamina (ability to resist fatigue, Brett et al. 1958; Hammond and Hickman 1966) and critical swimming speed (Farlinger and Beamish 1978). Prolonged training has been shown to cause hypertrophy of the skeletal muscle in fish (Greer-Walker 1971; Greer-Walker and Pull 1973; Davison and Goldspink 1977; Davison and Goldspink 1978; Greer-Walker and Emerson 1978). Exercised coho salmon achieved a higher burst swimming velocity and fatigued slower than unexercised fish (Blaxter 1969). Coho salmon (2.6 in [6.7 cm] mean TL) exercised at 0.8 fps (24.4 cm/s) exhibited increased sustained swimming speeds and were less susceptible to fatigue than unexercised fish (Brett et al. 1958).

The implications of fish exercise is that hatchery-reared fish are not as “physically fit” as wild stocks; hence, compared to wild stocks, hatchery stocks are: less able to avoid high currents, exhibit decreased stamina in a given flow, and are generally less able to successfully navigate through a bypass system. When designing new, or modifying existing bypass systems, the decreased swimming abilities of hatchery raised fish must be accounted for.

Stock

Different stocks of fish have been shown to have different swimming abilities. Above falls stocks of rainbow trout were shown to have a more efficient lactate dehydrogenase (LDH)—that is, better at lactic acid conversion under acidic conditions—than the below falls stock (Northcote et al. 1970). According to Tsuyuki and Willisroft (1977), this better LDH confers greater swimming stamina for the above falls stocks to maintain their position. Taylor and Larkin (1986) studied two different populations of juvenile chinook salmon: those that migrate straight to sea in their first spring and those that reside in their natal streams for over a year. The latter group had more positive rheotactic responses and were more aggressive.

Smolt Stage

Predicting how fast and how long a juvenile salmon can swim is confounded by smolt stage (Fig. 4). Numerous physiological and endocrine changes associated with smolting affect fish behavior, swimming ability, ecology, etc. Elevated thyroxine (T_4) levels are associated with smoltification (Dickhoff et al. 1981). Zaugg (1981) found that coho salmon released in June and July, following an increase and subsequent decrease in gill Na^+, K^+ -ATPase activity in a laboratory, began a rapid migration with elevated ATPase levels. Zaugg (1981) concluded steelhead trout actively migrating seaward possess elevated gill Na^+, K^+ -ATPase levels. Giorgi et al. (1988) concluded that smolting juvenile chinook salmon have elevated gill Na^+, K^+ -ATPase levels.

Pink, chum, coho, spring chinook, and sockeye salmon exhibit a remarkable reduction of swimming ability with the onset of smoltification (Fig. 4), with wild smolts collapsing at water velocities above 2 bls; this collapse does not seem to be due to fatigue (Thorpe and

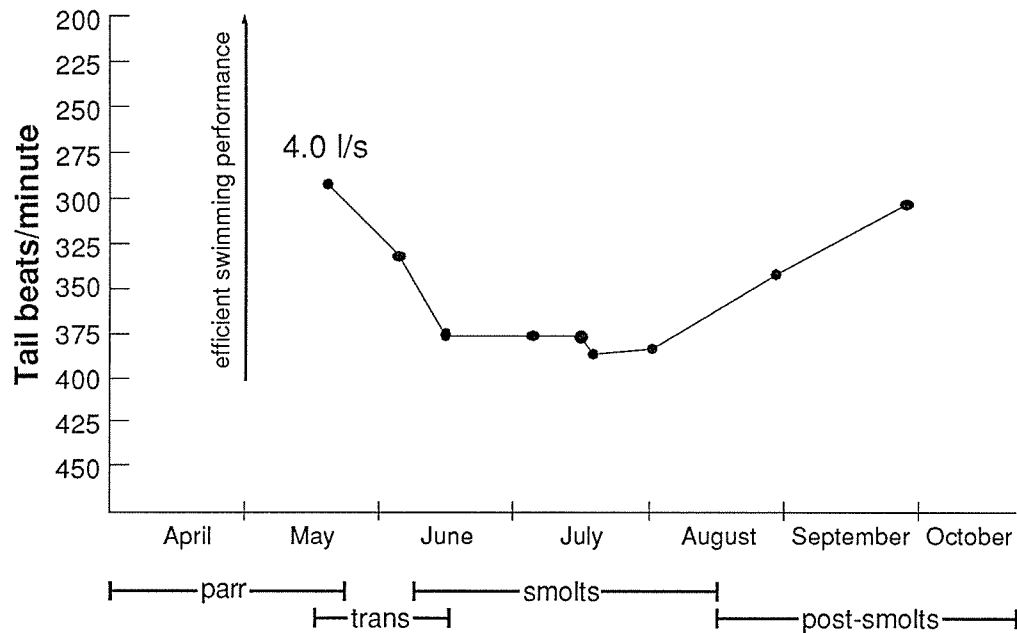


Figure 4. Change in swimming proficiency in coho salmon as a function of time with tail beat frequency the measure of swimming proficiency (59°F [15°C], Flagg and Smith 1981).

Morgan 1978). Coho salmon smolts characteristically show an increase in tailbeat (TB) frequency (analogous to a runner's stride length) at any given velocity, which is assumed to be a result of decreased swimming stamina at smolting (Flagg and Smith 1981). This swimming deficiency disappears once the fish have fully smolted. The decrease in swimming proficiency at 4 bls based on increase in tailbeat frequency (from 275 to 390 TB/min) for coho smolts was 40%. During smoltification, coho salmon experience a decrease in swimming proficiency reflected in increased tail beat frequency that is hormonally induced (Flagg and Smith 1981).

Secondary Effects of Smolting

Smolt stage affects swimming secondarily via alterations in behavior (Fig. 4). During the parr-smolt transformation, fish become less bottom-oriented and more surface-oriented, exhibit more pelagic and active territorial behavior, have a migratory disposition, and perhaps school (Schreck 1981). In addition, smolting fish exhibit increases in general activity, drinking behavior, feeding behavior, and especially learning by motivational or appetitive means (Schreck 1981). Parr-smolt transformation turns a bottom-dwelling parr into a more pelagic-oriented, migrating smolt, and the decrease in swimming proficiency associated with this change may make the fish incapable of maintaining its position in the stream, thus giving an impetus for outmigration (Flagg and Smith 1981).

THE RESPONSE OF FISH TO WATER CURRENTS

As with light, water movement has been shown to affect fish behavior. Craddock (1956) found that greater currents attracted greater numbers of outmigrating fingerlings.

Andrew and Green (1960) suggest a minimum velocity for attraction of 3.9 fps (1.2 m/s). Surface turbulence was found to attract Atlantic salmon parr and protected them from predatory birds (Gibson and Power 1975). When exposed to a choice box with different water velocities in a laboratory, young coho salmon sought out lower velocities, although they preferred slow-moving water to that of still water, and they had no preference for up- or downstream portions of the apparatus when both areas had identical water velocity (Carney and Adkins 1955).

A behavior of juvenile salmonids that complicated behavioral studies is the tendency of the fish to seek zones of lower water velocity in both experimental and *in situ* situations (Brett 1965). Thus one cannot assume that outmigrating fish will seek high current velocities necessarily. Fausch and White (1981) suggested that salmonid seek low water velocity areas so as to minimize swimming energy, yet maintain close proximity to fast currents thus maximizing access to invertebrate drift. Juvenile coho salmon, and steelhead and cutthroat (*Salmo clarki clarki*) trout were observed to exhibit habitat preferences in a stream in terms of velocity and depth. Coho salmon generally stayed in pools with low current velocities, in line with usual feeding of surface invertebrates (Bisson et al. 1988). Steelhead trout were more tolerant of higher velocities and tended to be bottom feeders. Cutthroat trout had intermediate preferences. Kalleberg (1958) and Everest and Chapman (1972) observed that territoriality of salmon decreased as water velocity decreased in the laboratory. Fish living in weir basins (low flow rates) change position more frequently, occur at greater densities, and swim greater distances than fish residing in faster moving water; they also left their positions more often than the fish in running water (Heggberget and Heggberget 1986).

When given a choice, adult coho and chinook salmon, and steelhead trout preferred high velocity (4-8 fps [1.2-2.4 m/s]) over low (2-6 fps [0.6-1.8 m/s]) (Collins and Elling 1960). The chinook salmon preferred water that was too fast for them in some cases. Young coho salmon in a water velocity choice box did not maintain their positions in still water as much as they did in areas of some velocity, except when the only alternative was water moving 1.7 fps (0.5 m/s) or more (Carney and Adkins 1955). In addition, the fish tended to maintain their position in low velocity areas better when visual cues were present (i.e., light was on); velocity can also be a point of reference for maintaining position.

MINIMUM VELOCITY THRESHOLDS

A number of studies have determined the minimum water velocities fish are capable of detecting. Both blind and seeing fish face into a current (Gregory and Fields 1962). Low velocities detected in the lab could probably be pushed even lower in the field where vision could play a role. Young salmon migrants can discriminate water velocities much lower than those which must be maintained in order to not delay them at dams (Gregory and Fields 1962). In darkness, wild chinook salmon (mean TL 2.9 in [73.7 mm], water temperature 55-58°F [12.8-14.4°C]) could discriminate flows of 0.017 fps (0.52 cm/s). Unblinded hatchery coho salmon could discriminate 0.013 fps (0.39 cm/s) (mean TL 4.7 in [118.5 mm], water temperature 46°F [7.8°C]). The controlling factor in setting the velocity in a reservoir is not what the salmon can detect, but how much delay can be imposed (Gregory and Fields 1962). Hanson and Jacobson (1985) concluded that chinook salmon

are capable of detecting and responding to constant velocities <1.0 in/s (2.5 cm/s) under high and low light conditions.

several species of roach (*Rutilus rutilus* L., and *R. rutilus capicus* L.), sturgeon (*Acipenser güldenstädti* B., and *A. stellatus* P.), rudd (*Scardinius erythrophthalmus* L.), stone-loach (*Nemachilus barbatulus* L.), and perch (*Perca fluviatilis*) were tested to determine the effects of light intensity and water temperature on current velocities critical to fish. As reference points moved in their field of vision, the fish exhibited an optomotor response. Reduction of the number of visual reference points from 50 to 0 per 3.28 feet (1 m) in the path of the verkhovka (*Leucaspius delineatus* Heck.) caused a reduction of the critical velocities by 25% (Pavlov et al. 1972).

SWIMMING BEHAVIOR AND ECOLOGY

Swimming behavior of outmigrating fish can be affected dramatically by their ecology. Many studies show that fish compete for areas in streams and rivers where there are eddies in the current and swift-moving currents nearby. Therefore, fish in this behavioral stage may seek out slower moving water (i.e. any eddy in or near a bypass system) and try to feed or compete for space; they do this to optimize their growth rate while expending as little energy as possible doing so.

The relationship between specific growth rate and resources is hyperbolic and fixed by two key points: the resource threshold or maintenance level at which no growth occurs, and the maximum specific growth rate expressed at high resource levels. So a fish in optimal stream positions that give maximum energy gain should also grow at maximum specific rates (Fausch 1984). The energy available to fish as drift is a linear function of water velocity:

$$E = m \cdot V$$

where E = the drift energy (calories per hour per square centimeter), and
 m = the slope of the drift versus velocity relationship.

The available drift energy

$$D = 1/8\pi r^2 \cdot a e^{-bx} \cdot V$$

is a function of fish body length ($1/2r$), distance downstream from the food source (x), and water velocity (V), the last being the maximum velocity within two body-length radii (Fausch 1984).

Dominant fish defending areas with the highest resource level had the highest specific growth rates, and the hierarchy of subordinates defending less desirable areas corresponded to their dominance ability (Fausch 1984). The salmonids in this experiment chose stream positions with respect to food supply, flow, and the dominance hierarchy. The author hypothesized that fish that compete best for the resources available to them are able to maximize potential profit and thus maximize fitness.

Prolonged swimming at rapid velocities can lead to stress and death in fish. Mortality due to swimming fatigue in smolting coho salmon from non-acute stress usually occurred at least 3 d following the stress induced by swimming fatigue (Flagg and Smith 1981).

CASE STUDIES

There have been numerous case studies that examined different types of "fish sorting" and diverting devices. We will briefly touch on some of these studies.

One type of metal conduit covering (resembling a cheese grater with the holes facing downstream) reduced flow near its surface, thus allowing fish to remain in the conduit longer (80% evacuation over 1 h compared to 5 min for fish exposed to a smooth bottom) (VanDerwalker 1970). The author noted that "Migration routes of juvenile salmon moving through an inclined conduit were influenced by flow patterns along the boundaries of the conduit."

An underwater size separator at Little Goose Dam relied on two behaviors of smolting salmonids: orienting into a water flow and diving as an avoidance reaction. Water jets shooting up between separator pipes allowed smolts to swim downward into separate chambers as the gap between pipes increased (Gessel et al. 1985). Separator pipes were 0.87-in (22.2-mm) metal tubes covered with plastic. Space between separator pipes was 0.50-in (12.7-mm) in the first chamber and 1.25-in (31.7-mm) in the second.

When nets were compared based on number of migrants caught per cubic feet of water screened, surface nets caught 16 times more migrants at 8000 cfs and 11 times more at 12,000 cfs (Fields 1966).

Fish guiding screens with the greatest porosity (one layer of webbing) worked best (87% of migrants, dark conditions, velocity 5.9 fps [1.8 m/s]) (Marquette and Long 1971).

Fields et al. (1954b) found that 3.3-in (85-mm) Pacific salmon exposed to a 1-min pulsed square wave direct current voltage of 1 Volt/cm (frequency 16 Hz, 35% duty cycle) were immobilized in 5-15 sec with no mortality. The fish-guiding efficiency of an electrical field generally decreased with increased water velocity. The use of electricity to guide juvenile trout and salmon may be feasible if water velocities do not exceed 1 fps (30 cm/s), but it does not appear practical for most streams (Pugh et al. 1970).

The lateral distribution of outmigrating pink and sockeye salmon was closely related to current speed above a threshold of 1.3 fps (0.4 m/s) (McDonald 1960).

TEMPERATURE

Pacific salmon are considered stenothermal and are intolerant of low temperatures in general. Spring chinook salmon are the least resistant to low temperatures of all Pacific salmon. Spring chinook and coho salmon have the greatest tolerance to high temperatures of all Pacific salmon (Brett 1952). The resistance time to a high temperature in salmon is lengthened by acclimation at a higher temperature, but a given temperature will still be lethal. None of the species of juvenile Pacific salmon can tolerate temperatures above 77.2°F (25.1°C) for 1 week (Brett 1952).

Brett (1952) determined the preferred temperature of juvenile Pacific salmon in laboratory aquaria. The preferred temperature of spring chinook salmon was 53.6-55.4°F (12-13°C) when acclimated to 68°F (20°C) (Brett 1952). Preferred temperature of coho,

sockeye, chum, and pink salmon was 53.6-57.2°F (12-14°C) when acclimated to 68°F (20°C).

One way of determining if stress is related to temperature is to measure plasma cortisol levels. Increased plasma cortisol levels is a primary response of vertebrates, including Pacific salmon, to stress (see reviews by Schreck 1981, 1982; Thomas et al. 1986). Outmigrating juvenile Pacific salmon are stressed from passage through fish guidance structures at hydroelectric projects. One measure of stress in fish is their blood cortisol levels: the higher the cortisol concentration the greater the stress level. Bjornn et al. (1984) found that mean plasma cortisol concentrations were usually below 10 ng/ml for undisturbed spring chinook at Eagle Creek National Fish Hatchery. After simulated bypass procedures, levels rose to 53-72 ng/ml. (Results were three- to fourfold smaller than seen at Snake River Dam [Congleton et al. 1984]).

TEMPERATURES ENCOUNTERED IN MAINSTEM COLUMBIA

The range of temperatures encountered in the Columbia River, especially by distant upriver migrating smolts, is believed to pose a threat to the immigrants (Zaugg 1981). Temperatures at Bonneville Dam are usually 54°F (12°C) by mid-May (5/5/73 and 4/28/77), but these temperatures can occur earlier during years of low water flow (Zaugg 1981). In addition, thermal gradients exist in the forebays of hydroelectric projects on the Columbia, and there may be some correlation between temperature and FGE. At McNary Dam, temperature levels were inversely related to the theoretical estimate of FGE from the vertical distribution. Higher surface water temperatures during the later period of the study may have caused the deeper distribution of salmon observed (Swan and Krcma 1984).

RATES OF TEMPERATURE CHANGE

Rates of temperature change are of concern for salmon, and outmigrating juveniles are certain to experience temperature changes as they pass through a project. In general, fish have specific temperature preferendum for different physiological processes, but outmigrating salmonids cannot control their temperature by moving into different temperature environments as they move through a dam: the bypass systems limit the range of temperatures available to the salmon.

Various studies have established ranges of temperature extremes that juvenile Pacific salmon can tolerate (Fig. 5). Figure 5 gives a guideline for the maximum instantaneous change, and the minimum/maximum temperatures tolerable for any period of time for chinook and coho salmon. For example, if a coho is acclimated to 37°F (3°C), that fish could withstand an instantaneous temperature increase to about 73°F (23°C). Conversely, if acclimated to 73°F (23°C), the fish could withstand a decrease to 37°F (3°C). It is important, however, to point out that these temperature changes can certainly affect behavior, swimming velocity, stress levels, etc. In general chinook and coho thermal tolerances are similar: no significant difference exists in their response to upper lethal temperature levels when acclimated to 50°F (10°C) and above (Brett 1952). Juvenile chinook salmon (1.25-1.50 in [31.75-38.10 mm] TL) can withstand instantaneous temperature changes of 25°F (no mortality over next 24 h), and maximum temperature tolerance is 83°F (28.3°C) (Kerr 1953). Juvenile spring chinook salmon (.6-2.0 in [4-5 cm] TL, about 0.035 oz [about one

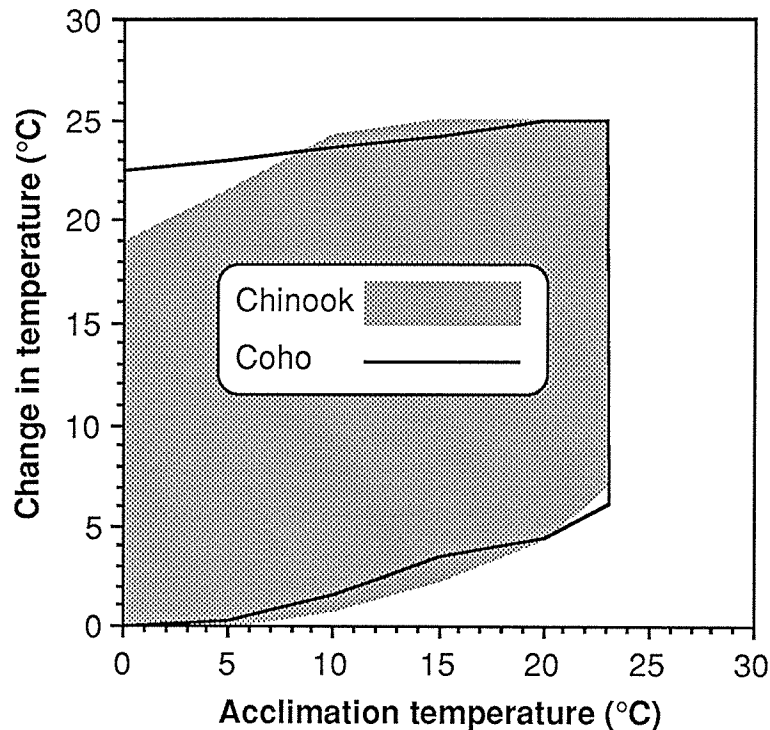


Figure 5. Acclimation temperature and the change in temperature that is not lethal for coho and chinook salmon (Brett 1956).

gram]) acclimated to any temperature from 41-75.2°F (5-24°C) should not experience death when immediately exposed to any temperature between 46.4°F (8°C) and 71.6°F (22°C) (Fig. 5). For coho salmon of the same size, the exposure temperature range is 44.6-73.4°F (7-23°C) (Brett 1952).

On a long-term scale, young spring chinook salmon have been cultured successfully at 75.2°F (24°C), and can survive at that temperature for 1 week. Age-0 and age-2 presmolt coho salmon can withstand a 41-73.4°F (5-23°C) temperature cycle. Age-0 and age-2 presmolt coho salmon starved for 22 d did not die over a 19-d exposure to diel temperature fluctuations of 43.7-68.0°F (6.5-20°C), nor did they exhibit common symptoms of stress such as flashing, disorientation or gasping at the surface (Thomas et al. 1986). Age-0 and age-1 presmolt coho salmon exposed to various temperature fluctuations had no significant difference in mortality or growth. However, there may have been chronic stress during the 19-d study as evidenced by slightly elevated plasma cortisol (Thomas et al. 1986).

LETHAL TEMPERATURES

Death can be caused either by extreme temperatures (high or low) or by extreme temperature changes. In a laboratory, fish will swim into lethal temperatures to feed or in response to the stimulus that feeding was about to commence (Brett 1952); however, fish will not expose themselves to lethal temperature changes for a time period sufficient to cause mortality. Lethal temperature for young spring chinook salmon in culture was 77.2°F (25.1°C), and 77.0°F (25.0°C) for coho salmon (Brett 1952). Age-0 and age-2

presmolt coho salmon acclimated to 51.8°F (11°C) water exhibited LT50 (lethal temperature at which 50% of subjects died) at 75.2°F (24°C), while those acclimated to 50-55.4°F (10-13°C) cycle showed LT50 at 82.4°F (28°C) for age-0, and 78.8°F (26°C) for pre-smolts (Thomas et al. 1986). No age-0 and age-2 presmolt coho salmon survived a 35.6-84.2°F (2°C-29°C) cycle (Thomas et al. 1986). Age-0 and age-2 presmolt coho salmon did not die from thermal stress until diel temperature fluctuations were 39.2-77°F (4-25°C) (Thomas et al. 1986).

FACTORS AFFECTING TEMPERATURE TOLERANCE

Acclimation Temperature

Acclimation temperature has an effect on temperature tolerance in salmonids. Three- to 5-mo post-hatch spring chinook and coho salmon were most resistant to high temperatures when acclimated between 41-75°F (5-24°C) (Brett 1952). Acclimation to a given temperature is a function of metabolic rate, with acclimation rates being slowest at low temperatures and fastest at higher temperatures (Brett 1946).

Fish Size/age

There are size differences that must be taken into account when determining a fish's ability to withstand temperature changes and extremes. The size of the Pacific salmon does not seem to affect heat tolerance, but it is a factor for cold tolerance (Brett 1952). Smaller fish die more often than larger fish at lower temperatures (Brett 1952). In the same study, there were two different rates of mortality for the cold-tolerance determinations, with a considerable delay to the second wave of mortality.

CONCLUSIONS

In order to design fish bypass systems, an underlying understanding of fish behavior is important. Fish bypass systems to date have largely been designed with little emphasis on the interaction of fish behavior and guidance systems. This literature review considered five aspects of fish behavior that could significantly affect fish guidance efficiency: hearing, vision, turbidity, rheotaxis, and temperature. There are several key issues to consider for each of these aspects when designing fish bypass systems.

The key characteristics of fish hearing and sound to consider are as follows. A sound stimulus must be within the frequency range of juvenile salmon hearing and have a sufficient sound pressure level (SPL) in order to be audible. In addition, the SPL must be at least 24 dB above ambient noise. Finally, pulsed or random bursts of sound are more effective at eliciting a response in fish compared to continuous sound. Sound generally will not alter fish behavior for long periods of time.

Pacific salmon can certainly see under starlight conditions (0.03 lux). It is important to consider the equations for light propagation in this review when designing light attraction/diversion systems. Fish subject to diversion must have adequate time and distance to respond to lights; this is a function of propagation, source intensity, and water velocity. Like sound, pulsed rather than continuous light is more effective at altering fish behavior.

Turbidity affects fish reaction and perception by altering visual acuity and rheotaxis. The level of turbidity must be considered for light propagation, range of vision, and response to currents. Salmon can respond rapidly to sudden changes in turbidity. While it is unlikely salmon will encounter lethal levels of turbidity at dams, it is possible they will encounter changes in turbidity that could slow their swimming rate or depth in the water column.

Of all the topics covered in this review, rheotaxis and water currents are the most important for successful fish bypass. Maximum burst swimming speeds for a 4-in (10-cm) pre- or post-smolt juvenile salmon would be 3.3-4.9 fps (100-150 cm/s). Water velocities above this at a bypass intake will certainly exceed the fish's swimming capacity. However, smolting fish often fatigue rapidly above 2 bls or 0.67 fps (20 cm/s) for a 4-in fish. Where fish fatigue is a concern, a "safe" maximum water velocity to target in fish bypass systems is 1 bls or 0.33 fps (10 cm/s) for a 4-in (10-cm) fish.

Temperature, like turbidity has an effect on the other topics considered in this review. As for sudden temperature changes, a general rule of thumb is that fish acclimated to 41°F (5°C) can be immediately exposed to up to 68°F (20°C [and vice versa]) without mortality. However, it is important to point out that temperature changes will induce stress in fish, and the amount of stress is not easily predicted. Thus sudden temperature changes should be avoided in a bypass system. In general, 59°F (15°C) is an optimum swimming temperature for Pacific salmon. Temperatures above 73°F (23°C) and below 37°F (3°C) are usually lethal for any period of exposure.

For all five topics discussed in these review, it is important to remember that fish behavior is highly variable even for a given fish in a given scenario. Pacific salmon have complex life histories and their perception and response to sound, light, turbidity, water currents, and temperature does change with their developmental stage. In addition, steelhead trout, and coho and chinook salmon are the three predominant species to consider for fish bypass on the Columbia River. These three different species react differently to stimuli in their environment. These general considerations are paramount in designing efficient fish bypass systems.

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COLLECTED BIBLIOGRAPHY FOR REVIEW OF FISH BEHAVIOR RELEVANT TO FISH GUIDANCE SYSTEMS

GENERAL BEHAVIOR

Bachman, R.A., W.W. Reynolds, and M.F. Casterlin. 1979. Diel locomotor activity patterns of wild brown trout (*Salmo trutta* L.) in an electric shuttlebox. *Hydrobiologia*. 66(1):45-47.

Coble, D.W., G.B. Farabee, and R.O. Anderson. 1985. Comparative learning ability of selected fishes. *Can. J. Fish. Aquat. Sci.* 42:791-796.

Fourteen species of freshwater fish were trained to execute a simple conditioned response in a shuttle box - to move in response to light to avoid an electrical shock. There was no relation between learning ability and phylogenetic position. Better learners included striped bass (*Morone saxatilis*), bigmouth buffalo (*Ictiobus cyprinellus*), common carp (*Cyprinus carpio*), and channel catfish (*Ictalurus punctatus*). Bluegill (*Lepomis macrochirus*) and northern pike (*Esox lucius*) were poor learners. Yellow perch (*Perca flavescens*) and redbelly tilapia (*Tilapia zilli*) could not be trained. Some fish retained their learned behavior for months, although performance deteriorated with time. Older channel catfish learned better than juveniles, but there was no difference between juvenile and older largemouth bass (*Micropterus salmoides*).

Colby, D.R., D.E. Hoss, and J.H.S. Blaxter. 1982. Pressure sensitivity of Atlantic herring, *Clupea Harengus* L., larvae. *Fish. Bull.* 80(3): 567-574.

Larval Atlantic herring, *C. harengus harengus* L., are known to change their vertical distribution by day and night. Two experiments were designed to test whether herring larvae would respond to imposed pressure changes by making appropriate compensatory vertical movements and whether such ability could be related to the development of the bulla system (stage I, bulla absent; stage II, bulla liquid-filled; stage III, bulla gas-filled). In the first experiment, pairs of larvae were exposed to a fixed sequence of pressure changes (ΔP) ± 13 cm H₂O to ± 66 cm H₂O. Members of simultaneously tested pairs tended to be influenced by one another when responding to pressure change. A second experiment tested the response of individual larvae to randomized sequences of pressure changes. Stage-III larvae moved most frequently to compensate for the pressure changes, but stage-I and stage-II larvae also responded to changes in pressure. Both experiments show that herring larvae of all three stages compensate for applied pressure changes by moving up when pressure is increased and down when it is decreased, but that they rarely move sufficiently far in the vertical plane to full compensate.

Congleton, J.L. 1973. Development of biological design criteria for fish screens and barriers. In: Jensen, L.D. (ed). *Entrainment and Impingement Proc. Second Entrain. Intake Screen Work.* Feb. 5-9, 1973, Baltimore, MD. pp 345-347.

Côté, Y., and C. Pomerleau. 1985. Survie et dispersion d'alevins de saumon Atlantique (*Salmo salar*) ensemencés en milieu naturel. *Naturaliste. Can. (Rev Écol. Syst.)*. 112:549-557.

