Orientation of Chum Salmon (*Oncorhynchus keta*) After Internal and External Magnetic Field Alteration

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Groups of hatchery reared juvenile chum salmon (*Oncorhynchus keta*) from Conuma River, British Columbia, were tested for compass directional preferences in experimental tanks. Chum salmon generally moved in the direction appropriate for migration through Nootka Sound to the North Pacific Ocean. Fry orientation was not disrupted by covers over the tanks. Stainless steel coded wire tags inserted into the heads of the salmon had little effect, regardless of whether they were magnetized or not. A 90° change in the external magnetic field influenced fry directional movements, but the magnitude and direction of the change were not readily explainable.


On a étudié dans des bassins expérimentaux les directions au compas préférées par des groupes de jeunes saumons keta (*Oncorhynchus keta*) élevés en pisciculture et provenant de la rivière Conuma, en Colombie-Britannique. En général, les saumonettes se déplacent dans la direction appropriée à une migration par le détroit Nootka vers le Pacifique nord. Des couvercles placés sur les bassins ne dérangent pas l'orientation des alevins. Des fils métalliques codés en acier inoxydable insérés dans la tête des saumons n'ont que peu d'effet, que ces fils soient magnétisés ou non. Un changement de 90° du champ magnétique extérieur influence les mouvements directionnels des poissons, mais l'ampleur et la direction de ces mouvements s'expliquent difficilement.

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The mechanisms guiding the migrations of Pacific salmon (*Oncorhynchus* spp.) have been the subject of considerable research. Although the upstream homing migrations of adults are guided principally by olfaction (Hasler et al. 1978), it has long been hypothesized that open water migrations are guided by other mechanisms (Hasler 1956). Experimental studies revealed that compass directional preferences facilitate the lake migrations of sockeye salmon (*O. nerka*) smolts (Groot 1965) and fry (Brannon 1972). These directional preferences are guided not only by celestial features such as the sun's position and light polarization patterns but also by the earth’s magnetic field (Quinn 1980, 1982; Quinn and Brannon 1982). However, an attempt to determine the basis of magneto-reception in sockeye was inconclusive (Quinn et al. 1981).

To date, with the exception of Healey’s (1967) pink salmon (*O. gorbuscha*) study, all research on juvenile salmon compass orientation has been conducted on sockeye. The goals of the present study were (1) to investigate the directional preferences of chum salmon (*O. keta*) fry about to migrate through an inlet to the open ocean to help determine the generality of compass orientation in juvenile salmon, and (2) to determine the relative roles of celestial and magnetic cues in directing the orientation of chum fry. In addition, the development of magnetized coded wire microtags as a tool for salmon management (Jefferts et al. 1963; Bergman 1968) provided an opportunity to (3) examine the possible influence on orientation of an internal magnetic field localized in the head of the fish.

Methods

**Experimental Subjects**

Adult chum salmon spawn in the fall, and fry emerge from gravel redds the following spring. Emergence occurs at night, and fry normally begin downstream movement to the ocean immediately (Neave 1966). After leaving estuaries, chum salmon generally move rapidly north, along the continental shelf of southeastern Alaska, before moving to offshore feeding areas (Hart 1980). These migratory tendencies make chum salmon fry likely subjects for orientation experiments.

In early April, 1982, 60,000 chum salmon fry from the Conuma River Hatchery (Fig. 1) were allocated for orienta-
TABLE 1. Magnetic field measurements of magnetized and unmagnetized microtags. (A) Magnetizations measured with a Schonstedt SVM-1 susceptibility/viscosity magnetometer. (B) Measurements of the magnetic field from the tip of one of the magnetized tags, using a Bell 620 gaussmeter with a Hall effect probe.

A. Magnetic moment (A·m²)

<table>
<thead>
<tr>
<th>Magnetized tags</th>
<th>Unmagnetized tags</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.64 x 10⁻⁵</td>
<td>1.56 x 10⁻⁷</td>
</tr>
<tr>
<td>6.13 x 10⁻⁶</td>
<td>0.35 x 10⁻⁷</td>
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<tr>
<td>5.70 x 10⁻⁷</td>
<td>1.88 x 10⁻⁷</td>
</tr>
<tr>
<td>4.48 x 10⁻⁸</td>
<td></td>
</tr>
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</table>

B. Distance (mm) Magnetic field (μT)

<table>
<thead>
<tr>
<th>Distance (mm)</th>
<th>Magnetic field (μT)</th>
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</thead>
<tbody>
<tr>
<td>10</td>
<td>0.5</td>
</tr>
<tr>
<td>9</td>
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<tr>
<td>8</td>
<td>1.0</td>
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<td>1.3</td>
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<td>6</td>
<td>1.6</td>
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<td>5</td>
<td>2.2</td>
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<td>4.7</td>
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<td>2</td>
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<tr>
<td>1.5</td>
<td>37.0</td>
</tr>
<tr>
<td>1</td>
<td>66.0</td>
</tr>
</tbody>
</table>

*Tag used for the measurements in (B).