To study the factors influencing *S. salar* fry survival in the Sainte-Anne-des-Monts River and to learn more about the dispersion of planted fish, experimental fry stockings have been done from 1973 to 1987. The fry were planted at an initial density of $160 * 100 \text{ m}^{-2}$. Variable losses (28-95%) occurred during the 40 to 80 days after stocking. River water temperature and fry weight have been identified as important factors affecting survival at this stage. From then on to one year old parr, mortality rates are less variable (69-99%), being function of parr population density during their first summer of life. Fry and parr did not tend to disperse extensively so that maximum dispersion should be given at stocking time in order that all available habitat is utilized. Fry should be released, in this river, at a density of $40-60 * 100 \text{ m}^{-2}$ to avoid heavy undue losses and at a water temperature about 10°C.

Durkin, J.T. 1981. Behavior of coho salmon smolts (*Oncorhynchus kisutch*) in the Columbia River and its estuary. *Estuaries*. 4(3):286.

Coho, *O. kisutch*, length measurements reveal large individuals tend to migrate downstream first and small individuals later. Based upon size most Columbia River coho smolts are hatchery rather than natural spawning origin. The principal

prey organisms utilized by smolts appear to be insects in the river, amphipods in the middle estuary, and amphipods with marine organisms near the mouth. Timed release experiments show rates of coho downstream movement increased from late March to mid-May. The results of beach seine catches suggest most migratory movement is associated with daylight. Marked coho recoveries within the estuary indicate an association with water exceeding 4 m depth and the absence of a distinct migratory route through the estuary.

Hocutt, C.H. 1980. Behavioral barriers and guidance systems. In: Power Plants: Effects on Fish and Shellfish Behavior. C.H. Hocutt, J.R. Stauffer, J.E. Edinger, L.W. Hall, and R.P.Morgan (eds). Academic Press. pp 183-205.

Lethlean, N.G. 1953. Electrical devices for controlling the movements of anadromous fish. *Nature*. 171(4353):591-2.

Metcalf, N.B., F.A. Huntingford, and J.E. Thorpe. 1987. The influence of predation risk on the feeding motivation and foraging strategy of juvenile Atlantic salmon. *Anim. Behav.* 35(3):901-911.

Juvenile Atlantic salmon, *Salmo salar*, changed their foraging strategy markedly after a brief exposure to a model trout predator, in ways that reduced their conspicuousness and hence risk of being preyed upon. After seeing the predator, the salmon were less likely to orientate to passing food particles, and having orientated, were less likely to attack them. They also reduced the extent of their movements, by only attacking those food particles that came close to them, and by delaying attacks until the food had reached its closest point.

GENERAL ECOLOGY

Bilton, H.T., and D.W. Jenkinson. 1979. Comparison of the growth of juvenile coho salmon in heated and ambient waters during their early life stages. *Fish. Mar. Serv. Report #1495*. 10 pp.

Coho, salmon (*Oncorhynchus kisutch*) eggs were incubated and fry were reared at ambient and elevated temperatures to determine at what stage an increase in rate of growth became apparent, and whether faster growth rate was sustained after the fry were returned to ambient temperature. It was found that a significant increase in developmental rate at 15.6°C was apparent even at the hatching stage and that in general increased growth was positively correlated with cumulative °days and that growth rate after the temperature was lowered was not sustained, a possible exception being provided by fish which had been accelerated up to hatching.

Dickhoff, W.W., T.A. Flagg, and L.S. Smith. 1981. Interaction between thyroid hormones and swimming on coho salmon. *Proc. Western. Reg. Conf. Comp. Endo. Corvallis, OR. 1981* (Abstract).

Di Giusto, E.L., K. Cairncross, and M.G. King. 1971. Hormonal influences on fear-motivated responses. *Psych. Bull.* 75(6):432-44.

Dodge, N.A. 1989. Managing the Columbia River to meet anadromous fish requirements. In: *Waterpower '89*. Eberhardt, A.J. (ed). pp 806-817.

Ebel, W.J. 1984. Review of effects of environmental degradation on the freshwater stages of anadromous fish. *Symp. of the Euro. Inland Fish. Advisory Comm. on Habitat Mod. and Freshwater Fisheries Aarhus (Denmark) 23 May, 1983. Habitat Mod.* pp 62-78.

Early research efforts begun in the 1950s and continued to the present of address the problems of environmental degradation on anadromous fish were centered mainly on fish behavioral work designed to provide solutions to fish passage problems. Information leading to solutions to passage problems for both adult and juvenile salmonids caused by dams and impoundments in the Columbia River was the highest priority of this research. Research on various fisheries enhancement measures was also begun in the late 1960s to increase production of Columbia River salmon. The main conclusions, remedial actions recommended and future research needs that were derived from this research are summarized.

Everest, F.H., and D.W. Chapman. 1972. Habitat selection and spatial interaction by juvenile chinook salmon and steelhead trout in two Idaho streams. *J. Fish. Res. Bd. Can.* 29:91-100.

Ewing, R.D., C.A. Fustish, S.L. Johnson, and H.J. Pribble. 1980. Seaward migration of juvenile chinook salmon without elevated gill (Na+K)-ATPase activities. *Trans. Am. Fish. Soc.* 109(4):349-356.

Ewing, R.D., M.D. Evenson, E.K. Birks, and A.R. Hemmingsen. 1984. Indices of parr-smolt transformation in juvenile steelhead trout (*Salmo gairdneri*) undergoing volitional release at Cole Rivers Hatchery, Oregon. *Aquaculture.* 40(3):209-221

Changes in common indices of parr -- smolt transformation were compared with the timing of outmigration of juvenile steelhead trout (*Salmo gairdneri*) from Cole Rivers Hatchery on the Rogue River, Oregon. Numbers of fish with silver coloration became maximal before the time of maximum migration. Nearly 80% of the migrating fish were entirely silvery (smolts) throughout the migration period, suggesting that silvering was associated with the migration process. Gill Na⁺,K⁺-ATPase activity reached a peak in non-migrant fish nearly 2 weeks before a peak in migrant fish was reached. Neither silvering nor gill Na⁺,K⁺-ATPase activity correlated well with maximum migration. Results suggested a number of physiological changes which occur in steelhead trout in the spring do not occur coincident with the onset of migration tendency.

Heggenes, J., and T. Traaen. 1988. Daylight responses to overhead cover in stream channels for fry of four salmonid species. *Holarctic Ecology.* 11:194-20.

Brown trout (*Salmo trutta*), Atlantic salmon (*Salmo salar*), brook trout (*Salvelinus fontinalis*) and lake trout (*Salvelinus namaycush*) fry entering the free-feeding stage, were tested for overhead cover preferences in stream channels at different temperatures and water velocities. Atlantic salmon showed strong preferences for overhead cover, brown trout moderate preferences, whereas lake trout had preferences only at high temperatures, i.e. 12.4-19.2°C. Brook trout showed no cover preferences. Temperature influenced cover preferences of Atlantic salmon and brown trout considerably. The fry tended to seek more cover at low temperatures, i.e. 6.0-8.3°C.

Hillman, T.W., J.S. Griffith, and W.S. Platts. 1987. Summer and Winter habitat selection by juvenile chinook salmon in a highly sedimented Idaho stream. *Trans. Am. Fish. Soc.* 116:185-195.

Summer and winter habitat utilized by age-0 spring chinook salmon *Oncorhynchus tshawytscha* was assessed in the Red River, an Idaho stream heavily embedded with fine sediment. During summer 1985, chinook salmon used habitats with water velocities less than 20 cm/s, depths of 20-80 cm, and close associations with cover (undercut banks). Densities were greater than 60 fish/100 m². As the fish became larger they selected faster, deeper water. Eighty percent of the chinook salmon emigrated from the study sites in October when stream temperatures were 4-8°C, apparently because suitable winter habitat was not available.

Kalleberg, H. 1958. Observations in a stream tank of territoriality and competition in juvenile salmon and trout (*Salmo salar* L. and *S. trutta* L.). *Rpt. Inst. Freshwater Res., Drottningholm.* 39:55-98.

Schreck, C.B. 1982. Stress and the rearing of salmonids. *Aquaculture.* 28:241-249.

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Arimoto, T., H. Shiba, and M. Inoue. 1979. On the optomotor reaction of fish relevant to fishing method V. Reaction of rainbow trout, *Salmo gairdneri*, toward the illusive movement of a flickering light. *J. Tokyo Univ. Fish.* 66(1):37-46.

Batty, R.S., J.H.S. Blaxter, and D.A. Libby. 1986. Herring (*Clupea harengus*) filter-feeding in the dark. *Marine Biol.* 91: 371-375.

The behavior of juvenile herring (*Clupea harengus* L.) feeding on *Artemia* sp. nauplii in both light and dark was recorded using an infra-red-sensitive television-recording technique. In the light, two modes of feeding were observed, particle biting and filtering, but in the dark only filtering was observed. Marked differences in swimming behavior were seen between light and dark. In the light, the fish continued to school while feeding in both modes; in the dark, the school dispersed, the fish swam slower in tight circular paths and fed only by filtering. In the dark filtering fish swam faster (0.11 m s^{-1}) than non-filtering fish (0.07 m s^{-1}). In the light, no difference in speed was measured between filtering and non-filtering fish (0.34 m s^{-1}). Owing to the lower filtering speeds in the dark, the removal rate of nauplii from the water was much lower than in light.

Beatty, D.D. 1966. A study of the succession of visual pigments in Pacific salmon (*Oncorhynchus*). *Can. J. Zool.* 44:429-455.

Blaxter, J.H.S. 1970. Light. In: *Marine Ecology*, vol.1, part 1. O. Kinne (ed). Wiley-Interscience, London. pp 213-320.

Blaxter, J.H.S. 1980. Vision and the feeding of fishes. In: *Fish behavior and its use in the capture and culture of fishes.* (eds.) J.E. Bardach, J.J. Magnuson, R.C. May. and J.M. Reinhart. ICLARM. pp 32-56.

Vision is vital for feeding of many near-surface teleosts. The visual threshold for feeding of about 0.1 lux is similar to the light intensity at which dark-adaptations of the retina takes place. The time available for feeding per 24-h day depends greatly on the seasonal changes of day length in high latitudes. In light-adapted fish, feeding efficiency depends on the shape and size of the visual field, the distance covered during searching, the feeding drive, and on characteristics of the prey such as its size, conspicuousness, and density. The visual axis, acuity, and contrast perception of predators are discussed together with camouflage of prey and the reaction distances for prey perception and volumes searched while feeding. Information on volumes searched per unit time and visual thresholds allows an estimate to be made of volume of water searched for food per 24-h day. This gives some insight into whether available prey biomass is adequate to support the predator population.

Blaxter, J.H.S., and B.B. Parrish. 1965. The importance of light in shoaling, avoidance of nets and vertical migration by herring. *J. Cons. Perm. Int. Explor. Mer.* 30(1):40-57.

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Brett, J.R., and M.A. Ali. 1958. Some observations on the structural and photomechanical responses of the Pacific salmon retina. *Fish. Res. Bd. Can.* 15(5):815-829.

Congleton, J.L., and E. J. Wagner. 1988. Effects of light intensity on plasma cortisol concentrations in migrating smolts of chinook salmon and steelhead held in tanks or raceways and after passage through experimental flumes. *Trans. Am. Fish. Soc.* 117:385-93.

The stress responses of migrating smolts of chinook salmon *Oncorhynchus tshawytscha* and steelhead *Oncorhynchus mykiss* (formerly *Salmo gairdneri*) to passage through three flumes (small baffled, large baffled, and unbaffled with corrugations) were determined by assaying plasma cortisol concentrations before and after fish passed through each flume. Flume design significantly affected post-passage cortisol concentrations in steelhead but not in chinook salmon smolts; concentrations were lowest in steelhead smolts that passed through the corrugated flume. In daytime tests, cortisol concentrations were significantly lower in chinook salmon smolts that passed through completely darkened flumes than in those that passed through partly darkened flumes. The cortisol response (post-passage minus pre-passage concentration) of both species to passage through darkened flumes was smaller in day tests than in night tests.

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Fields, P.E. 1954. The effect of electric lights upon the upstream passage of sockeye salmon through the University of Washington Fishladder. Univ. WA. School Fish. Tech. Rep. # 10. 15 pp.

Fields, P.E. 1964. Nature of the downstream migrant's response to light patterns at the Dalles Dam. Univ. WA. School Fish. Tech. Rep. # 57, pp 143-159.

Fields, P.E. 1966. Final report on migrant salmon light guiding studies (contract # D.A.-45-108 Civeng-63-29) at Columbia River dams. College of Fisheries, Univ of Washington. U.S. Army Corps of Eng. 31 pp.

Fields, P.E. 1966. Migrant salmon light-guiding studies at Columbia River Dams. In: Fisheries Engineering Research Program, Third Progress Report. US Army Corps Eng. N. Pac. Div. 21 pp.

Fields, P.E., R.J. Adkins, R.E. Carney, G.L. Finger, and D.E. Johnson. 1955. The effect of four light conditions upon the impingement of year plus steelhead trout, chinook and silver salmon. Univ. WA. School Fish. Tech. Rep. # 18. 9 pp.

Fields, P.E., R.J. Adkins, R.E. Carney, and G. L. Finger. 1955. The reaction of young silver salmon and steelhead trout to infrared light barriers. Univ. WA. School Fish. Tech. Rep. # 14. 8 pp.

Fields, P.E., D.E. Johnson, G. L. Finger, R.J. Adkins, and R.E. Carney. 1956. Field test of two intensities of shaded and unshaded lights in guiding downstream migrant salmon. Univ. WA. School Fish. Tech. Rep. # 21. 33 pp.

Fields, P.E., G. L. Finger, and R.J. Adkins. 1955. The effect of electric lights upon the upstream passage of three species of adult salmon through the University of Washington Fishladder. Univ. WA. School Fish. Tech. Rep. # 12.

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Fields, P.E., and A.K. Murray. 1956. The response of young silver salmon to a light barrier after three levels of light adaptation. Univ. WA. School Fish. Tech. Rep. # 27. Nov., 1956. 9 pp.

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- Fields, P.E., and G. L. Finger. 1956. The effectiveness of constant and intermittently flashing light barriers in guiding young silver salmon. Univ. WA. School Fish. Tech. Rep. # 22. 22 pp.
- Fields, P.E., and G.L. Finger. 1954. The reaction of young salmonidae to light. Univ. WA. School Fish. Tech. Rep. # 2. 21 pp.
- Fields, P.E., D.E. Johnson, and S.Z. El-Sayed. 1959. The 1958-59 McNary Dam light guiding studies. Univ. WA. School Fish. Tech. Rep. # 50. 29 pp.
- Fields, P.E., G. L. Finger, and L.A. Verhoeven. 1954. The effect of electric shock upon the light avoiding behavior of young silver and blueback salmon. Univ. WA. School Fish. Tech. Rep. # 3. 21 pp.
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- Finstad, W.O., and D.R. Nelson. 1975. Circadian activity rhythm in the horn shark, *Heterodontus francisci*: Effect of light intensity. Bull. S. Cal. Acad. Sci. 74:20-26.
- Gibson, R.J., and G. Power. 1975. Selection by brook trout (*Salvelinus fontinalis*) and juvenile Atlantic salmon (*Salmo salar*) of shade related to water depth. J. Fish. Res. Bd. Can. 32(9):1652-1656.
- Guthrie, D.M. 1986. Role of vision in fish behavior. In: The behavior of teleost fishes. Pitcher, T., (ed). Johns Hopkins University Press. pp 75-113.
- Hanson, C.H., and E. Jacobson. 1985. Orientation of juvenile chinook salmon, *Oncorhynchus tshawytscha* and bluegill, *Lepomis macrochirus*, to low water velocities under high and low light levels. Calif. Fish Game. 71(2):110-113
- A series of experiments was conducted to determine the influence of light intensity on the orientation response of juvenile chinook salmon, *Oncorhynchus tshawytscha*, to low water velocities. The orientation response of juvenile bluegill sunfish, *Lepomis macrochirus*, was also determined for comparison with the orientation response of juvenile chinook salmon. Bluegill were chosen for comparison since they are so ecologically different in their habitat preferences and, presumably, their behavioral response to low-velocity water currents.
- Hanyu, I., and M.A. Ali. 1963. Flicker fusion frequency of electroretinogram in light-adapted goldfish at various temperatures. Science. 140:662-663.
- Hoar, W.S., M.H.A. Keenleyside, and R.G. Goodall. 1957. Reactions of juvenile Pacific salmon to light. J. Fish. Res. Bd. Canada. 14(6):815-830.
- Ingle, D.J. 1985. The goldfish as a retinex animal. Science. 227:651-654.

In an experiment designed to test color constancy, goldfish were trained to approach a particular color within a richly colored but variable "Mondrian" background. They retained the ability to identify colors accurately even when the spectral composition of the illuminant was radically altered in generalization tests. Since the behavior of fish resembles that of human beings in these tests, Land's retinex theory seems to apply to a relatively primitive vertebrate as well as to humans.

Inoue, M., and T. Arimoto. 1976. The role of the optomotor reaction in the schooling fish. J. Tokyo Univ. Fish. 62(2):67-81.

Six experiments were conducted for five kinds of marine fishes to clarify the possibilities of using a 'frame screen' to provoke rounding movements of fish and of using it in the sea to concentrate fish for fishing purposes. The frame screen, which was made from a wire cylinder of diameter 1.2 m and height 0.8 m was set in the center of a pond and rotated at about 40 cm/s by hand. Two experimental ponds were used one was an outdoor pond (4 x 5 x 1.2 m) and another, an indoor pond (1.5 x 1.5 x 0.5 m). When the size of the pond was larger than that of the screen, the screen gained successful effects for oval filefish, *Novodon medestus*, and parrot bass, *Oplegnathus fasciatus*. For sardine, *Sardinops melanosticta*, anchovy, *Engraulis japonica* and mackerel, *Pneumatophorus japonicus japonicus*, it showed no effects. When the pond was not much larger than the screen, the screen was effective with anchovy.

Johnson, D.E., P.E. Fields, P.S. Karekar, and G.L. Finger. 1958. Conditions under which light attracts and repels pre-migratory salmon in clear and turbid, still and running water. Univ. WA. Sch. Fish. Tech. Rep. # 42. 15 pp.

Jones, F.R.H. 1956. The behavior of minnows in relation to light intensity. J. Exp. Biol. 33: 271-281.

Jong-Soo, P. 1985. Importance of illumination in the optomotor reaction of dace, *Tribolodon hakoensis*, to a moving visual screen. Bull. Kunsan Fish. J. Coll. 19(1):15-23.

Kawamoto, N.Y. 19?? The significance of the quality of sight for the attraction of fish. In: Modern Fishing Gear of the World. ????? pp 553-555.

Kawamura, G., Y. Mukai, and H. Ohta. 1983. Morphology of the eye and free neuromast of larval ayu and pale chub and its relation to behavior in water flow. Bull. Jap. Soc. Sci. Fish. 49(10):1527-1532.

Both ayu (*Plecoglossus altivelis*) and pale chub (*Zacco platypus*) lay their eggs on spawning beds in rivers with similar conditions of water flow and bottom sediments, the former migrating down-stream after hatching and the latter remaining in the river after emergence from the spawning bed. To find an explanation for these different behavior patterns, the eyes and neuromasts of the larvae were morphologically examined. At hatching, the larval ayu already have morphological well-developed free neuromasts with cupula and eyes with pure cone retina, while the larval pale chub have no developed sensory organs. After hatching, the eyes and neuromasts of the chub develop fast, and after exposure to water flow at 4 days old, the sensory organs are developed almost as well as those of ayu. Both sensory organs of the two larvae are considered sufficiently functional to enable the larvae to respond to water flow visually and mechanically. It is therefore suggested that there might be an active behavioral process governing the downward migration of the ayu, such as choice of downward water flow or active downward swimming.

Kawamura, G., Y. Mukai, and H. Ohta. 1984. Change in the visual threshold with development of rods in ayu, *Plecoglossus altivelis*. Bull. Jap. Soc. Sci. Fish./Nissuishi. 50(12):2133.

Rods have been reported to develop later than cones in the retina of many teleosts, increasing its sensitivity and leading to change in the visual behavior of the fish. The change in the visual threshold in ayu, *Plecoglossus altivelis*, with the development of rods is reported. Development of the retina with growth was examined histologically, and visual thresholds were determined by the light intensity at the extinction of rheotaxis. Rods appeared in the retina of 19-day-old larvae first, and increased in number afterward. The visual thresholds for 14, 22, 43, 74 day-old ayu were 7×10^{-1} , 7×10^{-1} , 1.2×10^{-2} and 8.4×10^{-4} lux respectively. An inverse relationship was seen between the visual threshold and the development of rods with age in this species.

Kusaka, T. 1964. Fish gathering and submarine illumination of fluorescent discharge lamps. Bull. Jap. Soc. Sci. Fish. 31(3):187-191.

Kwain, W., and H. R. MacCrimmon. 1969. Further observations on the response of rainbow trout, *Salmo gairdneri*, to overhead light. J. Fish. Res. Bd. Can. 26:3233-3237.

Levine, J.S., and E.F. MacNichol, Jr. 1979. Visual pigments in Teleost fishes: Effects of habitat, microhabitat, and behavior on visual system evolution. *Sens. Processes*. 3:95-131.

McIninch, S.P., and C.H. Hocutt. 1987. Effects of turbidity on estuarine fish response to strobe lights. *J. Appl. Ichthyol.* 3(1987):97-105.

The efficacy of a strobe light and a combined strobe light/bubble curtain system was evaluated under turbid water conditions as a fish avoidance scheme. Three estuarine species commonly impinged at electric generating facilities along the Atlantic coast of the United States were tested: Atlantic menhaden (*Brevoortia tyrannus*), spot (*Leiostomus xanthurus*), and white perch (*Morone americana*). The strobe light/bubble curtain combination was the most effective system studied in all cases. An interesting phenomenon was that fish avoidance to strobe light systems increased with turbidity over the range tested (clear, 39-45 and 102-138 NTU).

Nikonorov, I.V. 1964. Pump fishing with light and electric current. In: *Modern Fishing Gear of the World #2*. Kristjonsson, ed. Fishing News Ltd. London. pp 557-579.

Nikonorov, I.V. 1973. Interaction of fishing gear with fish aggregations. *Israel Prog. for Sci. Transl.* 1975. 111 pp.

Nunan, C.P., and D.L.G. Noakes. 1987. Effects of light on movement of rainbow trout embryos within, and on their emergence from, artificial redds. *Am. Fish. Soc. Symp.* 2:151-156.

Manipulations of the duration and direction of light did not substantially alter the movement or emergence behavior patterns of embryonic rainbow trout *Salmo gairdneri* within artificial substrate redds. Phototactic responses do not appear to control embryonic rainbow trout behavior. Movement and emergence patterns are suggested to be primarily due to geotactic behavior.

Patrick, P.H., A.E. Christie, D. Sager, C. Hocutt, and J. Stauffer Jr. 1985. Responses of fish to a strobe light/air-bubble barrier. *Fish. Res.* 3(1985):157-72.

The responses of selected freshwater (*Alosa pseudoharengus*, *Osmerus mordax*, *Dorosoma cepedianum*) and estuarine (*Morone americana*, *Leiostomus xanthurus*, *Brevoortia tyrannus*) species to air bubbles alone, strobe light alone, and a combined strobe light/ air-bubble barrier were investigated under laboratory conditions. Gizzard shad, alewife and smelt avoided an air-bubble barrier. Avoidance response varied with air-bubble spacing and illumination. All species tested exhibited avoidance behavior to strobe lights, which varied with current velocity, strobe flash rate, and acclimation of fish. Increased avoidance was evident for most species when strobe lights were combined with air bubbles as an exclusion barrier.

Pavlov, D.S., Yu.N. Sbikin, A.Ye. Vashchinnihov, and A.D. Mochek. 1972. The effect of light intensity and water temperature on the current velocities critical to fish. *J. Ichthyol.* 12:703-711.

Prinslow, T.E., E.O. Salo, C.J. Whitmus, M.E. Salo, and B.P. Snyder 1980. Effects of wharf lighting on outmigrating juvenile chum and pink salmon. *Proc. of the 1980 Northeast Pacific Pink and Chum Salmon Workshop* pp 82-83.

Protasov, V.R. 1970. Vision and near orientation of fish. *Israel Progr. for Scient. Transl.*, Jerusalem. 175 pp.

Puckett, K.J. and J.J. Anderson. 1988. Behavioral Responses of Juvenile Salmonids to Strobe and Mercury Lights. University of Washington, Fisheries Research Institute. Final Report FRI-UW-8717: 35 pp.

Regan, D. 1986. Visual processing of four kinds of relative motion. *Vision Res.* 26(1):127-145.

Evidence is presented supporting the idea that the human visual system has several specific sensitivities to different kinds of relative motion. These specific sensitivities include: sensitivity to a velocity difference between two different points A

and B on one eye's retinal image, the two velocities being directed along the line AB; sensitivity to the velocity difference at A and B between velocity components perpendicular to the line AB (i.e. shearing motion); sensitivity to rotary motion; sensitivity to the ratio between the velocities of the left and right retinal images of an object that is moving in depth. These specific sensitivities can be attributed to relatively hardwired neural filters that are "tuned" to different retinal image correlates of the three-dimensional structure and motion of solid objects in the environment. Such filters may be of use in distinguishing rigid non-rotating objects from nonrigid or rotating objects. They may also be of use in recovering information from the two-dimensional retinal image, including information about object boundaries, the three-dimensional structure of the environment, self-motion and object motion in depth. An alternative way of regarding certain of these specific sensitivities is that they might provide rough physiological equivalents of the values of $\text{div } V$ and $\text{curl } V$ at every point in the instantaneous velocity field of the retinal image and thus crudely analyze the retinal image flow pattern in terms of mathematical quantities that have the useful property of being relatively invariant against bodily translations of the whole retinal image caused by eye rotation.

Reynolds, W.W., and M.E. Casterlin. 1976. Activity rhythms and light intensity preferences of *Micropterus salmoides* and *M. dolomieu*. Trans. Am. Fish. Soc. 105:400-403.

Activity rhythms and light intensity preferences of largemouth (*M. salmoides*) and smallmouth (*M. dolomieu*) black basses were investigated in laboratory experiments designed to elucidate aspects of niche separation between these sympatric congeners. Both species exhibited crepuscular activity, but *M. salmoides* also showed a mid-day activity peak. *M. dolomieu* avoided bright light, and their peak activity periods occurred at the beginning and end of the dark periods. Activity of *M. salmoides* was much more depressed during the dark periods, and rose sharply at the onset of light periods. Activity records in constant light conditions showed these activity rhythms to be endogenous.

Richardson, N.E., and J.D. McCleave. 1974. Locomotor activity rhythms of juvenile Atlantic salmon (*Salmo salar*) in various light conditions. Biol. Bull. 147:422-432.

Rooney, D.J., and P.R. Laming. 1986. Cardiac and ventilatory arousal responses and their habituation in goldfish: Effects of the intensity of the eliciting stimulus. Physiol. Behav. 37:11-14.

Recordings were made of cardiac and ventilatory responses of goldfish to the onset of 10 sec illumination presented at 2 min intervals. These responses were measured by increases in cardiac interbeat interval, ventilatory interbreath interval and by reductions in ventilatory amplitude. Four groups of fish were subjected to intensities of 52, 78, 90 and 160 lux. It was found that the more intense the stimulus the greater was the magnitude of the initial physiological response and correlated with this the number of stimulus presentations required for habituation. The relationship between stimulus intensity, initial response magnitude and resistance to habituation was consistent for cardiac responses.

Sager, D.R., and C.H. Hocutt. 1985. Preferred wavelengths of visible light for juvenile Atlantic menhaden. N. Am. J. Fish. Manage. 5:72-77.

Sager, D.R., C.H. Hocutt, and J.R. Stauffer. 1987. Estuarine fish responses to strobe light, bubble curtains and strobe light/bubble-curtain combinations as influenced by water flow rate and flash frequencies. Fish. Res. 5:383-399.

This study examined strobe lights and strobe light/bubble-curtain combinations as behavioral guidance systems for estuarine fish. White perch (*Morone americana*), spot (*Leostomus xanthurus*) and Atlantic menhaden (*Brevoortia tyrannus*) were tested in a behavior experimental tank for avoidance to strobe lights, bubble curtains and strobe light/bubble-curtain combinations at different water flow rates, strobe flash frequencies and light acclimations. Avoidance of strobe light ranged from 8 to 36% for white perch, 8 to 100% for spot and 8 to 68% for menhaden. Chi-square analyses indicated significant avoidance rates by the three species at varying flash rates and flow rates. All species showed little avoidance of bubble curtains. Avoidances of 3-58% for white perch, 21-85% for spot and 9-81% for menhaden were obtained with the strobe light/bubble-curtain combinations. chi squared analyses indicated avoidance rates for the three species at varying flow rates and conditions. The strobe light and strobe light/bubble-curtain combinations elicited best avoidance results at flash rates of 300/min or greater and low flow rates. Strobe lights show promise as a guidance system for estuarine fish.

Sasaki, T. 1959 The use of light attraction for traps and setnets. In: Modern Fishing Gear of the world, vol. 1. Kristjansson, H. (ed). pp 556-558.

Taylor, P.B. 1987. Experimental evidence for juvenile chinook salmon, *Oncorhynchus tshawytscha* Walbaum, orientation at night and in sunlight after a 7° change in latitude. J. Fish Biol. 31(1): 89-111.

A group of 18 young chinook salmon *Oncorhynchus tshawytscha*, trained to orientate in the direction 270 degree, showed a unimodal orientation of 264 degree and a mean bimodal axis of orientation of 25 degree /078 degree (magnetic) within confidence limits of 218 degree arrow right 285 degree: 0.38 degree arrow right 105 degree when tested under controlled conditions in Auckland. Two year later 12 of these fish were transferred to a new test arena in Christchurch, south (7 degree latitude) of the original location, for individual re-testing at night in a light-proof room and also in sunlight in the absence of "local" Auckland cues/clues. These fish had been kept in artificial light but six fish were exposed to sunlight in Auckland 2 weeks before moving to Christchurch. At night each fish showed consistent non-random orientation and nine out of 10 fish showed a mean bimodal orientation that fell within the confidence limit established in Auckland the mean of means axis of orientation for 10 fish was 270 degree /090 degree. In sunlight each individual fish showed a consistent, non-random mean bimodal orientation that fell outside the confidence limits established in Auckland and, at night, in Christchurch. The principal findings in this study are given.

van Veen, Th., H.G. Hartwig, and K. Müller. 1976. Light-dependent motor activity and photonegative behavior in the eel (*Anguilla anguilla* L.). J. Comp. Physiol. 111:209-219.

Varanelli, C.C., and J.D. McCleave. 1974. Locomotor activity of Atlantic salmon parr (*Salmo salar* L.) in various light conditions and in weak magnetic fields. Anim. Behav. 22:178-186.

Verheijen, F.J. 1958. The mechanisms of the trapping effect of artificial light sources upon animals. Arch. Neerl. Zool. 13:1-107.

Waterman, T.H. 1972. Visual direction finding by fishes. In: Animal Orientation and Navigation. Gallen, S.R., K. Schmidt-Koenig, G.J. Jacobs, and R.E. Belleville (eds). NASA. pp 437-456.

Weber, L.J., and J.R. Smith. 1980. Possible role of the pineal gland in migratory behavior of salmonids. Sal. Ecos. N. Pac. 313-320.

Whitney, R.R. 1969. Schooling of fishes relative to available light. Trans. Am. Fish. Soc. 98(3):497-504.

Wickham, D.A. 1973. Attracting and controlling coastal pelagic fish with nightlights. Trans. Am. Fish. Soc. 4:816-825.

Woodhead, P.M.J. 1957. Reactions of salmonid larvae to light. J. Exp. Biol. 34:402-416.

Woodhead, P.M.J. 1966. The behavior of fish in relation to light in the sea. Oceanogr. Mar. Biol. Ann. Rev. 4:337-403.

M I G R A T I O N

Anonymous. 1960. Effects of structures at main Columbia River Dams on downstream migration of fingerlings. Prog. Rep. Fish. Eng. Res. Prog. N. Pac. Div. Portland Dist., Corps of Engineers. July. 18 pp.

Bakshantansky, E.L., V.D. Nesterov, and M.N. Nekludov. 1982. Change in the behavior of Atlantic salmon (*Salmo salar*) smolts in the process of downstream migration. Int. Council. Exp. Sea. M:5.

Bjornn, T.C., R.R. Ringe, and P. Hiebert. 1978. Seaward migration of Dworshak hatchery steelhead trout in 1976. Dworshak Nat. Fish Hatchery. U.S. Fish Wldlfe. Serv.

Duke, R.C. 1981. Columbia Basin salmon and steelhead identification and modeling. State of Idaho Dept. of Fish and Game. Final Narrative Report. 6/1/80-5/30/81.

Ewing, R.D., C.A. Fustish, S.L. Johnson, and H.J. Pribble. 1980. Seaward migration of juvenile chinook salmon without elevated gill (Na⁺K⁺)-ATPase activities. *Trans. Am. Fish. Soc.* 109(4):349-356.

The hypothesis that juvenile anadromous salmonids which are migrating to sea have higher levels of gill [Na⁺ K⁺]-ATPase activity than nonmigrants was examined for wild and hatchery spring and fall chinook salmon (*O. tshawytscha*) from the Rogue River, Oregon [USA]. Although migrant juvenile chinook salmon captured at river km 173 had elevated gill (Na⁺ K⁺)-ATPase activity, migration from the more upstream portions of the Rogue River occurred without significant changes in gill (Na⁺ K⁺)-ATPase activity. High water flows stimulated migration without increasing gill (Na⁺ K⁺)-ATPase activity. Tributary-to-main-stem migration of juvenile fall chinook salmon did not result in elevated gill (Na⁺ K⁺)-ATPase activities. Juvenile spring chinook salmon released from Cole Rivers Hatchery (km 254) migrated rapidly to km 18 on the Rogue River without changes in gill (Na⁺ K⁺)-ATPase activity. Although the relationship between seaward migration and elevated gill (Na⁺ K⁺)-ATPase activity is demonstrable in chinook salmon in many cases, such elevated ATPase activity may not be a prerequisite for seaward movement of juvenile chinook salmon.

Groot, C. 1965. On the orientation of young sockeye (*Oncorhynchus nerka*) during their seaward migration. *Behavior, Suppl.* XIV. 198 pp.

Groot, C., and K.Simpson. 1975. Movements of sockeye salmon (*Oncorhynchus nerka*) in the Skeena River estuary revealed by ultrasonic tracking. *J.Fish. Res. Bd. Can.* 32:233-242.

Hoar, W.S. 1951. The behavior of chum, pink and coho salmon in relation to their seaward migration. *J. Fish. Res. Bd. Can.* 8(4):241-263.

Hoar, W.S. 1953. Control and timing of fish migration. *Biol. Rev.* 28:437-452.

Hoar, W.S. 1956. The behavior of migrating pink and chum salmon fry. *J. Fish. Res. Bd. Can.* 13(3):309-325.

Liscom, K.L., L.C. Stuehrenberg, G. Esterberg, and C.J. Bartlett. 1981. Miniature radio tag used to study salmonid smolt movement in the Columbia River. *Underwater Telemetry Newsletter.* 11(1):1-3

During the spring of 1980, a total of 21 spring chinook salmon and steelhead smolts were tagged with the new miniature tags, released into the Columbia River about 6 miles upstream from John Day Dam, and tracked in the forebay as they approached the dam. The routes they swam during spill and nonspill periods as well as their general swimming behavior were monitored. Five of the smolts were tracked to the dam, and all went downstream through the turbines. No smolts were tracked over the spillway, although some appeared to be influenced by the currents created by the spill. One tagged fish was eaten by a seagull. Another fish turned upstream and was followed for 6 hours.

MacKinnon, D., and J.R. Brett. 1955. Some observations on the movement of Pacific salmon fry through a small impounded water basin. *J. Fish. Res. Bd. Can.* 12(3):362-368.

McDonald, J. 1960. The behavior of Pacific salmon fry during their downstream migration to freshwater and saltwater nursery areas. *J. Fish. Res. Bd. Can.* 17(5):655-676.

Thorpe, J.E. 1987. Migration in salmonids, with special reference to juvenile movements in freshwater. 1. International Symposium on Salmon and Trout Migratory Behavior Seattle, WA (USA) Jun 1981. Saumons., no. 49. Proceedings of the Salmon and Trout.

Timbergen (1963) pointed out that in order to understand behavior patterns it is necessary to study how the behavior adapts the organism to its environment, how the behavior evolved, how the behavior develops within the organism's own lifetime and what mechanisms underlie that behavior. Crews (1980) has recently attempted such an integrated study of reproductive

behavior in anoline lizards. The present short and selective review is an attempt to approach the subject of salmonid migrations at the juvenile freshwater stages from these four directions.

Thorpe, J.E., and R.I.G. Morgan. 1978. Periodicity in Atlantic salmon *Salmo salar* L. smolt migration. *J.Fish Biol.* 12:541-548.

Behavioral and physiological mechanisms postulated for the control of downstream migration of Atlantic salmon smolts are reviewed briefly, and some new evidence is presented for their refusal to undergo sustained swimming. Although these mechanisms imply passive displacement as the primary means of emigration, it is likely that active components must also exist as the rates of travel of smolts through loch systems are only slightly slower than those recorded for river systems. The timing of these movements within 24 h periods is reviewed and it is shown that the predominantly nocturnal emigration pattern is evident on occasions in alevin, fry and parr stages also. Thus at migration the diel periodicity probably represents a seasonal locomotor rhythm which, under changed behavioral and physiological circumstances, results in downstream displacement.

Tytler, P., J.E. Thorpe, and W.M. Shearer. 1978. Ultrasonic tracking of the movements of Atlantic salmon smolts (*Salmo salar* L) in estuaries of two Scottish rivers. *J. Fish. Biol.* 12:575-586.

Ultrasonic telemetry was used to follow the movements of two groups of smolts in the estuaries of two small Scottish rivers. Hatchery reared smolts released into a typical wedge flow, partially mixed estuary had movements which were dominated by the influence of tide on the direction of water flow. The net movements of wild native smolts in a two layer flow estuary, in which freshwater flow dominated, was downstream but were intermittent consisting of short steps and numerous long pauses. The hatchery reared smolts escaped from the estuary within a tidal cycle, moving out on an ebb tide. The wild smolts remained in the estuary for periods up to 108 h, none escaping within one tidal cycle.

RHEOTAXIS AND SWIMMING ABILITY

Anderson, J.J. 1988. A neural model for visual activation of startle behavior in fish. *J. Theor. Biol.* 131:279-288.

Anonymous. 1960. A study to investigate the effects of fatigue and current velocities on adult salmon and steelhead trout. *Prog. Rep. Fish. Eng. Res. Prog. N. Pac. Div. U.S. Army Corps Eng. July.* pp 112-120.

Bainbridge, R. 1958. The speed of swimming fish as related to size and the frequency and amplitude of the tail beat. *J. Exp. Biol.* 35:109-133.

Beamish, F.W.H. 1980. Swimming performance and oxygen consumption within the genus *Salvelinus*. In: Charrs: Salmonid Fishes of the Genus *Salvelinus*. Balon, E.K. (ed). Dr. W Junk Publ., The Hague. pp 739-748.

Beamish, F.W.H. 1984. Swimming performance of three southwest Pacific fishes. *Mar. Biol.* 78(3):311-313.

The logarithm of stamina for each of *Sardinops sagax* (4 to 6,600 s), *Scomber japonicus peruanus* (16 to 27,000 s) and *Odontestes regia* (7 to 9,900 s), adjusted to a length of 10 cm, decreased linearly over swimming speeds of 31 to 82, 25 to 78 and 24 to 75 cm s⁻¹, respectively (19°C). The regression coefficient was -0.064 for both *S. j. peruanus* and *O. regia* and -0.049 for *S. sagax*. Critical swimming speed (60 min, 5 cm s⁻¹) for *S. sagax* (10 cm), 32 cm s⁻¹, is within the range found for other species of similar length. The suggestion of a change in regression coefficient as swimming speed increased from prolonged to burst was not supported by the results of this study.

Beamish, F.W.H., J.C. Howlett, and T.E. Medland. 1989. Impact of diet on metabolism and swimming performance in juvenile lake trout, *Salvelinus namaycush*. *Can. J. Fish. Aquat. Sci.* 46:384-388.

Juvenile lake trout, *Salvelinus namaycush*, of similar size were fed one of three isocaloric diets, each differing in protein and lipid content. Oxygen consumption for a given speed did not differ significantly throughout the feeding trial nor among the diets implying a similarity in the quality and quantity of substrate catabolized for energy. Basal metabolism (0 cm/s) was also independent of diet and feeding interval. Critical swimming speed increased with dietary and carcass protein content to suggest a direct association with muscle mass and number of myofilaments.

Berry, C.R. Jr., and R. Pimentel. 1985. Swimming performance of three rare Colorado River fishes. *Trans. Am. Fish. Soc.* 114:397-402

A stamina tunnel was used to determine the prolonged swimming performance of age-0 humpback chubs, *Gila cypha*, bonytail chubs, *G. elegans*, and Colorado squawfish, *Ptychocheilus lucius* and of subadult Colorado squawfish. The "fatigue velocity" in body lengths per second at which 50% of the test fish were fatigued (FV50) was determined at 14, 20, and 26°C. The ranges of FV50 values for the three fishes (average total length in parentheses) were: humpback chubs (95 mm), 4.4-5.7; bonytail chubs (99 mm), 4.7-5.8; small Colorado squawfish (104 mm), 4.0-4.5; large Colorado squawfish (432 mm), 2.0-2.3. Absolute speed of large Colorado squawfish was about 2.4 times that of small Colorado squawfish. Swimming ability of the subyearlings increased with increased water temperature. These rare fish had prolonged-swimming abilities similar to other fish species.

Besner, M., and L.S. Smith. 1983. Modification of swimming mode and stamina in two stocks of coho salmon (*Oncorhynchus kisutch*) by differing levels of long-term continuous exercise. *Can. J. Fish. Aquat. Sci.* 40:933-939.

Coho salmon (*Oncorhynchus kisutch*) smolts from two different stocks were exercised continuously for 40 d at water velocities of 0.2 (control), 1.0, 1.5, and 2.0 body fork lengths per second. Their critical velocities and swimming characteristics were determined using a Blazka-type respirometer-stamina swimming chamber immediately after training and after 2 mo of rest. Endurance increased in exercised fish compared with control groups and the improvement was maintained after the period of rest. Swimming modes in freshwater differed between the two stocks, and it is suggested these were adaptations resulting from differing genetic backgrounds. Continuous moderate exercise modified swimming modes in sea-water. Long-term low water velocity regimes before release in the ocean might be a profitable rearing strategy for the survival of coho salmon because it allows an economy of energy during their oceanic migrations and improves their homeodynamic capacity.

Bisson, P.A., K. Sullivan, and J.L. Nielsen. 1988. Channel hydraulics, habitat use, and body form of juvenile coho salmon, steelhead, and cutthroat trout in streams. *Trans. Am. Fish. Soc.* 117:262-273.

Habitat use by juvenile coho salmon *Oncorhynchus kisutch*, steelhead *Salmo gairdneri*, and the coastal subspecies of cutthroat trout, *Salmo clarki clarki*, in small streams in western Washington was influenced by hydraulic characteristics of different types of channel units. Coho salmon preferred pools with average velocities less than 20 cm/s. Steelhead occurred in riffles and also utilized deep pools with relatively high velocities. Cutthroat trout were intermediate between coho salmon and steelhead in their use of swiftly flowing habitats. Variation in body shape and fin size among the three species generally fit the predicted morphologies that would be favored in different locations within the channel. The cutthroat trout's lack of morphological adaptation to either fast or slow water may help to explain why this species is dominated by coho salmon and steelhead in areas of sympatry.

Blaxter, J.H.S. 1969. Swimming speeds of fish. *FAO Fish. Report.* 62(2):69-100.

Bone, Q. 1966. On the function of the two types of myotomal muscle fibre in elasmobranch fish. *J. Mar. Biol. Ass. U.K.* 46:321-349.

Brett, J.R. 1964. The respiratory metabolism and swimming performance of young sockeye salmon. *J. Fish. Res. Bd. Can.* 21:1183-1226.

Brett, J.R. 1965. The swimming energetics of salmon. *Sci. Am.* 213:80-85.

Brett, J.R. 1982. The swimming speed of adult pink salmon, *Oncorhynchus gorbuscha*, at 20°C and a comparison with sockeye salmon, *O. nerka*. *Can. Tech. Rep. Fish. Aquat. Sci.* 1143:iii + 37 p.

Prolonged swimming speeds of female pink salmon (55 cm, 1879 g) were determined in a 27-cm diameter steel tunnel at $20 \pm 1^\circ\text{C}$. The speeds were corrected for cross-sectional blocking effect of the fish by comparing tailbeat frequencies for the same velocities in the tunnel and in an open flume. The mean maximum sustained speed (10-hr test time) was 1.12 m/sec (2.04 L/sec). Compared with sockeye salmon, pink salmon could only perform at about 80% of the level of prolonged speed achieved in the same tunnel by sockeye of comparable size.

Carney, R.E., and R.J. Adkins. 1955. Reactions of young silver salmon in ten velocity combinations. Univ. WA. School Fish. Tech. Rep. # 23. 15 pp.

Davison, W., and G. Goldspink. 1977. The effect of prolonged exercise on the lateral line musculature of the brown trout (*Salmo trutta*). J. Exp. Biol. 70:1-12.

Davison, W., and G. Goldspink. 1978. The effect of training on the swimming muscles of the goldfish (*Carassius auratus*). J. Exp. Biol. 74:115-122.

DeLacy, A.C., S.P. Felton, and G.J. Paulik. 1956. A study to investigate the effects of fatigue and current velocities on adult salmon and steelhead trout. Prog. Rep. FERP. US Army Corps Eng. N. Pac. Div. 13 pp.

Dill, L.M. 1974. The escape response of the zebra danio (*Branchydanio rerio*). I. The stimulus for escape. Anim. Behav. 22:711-722.

Dill, L.M. 1974. The escape response of the zebra danio (*Branchydanio rerio*). II. The effect of experience. Anim. Behav. 22:723-730.

Durand, J.P., and J. Parzefall. 1987. Comparative study of the rheotaxis in the cave salamander *Proteus anguinus* and his epigean relative *Necturus maculosus* (Proteidae, Urodela). Behav. Process. 15:285-291.

The reaction to different water currents of the cave salamander *Proteus anguinus* and his epigean relative *Necturus maculosus* has been tested in a choice chamber. Both species showed a positive reaction which started in *P. anguinus* with a current of 35 cm/min and in *N. maculosus* 60 cm/min. These thresholds are within the range measured for different species of fish in the absence of visual stimuli.

Duthie, G.G. 1987. Observations of poor swimming performance among hatchery-reared rainbow trout, *Salmo gairdneri*. Environ. Biol. Fish. 18(4):309-311.

The swimming performance, as judged by maximum sustained swimming speed, of rainbow trout from a fish farm in S.W. England, is low when compared to previously published values for this species. This may be a localized peculiarity resulting from hatchery selection and rearing procedures.

Egglishaw, H.J., and P.E. Shackley. 1982. Influence of water depth on dispersion of juvenile salmonids, *Salmo salar* L. and *S. trutta* L., in a Scottish stream. J. Fish. Biol. 21(2):141-156.

The dispersion of salmon and trout of 0+, 1+ and 2+ age classes was examined by electrofishing 12 sections of a stream in Perthshire, Scotland at the end of the growing season in September to October in 1972 and 1976. In 1972 sections ranged in surface area from 21 to 122 m² and had volumes of 5 by 0-17 by 3 m³ and when surveyed in 1976 surface areas were 15-106 m² and volumes 2 by 1-6 by 7 m³. In 1976 widths and areas of sections were 63 - 87% of the values for 1972, depths were 39-68% and volumes 28-52% of the earlier values. These differences were due to 1976 being drier and warmer. In both years, all sections contained 0+ and 1+ age classes of salmon and trout and some sections contained 2+ age salmon and trout. The total density of fish in a section ranged from 1 by 9 to 3° 9 m⁻² in 1972 and from 3° 72 to 6 by 08 m⁻² in 1976. There was an inverse relationship, significant in 1972 only, between the density of 0+ salmon and that of 1+ trout in the different sections. Densities of both 0+ and 1+ salmon in the sections were inversely correlated, and those of 0+ and 1+ trout were directly correlated, with area of water deeper than 10 cm.

Eriksson, T. 1984. Adjustments in annual cycles of swimming behavior in juvenile Baltic salmon in fresh and brackish water. Symposium on Rhythmically in Fishes (at) 113. Ann. Meeting of the Am. Fish. Soc. Milwaukee, WI (USA) 18-20 Aug 1983. pp 467-471.

The vertical distribution and swimming direction of 2-year-old smolted Baltic salmon *Salmo salar*, kept in circular tanks containing either fresh or brackish water, was monitored for a year. Fish in both groups were distributed in the upper part of a water column and moved with the current during the first part of the experiment, May to August. Salmon kept in brackish water continued this behavior throughout the year whereas fish maintained in fresh water changed their behavior drastically. From September, freshwater fish were distributed close to the bottom and tended to swim against the current. The following spring (April-May), fresh water kept fish again started to swim high in the water column. Apparently, there is an interaction between alternative circannual programs in Baltic salmon.

Faler, M.P., L.M. Miller, and K.I. Welke. 1988. Effects of variation in flow on distributions of northern squawfish in the Columbia River below McNary Dam. N. Am. J. Fish. Manage. 8(1):30-35.

The movements of 23 northern squawfish, *Ptychocheilus oregonensis*, were monitored by radiotelemetry below a Columbia River hydroelectric dam during the out-migration of juvenile anadromous salmonids in 1984 and 1985. The work was done as part of a study to relate predator abundances and distribution to juvenile salmonid mortalities associated with dams. Northern squawfish remained in protected shoreline areas in spring and early summer, when discharge rates were high, but moved close to the dam and the juvenile bypass outflow area in mid to late summer, when discharge rates were low. Trends in northern squawfish movements were similar during abrupt changes in discharge rate. Modification of structures to maintain high water velocities around bypass outflow areas should reduce potential predation on juvenile salmonids by northern squawfish.

Farlinger, S., and F.W.H. Beamish. 1978. Changes in blood chemistry and critical swimming speed of largemouth bass, *Micropterus salmoides*, with physical conditioning. Trans. Am. Fish. Soc. 107(4):523-527.

Physical conditioning at swimming speeds of 2 and 3 body lengths per second for periods up to 30 days increased critical swimming speed by as much as 15% over that found for unconditioned fish. Haemoglobin increased significantly with conditioning, suggesting an enhancement of aerobic capacity. Conditioning did not, in general, increase the production of lactate dehydrogenase in blood serum. Following periods of swimming at critical speeds, blood volume decreased in unconditioned bass but with conditioning remained relatively stable.

Fausch, K.D. 1984. Profitable stream positions for salmonids: Relating specific growth rate to net energy gain. Can. J. Zool. 62(3):441-451.

A model is developed to predict potential net energy gain for salmonids in streams from characteristics of water velocity and invertebrate drift. Potential net energy gain, or potential profit, is calculated for individuals of three species of juvenile salmonids in a laboratory stream aquarium, based on the energy available from drift minus the cost of swimming to maintain position. The Michaelis-Menten or Monod model is used to describe the relationship between potential profit and specific growth rate. Potential profit was a better predictor of specific growth rate for coho salmon (*Oncorhynchus kisutch*) than for brook trout (*Salvelinus fontinalis*) or brown trout (*Salmo trutta*). Coho salmon always achieved higher specific growth rates than either brook trout or brown trout in concurrent experiments, and maintained growth to lower resource thresholds. In each experiment, fish established intraspecific hierarchies and dominant fish held positions affording maximum potential profit.

Fields, P.E., R.J. Adkins, and G. L. Finger. 1954. The swimming ability of immature silver salmon (*Oncorhynchus kisutch*) measured in an experimental flume. Univ. WA. School Fish. Tech. Rep. # 9. 21 pp.

Flagg, T.A., and L.S. Smith. 1981. Changes in the swimming behavior and stamina during smolting of coho salmon. In: Salmon and Trout Migratory Behavior Symposium. Brannon, E.L., and E.O. Salo, eds. pp 164-172.

Fuiman, L.A., and P.W. Webb. 1988. Ontogeny of routine swimming activity and performance in zebra danios (Teleostei: Cyprinidae). Anim. Behav. 36:250-261.

Zebra danios, *Danio rerio*, 3-39 long, were studied to quantify ontogenetic changes in routine (spontaneous) swimming. Swimming speeds and mean acceleration rate increased during the larval period with the most rapid changes occurring when fish were between 5 and 15 mm long. At larger sizes, the rate of increase in performance was small. This pattern presumably resulted from morphological changes which also proceeded rapidly in larvae and levelled off towards adulthood. The implications of ontogenetic changes in swimming performance for the development of foraging and anti-predator behavior are discussed.

Gauley, J.R. 1966. Effect of water velocity on passage of salmonids in a transportation channel. *Fish. Bull.* 66(1):59-63.

Gibson, R.J. 1983. Water velocity as a factor in the change from aggressive to schooling behavior and subsequent migration of Atlantic salmon smolt (*Salmo salar*). *Nat. Can.* 110(2):143-148.

The agonistic behavior of smolts, of *S. salar* was compared with that of parr in stream tanks over the normal migration time of the smolts. Smolts had similar agonistic behavior to that of the parr. There was no migratory behavior observed, and smolts remained as aggressive as the parr. Diminished aggression appears not to be responsible for the downriver migration of smolts, and the change from territorial to schooling behavior observed in natural conditions is likely due to the change in buoyancy and the associated change in preferred water velocity.

Godin, J.G.J. 1980. Ontogenetic changes in the daily rhythms of swimming activity and of vertical distribution in juvenile pink salmon (*Oncorhynchus gorbuscha*, Walbaum). *Can. J. Zool.* 58(5):745-753.

Pink salmon fry exhibited, on the average, an irregular daily pattern of swimming activity, and swam near the water surface at night (nocturnal rhythm of vertical distribution) during the first week after gravel emergence. The nocturnal rhythm of vertical distribution indicated a relative negative response of the fry to high light intensities. A shift from an irregular pattern to a diurnal rhythm of swimming activity occurred 7 to 13 days after emergence. Coincident with this shift was an increasing tendency of the fry to swim in the upper half of the water column during daylight. This suggested a gradual weakening of the fry's negative response during the Second week. Thereafter, daily rhythms of swimming activity were diurnal, whereas rhythms of vertical distribution remained nocturnal. Periodogram analysis revealed that these behavioral rhythms were synchronized strongly with the artificial daily light-dark cycle. The onset of light appeared to synchronize the diurnal swimming activity rhythms, whereas the onset of darkness synchronized the nocturnal patterns of fish rising toward the water surface.

Godin, J.G.J. 1981. Circadian Rhythm of Swimming Activity in Juvenile Pink Salmon (*Oncorhynchus gorbuscha*). *Mar. Biol.* 64(3):341-349.

The circadian rhythm of swimming activity and the role of the daily illumination cycle in the synchronization of this rhythm were studied in individual juvenile pink salmon *O. gorbuscha*. Sixty eight percent of all fish examined (n = 38) were day-active when exposed to a 12 h L:12 h D cycle the remaining fish were nocturnally active. One half of the fish tested under laboratory conditions of continuous, constant light intensity (LL) and constant temperature showed unambiguously endogenous activity rhythms with circadian periods for up to 10 d. The remaining fish were arrhythmic. Mean period length of the free-running activity rhythms for diurnal fish in LL shortened with constant light intensity increasing from 6 to 600 lux, as predicted by the circadian rule. In contrast, mean free-running period for nocturnal fish did not vary significantly with similarly increasing constant light intensity. Mean swimming speed (activity level) of both diurnal and nocturnal fish increased significantly with increasing light intensity. This is suggestive of a positive photokinetic response. When subjected to a phase-delayed LD cycle, the fish resynchronized their daily rhythms of activity with this new LD cycle after only one transient cycle in most instances.

Godin, J.G.J. 1984. Temporal variations in daily patterns of swimming activity and vertical distribution in juvenile pink salmon (*Oncorhynchus gorbuscha*). *Can. J. Zool.* 62(1):72-79.

At times corresponding to their juvenile coastal and pelagic ocean phases, groups of juvenile pink salmon exhibited diel rhythms of generally diurnal swimming activity and nocturnal vertical movement in response to simulated seasonal variations in photoperiod and water temperature in the laboratory. Diurnal swimming activity was synchronized with the daily light cycle throughout most of the year, but not with ambient daily temperature cycles. On average, fish were increasingly more active during the day than at night with increasing duration of the photophase. Results are related to the migratory behavior of pink salmon, and it is concluded that photoperiod may be an important proximate factor in the timing of their seasonal migratory behavior.

Gray, J. 1953. The locomotion of fishes. In: Essays in Marine Biology (Richard Elhirst Memorial Lectures). Oliver and Boyd, London. pp 1-16.