The operation of tagging salmon with coded wire microtags normally has two parts: tag insertion and tag magnetization. During tag insertion, a spool of stainless steel wire with coded data mechanically imprinted on it is advanced by rollers. A 1-mm segment of wire is cut and then pushed forward by the rest of the spool. The head of an anesthetized fish is placed in a mold and the 1-mm wire tag is inserted by the force of the wire behind it. X-rays and dissection of tagged fry revealed the tags at or near the midline, above the upper jaw. At this location, a magnetized tag would generate an earth-strength field in much of the fry's head.

From April 6 to 10, chum fry were tagged with microtags. Each day, fry were sized and those under about 46 mm were rejected. The remainder were divided into three groups of 20 000. One group was tagged and the tags magnetized, the second group was tagged but the tags were not magnetized (to control for the effects of the tagging procedure), and the third group was handled similarly but was not tagged at all.

FIG. 1. Conuma River in relation to Tulpana Inlet, Nootka Sound, and Vancouver Island. Arrows indicate the general route of chum fry migration.

These fry, progeny of wild Conuma River fish, had hatched in early December and had been placed in outdoor feeding channels in late February and early March. During the experiment, the fry were held outdoors with an unobstructed view of the sky in six 1.8-m circular tanks with counterclockwise flowing water (2.7–4.5°C) and were fed daily. Fry averaged 51 mm fork length (SD = 3 mm) and 0.92 g (SD = 0.22 g) at the beginning of the experiment and grew to 54 ± 4 mm and 1.17 ± 0.29 g by the end.

TAGGING PROCEDURE

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The tags were magnetized by passing the fish through a 50-mT (500 gauss) circular magnet, ~1000× earth's field strength. This gave the tags a magnetic moment of ~5.5 × 10^-6 A·m², roughly 40× the moment of tags that had not been magnetized (Table 1). After the tag was magnetized, the fish passed a metal detector, termed "quality control device (QCD)." In a small number of cases, the tag was inserted improperly and immediately fell out or was not inserted at all. Because 0.5% of the fish from the group with magnetized tags failed the initial QCD check, it is reasonable to assume that a similar proportion of the fish whose tags were not magnetized were in fact untagged.

After each day of testing, 200 fry with magnetized tags were checked for tag loss with the QCD. The rate of total tag loss rose from about 3% to roughly 10% at the end of the experiment. Early tag loss due to improper implantation is to be expected, and the tags that are not shed early are soon overgrown by the fish's skull. The 3–10% figures estimate the proportions of all tagged fish that had lost their tags by the time they were tested.

**TESTING EQUIPMENT**

Chum salmon fry were tested for directional preferences in 12 cylindrical polyethylene plastic tanks, filled to a depth of 12 cm with creek water drawn from above the hatchery (Fig. 2). Each tank received 52 L/min via a standpipe extending 16 cm from the bottom of the tank. Water flowed...
The testing procedure was as follows. About 30 min after sunset, 800 fry from each of the three groups were divided into four plastic pans for a total of 12 pans with 200 fish each. The fish were placed in the tanks without water flow. Six of the tanks were immediately covered, the magnetic coils for six having already been activated. After 5 min, the water was turned on, permitting volitional movement from the tanks in eight directions (magnetic N, NE, E, SE, S, SW, W, NW). At about 06:00 PST, before the sun’s disk was visible over the horizon, the water was turned off, trapping the fish that had not moved in the center of the tank.

**Statistical Analysis**

The numbers of fish trapped in each direction and the number in the tank itself were tallied for each tank each morning. Mean bearings and statistical confidence levels were calculated for each test condition using the Rayleigh test (Batschelet 1965) on the raw data pooled over the 20 nights of testing. However, although counting individual fish reveals much about their movement patterns, this treats each datum point as independent, which they are not. Therefore, Hotelling’s test was also used to determine the significance of the results, using each test release as a datum point, weighted for the concentration of fish bearings in that release.

**Table 2.** Compass orientation of chum salmon fry in the normal and altered magnetic fields, comparing the results of tests conducted early and late in the experiment. Fish from all groups are pooled; covered and uncovered tests also combined. (*P < 0.001).