Gray, J. 1957. How fishes swim. *Sci. Am.* 197(2):48-54.

Greer-Walker, M. 1971. Effect of starvation and exercise on the skeletal muscle fibres of the cod (*Gadus morhua* L.) and the coalfish (*G. virens* L.) respectively. *J. Cons. Int. Explor. Mer.* 33(3):421-426.

Greer-Walker, M., and G. Pull. 1973. Skeletal muscle function and sustained swimming speeds in the coalfish, *Gadus virens* L. *Comp. Biochem. Physiol.* 44(A):495-501.

Greer-Walker, M., and L. Emerson. 1978. Sustained swimming speeds and myotomal muscle function in the trout, *Salmo gairdneri*. *J. Fish Biol.* 13:475-81.

Rainbow trout were trained for 3-4 weeks in a flume at swimming speeds of 1, 2 and 3 Ls^{-1} . for each experiment growth rates were estimated and by measuring the hypertrophy of red and mosaic skeletal muscle fibres their function was described at particular swimming speeds and compared with earlier experiments on coalfish using the same technique. Maximum growth, compared with controls in still water, occurred at swimming speeds of 1 Ls^{-1} . At this speed the trout mosaic muscle fibres hypertrophied by 40% but the red muscle fibres showed only a 25% hypertrophy. It is suggested that natural swimming speeds are close to 1 Ls^{-1} and the trout mosaic fibres are better adapted for use at this speed in comparison with coalfish white muscle fibres.

Gregory, R.W., and P.E. Fields, 1962. Discrimination of low water velocities by juvenile silver (*Oncorhynchus kisutch*), and chinook salmon (*Oncorhynchus tshawytscha*). College of Fisheries, Univ of Wash. U.S. Army Corps of Eng. Tech. Report 52. 58 pp.

Hammond, B.R., and C. P. Hickman, Jr. 1966. The effect of physical conditioning on the metabolism of lactate, phosphate, and glucose in rainbow trout, *Salmo gairdneri*. *J. Fish. Res. Bd. Can.* 23(1):65-83.

Heggberget, T.G., and T.M. Heggberget. 1986. Behavior of juvenile Atlantic salmon, *Salmo salar* L. in rapid- and slow-flowing sections of a small Norwegian stream. *Aqua. Fish. Manage.* 17(3)191-194.

Through ultrasonic tagging, fish living in running water and in slow-flowing water in man-made weir basins were tracked over a period of 3-6 days. Results showed that the fish living in the weir basins changed position more frequently and moved over larger areas than fish living in running water. As a consequence of the different behavioral patterns of fish in rapids and in weir basins, densities of salmon are lower in the weir basins than in the rapids. Therefore, weirs creating large areas of slow-flowing water should not be established in rivers where an optimal production of Atlantic salmon is the goal.

Hegggenes, J. 1988. Effects of short-term flow fluctuations on displacement of, and habitat use by, brown trout in a small stream. *Trans. Am. Fish. Soc.* 117:336-44.

Hegggenes, J., and T. Traaen. 1988. Downstream migration and critical water velocities in stream channels for fry of four salmonid species. *J. Fish Biol.* 32:717-727.

Fry of brown trout, Atlantic salmon, brook trout and lake trout were tested for downstream migration and critical velocities with a method of stepwise increasing water velocities. Critical velocities for fry entering the free-feeding stage, were between 0.10 and 0.25 m/s, varying among individuals and depending on species and water temperature. Downstream displacement started at lower velocities. Lake trout had the lowest critical velocity. Temperature influenced swimming performance. On average, a 7°C increase in temperature resulted in a 0.05 m/s increase in critical velocity. Flow-sensitivity gradually decreases with fry development; when the fry had reached a length of 40-50 mm they were able to tolerate water velocities higher than 0.50 m/s.

Hudson, R.C.L. 1973. On the function of the white muscles in teleosts at intermediate swimming speeds. *J. Exp. Biol.* 58:509-522.

Johnston, I.A., and T.W. Moon. 1980. Exercise training in skeletal muscle of brook trout (*Salvelinus fontinalis*) J. Exp. Biol. 87:177-194.

The differentiation of myotomal muscles in the brook trout (*Salvelinus fontinalis* Mitchill) has been investigated using p-phenylene diamine stained semi-thin sections and cytochemical and quantitative determinations of enzyme activities. 2. Evidence is presented that the range of fibre size in white muscle represents stages in growth rather than distinct fibre types. 3. Electromyography shows that both red and white muscles are recruited for sustained swimming. The threshold swimming speed for recruitment of white fibres is around 1.8 body length/s (L/s). 4. White muscle citrate synthetase and cytochrome oxidase activities are 25-35% that of red muscle. Hexokinase, phosphorylase and phosphofructokinase activities are 2, 4 and 2 times higher in white than red muscles. It is considered that the aerobic capacity of white muscle is sufficient to support sustained swimming, and that blood glucose could be an important fuel source. 5. Endurance exercise training has been investigated in fish swimming, continuously, for 21 days at 3 L/s. This training regime restricts spontaneous high-speed swimming activity and resulted in a general decline of white muscle glycolytic enzyme activities. Red fibres underwent hypertrophy relative to non-exercised controls ($530 \pm 64 \mu\text{m}^2$ non-exercised, $901 \pm 63 \mu\text{m}^2$ trained). Aerobic enzyme activities in red muscle and the fraction of fibre volume occupied by mitochondria ($30.2 \pm 0.8\%$) did not change in response to the training programme, but glycolytic enzyme activities were elevated. 3-OH Acyl CoA dehydrogenase activities increased in both red and white muscles indicating an enhanced capacity for fatty acid catabolism with training. 6. Plasma and muscle lactate levels were not statistically different between tank-rested and trained fish swimming a 3 L/s. 7. Adaptations of fish muscle to endurance training are discussed and compared with results for other vertebrates.

Johnston, I.A., W. Davison, and G. Goldspink. 1977. Energy metabolism of carp swimming muscles. J. Comp. Physiol. 114B:203-216.

Kelso, B.W., and T.G. Northcote. 1981. Current response of young rainbow trout from inlet and outlet spawning stocks of a British Columbia lake. Verh. Internat. Verein. Limnol. 21:1214-1221.

The aim of this work was to investigate the relationship between shoal size and vigilance. The behavior of minnows (*Phoxinus phoxinus*) foraging on an artificial food patch during the simulated stalking approach of a model predator (pike: *Esox lucius*) was recorded for shoals of 20, 12, 6 and 3 fish. Minnows in large shoals reduced their foraging sooner but remained feeding on the patch longer than in small shoals. The relatively late reaction of small shoals to the model and the rapid cessation of feeding once the predator was detected, indicates that small shoals were less vigilant than large shoals.

Kocik, J.F., and W.W. Taylor. 1987. Effect of fall and winter instream flow on year-class strength of Pacific salmon evolutionarily adapted to early fry outmigration: A Great Lakes perspective. 1. Internat. Symp. Common Strategies Anad. Catad. Fish.

Pink salmon, *Oncorhynchus gorbuscha*, sockeye salmon, *O. nerka*, and chum salmon, *O. keta* are essentially ecological equivalents in their use of riverine habitat. These Oncorhynchids are stream spawners that deposit their eggs in the early fall. The eggs incubate through winter, and emergence and outmigration of the juvenile salmon occur in early spring. Although these fish are transient in the riverine environment, the stream plays a critical role in controlling their production and year-class strengths by significantly influencing egg and alevin survival. In these early stages, survival is primarily a function of the quantity and quality of instream flow during the fall and winter in conjunction with redd superimposition and streambed overseeding. A model is proposed to explain the relationship between abiotic and biotic factors upon Oncorhynchid recruitment, based on our knowledge of pink salmon in the Great Lakes and a review of literature pertaining to early-outmigrating Oncorhynchids.

Konagaya, T. and Q. Cai 1987. Telemetry of the swimming movements of silver carp and bighead. Bull. Jap. Soc. Sci. Fish. 53(5) pp 705-709.

Lindsey, C.C. 1978. Form, function, and locomotory habits in fish. In: Fish Physiology. Hoar, W.S., and D.J. Randall (eds.). Academic Press, Inc. Vol. VII, Locomotion, pp 1-100.

Lyon, E.P. 1905. On rheotropism. I. Rheotropism in fish. Am. J. Physiol. 12.

MacKinnon, D., and W.S. Hoar. 1953. Responses of coho and chum salmon fry to current. J. Fish Res. Bd. Can. 10:523-538.

Mayama, H. 1987. Ascending behavior of juvenile masou salmon (*Oncorhynchus masou*) in experimental fishway. Sci. Rep. Hokkaido Salmon Hatchery. 41:137-153.

Ecological observations of ascending behavior of juvenile masu salmon (*Oncorhynchus masou*) under various hydraulic and light conditions were carried out using a small-scale experimental fishway. In tests on the effect of pool depth below the weir, a 10 cm pool depth, approximately equal to body length of the fish, resulted in the most successful passage over weir. The general tendency was not evident in the relation between waterflow supplied into the channel and ascending rate. However, under inadequate flow conditions of higher or lower discharge, ascent form of the fish changed from "swimming-type" to "jumping-type" and jump failure coincided with the change.

Mutsin'sh, A.N. 1979. Current velocities and the behavior of young fish. J. Ichthyol. 19(5):171-173.

Nahhas, R., N.V. Jones, and G. Goldspink. 1982. Growth, training and swimming ability of young trout (*Salmo gairdneri* R.) maintained under different salinity conditions. J. Mar. Biol. Ass. U.K. 62:699-708.

The specific growth rate of rainbow trout (*Salmo gairdneri* R.) (7-8 cm length) was investigated at 0.5, 18 and 32 ppt. salinities for a period of 28 days. Fish growth at 18 ppt. was less than that at 0.5 ppt. but growth at 32 ppt. was much impaired and mortality at this salinity reached 92% by the end of 21 days of the experiment. Exercise training of fish in fresh water at water velocities of 0.0, 1.4, 2.2 and 3.5 L s⁻¹ showed that the growth of exercising fish was considerably greater than that of the controls. Exercise training of the fish at 18 ppt. was not successful, and negative growth rates resulted.

Nahhas, R., N.V. Jones, and G. Goldspink. 1982. Some aspects of sustained training of rainbow trout, *Salmo gairdneri* Richardson. J. Fish. Biol. 20(3):351-358.

Groups of 6-7 cm length rainbow trout, *Salmo gairdneri* were simultaneously trained at four water velocities (0, 1.4, 2.2 and 3.5 L s⁻¹) for a period of 46 days. Oxygen consumption and swimming ability (fatigue time) were then measured. Only training at 3.5 L s⁻¹ increased the swimming ability of the fish. A study of the relative proportion of the white and red muscles indicated that the white muscle was increasing its mass at velocities in excess of 2.2 L s⁻¹. The oxygen consumption rate of the trained fish was lower than that of the untrained fish when considered over the whole velocity range.

Nashimoto, K. 1980. The maximum swimming force of rainbow trout. Bull. Jap. Soc. Sci. Fish. 46(8):949-954.

Northcote, T.G. 1981. Juvenile Current Response, Growth and Maturity of Above and Below Waterfall Stocks of Rainbow Trout, *Salmo gairdneri*. J. Fish Biol. 18(6):741-751.

Young rainbow trout were propagated from adults collected from above and below a waterfall, impassable to upstream fish migration on Kokanee Creek, tributary to Kootenay Lake, British Columbia. The two stocks of young (above and below waterfall) were reared in a hatchery under identical temperature, light and food conditions. Their directional response to water current was tested in a laboratory migration channel during their first summer and autumn, as well as the following spring. During tests in light, both stocks of young trout showed similar current responses, but in darkness the below falls stock showed much more downstream movement in the autumn than did the above falls stock. In addition, below falls trout had a higher growth rate, were slightly heavier at the same length and matured earlier than the above falls stock. The adaptive significance of these differences are discussed in relation to maintenance of trout populations above waterfalls and to selective pressures faced by migratory below waterfall populations.

Nunan, C.P., and D.L.G. Noakes. 1985. Response of rainbow trout (*Salmo gairdneri*) embryos to current flow in simulated substrates. Can. J. Zool. 63(8):1813-1815.

Direction of current flow did not affect the movement patterns of rainbow trout (*S. gairdneri*) embryos maintained in artificial substrate systems. Embryos successfully emerged from the substrate in total darkness, although light has previously been implicated as necessary for emergent behavior. Neither phototactic or rheotactic behavior appears necessary for "normal" movement and emergence of salmonid embryos. Movement patterns appear to be primarily due to geotactic-geokinetic behavior.

Ottaway, E.M., and A. Clarke. 1981. A preliminary investigation into the vulnerability of young trout (*Salmo trutta* L.) and Atlantic salmon (*S. salar* L.) to downstream displacement by high water velocities. *J. Fish. Biol.* 19(2):135-145.

The downstream movement of young trout and salmon in relation to water velocity was studied in simulated river channels. The results are interpreted as showing that these young salmonids pass through a short period when they are very vulnerable to downstream displacement by flow. Behavioral differences between the two species are considered with the influence on fish movement of changing rate of water velocity, light and temperature.

Ottaway, E.M., and D.R. Forrest. 1983. The influence of water velocity on the downstream movement of alevins and fry of brown trout, *Salmo trutta* L. *J. Fish Biol.* 23:221-227.

Trout eggs were planted in four experimental stream channels, each channel being run at a different but constant discharge. Survival of the eggs to hatching was low and apparently unrelated to surface water velocity. However, movement of young trout out of channels was affected by water velocity, the higher the velocity the greater the proportion of trout that were lost. Virtually all fry moved out of a channel with a mean surface water velocity of 0.73 m s^{-1} . The rate of loss was not constant over the experiment but increased as the young trout entered the free-feeding stage. At the end of the experiment loss of fry, after abrupt increases in discharge, was demonstrated in the lower velocity channels.

Pavlov, D.S. 1966. The relationship of young fish to a current of water and orientation to it. *Zool. Zhur.* 45(6).

Pavlov, D.S. 1969. Entrapment of fish fingerlings in pumping installations as related to features of their behavior and orientation in the stream of water. *Probs. Ichthyol. Am. Fish Soc.* 9(2): 237-243.

Priede, I.G. 1977. Natural selection for energetic efficiency and relationship between activity level and mortality. *Nature (Lond.)* 267:610-611.

Puckett, K.J., and L.M. Dill. 1984. Cost of sustained and burst swimming to juvenile coho salmon (*Oncorhynchus kisutch*). *Can. J. Fish. Aquat. Sci.* 41:1546-1551.

The relationship between oxygen consumption rate (milligrams per kilogram per hour) and sustained swimming speed (calculated from tailbeat frequency) was determined for 1.2-g juvenile coho salmon (*O. kisutch*) at 15°C . The data are best described by the following equation: $\log \text{ oxygen consumption rate} = 2.2 \pm 0.13$ (body lengths per second, bls). This relationship is very similar to that extrapolated for sockeye salmon (*O. nerka*) of the same size, thus potentially enabling researchers to utilize the extensive sockeye data base to predict metabolic rates of coho. The oxygen consumption rate during burst swimming (9 bls) was also determined. The burst swimming metabolic rate ($38,000 \text{ mg O}_2 \cdot \text{kg}^{-1} \cdot \text{h}^{-1}$) is nearly 40 times greater than the maximum sustained swimming metabolic rate.

Randall, D.J., and C. Daxboeck. 1982. Cardiovascular changes in the rainbow trout (*Salmo gairdneri* Richardson) during exercise. *Can. J. Zool.* 60:1135-1140.

Shimamura, T., K. Yoza, E. Hasegawa, M. Furuta, and H. Soeda 1987. On the swimming behavior of chum salmon in early migratory season off the coast of Abashiri, Hokkaido. *Bull. Jap. Soc. Sci. Fish.* 53(3) pp 411-415.

Skorobogatov, M.A., D.S. Pavlov, and A. Sh. Barekryan. 1987. Study of association of swimming ability of roach, *Rutilus rutilus*, with pressure and angle of inclination of current. *J. Ichthyol.* 27(4):40-46.

Smith, L.S. 1982. Decreased swimming performance as a necessary component of the smolt migration in salmon in the Columbia River. *Aquaculture.* 28(1-2):153-161.

Comparison of typical water velocities in the Columbia River system with observed migration rates for salmon and steelhead smolts previously has been interpreted as evidence for passive migration during part of each night. Recent research, however, has shown that coho salmon experience reduced swimming proficiency and fatigue levels during

smolting, particularly when smolts are transferred directly into seawater. Reexamining the migration times in light of the new swimming proficiency data suggests that smolts may swim mostly head first upstream during outmigration thus drifting downstream tailfirst.

Soeda, H., K. Yoza, T. Shimamura, E. Hasegawa, and K. Yoshihara 1985. On the vertical moving behavior of chum salmon in early migratory season off the coast of Shiretoko Peninsula. Bull. Jap. Soc. Sci. Fish. 51(9) pp 1425-1429.

Soeda, H., Yoza, K., T. Shimamura, and E. Hasegawa. 1987. On the swimming behavior of chum salmon in early migratory season off the coast of Hokkaido, Okhotsu Sea. Bull. Jap. Soc. Sci. Fish. 53(10):1827-1833.

Regarding the swimming behavior of test fish in a 1985 experiment, swimming direction showed a notable eastward element, and the mean horizontal swimming speed was faster than Ichihara's estimated value. The trend of vertical movement showed that the test fish swam comparatively deep before and after noon, just below the sea surface without vertical movement at mid-night, and with notable vertical movement at sunrise. As the results of experiments conducted in and after 1982, the migration of chum salmon (*Oncorhynchus keta*) was assumed to be as follows: chum salmon migrated to Kitamiyamoto Bank along the East Sahalin Current, and diverged to east and west at an area from Kitamiyamoto Bank to Cape Notoro or off-shore Monbetsu.

Symons, P.E.K. 1978. Leaping behavior of juvenile coho (*Oncorhynchus kisutch*) and Atlantic salmon (*Salmo salar*). J. Fish. Res. Board Can. 35(6):907-909.

Juveniles of coho (*O.kisutch*) and Atlantic salmon (*S.salar*) proved capable of leaping falls at least 5 body lengths in height. No species differences were apparent: both species leapt lower falls (12 cm) more readily than higher ones (27 and 57 cm) and proportionately more leaps occurred on days with temperatures between 14.0 and 17.0°C than on days with lower temperatures.

Taylor, E.B., and P.A. Larkin. 1986. Current response and agonistic behavior in newly emerged fry of chinook salmon, *Oncorhynchus tshawytscha*, from ocean- and stream-type populations. Can. J. Fish. Aquat. Sci. 43:565-573.

In Slim Creek, a tributary to the upper Fraser River east of Prince George, B.C., chinook salmon (*Oncorhynchus tshawytscha*) fry summer and overwinter in their natal stream before migrating seaward as yearlings; they are "stream-type" in juvenile life history pattern. From the Harrison River, a tributary to the lower Fraser River, chinook fry migrate to the Fraser River estuary sometime during their first spring or early summer; they are "ocean-type." Differences between Slim Creek and Harrison River Chinook fry are in a direction consistent with their different patterns of length of freshwater residence as juveniles, since aggressive behavior, positive rheotaxis, and bright fin coloration are important components of extended stream residence in salmonids.

VanDerwalker, J.G. 1970. Responses of fingerling coho and chinook salmon to modified flows in a simulated turbine intake. Trans. Am. Fish. Soc. 99(3):532-539.

Wankowski, J.W.J., and J.E. Thorpe. 1979. Spatial distribution and feeding in Atlantic salmon, (*Salmo salar* L.) juveniles. J. Fish Biol. 14(3):239-247.

The distribution, social behavior, and feeding behavior of juvenile Atlantic salmon were studied in a selection of stream and river habitats in northern Scotland using Scuba diving techniques. The results are discussed with respect to food acquisition and choice of feeding site. It is concluded that juvenile salmon feed predominantly on drifting material and that their daytime distribution reflects the current velocity related abundance of drift.

Wardle, C.S. 1974. Limit of fish swimming speed. Nature. 255:725-727

Wardle, C.S. 1977. Effects of size on the swimming speeds of fish. In: Scale Effects in Animal Locomotion. Proc. Internat. Symp. Cambridge University, Sept. 1975. Pedley, T.J. (ed). Academic Press. pp 299-313.

Weaver, C.R. 1962. Influence of water velocity upon orientation and performance of adult migrating salmonids. *Fish. Bull.* 63(1):97-121.

Webb, P.W. 1975. Hydrodynamics and energetics of fish propulsion. *Bull. Fish. Res. Bd. Can.* 190. 158 pp.

Webb, P.W. 1983. Speed, acceleration and maneuverability of two teleost fishes. *J. Exp. Biol.* 102:115-122.

Speed, acceleration rate and turning radius were measured for rainbow trout (*Salmo gairdneri*; length 25.7 cm) and smallmouth bass (*Micropterus dolomieu*; length 23.6 cm) attacking live minnows. The observations sampled a range of values for each kinematic variable up to the limits of maximum performance. Minimum turning radius was independent of speed and acceleration rate. Expressed as a ratio of total length, L, minimum radii were $0.18 \pm 0.2 L$ for trout and $0.11 \pm 0.02 L$ for bass^x (± 2 S.E.). Differences in minimum turning radius, R, between trout and bass were attributed to differences in the volume of the body and entrained water, V, and projected lateral surface area of the body and median fins, A. For subcarangiform swimmers, the dimensionless minimum specific turning radius $R/L = 2V/AL$.

Webb, P.W., P.T. Kostecki, and E.D. Stevens. 1984. The effect of size and swimming speed on locomotor kinematics of rainbow trout. *J. Exp. Biol.* 109:77-95.

Williams, I.V., and J.R. Brett. 1987. Critical swimming speed of Fraser and Thompson River pink salmon (*Oncorhynchus gorbuscha*). *Can. J. Fish. Aquat. Sci.* 44:348-356.

Critical swimming speeds were determined for male and female pink salmon (*Oncorhynchus gorbuscha*) captured from the Fraser and Thompson rivers and Seton Creek, British Columbia. The fish were categorized into two basic groups. Lower river fish were captured from the Fraser River at Fort Langley and Yale, and up-river fish were captured from the Thompson River at the Canyon and at Ashcroft and from Seton Creek near Lillooet, British Columbia. The critical swimming speeds of males and females in various stages of maturation were compared. In general, the up-river fish were stronger swimmers than the lower river fish. Gravid fish were stronger swimmers than spawning fish, which in turn were stronger swimmers than fish which were spawned out.

Yoza, K., H. Soeda, T. Shimamura, E. Hasegawa, and K. Yoshihara 1985. On the horizontal swimming behavior of chum salmon in early migratory season off the coast of Shiretoko Peninsula. *Bull. Jap. Soc. Sci. Fish.* 51(9) pp 1419-1423.

SMOLTING

Folmar, L.C., and W.W. Dickhoff. 1980. The parr-smolt transformation (smoltification) and seawater adaptation in salmonids. *Aquaculture.* 21:1-37.

The purpose of this review is to provide fishery biologists and fish culturists with a summary of those published reports relating to the morphological, behavioral and biochemical changes associated with smoltification and seawater adaptation in anadromous salmonids.

Hoar, W.S. 1976. Smolt transformation: evolution, behavior, and physiology. *J. Fish. Res. Bd. Can.* 33:1234-1252.

Literature concerned with the appearance of smolts (silvery color, streamlined body form), their physiology (salinity relationships, endocrinology), and their behavior (territorial and schooling) is discussed in relation to possible key steps in the evolution of the parr-smolt transformation and seagoing behavior. It is assumed that Salmonidae evolved in fresh water, that the genus *Oncorhynchus* originated in a large area of brackish water such as the Sea of Japan, and that schooling on *Oncorhynchids* (e.g. *O. gorbuscha* and *O. keta*) are the most specialized of the seagoing salmonids while species of char (*Salvelinus*) and trout (*Salmo*) are more primitive.

Schreck, C.B. 1981. Parr-smolt transformation and behavior. In: *Salmon and Trout Migratory Behavior Symposium*. Brannon, E.L., and E.O. Salo, eds. pp 164-172.

Wagner, H.H. 1974. Photoperiod and temperature regulation of smolting in steelhead trout (*Salmo gairdneri*). Can. J. Zool. 52:219-234.

Zaugg, W.S., and H.H. Wagner. 1973. Gill ATPase activity related to parr-smolt transformation and migration in steelhead trout (*Salmo gairdneri*): Influence of photoperiod and temperature. Comp. Biochem. Physiol. 45(B):955-965.

S O U N D A N D H E A R I N G

Abbott, R.R. 1970. Hearing of salmonids with reference to the use of sound in fish culture. MS Thesis, University of Washington, Seattle, WA. 48 pp.

Abbott, R.R. 1973. Acoustic sensitivity of salmonids. Ph.D Thesis. University of Washington - School of Fisheries. Seattle, WA. 113 pp.

Anderson, J.J. 1988. A computer model for fish trajectories at Rocky Reach Dam: Indications that fish avoid low frequency sound made by the submersible travelling screen. In: Proceedings of the Electric Power Research Institute Conference.

Anderson, J.J., R.T. Miyamoto, S.O. McConnell, and B.E. Feist. 1989. Measurement of low frequency sound at Bonneville, McNary, and Lower Granite Dams. University of Washington, School of Fisheries. UW-FRI-8906.

Anderson, S.S., and A.D. Hawkins. 1976. Scaring seals by sound. Presented at: The 1976 autumn symposium of the Mammal Society on aspects of seal biology London, UK 20 Nov 1976. Mammal Rev. 8(1-2):19-24.

In 1974 and 1975 a series of trials were made to investigate the effectiveness of sound as a deterrent to marauding seals at salmon netting stations. A feasibility trial was followed by experimental work on a captive juvenile common seal. A wide variety of sounds including pure tones, killer whale calls and recorded loud noises were transmitted and responses were recorded on videotape. While one sound appeared to elicit an alarm reaction, habituation was rapid. Field trials were carried out at netting stations at the mouth of the River Tweed which frequently suffer damage from Grey seals. Although the frequencies used spanned the entire hearing range of seals, no sound was consistently effective in scaring seals from the nets. It is concluded that the prospect of an acoustic deterrent is remote.

Ballantyne, P.K., and P.W. Colgan. 1978. Sound production during agonistic and reproductive behavior in the pumpkinseed (*Lepomis gibbosus*), the bluegill (*L. macrochirus*), and their hybrid sunfish. Biol. Behav. 3:113-135.

Banner, A. 1968. Attraction of young lemon sharks, *Negaprion brevirostris*, by sound. Copeia. 4:871-2.

Bauer, B.B. 1987. Measurement of particle velocity in underwater sound. In: Lateral Line Detectors. Cahn, P. (ed.). Indiana University Press, pp 459-65.

Bergeijk, W.A. van. 1967. Introductory comments on lateral line function. In: Lateral Line Detectors, Cahn, P. (ed). Indiana University Press, p. 73-81.

Blaxter, J.H.S, J.A.B. Gray, and E.J. Denton. 1981. Sound and startle responses in herring shoals. J. Mar. Biol. Ass. U.K. 61:851-869.

Startle responses of shoaling herring (*Clupea harengus* L.) to various well-defined sound stimuli were investigated. A sound consisting of only one cycle of a sine wave was as effective a stimulus as a sound of the same amplitude lasting many cycles. The variability of response to a given stimulus was small. If a wave train took several cycles to reach its maximum amplitude the threshold was raised considerably. If measured as pressures the amplitudes of single-cycle stimuli needed for

constant responses were almost independent of the duration of the stimuli (range tested: 2-40 ms). The authors conclude that herring can receive, in a transient sound, sufficient information to determine the amplitude of the sound and the general direction from which it comes. They argue that, while the directional sense demands information on particle velocities and pressure, responses are triggered by pressure alone.

Blaxter, J.H.S. 1981. The swimbladder and hearing. In: Hearing and Sound Communication in Fishes. Fay, R.R. (ed). Proc. Life Sci. pp 61-71.

Blaxter, J.H.S. , J.A.B. Gray, and A.C.G. Best . 1983. Structure and development of the free neuromasts and lateral line system of the herring. J. Mar. Biol. Assoc. U.K. 63:247-260.

Vital staining with Janus Green, Phase contrast and scanning electron microscopy were used to map the distribution of free neuromast organs from first hatching, 10 mm long larvae to 100 mm long juveniles of herring (*Clupea harengus* L.), with some further observations on juvenile sprat (*Sprattus sprattus* (L.)). Neuromasts are sparsely distributed on the head and trunk at hatching but soon proliferate on the trunk where, but a length of 13-15 mm, they occur one to every segment. Near metamorphosis there are at least three rows of neuromasts on the anterior trunk region, 6-9 single neuromasts on the caudal fin and as many as 50 on the head. The scales develop at about 40-50 mm and the neuromasts are then found singly or in groups of 2 or 3 on the surface of the scales of the anterior trunk. The lateral line develops at 22-24 mm and appears to incorporate existing free neuromasts on the side of the head. Unlike the cupulae of the free neuromasts, which are cylindrical, the lateral-line cupulae are thin erect plates lying along the axis of the canals.

Blaxter, J.H.S., and D.E. Hoss. 1981. Startle response in herring: The effect of sound stimulus, frequency, size of fish, and selective interference with the acoustico-lateralis System. J. Mar. Biol. Ass. U.K. 61: 871-879.

Herring (*Clupea harengus* L.) show a characteristic "startle" response when subjected to vibrational stimuli from a diaphragm in the wall of their tank. Threshold measurements on fish from 2.8 to 17 cm total length tested at frequencies from 70 to 200 Hz showed that the response was elicited by sound pressures between 2 and 18 Pa, the most sensitive fish being in the length range from 8-11 cm. Intermediate-sized fish of 12-13 cm also responded to sounds from a loudspeaker in air above the tank, the mean threshold being about 5 Pa. The stimulus was thought to be the sound pressure rather than the particle velocity component of the stimulus, the gas-filled pro-otic bulla acting as part of the pressure detecting system. Decoupling of this link by cutting window over the lateral recess did not affect the response much, nor did treatment of the lateral line by methylene blue or streptomycin as blocking agents.

Blaxter, J.H.S., and R.S. Batty. 1985. Herring behavior in the dark: responses to stationary and continuously vibrating obstacles. J. Mar. Biol. Ass. U.K. 65:1031-1049.

The behavior of herring subjected to stationary and vibrating obstacles in their swimming path was recorded in daylight and darkness using an infra-red sensitive TV system. The herring avoided stationary obstacles using visual stimuli and usually collided with such obstacles in darkness. They showed strong avoidance to a continuously vibrating sound source in darkness but the speed of turning was relatively slow and there was no evidence for habituation. As they approached the source they usually responded when the sound pressure reached 10-20 Pa, about 70 dB above the threshold. Particle velocity within the lateral line canals was calculated and was 40-60 dB above threshold. Herring seem to be able to adapt their avoidance behavior to suit the urgency of the situation.

Blaxter, J.H.S., and R.S. Batty. 1985. The development of startle responses in herring larvae. J. Mar. Biol. Assn. 65:737-50.

Fast-startle responses were found in herring larvae soon after hatching. Young larvae of 10-12 mm body length responded to tactile stimuli and to contact with medusae with escape speeds of 5.8 and 10.1 BL (body length)/s respectively. These larvae did not respond to acoustic stimuli. Older larvae, of 22-36 mm body length, responded to acoustic stimuli, but only if the otic bulla contained gas. The latency averaged 27 ms, the threshold of sound pressure was about 10 Pa and the escape speed about 12 BL/s. The older larvae did not make directional responses away from the sound source until the head lateral line, and its coupling with the bulla, were developed.

Blaxter, J.H.S., and R.S. Batty. 1987. Comparisons of herring behavior in the light and dark: Changes in activity and responses to sound. J. Mar. Biol. Assoc. U.K. 67(4):849-860.

Comparisons of the behavior of herring (*Clupea harengus* L.) were made in the light and dark by means of an infra-red sensitive TV system and video recording. Herring, which were schooling in the light, became less active in the dark, their

swimming speed decreased, they tended to disperse and the proportion of gliding compared with swimming fish increased. Herring which were not schooling in the light increased their swimming speed in the dark. When subjected to transient sound stimuli herring made fast-startle responses. The proportion of fish responding was lower in the dark. The directionality of the response (the proportion turning away from the sound source) was the same in the light and dark suggesting there was no visual component in the response.

Blaxter, J.H.S., E.J. Denton, and J.A.B. Gray. 1981. Acoustico-lateralis system in clupeid fishes. In: *Hearing and Sound Communication in Fishes*. Fay, R.R. (ed). Proc. Life Sci. pp 39-59.

Bleckman, H. 1980. Reaction time and stimulus frequency in prey localization in the surface feeding fish *Aplocheilus lineatus*. J. Comp. Physiol. 140:163-172.

The responses of *A. lineatus* to water surface waves were investigated. *A. lineatus* responds to surface waves from 10 Hz to at least 250 Hz. Reaction time to clicks within a target angle of 70 to 100° varies between 128 ms at 8.9 m and 242 ms at 0.06 m amplitude. The distance the fish swims toward the wave source decreases with increasing stimulus frequency.

Buerkle, U. 1987. Methods and software procedures for processing digital data from acoustic herring surveys. Can. Manus. Rep. of Fish. and Aq. Sci. No. 1902. 63 pp.

Buerkle, Udo. 1977. Detection of trawling noise by Atlantic cod (*Gadus morhua* L.). Mar. Behav. Physiol. 4:223-242.

Burner, C.J., and H.L. Moore. 1953. Attempts to guide small fish with underwater sound. U.S. Fish Wildlife Serv. Spec. Sci. Report: #111. 38 pp.

Burner, C.J., and H.L. Moore. 1962. Attempts to guide small fish with underwater sound. U.S. Fish Wildl Ser., Spec. Sci. Rep. Fish. 403:1-30.

Buwalda, R.J.A. 1981. Segregation of directional and nondirectional acoustic information in the cod. In: *Hearing and Sound Communication in Fishes*. Tavolga, W.N., A.N. Popper, and R.R. Fay (eds). Springer, New York, pp 139-186.

Buwalda, R.J.A., A.Schuijf, and A.D. Hawkins. 1983. Discrimination by the cod of sounds from opposing directions. J. Comp. Physiol. 150:175-184.

The ability of cod (*Gadus morhua* L.) to discriminate between sound waves coming from opposing directions was studied by means of cardiac conditioning in approximately free field conditions under a raft in a Scottish sea loch. The sound sources were positioned at 0° (frontal), 60° or 120° in the fish's median vertical plane, or at 60° or 90° in the transverse plane, other sources occupying diametrically opposed locations. Radial distances varied between 3.05 m and 4.20 m. It is concluded that the detection of sound propagation direction is based on the characteristic phase relationship between particle motion and sound pressure. Cues resulting from sound propagation itself are irrelevant, and do not appear to be perceived.

Campenhausen, C. von, I. Riess, and R. Weissert. 1981. Detection of stationary objects by blind cave fish, *Anoptichthys jordani*, (Characidae). J. Comp. Physiol. 143:369-374.

It was noticed that the blind Mexican Cave Fish repeatedly passes along objects new to it at a short distance. Observations and experiments are reported which support the hypothesis that water movements occurring between the stationary object and the fish as it passes convey information about the location and possibly the shape of the object, which is detected by the lateral line organ of the fish. Water movements of the expected type were recorded with the help of a model fish equipped with a mechanoelectric analogue of a free neuromast.

Chapman, C.J., and A.D Hawkins. 1967. The importance of sound in fish behavior in relation to capture by trawls. FAO Fish Rpt. E/42. 62(3):717-729.

Chapman, C.J., and A.D. Hawkins. 1973. A field study of hearing in the cod, *Gadus morhua*. J. Comp. Physiol. 85:147-67.

Chapman, C.J., and A.D. Hawkins. 1976. The importance of sound in fish behavior in relation to capture by trawls. In: Effects of Power Peaking on the Survival of Juvenile Fish at the Lower Columbia. US Army Corps Eng. North Pac. Div. pp 717-729.

Chapman, C.J., and O. Sand. 1974. Field studies of hearing in two species of flatfish, *Pleuronectes platessa* (L.) and *Limanda limanda* (L.). Comp. Biochem. Physiol. 47A:371-385.

Coombs, S., and A.N. Popper. 1979. Hearing differences among Hawaiian squirrelfish (family Holocentridae) related to differences in the peripheral auditory system. J. Comp. Physiol. 132A:203-207.

Auditory sensitivity as a function of frequency has been behaviorally determined for 2 species of fish from the teleost family Holocentridae which is characterized by marked variation in peripheral auditory structures. Best sensitivity measured for *Myripristis kuntzei* was -50 dB re: 1 dyne/cm SUP-2 for frequencies between 300 and 2,000 Hz, while best sensitivity measured for *Adioryx xantherythrus* was 28 dB at 500 Hz. Both species can detect sounds at 100 Hz while the high frequency end of the auditory range extends up to 3,000 Hz for *M. kuntzei* and to 800 Hz for *A. xantherythrus*. It is hypothesized that these differences in auditory capabilities are related to differences in sound transmission characteristics of the peripheral auditory system.

Coombs, S., and A.N. Popper. 1982. Comparative frequency selectivity in fishes: simultaneously and forward-masked psychophysical tuning curves. J. Acoust. Soc. Am. 71(1):133-141.

Behavioral methods were used to determine psychophysical tuning curves for three teleostean fish species (*Notopterus chitala*, *Adioryx xantherythrus*, and *Osteoglossum bicirrhosum*) for 300- and 500-Hz signals. Simultaneous masking techniques revealed that 300-Hz curves were similar for all species, with peak masking occurring when the frequency of the masker equaled 300 Hz. In contrast, there were considerable interspecific differences in simultaneously masked 500-Hz curves. The 500-Hz curve for *Adioryx* was a broadly tuned, V-shaped function with peak masking occurring in the frequency region of the signal, whereas the curve for *Notopterus* was a sharply tuned, multi-peaked function with peak masking occurring for both 500- and 300-Hz maskers. Comparisons of tuning curves obtained with both forward and simultaneous masking techniques for *Notopterus* revealed little or no difference between 300-Hz curves, but substantial differences between the 500-. These results suggest that there are interspecific and frequency-dependent differences in the frequency selective processes of fish auditory systems.

Coombs, S., and A.N. Popper. 1982. Structure and function of the auditory system in the clown knifefish, *Notopterus chitala*. J. Exp. Biol. 97:225-239.

Coombs, S., and R.R. Fay. 1985. Adaptation effects on amplitude modulation detection: Behavioral and neurophysiological assessment in the goldfish auditory system. Hearing Research. 19:57-71.

The ability of goldfish to detect the presence of amplitude modulations (AM) impressed on 200, 570 and 800 Hz tones was measured under stimulus conditions producing intermittent, short-term adaptation and continuous, long-term adaptation. Sensitivity to AM under intermittent conditions increased as a function of modulation rate, with thresholds of AM detection occurring between 10 and 25% modulation at 10 Hz and around 2% modulation at 100 Hz. The results show that adaptation affects AM detection and that phase-locking to the AM envelope is the most likely basis for behavioral detection.

Corwin, J.T. 1981. Audition in elasmobranchs. In: Hearing and Sound Communication in Fishes. Tavolga, W.N., A.N. Popper, and R.R. Fay (eds). Springer, New York, pp 81-105.

Delco, E.A. Jr. 1960. Sound discrimination by males of two cyprinid fishes. Texas J. Sci. 1(2):48-53.

Denton, E.J., and J.A.B. Gray. 1982. The rigidity of fish and patterns of lateral line stimulation. Nature. 297:679-681.

Various functions have been attributed to the lateral line organs of fish, including those of detecting touch and sound and flow past a swimming fish. It is generally agreed that lateral line neuromasts are excited by liquid within the canal moving

relative to the canal walls. For the sprat, such movements are proportional to local differences in motion between the fish and the surrounding seawater. The authors describe the motions of fish and seawater at various positions around vibrating sources. It is shown that fish are rigid longitudinally. Local differential movements between fish and seawater occur. Predictions based on these results suggest that when a fish is close to a source of vibration, the amplitudes, signs and patterns of stimulation along the lateral line system change with the position of the fish relative to the source.

Dijkgraaf, S. 1962. The functioning and significance of the lateral line organs. *Biopl. Revs. Cambridge. Philos. Soc.* 38(5).

Enger, P.S. 1966. Acoustic threshold in goldfish and its relation to the sound source distance. *Comp. Biochem. Physiol.* 18(4):859-68.

Enger, P.S. 1967. Effect of the acoustic near field on the sound thresholds in fishes. In: *Lateral Line Detectors*, Cahn, P. (ed). Indiana University Press, p. 239-248.

Enger, P.S. 1976. Sound reception in teleost fishes in relation to the sound source distance. In: *Effects of Power Peaking on the Survival of Juvenile Fish at the Lower Columbia*. US Army Corps Eng. North Pac. Div. pp 247-252.

Enger, P.S. 1981. Frequency discrimination in teleosts-central or peripheral? In: *Hearing and Sound Communication in Fishes*. Tavolga, W.N., A.N. Popper, and R.R. Fay (eds). Springer, New York, pp 243-255.

Enger, P.S., and R. Andersen. 1967. An electrophysiological field study of hearing in fish. *Comp. Biochem. Physiol.* 22:517-25.

Facey, D.E., J.D. McCleave, and G.E. Doyon. 1977. Responses of Atlantic salmon parr to output of pulsed ultrasonic transmitters. *Trans. Am. Fish. Soc.* 106(5):489-496.

The output from some pulsed ultrasonic transmitters commonly used in fish movement studies is faintly audible to humans. This study was undertaken to determine if the output from these and some other transmitters is detectable by Atlantic salmon (*Salmo salar*) parr. Classical conditioning of cardiac deceleration was attempted using the transmitter's output as the conditioned stimulus. The results from 29 experimental and 14 control fish suggest that the parr were unable to detect the output from these transmitters.

Fay, R.F., and S. Coombs. 1983. Neural mechanisms in sound detection and temporal summation. *Hearing Research.* 10:69-92.

The psychophysics and neurophysiology of sound detection in quiet and under noise masking were studied in goldfish *Carassius auratus*. Psychophysical masking is a linear function of masker level. For long duration signals, signal-to-noise ratios (S/N) at threshold are 15.5, 19, and 22.5 dB for 200, 400 and 800 Hz signals, respectively, and is -5 dB for a noise signal. Threshold declines with signal duration to about 700 ms. The slopes of the masked temporal summation functions are about unity, indicating that energy is constant at threshold. In quiet however, the slopes are generally less than 0.5, indicating that shorter signals are detected at lower energy. Neural correlates of the masked S/Ns and the slopes of temporal summation functions were sought in the response patterns of single saccular neurons. Rate- and synchronization-intensity functions were obtained for tone and noise signals in quiet and in noise. S/Ns at behavioral threshold correspond closely to those required to raise spike rate just above that evoked by the masker alone, but are well above those required to cause clear synchronization. Therefore, sound detection is probably based on spike rate and not synchronization criteria.

Fay, R.R. 1970. Auditory frequency discrimination in the goldfish (*Carassius auratus*), *J. Comp. Physiol. Psych.* 73(2):175-80.

Fay, R.R. 1977. Sound detection and sensory coding by the auditory systems of fishes. In: *Fish Behavior*. pp 197-236.

Fay, R.R. 1982. Neural mechanisms of an auditory temporal discrimination by the goldfish. *J. Comp. Physiol.* 147:201-216.

The capacities of the goldfish (*Carassius auratus*) auditory system for encoding and processing periodic temporal patterns were characterized using behavioral and neurophysiological analyses. Animals were classically conditioned to detect changes in the rates (20 to 200 Hz) at which tonal and noise signals were amplitude-modulated, at a variety of modulation depths (3 to 100%). For the same stimulus set, the variability with which saccular neurons represent envelope periodicity in inter-spike-intervals was measured. The just discriminable change in envelope period (ΔP) is approximately equal to the variance which spikes in saccular neurons are phase-locked to modulation envelopes. The error made in detecting changes in modulation rate is highly correlated with the error with which inter-spike-intervals in saccular fibers represent envelope periodicity at a wide variety of modulation rates and depths. This is evidence that the goldfish estimates the duration of acoustic inter-pulse-intervals through information contained in neural inter-spike-intervals.

Fay, R.R. 1985. Sound intensity processing by the goldfish. *J. Acoust. Soc. Am.* 78(4):1296-1309.

Fay, R.R., and A.N. Popper. 1974. Acoustic stimulation of the ear of the goldfish (*Carassius auratus*). *J. Exp. Biol.* 61:243-260.

Fay, R.R., C.M. Hillery, and K. Bolan. 1982. Representation of sound pressure and particle motion information in the midbrain of the goldfish. *Comp. Biochem. Physiol.* 71A:181-191.

Averaged evoked responses from multiple electrodes in the goldfish midbrain (torus semicircularis) area were recorded in response to acoustic stimulation by loudspeaker and to direct vertical vibration of the head. Relative pressure and displacement sensitivity was such that in the far field, the response to sound pressure would dominate the response to particle motion by 40-90 dB. Swimbladder deflation caused a flat (70-1000 Hz) loss in pressure sensitivity ranging from 20 to over 50 dB, and led to an enhanced response to vibration at low frequencies. The goldfish midbrain is not homogeneous with regard to relative pressure and motion sensitivity.

Fish, M.P., A.S. Kelsey Jr., and W.H. Mowbray. 1952. Studies on the production of underwater sound by North Atlantic coastal fishes. *J. Mar. Res.* 11(2):180-193.

Frings, H., and M. Frings. 1966. Underwater sound fields and behavior of marine invertebrates. *Proc. Symp. Mar. Bio-Acoust.* 2:261-282.

Frisch, K. von. 1938. The sense of hearing in fish. *Nature.* 141:8-11.

Gerald, J.W. 1971. Sound production during courtship in six species of sunfish (Centrarchidae). *Evolution.* 25:75-87.

Guest, W.C. 1978. A note on courtship behavior and sound production of red drum. *Copeia.* 2:337-338.

Harris, G.G., and W.A. van Bergeijk. 1962. Evidence that the lateral-line organ responds to near-field displacements of sound sources in water. *J. Acoust. Soc. Am.* 34(12):1831-1841.

Hashimoto, T., and Y. Maniwa. 1966. Research on the luring of fish shoals by utilizing underwater acoustical equipment. *Tech. Rep Fish. Boat.* 20(3).

Hashimoto, T., and Y. Maniwa. 1966. Research on the luring of fish shoals by utilizing underwater acoustical equipment. *Proc. Symp. Mar. Bio-Acoust.* 2:93-104.

Hawkins, A.D. 1973. The sensitivity of fish to sounds. *Oceanogr. Mar. Biol. Ann. Rev.* 11:291-340.

Hawkins, A.D. 1981. The hearing abilities of fish. In: *Hearing and Sound Communication in Fishes.* Tavolga, W.N., A.N. Popper, and R.R. Fay (eds). Springer, New York, pp 109-137.

Methods of investigating the hearing abilities of fish are outlined and the hearing capacities of fish are discussed, considering audiograms, auditory masking, the relevant stimuli, hearing and sound duration and discrimination of sound quality.

Hawkins, A.D. 1986 Underwater sound and fish behavior. In: *The Behavior of Teleost Fishes*. Pitcher, T.J. (ed). pp 114-151.

Communication by means of sound appears to be widespread in fish, low-frequency calls being produced in a variety of social contexts including competitive and aggressive behavior and courtship. Fish are acutely sensitive to sounds, though their hearing abilities are confined to low frequencies. They are able to discriminate between sounds of different amplitude and frequency, and between calls that differ in their pulse patterning - an ability that seems to be particularly important in enabling them to distinguish their own calls from those of other species. Fish are also able to determine the direction and even the distance of a sound source.

Hawkins, A.D., and A.A. Myrberg Jr. 1983. Hearing and Sound Communication Underwater, pp 347-405. In: *Bioacoustics: A Comparative Approach*. Lewis, B. (ed) Academic Press, New York.

Hawkins, A.D., and A.D.F. Johnstone. 1978. The Hearing of Atlantic Salmon, *Salmo salar*. *J. Fish. Biol.* 13: 655-673.

Hawkins, A.D., and C.J. Chapman. 1975. Masked auditory thresholds in the cod, *Gadus morhua* L. *J. Comp. Physiol.* 103:209-226.

Hawkins, A.D., and D.N. MacLennan. 1976. An acoustic tank for acoustic studies on fish. In: *Sound Reception in Fish*. Schuijf, A., and A.D. Hawkins (eds). Elsevier, Amsterdam, pp 149-169.

Hawkins, A.D., and K. Horner. 1981. Directional characteristics of primary auditory neurons from the cod ear. In: *Hearing and Sound Communication in Fishes*. Tavolga, W.N., A.N. Popper, and R.R. Fay (eds). Springer, New York, pp 311-328.

Directional characteristics of single units from the ear of the cod (*Gadus morhua*) were examined. Units from the utriculus and sacculus were studied with the fish stimulated by vibration at different angles in the horizontal plane. Results show that the sacculus and utriculus both contain bi-directional units which might provide a basis for vector weighing. The utriculus and lagena, as well as the sacculus, may play a vital role in determining the direction of sounds.

Haymes, G.T., and P.H. Patrick. 1986. Exclusion of adult alewife, *Alosa pseudoharengus*, using low-frequency sound for application at water intakes. *Can. J. Fish. Aquat. Sci.* 43:855-862.

Experiments to test the effectiveness of low-frequency, high-intensity sound in excluding alewife, *Alosa pseudoharengus*, from an experimental net structure were conducted on Lake Ontario near Pickering, Ont. Sound was generated by modified seismic devices called pneumatic poppers. The number of alewife entering the experimental structure was reduced by 71-99% when the poppers were operating. Sonar evidence from one test suggested that another species which was not caught in the collection nets was less influenced by the acoustic deterrent. The results suggest that low-frequency, high-intensity sound may be effective in reducing losses of adult alewife at water intakes.

Horner, K., A.D. Hawkins, and P.J. Fraser. 1981. Frequency characteristics of primary auditory neurons from the ear of the cod, *Gadus morhua* L. In: *Hearing and Sound Communication in Fishes*. Fay, R.R. (ed). *Proc. Life Sci.* pp 223-241.

Hoss, D.E., and J.H.S. Blaxter. 1982. Development and function of the swimbladder-inner ear-lateral line system in the Atlantic menhaden, *Brevoortia tyrannus* (Latrobe). *J. Fish. Biol.* 20: 131-142.

The swimbladder-acoustico-lateralis system of the Atlantic menhaden, *Brevoortia tyrannus*, is described and compared with that of the Atlantic herring, *Clupea harengus*. The system develops in the larva at a much earlier stage than the herring,

being functional by about 2 mm TL. The volume of the gas-filled pro-otic bullae is five times that of the herring, and the gas ducts to the swimbladder, instead of being short and separate, are three times the length and join to form a common duct well in front of the swimbladder. The menhaden swimbladder is baggy and totally compliant when subjected to pressure changes. There is no toughened anterior end as in the herring, but the swimbladder is steeply angled in the body cavity, causing gas to collect at the anterior end after a pressure increase, unless the fish is diving very steeply.

Ishioka, H., Y. Hatakeyama, and S. Sakaguchi. 1988. The hearing ability of the red sea bream *Pagrus major*. Nipp. Suisan Gakkaishi. 54(6):947-951.

The auditory sensitivity of the red sea bream, *Pagrus major*, was determined by heart-beat conditioning using a sound coupled with a delayed electric shock. Sufficient care was taken in order to obtain a stable acoustic condition. Sound was projected from an air-speaker in a sound-proof chamber in which the experimental tank was placed on an air spring. The audible range of the red sea bream extended from 50 to 1000 Hz with a peak sensitivity of -14.2 dB (0 dB = 1 μ bar) at 200 Hz. On the basis of its responses to unconditioned sounds, it is suspected that the red sea bream is able to distinguish sound quality.

Ishioka, H., Y. Hatakeyama, and S. Sakaguchi. 1987. Development of the startle response to sound stimuli in the red sea bream, *Pagrus major*, Temminck and Schlegl. Bull. Nansei Reg. Fish. Res. Lab. 21:17-23.

The startle response of the red sea bream (*Pagrus major*) was examined in order to clarify the development of behavioral change upon application of audio-stimulation. Pre-larvae did not respond to the audio-stimuli even at the maximum amplitude attainable by apparatus. After metamorphosis from pre-larval to larval stage, however, the startle response appeared and was found to depend on the amplitude of the stimulus. The threshold was between 55 and 60 dB at the examined frequencies.

Ishioka, H., Y. Hatakeyama, S. Sakaguchi, and S. Yajima. 1986. The effect of sound stimulus on the behavioral disturbance of red sea bream, *Pagrus major*. Bull. Nansei Reg. Fish. Res. Lab. No. 20:59-71.

The behavioral changes of the young red sea bream (*Pagrus major*) were examined experimentally in a tank to clarify the effect of sound stimulus on the fish. Sound stimuli applied were pure tones which were generated electrically, and projected from an underwater speaker set in the tank. Sound pressures ranged from 40 to 70 dB. The fish responses were obtained by eye observation and by feeding activity recorded electrically. The rate of the occurrence of fish threatened increased with increasing sound pressure and the response was most sensitive at 200 Hz. Feeding activity was also disturbed at higher sound pressure and at the frequency of 200 Hz. However, the response was not so sensitive as behavior disturbance. Duration of sound projection had little effect on the behavioral disturbance.

Iversen, R.T.B. 1966. Response of yellowfin tuna (*Thunnus albacares*) to underwater sound. In: Marine Bioacoustics, W.N. Tavolga (ed.). Proc Second Symp. Mar. Bio-Acoust., Vol. 2, pp 105-121

Iversen, R.T.B. 1976. Auditory thresholds of scombrid fish *Euthynnus affinis*, with comments on the use of sound in tuna fishing. In: Effects of Power Peaking on the Survival of Juvenile Fish at the Lower Columbia. US Army Corps Eng. N. Pac. Div. pp 849-859.

Jacobs, D.W., and W.N. Tavolga. 1967. Acoustic intensity limens in the goldfish. Anim. Behav. 15:324-335.

Kleerekoper, H. 1955. Threshold curves for hearing in four species of cyprinidae. Anat. Rec. 122:460.

Konagaya, T. 1980. Jumping response of ayu to sound. Bull. Japan. Soc. Sci. Fish. 46(1):31-34.

While ascending streams from the sea to the upper river, the fry of ayu (*Plecoglossus altivelis*) has a strong anadromous character and shows jumping response not only to water falls but also to underwater sound. Generally, the auditory sensitivity of fish has been studied with electrophysiological or psychophysical experiments. It may also be possible to study it by the behavioral observation of the jumping response of the fish to underwater sound. From these observations,

the following results were obtained: (1) The most sensitive frequency of the fish to underwater sound was about 200 Hz. However, the sensitivity of the fish was not clear above 600 Hz. (2) The lowest threshold level of underwater sound for jumping response was 72 dB (re 1 μ Pa) at a frequency of 200 Hz. (3) The numbers of fish responding to the sound pressure were distributed following a normal curve in the range of 70 to 80 dB (re 1 μ Pa).

Kuiper, J.W. 1967. Frequency characteristics and functional significance of the lateral line organ. In: Lateral Line Detectors, Cahn, P. (ed). Indiana University Press, p. 105-121.

Ladich, F. 1988. Sound production by the gudgeon, *Gobio gobio* L., a common European freshwater fish (Cyprinidae, Teleostei). J. Fish Bio. 32(5):707-715.

Acoustic signals emitted by the gudgeon (*Gobio gobio*) are described and the context of sound production is considered. In aquaria, gudgeons produce creaking sounds of differing duration, which are always built up of single bursts. Each burst is composed of a series of rapidly repeated short pulses. Vocalization is correlated with the level of activity: it increases at higher temperatures and decreases when fish are disturbed. After acclimatization to the aquarium, fish which formerly showed a diurnal pattern of activity became active at all times of the day and night. Gudgeon called as a reaction to digging by other members of the group and a variety of disturbances.

Laming, P.R., and G. Morrow. 1981. The contribution of the swimbladder to audition in the roach, (*Rutilus rutilus*). Comp. Biochem. Physiol. 69(A):537-541.

The averaged auditory evoked response of roach, (*Rutilus rutilus*) was monitored, in the acoustico-lateralis region of the medulla, in response to sounds of frequencies of between 60 and 1000 Hz. When the fish was held in air, the responses were greater than when held in water. Deflation of the swimbladder reduced the magnitude of the evoked response, an effect reversed by reinflation. Hyperinflation also reduced the response, especially to sounds of low frequency. It is suggested that the swimbladder of fish of this species is normally in the optimum condition for sound reception and it is the swimbladder wall which acts as the primary resonator, not the gas column within it.

Laming, P.R., and M. Brooks. 1985. Effects of visual, chemical and tactile stimuli on the averaged auditory response of the teleost *Rutilus rutilus*. Comp. Biochem. Physiol. 82A(3):667-673.