<table>
<thead>
<tr>
<th>Magnetic field</th>
<th>Test nights</th>
<th>Sample size</th>
<th>Mean bearing</th>
<th>Rayleigh’s r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>4/9–19</td>
<td>11 627</td>
<td>241°</td>
<td>0.147*</td>
</tr>
<tr>
<td></td>
<td>4/20–28</td>
<td>8 711</td>
<td>276°</td>
<td>0.142*</td>
</tr>
<tr>
<td>Altered (N→W)</td>
<td>4/9–19</td>
<td>11 591</td>
<td>278°</td>
<td>0.125*</td>
</tr>
<tr>
<td></td>
<td>4/20–28</td>
<td>8 724</td>
<td>285°</td>
<td>0.111*</td>
</tr>
</tbody>
</table>

**Experimental Procedure**

Six coils were turned on and the remainder were disconnected to serve as controls. The three groups of fish (untagged, tagged—not magnetized, and tagged—magnetized), the covers, and the activated coils were changed systematically on a daily basis so that all tanks were used to test all fish groups under all conditions. Tests were performed with all tanks for 20 nights from April 9 to 28.
Results and Discussion

**Baseline Directional Preference**

The orientation of untagged fish tested without covers in the normal magnetic field may be considered the baseline directional preference, against which the effects of covers, altered external magnetic field, or tags may be evaluated. Of the 4000 fish tested in the baseline condition, 3406 (85%) moved out of the tanks and into the catch buckets. Second-order analysis revealed a nonrandom distribution of test releases, with a mean bearing of 257° (Fig. 3A). Counting the fish individually yielded a 256° mean bearing (Fig. 3B). However, the distribution of individual fish was not completely normal, as the SW and NW exit ports were both preferred over the W port.

Chum fry migration out of Tlupana Inlet and Nootka Sound requires generally southwestern movement (Fig. 1). This is followed by relatively rapid northwesterly movement up the coast of Vancouver Island, and north along the coasts of British Columbia and Alaska (Hartt 1980). Thus the westerly mean bearing of chum fry in the baseline condition (no tag, no cover, normal magnetic field) is geographically appropriate. The preference for both SW and NW over W is somewhat unusual, as a normal distribution was expected. The fry had been held in freshwater about 6–8 wk after emergence from the gravel, thus delaying their normal migration. Groot (1965) found that the migrations of sockeye salmon smolts out of a complex lake system were aided by compass directional preferences that changed with time, as appropriate for movement through the lake system. It is possible that some of the fry were displaying SW migratory orientation appropriate for Tlupana Inlet and other, presumably older, fry were displaying NW orientation up the coast of Vancouver Island. Fish tested in the normal magnetic field early in the season were oriented in a more southerly direction than those tested later (Table 2) but this may also be an artifact of the extended freshwater rearing period.

In any case, the generally westerly orientation would facilitate movement along the north side of Tlupana Inlet and Nootka Sound. It is reasonable to assume that temperature and salinity influence orientation behavior, and preference for saline water probably prevents the fry from ascending other inlets with tributaries to Nootka Sound (McInerney 1964). The presence of spontaneous directional preferences appropriate for migration in chum salmon fry is not unexpected, as sockeye and pink salmon also have directional preferences that facilitate the migrations of populations in particular systems (Groot 1965; Healey 1967; Brannon 1972; Quinn 1980; Brannon et al. 1981; Quinn and Brannon 1982). Studies of the actual movement patterns of sockeye smolts in Babine Lake indicated that they were well oriented (Groot and Wiley 1965; Groot 1972).

**Effects of Covers and Altered External Magnetic Field**

The orientation patterns of untagged chum fry tested with and without covers were virtually identical in the normal magnetic field (Fig. 4A). In the altered field, a northerly shift of some 25° was evident, relative to tests in the normal field (Fig. 4B). Analysis of the individual (first-order) data indicated that the bearings in the normal and altered field (uncovered and covered tests combined) were different ($F_1, \approx = 97.37$, $P < 0.001$). However, the more conservative Hotelling’s two-sample test of second-order data detected no significant differences among any of the test groups of untagged fish. Besides the change to a more northerly bearing in the altered field, the only other effect was a slight reduction in concentration around the mean bearing when the fish in the altered field were permitted a view of the sky. However, the variance did not significantly differ from those in other test conditions (test by Watson and Williams, described by Emlen and Penney 1964).

The directional preferences of chum fry were also analyzed for within-season variation by dividing the testing period into early (4/9–4/19) and late (4/20–4/28) tests. (Because of inter-tank variation and the randomization schedule, an 11–9 division of test nights yields more representative averages than a 10–10 division.) Pooling covered and uncovered tests and all tag groups, the mean bearing of tests in the normal field changed from 241° to 276°, and the bearings in the altered field changed from 278° to 285° (Table 2).

In the normal magnetic field, covering the tanks had no effect on chum fry orientation. This is consistent with results of studies with sockeye fry (Quinn 1980). Sockeye smolts, on the other hand, often orient 180° away from the expected direction under covers (Groot 1965; Quinn and Brannon 1982). Because the “back azimuth” phenomenon is not well understood, it is not possible to state whether its absence in chum fry is significant or not.