The averaged evoked responses of the medullary and anterior tectal surfaces of roach (*Rutilus rutilus*) were recorded to 64 "click" stimuli. The medullary response of five peaks and the single tectal peak showed no change in latency or duration when non-auditory stimuli were presented. The medullary response amplitude was increased by presenting a moving shadow or dilute chemical solutions to skin or nares, yet reduced by water similarly applied, vibration or a flashing light. Tectal response amplitudes increased with the presentation of a moving shadow, flashing light or chemical solutions. The adaptive functions of cross-modality inhibition and facilitation were discussed.

Laming, P.R., and P. Ennis. 1982. Habituation of fright and arousal responses in the teleosts *Carassius auratus* and *Rutilus rutilus*. J. Comp. Physiol. Psychol. 96(3):460-466.

The habituation of fright and arousal responses of goldfish (*Carassius auratus*) and roach (*Rutilus rutilus*) to the repeated operation of a plunger in the water was studied. The early response was of fright, which habituated, and the response characteristic of arousal appeared, which then habituated as well. Longer intervals between stimuli required more presentations of the stimulus for habituation to occur in goldfish. Roach required more presentations of the stimulus than goldfish for the responses to habituate, and telencephalic ablation severely impaired habituation of arousal, though not fright responses, in this species. The results are discussed in relation to recent work on arousal, habituation, and telencephalic function in fish.

Laming, P.R., and S.O.E. Ebbesson. 1984. Arousal and fright responses and their habituation in the slippery dick, *Halichoeres bivittatus*. Experientia. 40(1984):767-769.

Behavioral arousal and fright and their physiological correlates have been extensively studied in domesticated cyprinids. In these fish arousal is associated with slight changes in orientation or an increase in stabilizing movements. Novel stimuli may elicit arousal or the more violent response of fright. This escape response consists in cyprinids of a rapid lateral flexion of the tail or tail-flip. Both arousal and fright habituate in cyprinids, and if the initial responses are of fright then these habituate to be replaced by arousal, which itself habituates. *Halichoeres bivittatus* is a diandric protogynous hermaphrodite, its reproductive biology has been extensively studied. The labrids are extremely active and alert fish and

this makes them ideal subjects for testing the generality of descriptions of behavioral arousal and fright, and the motor components of these responses.

Leaton, R.N., and W.F. Supple, Jr. 1986. Cerebellar vermis: essential for long term habituation of the acoustic startle response. *Science*. 232:513-515.

The acoustic startle response in rats shows both short-term habituation, which recovers in seconds or minutes, and long-term habituation, which is effectively permanent. Lesions of the cerebellar vermis significantly attenuated long-term habituation without affecting the short-term process or altering initial response levels. In this response system the cerebellar vermis is part of an essential circuit for long-term habituation.

Loeffelman, P.H. 1990. Aquatic animal guidance using a new tuning process and sound system. Environmental and Technical Assessment Div. American Electric Power Service Corp. 1 Riverside Plaza, Columbus, OH 43215. 60 pp.

Lowenstein, O. 1967. The concept of the acoustico-lateral system. In: *Lateral Line Detectors*, Cahn, P. (ed). Indiana University Press, p. 3-12.

Miyagawa, M., and A. Takemura. 1986. Acoustical behavior of the scorpaenoid fish, *Sebasticus marmoratus*. *Bull. Japan. Soc. Sci. Fish.* 52(3):411-415.

Calls of the scorpaenoids fish, *Sebasticus marmoratus*, were classified into single knock sound and a train of knock sounds each of which lasts for about 100-160 msec followed by a silent period of 200-500 msec. Each knock sound was made of a frequency component of less than 1 kHz. The fish emitted vigorous calls for about one or two h at dawn and dusk. Little remarkable seasonal variation in the occurrence of the sounds emitted was observed. The calls which were used mainly to threaten away invaders, were made by a contraction and relaxation of the sonic muscle, and amplified by the swim-bladder. The peak frequency of a call was decided mainly by the cycle of contraction and relaxation of the sonic muscle and secondly by the length of the swim-bladder.

Mohr, H. 1969. Detection of fish and observation of fish behavior by echo analysis and passive listening. *FAO Fish. Report*. 62(2):101-113.

Montgomery, J.C., and J.A. MacDonald. 1987. Sensory tuning of lateral line receptors in antarctic fish to the movements of planktonic prey. *Science*. 235(Jan):195-196.

The suitability of the lateral line system of fish and aquatic amphibia for the detection of planktonic prey was examined in the Antarctic fish *Pagothenia borchgrevinki* (family Nototheniidae). The best response of primary afferent lateral line neurons to waterborne vibrations were recorded at frequencies within the range of those produced by swimming crustacea. Simultaneous recordings from a swimming zooplankter held close to the fish and from primary afferent neurons provided direct confirmation that swimming movements of crustaceans are a potent natural stimulus of the lateral line system.

Moore, H. L., and H. W. Newman. 1956. Effects of sound waves on young salmon. *U.S. Fish Wildlife Serv. Spec. Sci. Report*: 172. 19 pp.

Moorehouse, V.H.K. 1932. Do fish react to noise? *Biol. Bd. Can. Prog. Rep.* 13 *Pac. Biol. Stat.* pp 14-15.

Moulton, J.M. 1956. The movements of menhaden and butterfish in a sound field. *Anat. Rec.* 125:592.

Moulton, J.M. 1963. Acoustic behavior of fishes. In: *Acoustic Behavior of Animals*. Busnel, R.G. (ed). Elsevier, Amsterdam, pp 655-693.

Mozgovoy, V.A. 1986. Determining the parameters of fish in sound-scattering layers and their behavior during migration based on scattered acoustic signal spectra. *Oceanology*. 26(5):567-574.

The authors propose a method for determining the resonance frequencies of sound-scattering layer (SSL) fish swimbladders based on the ratio of the acoustic signal spectrum scattered by the sound-scattering layer to the sounding signal spectrum. Results are given for an experiment undertaken in the northeastern Tropical Pacific Ocean. Resonance frequencies for SSL fish swimbladders have been determined, the volume of the fish swimbladders has been calculated, fish lengths and concentration have been estimated, and three size groups of resonant scatterers have been distinguished. A decrease in the scatterer resonant frequency was recorded just before the morning descent of the SSR, apparently caused by the fish "pumping" their swimbladders. One group of fish migrated in the "constant volume" regime and another in the "constant mass" regime.

Myrberg, A.A. Jr. 1972. Using Sound to Influence the Behavior of Free-Ranging Marine Animals, pp 435-468. In J.E. Winn and B.L. Olla (eds.) Behavior of Marine Animals, vol. 2. Plenum, New York.

Myrberg, A.A. Jr. 1978. Underwater sound - Its effect on the behavior of sharks. In: Sensory Biology of Sharks, Skates, and Rays. E.S. Hodgson and R.F. Mathewson, eds. pp 391-417.

Myrberg, A.A. Jr. 1981. Sound communication and interception in fishes. In: Hearing and Sound Communication in Fishes. Tavolga, W.N., A.N. Popper, and R.R. Fay (eds). Springer, New York, pp 395-426.

Following a definition of communication, a framework is presented upon which analyses of communication could develop in the future. Application of the framework to sound communication in fish is discussed, considering signalling predators, signalling prey, signalling prospective mates, signalling companions and signalling competitors; application to sound interception is also discussed.

Myrberg, A.A. Jr., A. Banner, and J.D. Richard. 1969. Shark attraction using a video-acoustic system. Mar. Biol. 2(264):264-276.

Myrberg, A.A. Jr., and R.J. Riggio. 1985. Acoustically mediated individual recognition by a coral reef fish (*Pomacentrus partitus*). Anim. Behav. 33:411-416.

Acoustically mediated individual recognition has been demonstrated in the field by males of the bicolor damselfish *Pomacentrus partitus* Poey. Playbacks of non-resident sounds from a given fish's territory elicited a greater response from its nearest neighbour than playbacks of the resident's sound - in accordance with the predictions of the "dear-enemy" effect. Testing also included switching the sounds of the two nearest neighbors relative to each respective male's territory. Results demonstrated that all males in the colony individually recognized the sounds of their two nearest neighbors.

Myrberg, A.A. Jr., M. Mohler, and J.D. Catala. 1986. Sound production by males of a coral reef fish (*Pomacentrus partitus*): Its significance to females. Anim. Behav. 34:913-923.

Field evidence has demonstrated that free-ranging females of the bicolor damselfish, *Pomacentrus partitus*, use the courtship sounds of conspecific males to locate male nest sites during the spawning period. Evidence is also provided that females can distinguish, not only between such sounds and similar sounds on the reef, but also between courtship sounds of different conspecific males, the latter indicating a role in mate assessment by the acoustical modality.

Nakazato, M., and A. Takemura. 1987. Acoustical behavior of Japanese parrot fish, *Oplegnathus fasciatus*. Bull. Jap. Soc. Sci. Fish. 53(6):967-973.

The calls of the Japanese parrot fish, *Oplegnathus fasciatus* consist of a pulse or a series of pulse sounds. The calls were divided into three patterns by the method of pulse sound projection, namely single popped call, complex popped call and repeated popped call. Each pulse sound was made of a frequency component from less than 30 Hz to about 1 kHz. The duration of the pulse sound was usually 13-20 msec. In the complex popped call, the interval between each pulse sound was 11-367 msec. In the repeated pulse call, the repetition rate of each pulse sound was from 0.5 to 1.4 per second. The frequency of sound emitting became high before and after sunrise and sunset. Vigorous calls were emitted during the spawning period. The calls, which are mainly used for threatening invaders, are made by the rapid movement of the operculum and amplified by the swim-bladder.

- Nelson, D.R. 1965. Hearing and the acoustic orientation in the lemon shark, *Negaprion brevirostris* (Poey), and other large sharks. Diss. Abstracts. Zoology. 333-B.
- Nelson, D.R., and R.H. Johnson. 1972. Acoustic attraction of Pacific reef sharks: Effect of pulse intermittency and variability. *Comp. Biochem. Physiol.* 42(A):85-95.
- Nelson, D.R., and R.H. Johnson, and L.G. Waldrop. 1969. Responses in Bahamian sharks and groupers to low-frequency, pulsed sounds. *Bull. So. Calif. Acad. Sci.* 68(3):131-137.
- Nelson, D.R., and S.H. Gruber. 1963. Sharks: Attraction to low-frequency sounds. *Science.* 142:975-977.
- Nelson, D.R., R.H. Johnson, and L.G. Waldrop. 1969. Responses in Bahamian sharks and groupers to low-frequency, pulsed sounds. *Bull. So. Calif. Acad. Sci.* 68(3):131-137.
- Neproshin, A. Y., and N.I. Kulikova. 1975. Sound-producing organs in salmonids. *J. Ichthyol.* 15:481-485.
- Nomura, M. 1980. Influence of fish behavior on use and design of setnets. In: *Fish Behavior and Its Use in the Capture and Culture of Fishes.* Bardach, J.E., J.J. Magnuson, R.C. May, and J.M. Reinhart (eds). pp 446-471.
- Okonski, S. 1976. Echo sounding observations of fish behavior in the proximity of the trawl. In: *Effects of Power Peaking on the Survival of Juvenile Fish at the Lower Columbia.* US Army Corps Eng. North Pac. Div. pp 377-407.
- Olsen, K. 1971. Influence of vessel noise on behavior of herring. In: *Modern Fishing Gear of the World #3.* Kristjonsson, ed. Fishing News Ltd. London. 1971. pp 291-294.
- Olsen, K. 1976. A comparison of acoustic threshold in cod with recordings of ship-noise. In: *Effects of Power Peaking on the Survival of Juvenile Fish at the Lower Columbia.* US Army Corps Eng. North Pac. Div. pp 431-451.
- Olsen, K. 1979. Observed avoidance behavior in herring in relation to passage of an echo survey vessel. *Internat. Coun. Explor. Sea. C.M.* 1979/B: 18. *Fish. Tech. Comm.* 21 pp.
- Ona, E., and R. Toresen. 1988. Reactions of herring to trawling noise. *Internat. Coun. Explor. Sea. Fish Cap. Comm. C.M.* 1988/B:36 Session P. 8 pp.
- Parker, G.H. 1903. The sense of hearing in fishes. *Am. Nat.* 37(435):185-204.
- Platt, C., and A.N. Popper. 1981. Otolith organ receptor morphology in herring-like fishes. In: *The Vestibular System: Function and Morphology.* Gualtierotti, T. (ed). Springer, New York. pp 64-76.
- Platt, C., and A.N. Popper. 1981. Fine structure and function of the ear. In: *Hearing and Sound Communication in Fishes.* Tavolga, W.N., A.N. Popper, and R.R. Fay (eds). Springer, New York, pp 3-71.
- Popper, A.N., and R.G. Northcutt. 1983. Structure and innervation of the inner ear of the bowfin, *Amia calva.* *J. Comp. Neurol.* 213:279-286.

Popper, A.N., and R.R. Fay. 1984. Sound detection and processing by teleost fish: A selective review. In: *Comparative Physiology of Sensory Systems*. Crans-sur-Sierre, Switzerland. pp 67-102.

The authors provide a general outline of what is known about hearing in fishes, and to identify what they consider to be some of the most interesting and pressing questions that could occupy their research efforts for the next several years. While it is tempting to form generalizations concerning fish audition, it is likely that there is no such thing as "the" fish ear or hearing capabilities in "the" fish. Furthermore, it is now not even clear that individual otolith organs have the single roles ascribed to them in the earlier literature.

Popper, A.N., and S. Coombs. 1980. Auditory mechanisms in teleost fishes. *Am. Scient.* 68:429-440.

Popper, A.N., and S. Coombs. 1982. The morphology and evolution of the ear in actinopterygian fishes. *Amer. Zool.* 22: 311-328.

This paper considers various aspects of the anatomy and ultrastructure of the actinopterygian ear and makes a number of suggestions on the possible adaptive significance of the structural specializations. The focus of the arguments is based upon the substantial inter-specific variation in teleost auditory systems as measured anatomically, behaviorally, and physiologically. It is potentially of considerable significance that the major points of inter-specific variation in the teleost ear are associated with the gross morphology and ultrastructure of the otolithic organ most often implicated in sound detection, the sacculus.

Richard, J.D. 1968. Fish attraction with pulsed low frequency sound. *J. Fish. Res. Bd. Can.* 25(7):1441-1452.

Rogers, P.H., A.N. Popper, M.C. Hastings, and W.M. Saidel. 1988. Processing of acoustic signals in the auditory system of bony fish. *J. Acoust. Soc. Am.* 83(1):338-349.

In order to determine unambiguously the bearing of a sound source, a fish must be able to resolve acoustic pressure and the components of the acoustic displacement vector from the signals detected by the otolithic organs. A new hypothesis for the processing of acoustical information by bony fish is presented. It is demonstrated that much of the processing required to do this may be implicit in the structure of the ear and its associated neural innervation.

Saidel, W.M., and A.N. Popper. 1983. The saccule may be the transducer for directional hearing of nonostariophysine teleosts. *Exp. Brain Res.* 50:149-152.

Saidel, W.M., and A.N. Popper. 1987. Sound reception in two anabantid fishes. *Comp. Biochem. Physiol.* 88A(1):37-44.

Sand, O. 1974. Directional sensitivity of microphonic potentials from the perch ear. *J. Exp. Biol.* 60:881-989.

Sand, O. 1981. The lateral line and sound reception. In: *Hearing and sound communication in fishes*, 459-480. Proc, Life. Sci. Springer-Verlog, New York, N.Y.

A review is presented of experiments investigating the functions of the lateral line in fish. Sensitivity to local water movements, surface waves and low frequency sound is considered. Results confirm electrophysiological data showing the trunk lateral line to be an extremely sensitive vibration detector.

Sand, O. 1981. The lateral line and sound reception. In: *Hearing and sound communication in fishes*, 459-480. Proc, Life. Sci. Springer-Verlog, New York, N.Y.

Sand, O., and A.D. Hawkins. 1973. Acoustic properties of the cod swimbladder. *J. Exp. Biol.* 58:797-820.

Sand, O., and P.S. Enger. 1973. Evidence for an auditory function of the swimbladder in the cod. *J. Exp. Biol.* 59:405-414.

Schneider, H. 1967. Morphology and physiology of sound-producing mechanisms in teleost fishes. In: *Marine Bioacoustics, Vol 2. ??????* (ed). Pergamon Press. pp 135-58.

Schuijf, A. 1981. Models of acoustic localization. In: *Hearing and Sound Communication in Fishes.* Tavolga, W.N., A.N. Popper, and R.R. Fay (eds). Springer, New York, pp 267-310.

In order to construct models of fish acoustic localization systems the principle is used that the mechanism for acoustic localization must be adapted to take advantage of the modes of wave propagation in the fish's environment. Before examining models of wave propagation in the environment of the fish, a summary of the important concepts and results of the model building is presented. How the sound reaches the fish in the habitat and subsequently how the external sound variables relate to the internal vibratory quantities that activate the hair cells are considered.

Schuijf, A., and A.D. Hawkins. 1983. Acoustic distance discrimination by the cod. *Nature, London.* 302:143-4.

Schuijf, A., and R.J.A. Buwalda. 1980. Under-water localization - a major problem in fish acoustics. In: *Comparative Studies of Hearing in Vertebrates.* Popper, A.N., and R.R. Fay (eds). Springer-Verlag, New York, pp 43-77.

Schwarz, A.L., and G.L. Greer. 1984. Responses of Pacific herring, *Clupea harengus pallasii*, to some underwater sounds. *Can. J. Fish. Aquat. Sci.* 41:1183-1192.

The authors describe the behavioral responses of net-penned Pacific herring (*Clupea harengus pallasii*) to a variety of tape-recorded sounds. Sounds recorded in the field from a herring fishing fleet included moving and stationary (idling) vessels, sonar, echo sounder, and deck gear. Natural sounds included rain on the water surface, gull (*Larus spp.*) cries, killer whale (*Orcinus orca*) vocalizations, barks of Steller's sea lions (*Eumetopias jubatus*), and sounds made by herring themselves. Sounds of more uniform structure were created with an electronic synthesizer and played back to herring to determine the relative effectiveness of various combinations (triads) of amplitude and frequency (increasing, decreasing, constant) and temporal pattern (continuous, regularly, or irregularly pulsed tones).

Sewell, W.F., and E.A. Mroz. 1987. Neuroactive substances in inner ear extracts. *J. Neurosci.* 7(8):2465-2475.

To identify the neurotransmitter released by sensory hair cells, as well as to find other substances that might influence neural function of the inner ear, the authors have prepared extracts from inner ears of fishes (which have large numbers of hair cells), fractionated the extracts, and studied the effects of the fractionated extracts on the discharge rate of afferent fibers innervating hair cells in the lateral line organ of the African clawed frog *Xenopus laevis*. The extracts contain active substances. Some extracts also contain a high-molecular-weight inhibitory substance.

Stober, Q.T. 1969. Underwater noise spectra, fish sounds and response to low frequencies of cutthroat trout (*Salmo clarki*) with reference to orientation and homing in Yellowstone Lake. *Trans. Am. Fish. Soc.* 4:652-663.

Strelioff, D., and W.G. Sokolich. 1981. Stimulation of lateral-line sensory cells. In: *Hearing and Sound Communication in Fishes.* Tavolga, W.N., A.N. Popper, and R.R. Fay (eds). Springer, New York, pp 481-522.

Sweeney, T.K., E.A. Mroz, and W.F. Sewell. 1987. Isolation and culture of auditory cells from the goldfish (*Carassius auratus*). *Hearing Research.* 28:153-160.

Tateda, Y., A. Nakazono, and H. Tsukahara. 1985. Acoustic conditioning of young red sea bream. *Rpt. Fish. Res. Lab., Kyushu Univ.* 7:27-36.

- Tavolga, W.N. 1971. Sound production and detection. In: Fish Physiology, V. Hoar, W.S., and D.J. Randall (eds). pp 135-205.
- Tavolga, W.N. 1980. Hearing and Sound Production in Fishes in Relation to Fisheries Management, pp 102-123. In: Fish Behavior and It's Use in the Capture and Culture of Fishes. J.E. Bardach, J.J. Magnuson, R.C. May and J.M. Reinhart (eds).
- Tavolga, W.N. 1981. Retrospect and prospect-listening through a wet filter. In: Hearing and Sound Communication in Fishes. Tavolga, W.N., A.N. Popper, and R.R. Fay (eds). Springer, New York, pp 573-588.
- Tavolga, W.N., and J. Wodinsky. 1963. Auditory capacities in fishes: Pure tone thresholds in nine species of marine teleosts. Bull. Am. Mus. Nat. Hist. 126(2):179-239.
- VanDerwalker, J.G. 1964. Studies of the response of fish to low frequency vibrations. Proc. Fish-Passage Res. Program. Rev. Prog. U.S. Bur. Comm. Fish. Seattle, WA., 3(26):1-8
- VanDerwalker, J.G. 1967. Response of salmonids to low frequency sound. In: Marine Bio-acoustics, Vol. II. Tavolga, W.N. (ed). Pergamon Press, Oxford. pp 45-58.
- Wardle, C.S. 1983. Fish reactions to Towed fishing gears. In: Experimental Biology at Sea. A. Macdonald and I. G. Priede (eds). Academic Press, New York, pp 167-195.
- Weissert, R., and C. von Campenhausen. 1981. Discrimination between stationary objects by the blind cave fish, *Anopichthys jordani* (Characidae). J. Comp. Physiol. 143:375-381.
- Blind Mexican cave fish were trained to discriminate between grids of vertical bars placed at various distances from each other. Discrimination was possible only if the freely swimming fish was allowed to glide past the grids in close proximity.
- Westerfield, F. 1921. The ability of mudminnows to form associations with sounds. J. Comp. Psychol. 2:187-190.
- Winn, H.E., and J.F. Stout. 1960. Sound production by the satinfin shiner, *Notropis analostanus*, and related fishes. Science. 231:222-223.
- Wisby, W.J., J.D. Richard, D.R. Nelson, and S.H. Gruber. 1964. Sound perception in elasmobranchs, In: Marine Bio-acoustics. Tavolga, W.N. (ed). Pergamon Press, New York. pp 255-268.
- Yuzhen, C., C. Ruoqi, W. Faji, and H. Desheng. 1981. An electrophysiological study on the hearing power of perch, *Lateolabrax japonicus*. Mar. Fish. Res. 2:70-76.

TEMPERATURE

- Anonymous. 1960. Experimental studies on the survival of the early stages of chinook salmon after varying exposures to upper lethal temperatures. Prog. Rep. Fish. Eng. Res. Prog. N. Pac. Div. U.S. Army Corps Eng. Washington Dept. Fish. July. 7 pp.
- Bernatchez, L., and J.J. Dodson. 1985. Influence of temperature and current speed on the swimming capacity of lake whitefish (*Coregonus clupeaformis*) and cisco (*C. artedii*). Can. J. Fish. Aquat. Sci. 42:1522-1529.

The authors tested the influence of temperature and water velocity on metabolic rate and swimming performance of lake whitefish (*Coregonus clupeaformis*) and cisco (*C. artedii*) using respirometry techniques. Tests were conducted at 5, 12, and 17°C (speed range 20-102 cm * s⁻¹) for lake whitefish and at 12°C (speed range 20-63 cm * s⁻¹) for cisco. The net aerobic cost of swimming, obtained by subtracting standard from total oxygen consumption, was twice as high for cisco as that for lake whitefish at any swimming speed. However, the standard metabolic rate of lake whitefish was almost the double that of cisco acclimated to the same temperature. Results support the hypothesis that the combined effect of high water velocities and low ambient temperature on coregonines' metabolism and swimming performance may be a more important factor than specific spawning temperature in the timing of the early reproductive migration of anadromous coregonines.

Black, E.C. 1953. Upper lethal temperatures of some British Columbia freshwater fishes. J. Fish. Res. Bd. Can. 10(4):196-209.

Brett, J.R. 1946. Rate of gain of heat-tolerance in goldfish (*Carassius auratus*). Pub. Ont. Fish. Res. Lab. 64:9-28.

Brett, J.R. 1952. Temperature tolerance in young Pacific salmon, genus *Oncorhynchus*. J. Fish. Res. Bd. Can. 9(6):265-323.

Brett, J.R. 1970. Temperature: Animals: Fishes. In: Marine Ecology. O. Winne (ed). pp 515-560.

Brett, J.R., W.C. Clarke, and J.E. Shelbourn. 1982. Experiments on thermal requirements for growth and food conversion efficiency of juvenile chinook salmon, *Oncorhynchus tshawytscha*. Can. Tech. Report Fish. Aquat. Sci. 1127:33 pp.

Feeding and growth experiments on Nechako River and Big Qualicum River Chinook juveniles were conducted for 28 days at temperatures from 16°C to 24°C (Nechako) and 14°C to 25°C (Big Qualicum). On maximum daily ration, optimum temperature for growth was approximately 19°C, above which feeding and growth decreased particularly above 22°C. Mortalities reached 64% at 25°C, in agreement with earlier studies on lethal temperatures. In comparison with Qualicum chinooks, Nechako juveniles had a lower growth rate and food conversion efficiency at all but the highest temperatures.

Brett, J.R., M. Hollands, and D.F. Alderdice. 1958. The effect of temperature on the cruising speed of young sockeye and coho salmon. J. Fish. Res. Bd. Can. 15(4):587-605.

Elliott, J.M. 1981. Some aspects of thermal stress on freshwater teleosts. In: Stress and Fish. Pickering, A.D. (ed). Academic Press. pp 209-45.

Fry, F.E.J., and J.S. Hart. 1948. Cruising speed of goldfish in relation to water temperature. J. Fish. Res. Bd. Can. 7(4):169-175.

Fry, F.E.J. 1967. Responses of vertebrate poikilotherms to temperature. In: Rose, A.H. (ed). Thermobiology. academic press, London. pp 375-409.

Fuiman, L.A. 1986. Burst-swimming performance of larval zebra danios and the effects of diel temperature fluctuations. Trans. Am. Fish. Soc. 115:143-148.

Zebra danios *Danio (Brachydanio rerio)* were spawned and their eggs and larvae were reared in a simulated natural thermal regime, increasing from 21 to 30°C for 7 h and decreasing to 21°C for 17 h, daily. Burst-swimming performance was provoked by electrical stimulation of larvae. Distance travelled in a specified time (S_t), maximum velocity, and maximum acceleration increased with temperature. Size-specific maximum velocity was considerably higher than previously reported for larvae. A predictive model relating S_t to temperature was developed.

Gibson, R.J. 1978. The behavior of juvenile Atlantic salmon (*Salmo salar*) and brook trout (*Salvelinus fontinalis*) with regard to temperature and to water velocity. Trans. Am. Fish. Soc. 107(5):703-712.

Atlantic salmon parr and brook trout were observed in stream tanks at the Matamek Research Station, Quebec. In the autumn, at 10°C Atlantic salmon parr began sheltering in rubble, and at 9°C the majority had disappeared into hiding.

Brook trout also had this tendency to hide at cold temperatures, but not as strongly as the salmon. In slow water flows (<5 cm/s), Atlantic salmon parr tended to hide in the rubble substrate at any temperature, and aggression decreased. In both slow and faster water velocities during summer and autumn the commonest agonistic act by Atlantic salmon parr was 'charge and chase.' Brook trout in July showed 'nip' as the commonest agonistic act, but in September and October 'approach' and 'charge and chase' were more common, possibly due to aggression associated with spawning. Shade was attractive to both species in shallow water, but given the choice of a shallow (30 cm) tank with a shade cover, and a deeper (50 cm) tank with no shade, the majority of brook trout and Atlantic salmon selected the deeper tank. In one experiment in a shallow-water tank, turbulent water surface was more attractive to Atlantic salmon parr than shade.

Gregory, M.A., and P.D.A. Anderson. 1984. modified electronic shuttlebox for joint thermoregulatory and toxicological studies. *Can. J. Zool.* 62(10):1950-1953.

This paper presents a modified electronic shuttlebox for studies of behavioral thermoregulation in fish. The apparatus incorporates continual water replacement, the water temperature being controlled by the fish. Such a design facilitates long-term studies, with or without a chemical agent. Additionally, the absence of a temperature gradient permits strict response-conditioning experimentation. Fingerling rainbow trout (*Salmo gairdneri*) maintained a mean temperature of $18.1 \pm 0.6^\circ\text{C}$, thermoregulating with a degree of regularity and precision similar to the findings of other workers using different devices. Fish have been able to successfully thermoregulate in this apparatus for periods of up to 6 weeks.

Griffiths, J.S., and D.F. Alderdice. 1972. Effects of acclimation and acute temperature experience on the swimming speed of juvenile coho salmon. *J. Fish. Res. Bd. Can.* 29:251-264.

Hanyu, I., and M.A. Ali. 1964. Electroretinogram and its flicker fusion frequency at different temperatures in light-adapted salmon (*Salmo salar*). *J. Cell Comp. Physiol.* 63(3):309-322.