When the magnetic field was rotated 90° counterclockwise, the chum salmon oriented roughly 25° clockwise of their bearing in the normal field (first-order analysis: 255°–281°, second-order analysis: 256°–279°). The difference between normal and altered field orientation was greater in earlier tests than in later ones, however. Based on sockeye studies (Quinn 1980), a 90° change in orientation in the altered field under covers would be expected, and the responses with a view of the sky might depend on cloud cover. Thus the change in orientation in the altered field was predicted, but its direction and magnitude were not. Although it is not possible to determine the reasons for the behavior of fry in the altered field, it is reasonable to assume that they entrained to some local cue during the days prior to testing. The directional

**Fig. 4.** Orientation of three groups of chum salmon fry (untagged, tagged with unmagnetized nose tags, and tagged with magnetized tags), tested with and without covers, in (A) the normal magnetic field, and (B) the altered magnetic field. The dots on the perimeters of the circles represent the second-order mean bearings of individual nights of testing ($N = 20$ in all cases).
preferences displayed in the arenas were thus some combination of orientation to the magnetic field and to the entrained local cue.

**THE INFLUENCE OF UNMAGNETIZED AND MAGNETIZED INTERNAL TAGS**

Although handling and insertion of a 1-mm wire tag into the head of a salmon fry might seem to be a potentially lethal operation, the total mortality from April 7 to 28 was quite low in all three test groups: untagged = 131; tagged— not magnetized = 164; tagged—magnetized = 160. The directional preferences of tagged fish were similar to those of untagged fish (Fig. 4). The Watson-Williams test of first-order data indicated that all six test conditions in the normal field were statistically similar ($F_5, \infty = 1.14$), but it indicated variation in the altered field conditions ($F_5, \infty = 9.39, P < 0.001$). However, the pooled normal and altered field results were very different ($F_{11, \infty} = 147.91, P < 0.001$, Fig. 5). The more conservative two-sample second-order test indicated no differences within the normal and altered field groups. Although the pooled normal field data and altered field data differed from random (normal field: $F_{2,110} = 29.04, P < 0.001$; altered field: $F_{2,118} = 19.07, P < 0.001$), the mean bearings were not significantly different ($F_{2,237} = 2.11, P > 0.10$).

Both first- and second-order analysis revealed weakest orientation in the altered field with a view of the sky. This pattern persisted in all groups of fish, but was most pronounced in the untagged fish (Fig. 4). In general, the concentration around the mean bearings was somewhat greater in tests with untagged fish, but the differences were very slight and not statistically significant.

Of the 20 nights of testing, eight had completely clear skies from evening release to morning termination, eight had completely overcast skies during these hours, and four had mixed cloud cover. The effect of cloud cover on orientation is best examined by considering tests in the altered magnetic field, as these present the fish with a conflict between sky cues and magnetic cues. In the altered field with no cover (all tag groups combined), orientation displayed under clear skies ($274^\circ, r = 0.116, P < 0.001$) differed only slightly from that under overcast skies ($288^\circ, r = 0.126, P < 0.001$).

The directional preferences of tagged fish were virtually identical with those of untagged fish. The slight decrease in concentration around the mean bearings for both groups of tagged fish was apparently a consequence of the tagging process itself. Considering the nature of the tagging process, it is perhaps surprising that the behavioral effects were so slight. As the fry apparently entrained to a local cue, the lack of effect of magnetized tags on compass orientation is difficult to interpret. Had the fish been forced to rely on the earth’s magnetic field, the magnetized tag’s influence on the magnetic field of much of the salmon’s head might have affected orientation. However, the fish seem to be able to compensate for disturbance or loss of one sensory input by relying on others. Magnetic tags have been used routinely for years in coho and chinook salmon, with no substantial effect on homing success (Bergman 1968). These fish are tagged at a much larger size than the chum fry, however, and chum tagging has not been practiced long enough to have evidence of an effect on homing. Based on the present study, a substantial negative impact of tagging on chum salmon homing seems unlikely.

**PATTERNS OF MIGRATORY ACTIVITY**

On the average, 85% of the fish released into the tanks in the evening had left by morning, but the proportion was not constant. Although it did not vary according to external magnetic field, cover, or tag group, migratory activity varied from night to night (Fig. 6). There was no smooth pattern, but activity generally declined over the 20 nights of testing. Water temperatures increased only very slightly during this period,
the daily changes in activity did not seem to correspond to temperature fluctuations. The phases of the moon also had no clear relationship with fish movements. However, the cloud cover did correlate with activity. On clear nights, 80.7% of the fish left the tanks, and 87.6% left on totally overcast nights ($z = 18.62, P < 0.001$, difference of proportions test). On nights with mixed cloud cover, 86.8% of the fish left the tanks. Unfortunately, the present data set is not adequate to separate the effects of weather and date.

**Acknowledgments**

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**References**