Heming, T.A., and J.E. McInerney. 1982. Effect of temperature on initial feeding in alevins of chinook salmon (*Oncorhynchus tshawytscha*). *Can. J. Fish. Aquat. Sci.* 39:1554-1562.

Growth and survival of chinook salmon (*O. tshawytscha*) during the transition to active feeding were examined in relation to the timing of initial food presentation at 6, 8, 10 and 12°C . The transition to active feeding in these salmon involved a period of "precocious feeding" during which ingestion of food had no effect on fish size, growth rate, or survival. Initial utilization of food for growth and survival did not coincide with any specific stage of development, but rather it occurred earlier and at a less mature stage of development at higher temperatures. Delays in initial food presentation beyond this point reduced fish size and survival. Temperature and the timing of initial food presentation interacted to create a zone of optimum feeding. Biomass production was maximized when alevins began to feed within this zone, independent of the precise time of initial food presentation or temperature. This optimum feeding zone existed at temperatures below 12°C , between 905 thermal units (TU) postfertilization and a point (F, TU) which varied with temperature (T, $^\circ\text{C}$) as $F = 1201.1 - 20.3 T$.

Holtby, L.B. 1988. Effects of logging on stream temperatures in Carnation Creek, British Columbia, and associated impacts on the coho salmon (*Oncorhynchus kisutch*). *Can. J. Fish. Aquat. Sci.* 45(3):502-515.

Clear-cut logging of 41% of the basin of Carnation Creek, British Columbia, resulted in increased stream temperatures in all months of the year. Increases above prelogging temperatures ranged from 0.7°C in December to 3.2°C in August. Earlier emergence of coho salmon (*Oncorhynchus kisutch*) fry associated with temperature increases lengthened their summer growing season by up to 6 wk. Fingerlings were significantly larger by the fall in the years after logging compared with the years before logging. The increased size of fingerlings was associated with improved overwinter survival. Following logging, yearling smolt number doubled, although 2-yr-old smolt number decreased. The life history model is used to quantify the effect of stream temperature changes related to logging on the population size of adult coho salmon. The predicted effect of those temperature changes was a 9% increase in adult coho numbers prior to the fishery.

Jonsson, B., and J. Ruud-Hansen. 1985. Water temperature as the primary influence on timing of seaward migrations of Atlantic salmon (*Salmo salar*) smolts. *Can. J. Fish. Aquat. Sci.* 42:593-595.

Using multiple regression models, the authors tested water temperature, water flow, cloudiness, and lunar cycle for significant correlation with the timing of the yearly descent of Atlantic salmon (*Salmo salar*) smolts in the Norwegian Insa River, 1976-1983. Water temperature between 9 April and 16 May explained 91, 95, and 89% of the yearly variation in date of 25, 50, and 75% cumulative smolt descent, respectively. The regression models were not very sensitive to variations of

the date of the start or stop of recording of temperature. The start of the yearly smolt run was not triggered by a specific water temperature or a specific number of degree-days, but was controlled by a combination of temperature increase and temperature level in the river during spring. There was no significant correlation between smolt descent and any of the other environmental variables tested.

Kilgour, D.E., R.W. McCauley, and W. Kwain. 1985. Modeling the lethal effects of high temperature on fish. *Can. J. Fish. Aquat. Sci.* 42: 947-951.

A mathematical model relating mean survival times of samples of fish at lethally high temperatures was developed. It permits the estimation of upper incipient lethal temperature (UILT, °C) from the results of short-term experiments. Application of the model to data sets obtained from the literature yields "predicted" UILTs usually within 0.5° and almost always within 1 degree of observed values. The model was also applied to determine threshold toxicities (LC50, 144 h) of copper ion from tests of shorter duration.

Legault, M., and L.M. Lalancette. 1985. Temps d'ajustement de la flottabilité des saumons atlantiques (*Salmo salar*) et flottabilité comparée de saumons atlantiques d'élevage et sauvages. *Can. J. Fish. Aquat. Sci.* 42(3):619-623.

The authors determined the time of adjustment of buoyancy of juvenile hatchery-reared Atlantic salmon (*S. salar*) and investigated whether if their higher position off the substratum, compared with wild fish, might better result from a higher buoyancy. In flowing water, hatchery-reared Atlantic salmon adjust their buoyancy within 24 h. No difference in buoyancy exists between juvenile hatchery-reared and wild Atlantic salmon in still water. However, juvenile hatchery-reared Atlantic salmon are more buoyant in flowing water than wild Atlantic salmon. Even after 3 mo in a stream, the buoyancy of juvenile hatchery-reared Atlantic salmon did not change. Acquired hatchery behavior appears to be responsible for their difference in buoyancy.

Rimmer, D.M., R.L. Saunders, and U. Paim. 1985. Effects of temperature on the holding performance of juvenile Atlantic salmon (*Salmo salar*). *Can. J. Zool.* 63(1):92-96.

The ability of wild and hatchery yearling Atlantic salmon (*Salmo salar*) to hold a position against water currents was tested in relation to water temperature and season. This species would not swim, but held positions on the bottom of the test apparatus. Their performance was, therefore, rated on the basis of critical holding velocity instead of critical swimming velocity, often used for other species. Qualitatively, the relationships of critical holding velocity with both temperature and season were similar for wild and hatchery fish. However, wild fish were consistently more able to hold positions against water currents so that the mean water velocities at which they were unable to stem water currents were 25-84% greater than those for hatchery fish. The sharp decrease in performance at 8°C explains the previous observation that this species suddenly moves into the stream bed when temperature falls during the autumn.

Sato, R., T. Shibuya, and U. Akutsu. 1986. Smoltification of underyearling masu salmon (*Oncorhynchus masou*) at different temperatures. *Bull. Natl. Res. Inst. Aquaculture.* 9:21-27.

Effect of temperature and growth on smoltification of underyearling masu salmon (*Oncorhynchus masou*) was studied using six different temperature regimes. Fertilized eggs were placed at three different temperatures, 9°C, 12°C, and 15°C till hatching in late September, and the hatched-out fry were reared under the same conditions until late March, and then each treatment group was divided into blocks. Fish of the first blocks were reared at 9°C and the second blocks were reared at about 15°C until early July. The percentage of smolt observed in these groups by the end of the rearing period were as follows: 9-9°C, 0% 12-9°C, 57% 15-9°C, 79% 9-15°C, 0% 12-15°C, 0% 15-15°C, 12%. Average body length of smolt in 15-15°C was largest, followed by that of 15-9°C and of 12-9°C in decreasing order. These results indicate not only that growth is stimulated by rearing at a high temperature in the early stage, but also that other factors such as cold water treatment may be necessary for more efficient smolt production.

Schaefer, K.M. 1986. Lethal temperatures and the effect of temperature change on volitional swimming speeds of chub mackerel, *Scomber japonicus*. *Copeia.* 1:39-44.

Lower and upper lethal temperatures and measurements of volitional swimming speeds were determined for *Scomber japonicus* subjected to a progressive temperature change of 1 C * d⁻¹. The mean lower and upper lethal temperatures were approximately 6 and 29°C, respectively. *S. japonicus* showed a significant positive relationship between temperature and swimming speed, within its range of thermal tolerance. There were no significant differences in swimming speed from 12 - 23°C. Significant differences were observed in swimming speeds between mid-day and late afternoon.

Schneider, M.J., and T.J. Connors. 1982. Effects of elevated water temperature on the critical swim speeds of yearling rainbow trout, *Salmo gairdneri*. J. Therm. Biol. 7(4):227-228.

Shuter, B.J., J.A. MacLean, F.E.J. Fry, and H.A. Regier. 1980. Stochastic simulation of temperature effects on first-year survival of smallmouth bass. Trans. Am. Fish. Soc. 109(1):1-34.

The physiological basis for well-known correlations between summer air temperature indices and year-class strength in northern smallmouth bass (*M. dolomieu*) populations was examined. Field and laboratory studies demonstrated the existence of 2 critical stages in early life when smallmouth bass are particularly vulnerable to features characteristic of many natural water temperature regimes. The first stage extends from fertilization until the young leave the nest; high mortality results from exposure to extreme temperatures. The second stage extends over the first winter, when the young subsist on accumulated energy reserves. Because the ratio of energy stored to basal metabolic rate increases with size, large fish can withstand winter starvation better than small fish. The results from these and other studies were incorporated into a deterministic model of the relations between temperature and 1st-yr survival of smallmouth bass. Analysis of water temperature time series data from many locations led to the development and parameterization of a stochastic model capable of simulating variations in water temperature characteristic of the littoral zones of typical North American lakes. The stochastic physical and deterministic biological models were used together to assess the effects on 1st-yr survival of changes in climate and of realistic changes in the magnitude and frequency of short-term temperature fluctuations. The model successfully predicted the observed northern limit of the species' range. It also generated approximate environmental criteria for judging when year-to-year variation in survival, over one or both of the critical life history stages identified, is likely to reach a level sufficiently great to determine the pattern of year-to-year variation in recruitment to the adult stock. The combined model was also used to assess the effects of thermal loading from a nuclear power plant on a particular population.

Smirnov, B.P., I.A. Barybina, and L.B. Klyashtorin. 1987. Relationship between standard metabolism and temperature in juvenile Pacific salmon. J. Ichthyol. 27(2):15-22.

The relationship between temperature and standard metabolism in young Pacific salmon (*Oncorhynchus*) was studied. The temperature dependence of metabolism of young fish, long acclimatized to temperatures from 2 to 24°C, is well approximated by the exponential dependence $Q_w = Q_0 e^{kt}$ and by the Arrhenius equation. For practical purposes, it is more appropriate and convenient to use the exponential relationship. The temperature coefficient Q_{10} for juvenile fish of varying body weight is constant at 2.29 in the entire temperature range. The nature of temperature dependence in different species with varying body weight is similar. The dependence of oxygen consumption rate on temperature and body weight is approximated by the equation $Q@u- = 0.035W^{0.755 \pm 0.011} e^{(0.083 \pm 0.003)t}$ with the multiple correlation coefficient of 0.99. The published data on temperature dependence of metabolism in salmon and the reasons for various contradictions are discussed.

Taylor, E.B. 1988. Water temperature and velocity as determinants of microhabitats of juvenile chinook and coho salmon in a laboratory stream channel. Trans. Am. Fish. Soc. 117:22-28.

In an artificial stream channel, the distribution of juvenile coho salmon *Oncorhynchus kisutch* and chinook salmon *O. tshawytscha* at various water temperatures and average water velocities was monitored with respect to use by the fish of water velocities, cover objects, and a simulated side pond area in two successive years. Low water temperatures and, to some extent, increases in water velocity may be important stimuli for microhabitat shifts often reported in stream observations of juvenile salmonids during the fall-winter transition.

Thomas, R.E., J.A. Gharrett, M.G. Carls, S.D. Rice, A. Moles, and S. Korn. 1986. Effects of fluctuating temperature on mortality, stress, and energy reserves of juvenile coho salmon. Trans. Am. Fish. Soc. 115:52-59.

The effects of fluctuating diel temperature cycles on survival, growth, plasma cortisol and glucose concentrations, liver weight, and liver glycogen of juvenile coho salmon *Oncorhynchus kisutch* were determined. Temperature cycles (10-13°, 0-15°, 8-17°, and 6.5-20°C) were selected to simulate observed temperatures in clear-cuts of southeastern Alaska. Different levels of feeding, including starvation, were used in each of the tests. LT50s (peak temperature within a cycle producing 50% mortality) were 28°C for age-0 fish (350 mg) and 26°C for age-II fish (22-g presmolts). Cyclic temperatures for 40 d, averaging 11°C daily, did not influence growth of age-0 fish on any food ration as compared to controls held at a constant 11°C. Plasma cortisol and glucose concentrations were significantly greater in fish maintained for 20 d in the 6.5-20°C cycle but not different in fish in 10-13° and 9-15°C cycles or a constant 11°C. These elevated concentrations may be indicators of long-term stress.

Zaugg, W.S. 1981. Advanced photoperiod and water temperature effects on gill Na⁺-K⁺ adenosine triphosphatase activity and migration of juvenile steelhead (*Salmo gairdneri*). Can. J. Fish. Aquat. Sci. 38(7):758-764.

Under raceway conditions, an advanced photoperiod schedule caused migratory movements and elevation in gill Na⁺-K⁺ adenosine triphosphatase activity (Na⁺-K⁺ ATPase) to occur about 1 month earlier than normal in yearling summer steelhead (*Salmo gairdneri*) from Dworshak National Fish Hatchery (Idaho). Exposure of migrants to 13°C for 20 d resulted in serious impairment of continued migratory behavior and a reduction of gill Na⁺-K⁺ ATPase activity. Migrants outnumbered nonmigrants at fork lengths of 16 cm and longer. It is proposed that the potentially detrimental effects of warming river temperature during the normal migratory season and delayed migration caused by dams and impoundments might be partially overcome by inducing early smolt transformation and migration with the use of advanced photoperiods.

TURBIDITY

Berg, L., and T.G. Northcote. 1985. Changes in territorial, gill-flaring, and feeding behavior in juvenile coho salmon (*Oncorhynchus kisutch*) following short-term pulses of suspended sediment. Can. J. Fish. Aquat. Sci. 42(8):1410-1417.

The territorial, gill-flaring, and feeding behavior of juvenile coho salmon (*Oncorhynchus kisutch*) in a laboratory stream was disrupted by short-term exposure to suspended sediment pulses. At the higher turbidities tested (30 and 60 nephelometric turbidity units (NTU)), dominance hierarchies broke down, territories were not defended, and gill flaring occurred more frequently. Only after return to lower turbidities (0-20 NTU) was social organization reestablished. The reaction distance of the fish to adult brine shrimp decreased significantly in turbid water (30 and 60 NTU) as did capture success per strike and the percentage of prey ingested. Implications of these behavioral modifications suggest that the fitness of salmonid populations exposed to short-term pulses of suspended sediment may be impaired.

Bisson, P.A., and R.E. Bilby. 1982. Avoidance of suspended sediment by juvenile coho salmon. N. Am. J. Fish. Manage. 2(4):371-374.

Some water quality standards established by the states permit only minor increases in suspended sediment when background turbidity is low, allow greater absolute increases as background levels rise, and do not consider acclimation of stream biota to high turbidity. Juvenile coho salmon (*Oncorhynchus kisutch*) were subjected to experimentally elevated concentrations of suspended sediment and did not avoid moderate turbidity increases when background levels were low, but exhibited significant avoidance when turbidity exceeded a threshold that was relatively high (> 70 NTU) and was varied according to previous suspended sediment exposure.

Breitburg, D.L. 1988. Effects of turbidity on prey consumption by striped bass larvae. Trans. Am. Fish. Soc. 117:72-77.

Striped bass, *Morone saxatilis*, breed in water often affected by human activities that increase turbidity. Laboratory experiments were conducted to examine the effect of turbidity on the numbers and sizes of prey consumed by striped bass larvae during 25-min feeding trials. Larvae feeding on natural prey assemblages, primarily composed of copepods, consumed approximately 40% fewer prey in suspended solids concentrations of 200 and 500 mg * L⁻¹ than in 0 or 75 mg * L⁻¹. In contrast, larvae feeding on *Daphnia pulex* captured the same average number of prey at all suspended solids concentrations tested. Turbidity also had no effect on the size of copepods or *D. pulex* eaten.

Gradall, K.S., and W.A. Swenson. 1982. Responses of brook trout and creek chubs to turbidity. Trans. Am. Fish. Soc. 111:392-95.

The influence of red-clay turbidity on behavior and distribution of brook trout, *Salvelinus fontinalis*, and creek chubs, *Semotilus atromaculatus*, was measured in the laboratory. Creek chubs preferred highly turbid water (56.6 formazin turbidity units-FTU) over moderately turbid water (5.8 FTU) but brook trout did not show a preference. In moderately turbid water, both species were more active, and used overhead cover less, than in clear water. The results indicate turbidity may represent an important isolating mechanism that promotes production of creek chubs.

Hale, S.S. 1987. Time-series analysis of discharge, turbidity, and juvenile salmon outmigration in the Susitna River, Alaska. 1. Int. Symp. on Common Strategies of Anadromous and Catadromous Fishes Boston, MA (USA) 9-13 Mar 1986. Am. Fish. Soc. SYMP.

During 3 years of study of juvenile salmon outmigration from the middle reach of the Susitna River, a correspondence was noted between peaks of river discharge and peaks of outmigration. Two large hydroelectric dams proposed for a region above the salmon-rearing areas would markedly change the downstream discharge, temperature, and turbidity regimes. Box-Jenkins models were developed for the 1983 and 1984 time series of river discharge, turbidity, outmigration rates of *Oncorhynchus tshawytscha* and *O. nerka* fry to better understand the forces that shape the series and to statistically describe natural conditions. About 74% of the variance in discharge and 85% of the variance in turbidity for one day were explained by the values of each on the previous day. This percentage was 44% for chinook salmon outmigration and 43% for sockeye salmon outmigration the lower numbers indicated the effect of behavioral decisions on biological time series.

Herbert, D.M.W., and J.C. Merkens. 1961. The effects of suspended materials on aquatic life. *Internat. J. Air Water Pol.* 5:46-55.

Noggle, C. 1978. Behavioral, physiological and lethal effects of suspended sediment on juvenile salmonids. Masters Thesis, University of Washington, Seattle. 87 pp.

Sigler, J.W., T.C. Bjornn, and F.H. Everest. 1984. Effects of chronic turbidity on density and growth of steelheads and coho salmon. *Trans. Am. Fish. Soc.* 113: 142-150.

Chronic turbidity in streams during emergence and rearing of young anadromous salmonids could affect the numbers and quality of fish produced. The authors conducted laboratory tests to determine the effect of chronic turbidity on feeding of 30-65 mm long steelheads *Salmo gairdneri* and coho salmon *Oncorhynchus kisutch* in straight and oval channels. Fish subjected to continuous clay turbidities grew less well than those living in clear water, and more of them emigrated from channels during the experiments.

Swenson, W.A. 1978. Influence of turbidity on fish abundance in western Lake Superior. US EPA, Ecological Research Series, EPA 600/3-78-067.

C A S E S T U D I E S

Anderson, J.J. 1988. Diverting migrating fish past turbines. *Northwest Environ. J.* 4:109-128.

Andrew, F.J., and G.H. Green. 1960. Sockeye and pink salmon production in relation to proposed dams in the Fraser River system. *Bull. Inter. Pac. Sal. Fish. Comm. Bulletin XI*, 259 pp.

Anonymous. 1960. Evaluation of the ability of an artificial outlet to attract downstream migrant salmonids from the reservoir of Lookout Point Dam. *Prog. Rep. Fish. Eng. Res. Prog. N. Pac. Div. Army Corps Eng. Fish Comm. Oregon.* July. 4 pp.

Anonymous. 1960. Fish passage through turbines. *Prog. Rep. Fish. Eng. Res. Prog. N. Pac. Div. Army Corps Eng. Walla Walla Dist.* July. 3 pp.

Anonymous. 1960. Fishway attraction water supply study. *Prog. Rep. Fish. Eng. Res. Prog. N. Pac. Div. Army Corps Eng. Walla Walla Dist.* July. 3 pp.

Anonymous. 1960. Guiding downstream migrant salmon and steelhead trout. *Prog. Rep. Fish. Eng. Res. Prog. N. Pac. Div. U.S. Army Corps Eng. College of Fisheries, Univ. Washington.* July. 19 pp.

Anonymous. 1960. Powerhouse fish collection system and transportation flows, Bonneville Dam. *Prog. Rep. Fish. Eng. Res. Prog. N. Pac. Div. U.S. Army Corps Eng. Portland Dist.* July. 4 pp.

Anonymous. 1960. Research relating to mortality and downstream migrant salmon passing McNary and Big Cliff Dams. Prog. Rep. Fish. Eng. Res. Prog. N. Pac. Div. U.S. Army Corps Eng. Washington Dept. Fish. July. 5 pp.

Anonymous. 1960. Results of a tagging program to enumerate the #'s and to determine the seasonal occurrence of anadromous fish in the Snake River and its tributaries. Prog. Rep. Fish. Eng. Res. Prog. N. Pac. Div. Army Corps Eng. Fish Comm. Oregon. July. 3 pp.

Anonymous. 1960. Submerged orifice research powerhouse fish collection system, Bonneville Dam. Prog. Rep. Fish. Eng. Res. Prog. N. Pac. Div. U.S. Army Corps Eng. Portland Dist. July. 5 pp.

Anonymous. 1960. The control of downstream migrants by means of mechanical screens. Prog. Rep. Fish. Eng. Res. Prog. N. Pac. Div. Army Corps Eng. Oregon State Game Comm. July. 12 pp.

Anonymous. 1977. Snake and Columbia are horrible example. *Western Fisheries*. 94(5):1927-29.

Before dams were constructed on the Snake and Columbia rivers, juvenile chinook salmon and steelhead trout migrated to the ocean in early spring and summer under natural conditions. Water flow was high, water temperatures were favorable, turbidity sufficient for protection from predators, and there was little slow-moving water to delay the migration. This environment has been changed drastically by the construction of the dams. Fingerlings on their journey are subject to high mortality from passing through turbines, predation in tailraces and nitrogen supersaturation resulting from spilling at the dams. Delay is also caused by reduced water velocity. This paper examines some data on quantities of salmon and trout migrating in the river over the past 6 years, and briefly considers some work in progress intended to minimize losses at turbines, the use of intermediate dams and by-pass systems. Flow control is also discussed. It is recognized that there are conflicts between users of this water system, particularly from irrigators and fishery scientists.

Anonymous. 1985. Smolt monitoring program, annual report 1985. Part 2. In: *Migrational Characteristics of Columbia Basin Salmon and Steelhead Trout, 1985. Volume 1*. NTIS No: DE86011444/HDM.

The annual Smolt Monitoring Program is the result of implementation of Section 304(d)(2) of the Northwest Power Planning Council Fish and Wildlife Program. This is the second year of the annual systemized program conducted by the Fish Passage Center (formerly Water Budget Center). Index reaches have been established. Travel time indices are calculated for year to year comparison. Marked groups of steelhead, spring chinook, fall chinook, and summer chinook are monitored at sampling points throughout the system. Because this program is intended to be representative of the juvenile migration, marked groups represent major hatchery production stocks. Arrival time and duration of marked groups are reported. Annual travel time indices are reported from Rock Island Dam to McNary Dam, and from Lower Granite Dam to McNary Dam. Hatchery and brand release information is reported.

Anonymous. 1986. Migrational characteristics of Columbia Basin salmon and steelhead trout. In: *Smolt Monitoring Program: Annual Report, 1986: Vol. 1*. NTIS No: DE87009908/HDM.

This report presents the results of post-seasonal analyses including timing and relative magnitude of the outmigration, travel time for marked hatchery releases, and survival in mid-Columbia and lower Snake River index reaches. Travel time of marked yearling and sub-yearling chinook salmon (*Oncorhynchus tshawytscha*), sockeye salmon (*Oncorhynchus nerka*), and steelhead trout (*Salmo gairdneri*) is measured between specific sampling points in the system. Marked groups usually represent major hatchery production stocks. Survival estimates are computed for specific spring chinook and steelhead marked groups. Arrival time and duration of outmigration of the chinook, sockeye, coho (*Oncorhynchus kisutch*) and steelhead runs are reported at key sampling points. Hatchery and brand release information for 1986 is also listed.

Anonymous. 1986. Migrational characteristics of Columbia Basin salmon and steelhead trout, 1986, Volume 2, In: *Brand Recapture Data: Smolt Monitoring Program Annual Report, 1986*. NTIS No: DE87009909/HDM.

Smolt Monitoring Program Annual Report, 1986, Volume I, describes the results of travel time monitoring and other migrational characteristics of yearling and sub-yearling chinook salmon (*Oncorhynchus tshawytscha*), sockeye salmon

(*Oncorhynchus nerka*), and steelhead trout (*Salmo gairdneri*). This volume presents the data from Fish Passage Center freeze brands used in the analysis of travel time for Lewiston, Lower Granite, Lower Monumental, Rock Island, McNary, and John Day dams. Summary of data collection procedures and explanation of data listings are presented in conjunction with the mark recapture data. Data for marked fish not presented in this report will be provided upon request. Daily catch statistics (by species), flow, and sample parameters for the smolt monitoring sites, Clearwater, Lewiston, Lower Granite, Lower Monumental, Rock Island, McNary, John Day, and Bonneville also will be provided upon request.

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- Congleton, J. L., E. J. Wagner, and R. R. Ringe. 1987. Evaluation of fishway designs for downstream passage of Spring chinook salmon and steelhead trout smolts, 1987: Final Report. NTIS No: DE89001554/HDM.
- The stress response of chinook salmon and steelhead trout smolts to passage through three different flumes was tested by assaying plasma cortisol concentrations before and after flume passage. In addition, de-scaling of fish was recorded before and after flume passage, and the ability of the flumes to pass adult chinook salmon and debris was determined. The three flumes were a corrugated metal flume (CMF), a 4-foot wide baffled flume (BF4), and a 2-foot wide baffled flume (BF2). Each flume was tested under conditions: 1) at night, 2) during the day with a perforated metal cover, which reduced the amount of light entering the flume by about half (partially darkened), and 3) during the day with the perforated cover and additional double layer of black plastic (completely darkened). Plasma cortisol concentrations were not significantly elevated in chinook salmon smolts after passage through any of the flumes ($P > 0.2$, ANOVA). In daytime tests of partially and completely darkened flumes cortisol concentrations were consistently decreased following flume passage. We attribute this to pre-test stress (holding of fish in small tanks) and to the absence of a strong stress response to flume passage. Flume design did not have a significant effect on cortisol concentrations ($P = 0.9$). Total darkening of the flumes during daytime was beneficial: cortisol concentrations were lower ($P = 0.03$) in chinook salmon smolts passing through completely darkened flumes than in smolts passing through partially darkened flumes.
- Damkaer, D.M., and D.B. Dey. 1984. Adult salmonid delay at John Day Dam (1984). In: *Fish Passage Development and Evaluation Program, Annual Progress Report.* US Army Corps Eng. N. Pac. Div. 22 pp.
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Fields, P.E. 1956. Guiding downstream migrant salmon and steelhead trout. A research summary. Prog. Rep. FERP. US Army Corps Eng. N. Pac. Div. 17 pp.

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Fields, P.E., G. L. Finger, R.J. Adkins, R.E. Carney, and R. Pyke. 1955. A factorial study of the response of steelhead trout, chinook and silver salmon fingerlings to chain barriers in moving water. Univ. WA. School Fish. Tech. Rep. # 13. 7 pp.

Fields, P.E., G. L. Finger, R.J. Adkins, R.E. Carney, and R. Pyke. 1955. A factorial study of the response of steelhead trout, chinook and silver salmon fingerlings to chain barriers in moving water. Univ. WA. School Fish. Tech. Rep. # 11. 11 pp.

Gerold, M., and K. Niggol. 1964. Comparative response of blinded and non-blinded fingerling salmon to a louver barrier and to a sharp increase in water velocity. Fish-Passage Res. Program. U.S. Bur. Comm. Fish. Seattle, WA. 5 pp.

Gessel, M.H., W.E. Farr, and C.W. Long. 1985. Underwater separation of juvenile salmonids by size. Mar. Fish. Rev. 47(3):38-42.

Juvenile salmonids collected at dams on the Snake and Columbia Rivers (Oregon and Washington USA), require separation by size prior to transportation. A method of separating most of the smaller downstream migrating juvenile Pacific salmon, *Oncorhynchus* spp., from the larger steelhead, *Salmo gairdneri*, at hydroelectric dams is described. The device utilizes behavioral responses that allow fish to remain in water during the separation process. This system is presently being installed at collector dams on the Columbia and Snake River.

Giorgi, A.E., G.E. Swan, W.S. Zaugg, T. Coley, and T.Y. Barila. 1988. Susceptibility of Chinook Salmon Smolts to Bypass Systems at Hydroelectric Dams. North Am. J. Fish. Management. 8:25-29.

Several hydroelectric dams in the Snake-Columbia river system are equipped with submersible traveling screens that project into the turbine intakes. The screens are designed to divert juvenile migrant Pacific salmon *Oncorhynchus* spp. and steelhead *Salmo gairdneri* from the intake upward into gatewells and the adjoining central bypass system. Assays of gill $\text{Na}^+\text{-K}^+$ -ATPase were performed on yearling chinook salmon (*O. tshawytscha*) collected during several routine fish guidance efficiency tests in 1985 and 1986. Data suggest there is a relationship between the physiological status of smolting yearling chinook salmon and their susceptibility to guidance by traveling screens. Assessments of salmonid out-migrations may be biased if they are based on samples from traveling-screen guidance systems.

Gray, G.A., G.M. Sonnevil, H.C. Hansel, C.W. Huntington, and D.E. Palmer. 1984. Feeding activity, rate of consumption, daily ration and prey selection of major predators in the John Day Pool. U.S. Fish Wildlife. Serv. Ann. Report.

This study was initiated to determine the extent of predation by resident populations of native and introduced fish on juvenile salmonids in main stem Columbia River Reservoirs. The John Day Reservoir and tailrace was selected as the study area. Results indicated that juvenile salmonids were consumed by all four predatory fish species studied: northern squawfish (*Ptychocheilus oregonensis*), walleye (*Stizostedion vitreum vitreum*), smallmouth bass (*Micropterus dolomieu*), and channel catfish (*Ictalurus punctatus*). However, degree of predation varied among predators as a function of spatial distribution, apparent abundance size, and temporal feeding behavior.

Hanson, C.H., and H.W. Li. 1983. Behavioral response of juvenile chinook salmon, *Oncorhynchus tshawytscha*, to trashrack bar spacing. Calif. Fish. Game. 69(1):18-22.

The behavioral response of juvenile chinook salmon, *O. tshawytscha*, to vertical trash racks having interbar spacings ranging from 5.1 to 30.5 cm is reported. Experiments were conducted in a laboratory channel with an average water velocity of 32 cm/sec under light intensities of 14.0 and 1.0×10^{-2} footcandles. Transit times were not significantly different between light levels, but differences between bar spacings were significant. Observed changes in rheotactic posture and

hesitancy to pass through a trash rack with bar spacing less than 15 cm would increase the susceptibility of juvenile fish to predation.

Hays, S., and K.B. Truscott. 1987. Rocky Reach prototype fish guidance system: 1986 developmental testing. Chelan County Public Utility District #1. March, 1987.

Heggberget, T.G. 1984. Populations of presmolt Atlantic salmon (*Salmo salar* L.) and brown trout (*Salmo trutta* L.) before and after hydroelectric development and building of weirs in the River Skjoma, North Norway. *Regulated Rivers*. 1984:293-308.

In 1977 the River Skjoma was regulated in such a way that the elevated parts of the water shed were eliminated, which caused increased water temperatures and reduced silt transportation in summer. After reduction of the waterflow, the density of pre-smolt salmonids increased from approximately equals 8 fish/100 m² to approximately equals 30 fish/100 m². The increase of the proportion of salmon from 40 to 60 in the period from 1976 through 1980 is likely due to method used. The productive area of the river was reduced by approximately equals 2/3 in the same period. In the weir magazines, trout (*Salmo trutta*) became the dominating species, while salmon (*S. salar*) dominated at the river stations. The growth of presmolt salmon and trout increased by 1.5-2.0 cm for each year-class in the period from 1978 through 1980. This was mainly due to the increased water temperatures, which were caused both by the hot summers in 1978 and 1979 and the elimination of the elevated, cold tributaries.

Hunt, R.T. 1985. Evaluating the feasibility of a hydroelectric facility where fishery issues are a concern. In: *Waterpower '85*. Roluti, M.J. (ed). pp 1845-1855

Imamura, Y., and M. Ogura. 1959. Study on the fish-gathering effects of air curtain. *J. Tokyo Univ. Fish.* 45(2):173-177.

Johnsen, R.C., and C.L Ranck. 1985. Monitoring of downstream salmon and steelhead at federal hydroelectric facilities. Annual Report 1985. NTIS No: DE86008824/HDM.

Juvenile salmonids were monitored on their seaward migration at Lower Granite, McNary, and John Day Dams: sampling at these sites provided data primarily for evaluation of smolt survival, travel time, and migrational timing. At Lower Monumental Dam catch data was to provide a general indication of smolt passage and comparison with the hydroacoustics passage index.

Johnson, L., T.H. Schadt, and R. Sullivan. 1987. Hydroacoustic evaluation of the fish guiding efficiency of submersible travelling screens at Little Goose Dam. *Int. Symp. Fish. Acoust.* Seattle, WA, 1987. 53 pp.

Johnsen, R. C., L. A. Wood, and W. W. Smith. 1986. Monitoring of downstream salmon and steelhead at federal hydroelectric facilities, 1986: Annual Report. NTIS No: DE87009922/HDM.

The 1986 smolt monitoring project provided data on the seaward migration of juvenile salmon and steelhead at Lower Granite, Lower Monumental, McNary, John Day, and Bonneville Dams. The number of fish sampled by species, brand recaptures, and pertinent flow data were provided for the purpose of evaluating smolt survival, travel time, and migrational timing.

Keevin, T.M., and J.E. Thomerson. 1985. Assessment of probable fishery impacts of hydroelectric development at Lock and Dam No. 26 (replacement), Mississippi River. In: *Waterpower '85*. Roluti, M.J. (ed). pp 1835-1844.

Kerr, J.E. 1953. Studies on fish preservation at the Contra Costa Steam Plant of the Pacific Gas and Electric Company. Ca. Dept. Fish Game. *Fish Bull.* #92, 67 pp.

Krcma, R. 1984. Evaluation of the juvenile collection and bypass systems at Bonneville Dam - 1984. In: *Fish Passage Development and Evaluation Program*, Ann. Prog. Rep. US Army Corps Eng. N. Pac. Div. 21 pp.

Lindsay, R.B., W.J. Knox, M.W. Flesher, B.J. Smith, and E.A. Olsen. 1985. Study of wild Spring chinook salmon in the John Day River system. Final Report, 1985. NTIS No: /HDM.

A study of wild spring chinook salmon was conducted in the John Day River, Oregon: (1) recommend harvest regulations to achieve escapement goals in the John Day River; (2) recommend adjustments in timing of fish passage operations at Columbia River dams that will increase survival of John Day migrants; (3) recommend habitat or environmental improvements that will increase production of spring chinook salmon; (4) determine escapement goals for wild spring chinook salmon in the John Day River; and (5) recommend procedures for hatchery supplementation in the John Day River in the event it becomes necessary to artificially maintain the run of spring chinook salmon. Juveniles were captured as smolts during migration and as fingerlings during summer rearing. Juveniles were coded-wire tagged, and recoveries of tagged adults were used to assess contribution to ocean and Columbia River fisheries, timing of adult migrations through the Columbia River in relation to fishing seasons, and age and size of fish in fisheries. Scoop traps and seines were used to determine timing of smolt migrations through the John Day River. In addition, recoveries of tagged smolts at John Day Dam, The Dalles Dam, and Jones Beach were used to determine migration timing through the Columbia River. We examined freshwater life history of spring chinook salmon in the John Day River and related it to environmental factors. We looked at adult holding areas, spawning, incubation and emergence, fingerling rearing distribution, size and growth of juveniles and scales. Escapement goals for the John Day River as well as reasons for declines in John Day stocks were determined by using stock-recruitment analyses. Recommendations for hatchery supplementation in the John Day were based on results from other study objectives.

Long, C.W., and R.F. Krcma. 1969. Research on a system for bypassing juvenile salmon and trout around low-head dams. *Comm. Fish. Rev.* 31(6):27-29.

Long, C.W., and R. Krcma. 1979. Research to develop passive bar screens for guiding juvenile salmonids out of turbine... low head dams on the Columbia and Snake Rivers. In: *Fish.Pass. Dev. Eval. Prgm., Sixth Prog. Rep.* US Army Corps Eng. N. Pac. Div. 350 pp.

Lund, M., and T.G. Heggberget. 1985. Avoidance response of two-year-old rainbow trout, *Salmo gairdneri* Richardson, to air-supersaturated water: hydrostatic compensation. *J. Fish. Biol.* 26:193-200.

Vertical swimming responses of 2-year-old rainbow trout *Salmo gairdneri* were tested with air saturated and air supersaturated water in tank experiments. The level of supersaturation varied between 115 and 125% total gas pressure. No consistent vertical avoidance response was observed in the fish tested, but the mortality of fish restricted to the upper 30 cm of the tanks was significantly greater than fish free to sound to the whole depth of the tanks. It is concluded that the Norwegian stock of rainbow trout do not avoid air-supersaturation at levels from 115 to 125% TGP by active hydrostatic pressure compensation.

Marquette, W.M., and C.W. Long. 1971. Laboratory studies of screens for diverting juvenile salmon and trout from turbine intakes. *Trans. Am. Fish. Soc.* 100(3):439-447.

Mathews, G.M., G.A. Swan, and J.R. Smith. 1977. Improved bypass and collection system for protection of juvenile salmon and steelhead trout at Lower Granite Dam. *Mar. Fish. Rev.* 39(7):10-14.

Maule, A.G., C.B. Schreck, C. S. Bradford, and B.A. Barton. 1988. Physiological effects of collecting and transporting emigrating juvenile chinook salmon past dams on the Columbia River. *Trans. Am. Fish. Soc.* 117:245-61.

Emigrating juvenile salmonids are collected at McNary Dam on the Columbia River and transported past the three downstream dams to avoid mortalities caused by passage through power-generating turbines. During the 1982-1984 seaward migrations of juvenile fall and spring chinook salmon *Oncorhynchus tshawytscha*, authors used an array of physiological measurements (plasma cortisol and glucose, white blood cell counts) and challenge tests (saltwater challenge, secondary stress, and swimming endurance) to identify the stressful elements in these activities. Although there were no significant differences in responses of fish collected at various times during the migrations, apparent differences between the responses of fall and spring chinook salmon suggested that the latter were more sensitive to the stresses of collection.

Mayo, R.D. 1973. Conventional fish screening systems and some promising alternatives. In: Jensen, L.D. (ed). Entrainment and Impingement Proc. Second Entrain. Intake Screen Work. Feb. 5-9, 1973, Baltimore, MD. pp 277-279.

McConnaha, W. E., L. R. Basham, and J. Jordan. 1984. Migrational Characteristics of Columbia Basin Salmon and Steelhead Trout, 1984. Part 2. Smolt Monitoring Program. 1984 Annual Report. NTIS No: DE85017331/HDM

The report describes the travel time of marked yearling and sub-yearling chinook salmon (*Oncorhynchus tshawytscha*), sockeye salmon (*O. nerka*), and steelhead trout (*Salmo gairdneri*) between points within the system, and reports the arrival timing and duration of the migrations for these species as well as coho salmon (*O. kisutch*). A final listing of 1984 hatchery releases is also included.

McLain, A.L., and W. L. Nielson. 1953. Directing the movements of fish with electricity. U.S. Fish Wildlife Serv. Spec. Sci. Report: #93. 24 pp.

Meyer, E.B. 1989. Evaluation of data collected on the thermal stress problem for juvenile chinook salmon at McNary Dam, Washington. CEWES-HS-R (1105-2-10b). June 19, 1989. 38 pp.

Miller, D. R., and C. W. Sims. 1983. Effects of flow on the migratory behavior and survival of juvenile Fall and Summer chinook salmon in John Day Reservoir. Annual Report, FY 1983. NTIS No: DE85015779/HDM.

The effects of instream river flow on the passage time, survival, and migrational behavior of juvenile fall and summer (O-age) chinook salmon in John Day Reservoir is being studied. In 1983, the final year of juvenile sampling in the reservoir, research activities continued to refine flow/travel time relationships and distributional behavior of O-age chinook salmon. Fifteen groups (72,559 fish) of marked O-age chinook salmon were wire-tagged, branded, and released into the tailrace at McNary Dam, and thirty-two groups (22,206 fish) were branded and released into the reservoir at various other sites. Sampling at John Day Dam, utilizing the airlift pump system in the B and C slots of Turbine Intake Unit 3, captured 82,698 subyearling chinook salmon including 640 mark recoveries. Additional marks (458) were recovered from purse seine samples taken at various sites throughout the reservoir. Weekly mean fork lengths of O-age chinook salmon captured at McNary and John Day Dams and in the reservoir by purse seine ranged from 103 mm in mid-June to 166 mm in mid-December. Fish captured at the John Day Dam monitoring facility and by purse seine throughout the reservoir were in excellent condition. Preliminary analysis of stomach samples taken in 1982 and 1983 from purse seine catches indicates active feeding is taking place. The average passage time of the fastest moving marked O-age chinook salmon from McNary Dam to John Day Dam was 11 days (based on 25th percentile of mark recaptures). The average reservoir residence time was 22 days. Regression analysis was used to develop a description of the relationship of river flow to the rate of downstream movement of O-age chinook salmon in John Day Reservoir in 1983. The slope of this line and the correlation coefficient (R) were not significantly different from zero. (ERA citation 10:045152)

Miller, D.R., and A.E. Giorgi. 1985. Effects of flow on the migratory behavior and survival of juvenile Fall and Summer chinook salmon in John Day reservoir. Annual Report 1985. NTIS No: DE86011382/HDM.

As part of a study to define the effects of instream flows on the passage time, migration behavior, and survival of phi age chinook salmon migrating through John Day Reservoir from June through August juvenile fish were tagged and released below McNary Dam in 1981. This report discusses adult returns through 1984.

Miller, D. R., and A. E. Giorgi. 1987. Effects of Flow and Spill on the Migratory Behavior and Survival of Juvenile Fall and Summer Chinook Salmon in John Day Reservoir: Annual Report, 1987. NTIS No: DE89009896/HDM.

Juvenile fall chinook salmon, *Oncorhynchus tshawytscha*, were freeze branded, coded wire tagged, and released into the Columbia River in the tailrace below McNary Dam during the summers of 1981--1983. The objectives of the study were to examine the effects of river flow on the passage time and migrational behavior of the juveniles and to subsequently assess any relationship to adult survival. This report details adult recovery data to June 1987.

Monan, G.E. 1964. Horizontal and vertical distribution of downstream migrants, Snake River, Spring 1964. Fish-Passage Res. Program. U.S. Bur. Comm. Fish. Seattle, WA.

Mussalli, Y.G., and E.P. Taft III. 1977. Fish Return systems. In: Hydraulics in the Coastal Zone. Proc. 25th Ann. Hydraul. Div. Spec. Conf. Texas A and M Univ. Am. Soc. Civil Eng. New York, N.Y. pp 288-295.

Nelson, V.L. 1985. Freeze brand marking of steelhead trout and chinook salmon juveniles for water budget studies: Idaho. Annual Report, FY 1985. NTIS No: DE86015103/HDM.

During the fall of 1984 and spring of 1985, 362,428 chinook salmon (*Oncorhynchus tshawytscha*) and steelhead trout (*Salmo gairdneri*) juveniles were freeze branded for Water Budget Center - Downstream Smolt Monitoring Studies. Of these, 106,361 fish received a coded wire tag. Release of the freeze brand groups began March 20, 1985 and were completed by June 4, 1985. After brand loss and mortality, there were 133,025 spring chinook, 25,600 summer chinook, 33,850 fall chinook, 65,125 A-run steelhead, and 62,400 B-run steelhead released with brands.

Nelson, P.C., and R.F. Raleigh. 1986. Habitat suitability index models and instream flow suitability curves: pink salmon. NTIS No: PB86-129517/HDM.

A review and synthesis of existing information were used to develop a Habitat Suitability Index (HSI) model and instream flow suitability curves for pink salmon (*Oncorhynchus gorbuscha*). The model consolidates habitat use information into a framework appropriate for field application, and is scaled to produce an index between 0.0 (unsuitable habitat) and 1.0 (optimum habitat).

Nettles, D. C., and S. P. Gloss. 1986. Outmigration of landlocked Atlantic salmon (*Salmo Salar*) smolts and effectiveness of an angled trash rack/fish bypass structure at a small scale hydroelectric facility. NTIS No: DE86012890/HDM.

Modes of downstream passage (penstock, spillway, diversion chute) by Atlantic salmon (*Salmo salar*) smolts were monitored using radio telemetry to assess the effectiveness of an angled trash rack/fish bypass structure at a small hydroelectric dam on the Boquet River, New York. Telemetry of 170 Atlantic salmon smolts and visual observations of stocked smolts were used to determine aspects of Atlantic salmon outmigration behavior. Smolts initiated mass migrations after river temperatures reached or exceeded 10 sup 0 C. Many radio-tagged smolts interrupted movements upon reaching ponded waters and/or the dam. River flow did not ($P > .05$) affect the frequency of migratory movements, passages, or rate of movement. Migrations were of approximately 30 days duration. Passages at the dam occurred primarily at night (61%) with diurnal passages (17%) and crepuscular passages (17%) of secondary importance. Timing of 5% of the passages was undetermined. All passages which occurred when angled trash racks were in place were through the bypass or over the spillway. Six (6) passages occurred when trash racks perpendicular to the penstock were in place: 3 of these were penstock passages. The angled trash rack and bypass structure served to reduce entrainment.

Niggol, K. 1964. Response of juvenile migrants to flow accelerations. Fish-Passage Res. Program. U.S. Bur. Comm. Fish. Seattle, WA. 7 pp.

Patrick, P.H. 1981. Responses of fish to diversion barriers. Ont. Hydro Res. Div. Report # 81-190-K. 77 pp.

Prentice, E.F., and F.J. Ossiander. 1973. Fish diversion systems and biol. invest. of horizon traveling screen model VII. In: Jensen, L.D. (ed). Entrainment and Impingement Proc. Second Entrain. Intake Screen Work. Feb. 5-9, 1973, Baltimore, MD. pp 205-214.

Pugh, J.R., and J.R. Smith. 1964. Horizontal and vertical distribution of yearling salmonids in the upper end of Mayfield reservoir. Fish-Passage Res. Program. U.S. Bur. Comm. Fish. Seattle, WA. 13 pp.

Pugh, J.R., G.E. Monan, and J.R. Smith. 1970. Effect of water velocity on the fish-guiding efficiency of an electrical guiding system. Fish. Bull. 68(2):307-324.

Raemhild, G.A., G. E. Johnson, and C. M. Sullivan. 1984. Hydroacoustic monitoring of downstream migrant salmon and steelhead at Wells Dam in spring 1984. Annual Report. NTIS No: DE85016327/HDM.

The downstream migration of salmon and steelhead in spring 1984 at Wells Dam on the mid-Columbia River was monitored using hydroacoustics. The primary objective of this research was to document run timing and describe the distribution of smolts at the dam. The study occurred from April 2 to June 15, 1984. Four transducers were deployed at the bases of pier noses at Turbines 3, 5, 7, and 9 and aimed up 24 exp 0 into the forebay. They were sampled once every hour, 24 hours per day, for 75 days. An index of fish passage was reported daily to the Water Budget Center in Portland, Oregon. This index was computed as follows. For each 24-h period, separate fish passage rates (number/time) at each of the four sampling locations were estimated by dividing the sum of the "weighted" fish detections by total sample time. These four values then were averaged to produce the daily index (number/day/location). The first substantial increase in fish passage occurred on April 25, 1984 due to the chinook released from the Winthrop hatchery on April 23. During May, run timing was fairly uniform except for peaks on May 2, 14, 18, and 22. The unexpected peak in run size that occurred from May 29 to June 2 could have been caused by juvenile mountain whitefish. Although the proportion of each species varied, chinook passage probably peaked in late April, and steelhead in the first two weeks of May; sockeye passage was variable throughout the study. The data indicated that most downstream migrants were distributed high in the water column and toward the western end of the dam. Average hourly passage rates for day and night were similar, but more fish passed the dam during the longer period of daylight than the shorter period of darkness.

Raymond, H.L. 1988. Effects of hydroelectric development and fisheries enhancement on spring and summer chinook salmon and steelhead in the Columbia River Basin. *N. Amer. J. Fish. Manage.* 8:1-24.

Trends in abundance of spring and summer chinook salmon *Oncorhynchus tshawytscha* and steelhead *Salmo gairdneri* returning to the Snake River and mid-Columbia River above Priest Rapids Dam were determined by analyzing the percentage of adults returning from the smolt out-migrations of 1962-1984. Runs declined as a result of hydroelectric development of the river; the main cause for the decline was the mortality of juveniles migrating downstream through as many as nine dams and impoundments en route to the ocean. Enhancement measures to offset dam-related mortality of smolts began in 1970 on the Snake River and in 1975 on the mid-Columbia River. These measures included increased numbers of smolts released from hatcheries, spillway deflectors to reduce dissolved gas saturation, fingerling bypasses at dams, transportation of smolts around dams, supplemental river flows to minimize delay for smolts passing through reservoirs, and supplemental spill at dams to minimize turbine mortality of smolts at dam without fingerling bypasses. These actions have reversed the decline of steelhead but not of salmon.

Raymond, H.L., W.W. Bentley, and C.S. Thompson. 1973. Effects of power peaking operations on juvenile salmon and trout migrations. Prog. Report. U.S. Army Corps Eng. Nat. Mar. Fish. Serv. 31 pp.

Richards, R.T. 1977. Fish screening - the state of the practical art. In: *Hydraulics in the Coastal Zone*. Proc. 25th Ann. Hydraul. Div. Spec. Conf. Texas A. and M Univ. Am. Soc. Civil Eng. New York, N.Y. 296-303.

Richey, E.P., and R.H. Murphy. 1964. Porous plate studies (summary). Fish-Passage Res. Program. U.S. Bur. Comm. Fish. Seattle, WA. 7 pp.

Rogers, A., and A. Cane. 1979. Upstream passage of adult salmon through an unlit tunnel. *Fish. Manage.* 10(2):87-92

After conversion of a lake, previously a part of a river system in Gwynedd, North Wales, to a pumped storage reservoir, salmon will be faced with a 2.2.km long diversion tunnel in order to reach parts of their former spawning grounds. The unlit tunnel is described, with notes on water velocities under various discharge conditions. A fish counter, mounted at the peak of the fish pass in the upstream (intake) weir of the tunnel, has indicated that, in the first spawning season following construction of the tunnel, numbers of adults have succeeded in negotiating tunnel and weir, despite the hitherto-assumed unattractive conditions of low velocity and complete darkness.

Ruggerone, G.T. 1986. Consumption of migrating juvenile salmonids by gulls foraging below a Columbia River dam. *Trans. Am. Fish. Soc.* 115(5):736-742.

Consumption of migrating juvenile Pacific salmon *Oncorhynchus* spp. and steelhead *Salmo gairdneri* by gulls was estimated below the turbine area of Wanapum Dam on the Columbia River in 1982. The number of salmonids consumed by gulls ranged from 50 to 562 fish/h. Multiple-regression analysis indicates that the number of salmonids consumed by gulls is significantly affected by the passage rate of fish through the turbines and spillgates, and by light intensity. The number of salmonids consumed by gulls foraging below the turbines during 25 d of peak salmonid migration was approximately 111,750 to 119,250 fish or 2% of the estimated spring migration.

Ruggles, C.P., and P. Ryan. 1965. An investigation of louvers as a method of guiding juvenile Pacific salmon. *Can. Fish Cult.* 33:1-68.

Schreck, C.B., and H.W. Li. 1984. Columbia River salmonid outmigration: McNary Dam Passage and enhanced smolt quality. In: *Fish Passage Development and Evaluation Program, Ann. Prog. Rep. US Army Corps Eng. N. Pac. Div.* 15 pp.

Schuler, V.J., and L.E. Larson. 1975. Improved fish protection at intake systems. In: *Journal of Environmental Engineering Division, December, 1975.* pp 897-910

Shepard, S. 1989. Radio telemetry as a tool for fisheries mitigation. In: *Waterpower '89.* Eberhardt, A.J. (ed). pp 818-827.

Shew, D.M., R.D. Peters, and A.R. Turner, Jr. 1984. Evaluations of adult fish passage at Bonneville Lock and Dam and John Day Dam. In: *Fish Passage Development and Evaluation Program, Ann. Progress Rep. US Army Corps Eng. N. Pac. Div.* 14 pp.

Slatick, E. 1970. Passage of adult salmon and trout through pipes. *U.S. Fish Wildlife Spec. Sci. Rep.* 592:1-18.

Slatick, E. 1971. Passage of adult salmon and trout through an inclined pipe. *Trans. Am. Fish. Soc.* 100(3):448-455.

Smith, J.R., and W.E. Farr. 1975. Bypass and collection system for protection of juvenile salmon and trout at Little Goose Dam. *Mar. Fish. Rev.* 37(2):31-35.

Swan, G.A., and R.F. Krcma. 1984. Development of an improved fingerling protection system for Lower Granite Dam - 1984. In: *Fish Passage Development and Evaluation Program, Ann. Progress Rep. US Army Corps Eng. N. Pac. Div.* 11 pp.

Swan, G.A., and R.F. Krcma. 1984. Fish guiding and orifice passage efficiency tests with subyearling chinook salmon, McNary Dam. In: *Fish Passage Development and Evaluation Program, Ann. Progress Rep. US Army Corps Eng. N. Pac. Div.* 12 pp.

Swan, G.A., T.G. Withrow, and D.L. Park. 1982. Survey of fish protective facilities at water withdrawal sites on the Snake and Columbia Rivers. *NOAA TECH. REP. 1986. NOAA-TR-NMFS-39.* 37 pp.

Proliferation of water withdrawals and new pump intake and screen designs had occurred with the growth of irrigated agriculture along the Columbia and Snake Rivers. Concern for the protection of anadromous and resident fish populations resulted in formulation of a survey of the water withdrawal systems. The survey included distribution studies of juvenile fish near pump sites and field inspection of those sites to determine adequacy of screening for protection of fish. A total of 225 sites were inspected in 1979 and 1980, with a follow-up inspection of 95 sites in 1982. Results indicated a definite trend toward lack of concern for the condition of fish protective facilities. Only 4 out of 22 sites not meeting criteria in 1979 had been upgraded to acceptable conditions. Of more concern, 13 of the sites meeting criteria in 1979 were below criteria when reinspected in 1982.

Taft, E.P. 1989. Successful behavioral devices for fish protection. In: *Waterpower '89.* Eberhardt, A.J. (ed). p.1144.

- Taft, E.P. III, and Y.G. Mussalli. 1977. Biological and eng. investigation of angled flush fish diversion screens. In: *Hydraulics in the Coastal Zone. Proc. 25th Ann. Hydraul. Div. Spec. Conf. Texas A and M Univ. Am. Soc. Civ. Eng. N.Y., N.Y.* 304-312.
- Taft, E.P., B.N. Mochrie, T. Wright, and M. Bronoski. 1985. Preventing fish mortality at a large pumped storage plant. In: *Waterpower '85. Roluti, M.J. (ed).* pp 1815-1824.
- Vinsonhaler, R., and D. Sutherland. 1964. Exploratory tests of velocity selection as a means of guiding juvenile fish. *Fish-Passage Res. Program. U.S. Bur. Comm. Fish. Seattle, WA.*
- Williams, J.G., D.R. Chambers, and M.H. Gressel. 1988. Juvenile salmonid bypass system research at Bonneville Second Powerhouse. In: *Proceedings of the Electric Power Research Institute Conference on Fish Protection at Steam and Hydro Plants, San Francisco.*

M I S C E L L A N E O U S

- Johnson, G.E., F.W. Olsen, and E.S. Kuehl. 1989. Fishery assessments at hydroelectric projects using electrofishing, nets, and hydroacoustics. In: *Waterpower '89. Eberhardt, A.J. (ed).* pp 796-805.
- Konagaya, T. 1982. A new telemetric method of determining the positions of swimming fish. *Bull. Jap. Soc. Sci. Fish.* 48(11):1545-50.

A new tracking method of biotelemetry is described. The apparatuses used were composed of an acoustic transmitter (pinger), three sonobuoys, wireless receivers and two time-interval counters. The sonobuoys were designed to relay acoustic pulses from the pinger to a base station on land by wireless. These buoys were moored several hundred meters apart so as to form a triangle on the surface of the water. A fish carrying the pinger was tracked in the circumscribed circle of the triangle. The wireless signals from the buoys were caught with three receivers at the base station. The successive positions of the fish were calculated from the differences in the received times of the signals. The results of the tests showed that this method gives good positional information. It is possible to plot the successive positions of the fish on a X-Y plotboard with a computer.

- Royce-Malmgren, C.H., and W.H. Watson, III. 1987. An interactive video-computer tracking system for quantification of locomotor behavior. *J. Chem. Ecol.* 13(5):1029-44.

The authors have developed a flexible, moderately priced, behavioral analysis system that has been used to determine the response of salmonids to certain olfactory stimulants. The system, which is call ITS for interactive computer-video tracking system, consists of a 128K Apple IIe computer with software, a video camera and videocassette recorder, and a special-effects generator. Experiments are video taped and then, during playback, the special effects generator is used to simultaneously display the video image and the graphics output of the computer on a monitor. The user tracks the animal of interest using an electronic pen, and the position of that animal in the test chamber, in the form of x-y coordinates, is determined by the computer at user-defined time intervals. In this paper the authors describe ITS and then demonstrate how it can be used to demonstrate that changes in ambient pH alter the behavioral response of juvenile Atlantic salmon to olfactory stimuli.